Report of the

Autonomous Navigation Demonstration Relevance Assessment Team

(ANDRAT)

Commissioned by the Chief Technologist within
NASA's Science Mission Directorate (SMD)

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FOREWORD

In February 2024, the Autonomous Navigation Demonstration Relevance Assessment Team (ANDRAT) was established at the discretion of the Chief Technologist for NASA's SMD. The purpose of the ANDRAT was to determine the potential relevance of a demonstration mission to reduce risks for future science missions that cannot rely on the Global Positioning System (GPS). The assessment was to focus on mitigating risks while exercising "autonomous navigation" onboard a spacecraft in transit to the Moon followed by orbit insertion and orbit maintenance.

"Autonomous onboard navigation" is broadly defined as the ability for a spacecraft to determine its orbit and plan a path to achieve navigation goals while operating independently of external control and without the use of external informational aids, potentially even during anomalous conditions. Autonomous navigation offers significant promise to make immediate impacts in mission operations across SMD. Within SMD, the primary beneficiaries would be the Planetary Science Division and the Exploration Science Strategy Integration Office. Missions by the Astrophysics, Heliophysics, and Earth Science Divisions that fly outside of GPS range would also benefit. No spacecraft to date has demonstrated autonomous navigation across multiple mission phases. A demonstration mission offers opportunity to reduce risk and help enable broader adoption.

A flight demonstration of GPS-deprived autonomous navigation could reduce risks in the following areas for future missions: precision self-localization, fault management, onboard planning, and onboard sequencing. Lessons learned from such a demonstration could include the determination of the minimum required sensor suite needed for a basic level of operations. Lessons learned could also inform future mission solicitations requirements with the intention to reduce, at a minimum, the cost of extended operations. This demonstration would pave the way for the use of autonomous navigation to enable missions that cannot be performed using standard ground-based techniques.

The study team addressed the following eight questions:

1. What are the top risks associated with using autonomous navigation for transit and orbit insertion on future NASA planetary science missions?
2. What are the top risks associated with using autonomous navigation for future NASA Astrophysics, Earth science, and Heliophysics science missions that cannot use GPS?
3. What are the top risks for future low-cost NASA missions that autonomously transfer from Low-Earth Orbit (LEO) to a lunar orbit?
4. What architecture(s) and requirements are necessary for a technology demonstration (tech demo) to retire the risks identified above?
5. Would a demonstration of autonomous navigation using a small spacecraft to autonomously navigate from LEO to a lunar orbit buy down any of those risks? If so, which navigation technologies would be most useful to demonstrate and what data would be most beneficial to collect? Specifically comment on the readiness and

usefulness of navigation tools such as pulsar navigation, atomic clocks, fault management, and validation/verification technologies.

6. Beyond the demonstration of needed technologies to buy down the identified risks, what science might be accomplished on an autonomous navigation technology demonstration from LEO to lunar orbit?
7. Would a demonstration other than from LEO to lunar orbit be more effective in reducing the risks identified in questions 1-3? If so, what would that demonstration be? What science (if any) might it accomplish as a secondary goal? What technology gaps exist?
8. How might the inclusion of a demonstration of onboard autonomous science data processing augment an autonomous navigation demonstration mission? For instance, using science obtained in-transit to modify the navigation goals?

The following team was gathered to support the ANDRAT investigation. Expertise includes systems engineering, Guidance, Navigation, and Control (GNC), science, payloads/instruments, trajectory design, ground and autonomous onboard navigation, autonomous systems, mission systems, and mission operations. The ANDRAT's purpose was addressed by answering the above set of questions and by providing recommendations to NASA SMD.

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Executive Summary: Findings and Recommendations

The ANDRAT investigation developed these findings through team engagement that consisted of weekly meetings. Agenda topics included the following:

- Literature reviews addressing various types and approaches to autonomous navigation including navigation methods and technical assessments
- Descriptions of elements of onboard navigation and definitions of levels of autonomy to facilitate preparing recommendations
- A list of barriers and mitigations to missions utilizing autonomous navigation
- Definitions of mission phases across robotic science missions, including scientific needs and mission needs
- Outline of mission phase-specific risks of implementing autonomous navigation
- Recommendations of the appropriate level of autonomy and whether demonstration or other activity would mitigate risks
- Subject Matter Expert (SME) presentations

The following are the key findings from the ANDRAT team study:

Finding #1: Risks and barriers are dominated by cost, perception, and technology. Risks and barriers need mitigation before a higher level of adoption of autonomous navigation is possible.

Finding #2: The current Technology Readiness Level (TRL) of onboard navigation technology does not support end-to-end autonomous operations. NASA investment in an autonomous navigation demonstration can help with future mission adoption by raising the Technology Readiness Level (TRL) of the hardware, software, execution, and fault-protection solutions.

Finding #3: High-risk aspects of autonomous navigation can be mitigated with a low-Earth to cislunar space demonstration, and such a low-Earth to cislunar space demonstration can extend lessons learned to other mission types.

- A low-Earth orbit to cislunar space demonstration would exercise autonomy during several common mission phases. Phases should include quiet cruise, cruise Trajectory Correction Maneuvers (TCMs), approach, orbit insertion, and science orbit maintenance.
- A demonstration with the capability to autonomously transition between distinct phases and make successful decisions over multiple phases in different dynamical regimes or different cadences of decision-making would be a new contribution of a technology demonstration mission.
- A demonstration will show how onboard autonomous decisions can increase the accuracy of navigation tasks, improve propellant usage, and reduce the potential for compounding errors. Additional benefits of making these routine decisions autonomously onboard the spacecraft include reducing the workload of ground

operators when performing low-level or repetitive tasks and reducing use of the Deep Space Network (DSN) for frequent communications.
- A demonstration of extended, limited automation (identified as "Level 3" in this report) would illuminate failure modes and other cases requiring intervention by the ground operator. Such a demonstration could be used to inform future more autonomous applications.
- The demonstration can also accomplish meaningful and timely science such as lunar hydration cycle investigations and lunar far-side studies.
- This technology maturation demonstration is also likely to be feasible with a lower-cost SmallSat architecture.

The ANDRAT recommends the following to NASA SMD:

Recommendation #1: Use of autonomous onboard navigation provides benefits such as increased mission robustness, anticipated reduced mission costs, reduced navigation operation costs, and reduced demand upon the Deep Space Network (DSN). A follow-on study should be undertaken to quantify these reductions in cost and DSN usage.

Recommendation #2: NASA should invest in technology development for autonomous spacecraft navigation, autonomous systems, and computational hardware would reduce uncertainty and burden for future projects.

Recommendation #3: An architecture for autonomous navigation hardware and algorithms/software is needed to inform the robotic science mission community of the best practices and approaches to maximize the correctness and robustness of an implementation. NASA should help drive and coordinate these best practices and approaches for the larger robotic science mission community.

Recommendation #4: High-risk aspects of autonomous navigation can be mitigated with a low-Earth to cislunar space demonstration, and NASA should invest in such a demonstration.

Recommendation #5: NASA can help offset risk and cost by providing incentivized funding for upcoming robotic science Announcements of Opportunity (AOs) in order to offset the projects' implementation of autonomous navigation.

Autonomous Onboard Navigation Overview

The following sections will define key parameters and areas of consideration related to this study of autonomous navigation. These areas include onboard navigation, navigation autonomy, risks, state-of-the-practice, barriers, and technology demonstration opportunity.

Onboard Navigation

Before defining onboard navigation, a brief description of the ground navigation process is needed. The first step in the pre-flight period is always to compute a reference design orbit for the mission. This reference design orbit establishes a designed trajectory that meets all mission requirements. The requirements include the science goals as well as engineering constraints such as power, thermal margins, and the overall amount of Delta-Velocity (Delta-V) (and hence propellant) needed.

During flight, the ground Navigation Team's responsibility is to determine the current translational state of the spacecraft (i.e., position and velocity) and propagate the trajectory into the future. This is the Orbit Determination (OD) step. At predefined times, TCMs are computed to maintain the spacecraft on its reference trajectory. If the trajectory has deviated far enough from the reference, the team will redesign a new reference trajectory starting from the current known state of the spacecraft.

OD is performed using observational data. For ground navigation, these data are typically two-way coherent Doppler and range, augmented by Delta Differential One-way Range (DDOR). For some missions, an onboard camera is used to image celestial bodies in order to compute inertial bearing measurements. This activity is typically performed when the orbit of the target celestial body is poorly determined, as in the case of small bodies and natural satellites of the outer planets. All data are fit using a least-squares type process to a high-fidelity mathematical model of the orbit.

An important distinction to be made is that for deep space missions, the determination of the spacecraft's attitude is separable from its translational motion. Thus, sensors used for attitude determination (e.g., star trackers, Inertial Measurement Unit [IMUs], and sun sensors) are largely insensitive to the spacecraft's position. These data are therefore not used in the OD process. It should also be noted that while computation of TCMs is a navigation function, the details of its execution (e.g., pressurizing tanks, opening valves, detailed modeling of the burn itself) is typically performed by the attitude control function.

For onboard navigation, the OD and maneuver design functions (and potentially the reference trajectory redesign) are moved onboard to be partially or wholly self-contained on the spacecraft. At present, the sole data type used onboard in deep space applications has been optical data. Past examples and several studies indicate that many missions can meet their navigation requirements using optical data alone [1][2]. However, it is expected that in the future additional data will also be used for increased accuracy, redundancy, and/or robustness. These additional data may include one-way uplinked radio signals extracted for Doppler and range information, as well as pulsar-based positioning [3][4].

For onboard navigation, it is also critical that the navigation function is properly architected to integrate with the rest of the flight system. Key pieces of information include knowledge of the past and future attitude of the spacecraft, details of the thrusting events (and whether planned TCMs occurred as planned or not), and access to high accuracy time. The interface goes both ways; the flight system needs access to the onboard OD solution, commands to perform TCMs, and attitude changes. The attitude change information is needed, for example, if the spacecraft must be slewed to image celestial bodies.

If the onboard system is acting only for very short periods of time (i.e., minutes to hours), the systems' events can be incorporated into a simple sequence. However, if operating for extended periods (i.e., days, months, even years), then interfaces with some type of executive function are necessary. The executive function can range from fairly simple (e.g., executing sequences pre-loaded from the ground), or more complex in order to allow decisions based on results, reacting to external events, etc. As the onboard navigation system exhibits more autonomy, the emphasis on executive function becomes greater.

There must also be two-way communication between the onboard fault management system and the navigation functions. This communication may or may not be folded into the executive.

Assessing risks for onboard navigation

In order to assess risks for onboard navigation, the team performed the following:

- The team examined the risks and barriers that have prevented missions from using onboard autonomous navigation. These issues were identified through the team's own personal experiences, conversations with scientists and engineers involved in deep space missions, and a presentation to the team.
- The team realized that defining risks and barriers will vary depending on the characteristics and capabilities of the onboard autonomous system. To facilitate a clear discussion, the team developed definitions of relevant levels of autonomy that are roughly analogous to what is used in the automotive industry. The team considered the functions of the spacecraft and ground operators at each Level of Autonomy when performing relevant tasks for onboard navigation.
- The team identified the various types of missions (e.g., lunar, planetary orbiter), and the mission phases leading up to the actual science phase(s).
- For each mission type, phase, and autonomy level, the team assessed the needs, benefits, and risks associated with implementing onboard navigation.
- Finally, the team reached consensus on the autonomy level that the team believed was the most appropriate for a technology demonstration mission in the near future. The team assessed the risks for implementing this level.

Navigation Autonomy

Consider an analogy to autonomous vehicles on the ground. On the road, the autonomous vehicle must do the following:

- Navigate from Point A to Point B by estimating position and velocity
- Follow a planned route
- Adjust path while among traffic
- Replan the route when obstacles or unexpected conditions occur
- Operate with limited fuel
- Ensure the safety of passengers, humans outside the car, and infrastructure

While completing these tasks, the vehicle could make 1) only simple decisions onboard for brief periods but rely on a human for complex decisions, 2) all complex decisions onboard, while learning and adapting over time, or 3) make decisions with some balance between these two extremes. These options describe the balance between onboard decision-making and human support, and this spectrum has been captured by the well-known Society of Automative Engineers (SAE) Levels of Driving Automation.

Similarly, a spacecraft must navigate from State A to State B by estimating position and velocity, following a planned trajectory and implementing associated maneuvers, readjusting the maneuvers as needed, replanning the path if outside the operating envelope, satisfying hardware and path constraints, ensuring safety of the spacecraft and celestial objects, and supporting a successful mission. During the ANDRAT's discussion of a technology demonstration mission's role in buying down the risks of the spacecraft's ability to autonomously execute these tasks, it became clear that a definition in the form of levels of autonomous navigation would be valuable. These levels of autonomous navigation are defined in Table 1 below. For each level, the role of the onboard decision-maker and ground support are described. The rightmost column also maps prior missions onto these levels for context.

Based on these definitions, the team recommends that a technology demonstration mission target Level 3 autonomy. This level enables the onboard navigation system to make simple decisions over multiple mission phases when within the expected operating envelope, but the approach relies on a ground support team to make more complex decisions when outside of that envelope. In the following tables, this autonomy level is highlighted in light blue for clarity.

Based on the current state of practice and technology readiness levels, the team deduced that only autonomy Levels 2-4 are likely to offer reasonable candidates for a technology demonstration mission in the short term. Autonomy Levels 2 (i.e., "brief, limited automation") and 3 (i.e., "extended, limited automation") possess a similar balance between the role of the onboard decision-maker and ground support. The onboard navigation system makes simple decisions within an expected operating envelope, but the system relies on the ground operators to make more complex decisions and plans under unexpected conditions. However, autonomy Level 3 involves performing these tasks within multiple mission phases and when transitioning between these phases.

Autonomy Level 2 has been demonstrated by multiple planetary science missions. Autonomy Level 3 has been partially demonstrated during a longer period of duration but not during operation across multiple phases. In the case of autonomy Level 4, the spacecraft would need to make more complex decisions and communicate them to a ground operator for verification and support.

Narrowing the viable options for a technology demonstration mission to autonomy Levels 3 and 4, the team discussed how each navigation task would be completed at each autonomy level. These mappings appear in Table 2 below, focusing on Levels 3 and 4. For many of the navigation tasks that would be performed onboard in Level 4, the ANDRAT expects that substantial time and investment in technology development would be required to raise the TRL to a sufficient level for use during a mission. However, the autonomous navigation tasks that would be completed onboard in Level 3 are expected to be feasible within the short term.

Multiple spacecraft missions operating at Level 3 autonomy would illuminate the failure modes and other cases requiring intervention by a ground operator. This information could be used to identify failure modes that could be handled onboard by future Level 4 implementations.

Table 1: Navigation autonomy levels for a spacecraft

Level		**Spacecraft role**	**Ground operator role**	**Example missions**
0	No automation		Process/analyze data, make decisions, upload to spacecraft	
1	Low-level automation	Prescribed (e.g., rule-based) low-level processing and analysis	Make decisions using information from low-level analyses on spacecraft; independently verify	Stardust, Lucy
2	Brief, limited automation	Automated processing, analysis, and prescribed decisions during specific/single phases of the mission in the expected operating envelope	Perform all functions during all other phases and decide if/when to enter automation	Deep Space 1, Deep Impact, OSIRIS-REx, DART
3	Extended, limited automation	Automated processing, analysis, and prescribed decisions across the majority of the mission in the expected operating envelope	Outside of expected operating envelope, intervene with tasks or updated software parameters	Deep Space 1 (extended duration, but single phase)
4	Supervised autonomy	Performs processing and analysis, provides recommendations on complex decisions, and conveys explanation even outside of the expected operating envelope	Review and independently verify recommendations before sending decisions; can intervene/override when needed (e.g., major faults)	
5	Full autonomy	Processing, analysis, and complex decision-making even outside of the expected operating envelope; perform onboard verification of decisions	Update high-level objectives or target orbits; intervention from ground is only necessary when failure is expected	
6	Intelligent autonomy	Processing, analysis, and complex decision-making even outside of the expected operating envelope; onboard verification while learning and adapting	Update high-level objectives or target orbits; intervention from ground is only necessary when failure is expected	

Table 2: Comparing onboard navigation tasks for autonomy Levels 3 and 4.

	Onboard Task	**Level 3**	**Level 4**
Orbit Determination (OD)	Generating orbit estimates	Within expected operating envelope; ground computations otherwise	Can robustly adjust filtering approach, parameters, and/or solution outside of expected operating envelope
	Filter convergence and failure tests	Simple tests	Complex tests along with assessment of confidence in result
	Response to failure, low confidence, or deviation from expected operating envelope	Engage ground operators	Generate solution but require approval and verification from ground operators
Trajectory and Maneuver Design	Design maneuvers to target reference trajectory	Within the expected operating envelope; ground computations otherwise	Generate robust and safe maneuvers but require approval from ground outside of expected conditions
	Computational and solution failure tests	Basic min/max maneuver vector checks	Complex tests onboard with assessment of confidence in result
	Update reference trajectory after system executive decision	Slightly redesign trajectories onboard within the same mission constraints, with ground verification	Substantially redesign onboard and with alternate constraints, require ground verification
System-Level Planning	Planning and scheduling	Initialized with ground-generated sequence; minor updates onboard; ground support for major changes	Robust planning and scheduling onboard from general goals (e.g., Task Network) and with newly-designed trajectories or maneuver sequences
	Verification of plans	None	Onboard in expected conditions; otherwise, engage ground with rationale
Interaction with System-Level Executive for Anomaly Response		Two-way communication between system executive and navigation; minor adjustments allowed Enter safe mode and revert to ground for major faults	Two-way communication between system executive and navigation Generates robust and feasible response to all faults but requires ground approval for major changes
Sensor and Actuator Calibration		Designed on the ground, but partially or fully executed onboard; the mission proceeds following successful calibrations	Onboard design and execution; major updates require ground approval. Multiple failed calibration attempts require ground support.

State of the Practice

Over the past several decades, several deep space missions have employed some level of onboard navigation for certain portions of the mission. These missions include:

- Deep Space 1 (DS1) used onboard navigation to guide a portion of its interplanetary cruise. DS1 tracked the nucleus of comet Borrelly during flyby[5].
- Stardust used onboard navigation to track the nuclei of asteroid Annefrank and comets Wild 2 and Tempel 1 during flybys.[6]
- Deep Impact used onboard navigation to impact the nucleus of comet Tempel 1. Deep Impact also tracked the nuclei of comets Tempel 1 and Hartley 2 during flybys.[7]
- Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) used onboard navigation to guide the spacecraft to its sampling point on the surface of asteroid Bennu.[8]
- Double Asteroid Redirection Test (DART) used onboard navigation to impact Dimorphos, the moon of asteroid Didymos.[9]
- Lucy used onboard navigation to track the asteroid Dinkinesh during flyby.[10]

With the exception of DS1, all the above scenarios employed onboard navigation because onboard navigation was needed to accomplish the respective science objectives. Onboard navigation was thus used only for a very short period of time (i.e., minutes to hours), and the remainder of each mission was navigated using standard ground-based techniques.

The objective of DS1 was to demonstrate multiple technologies including an onboard navigation system. This system was on for several months. After an initial period of characterization and enhancements, the system guided the spacecraft independently of the ground.

The question can then be raised regarding why ANDRAT is recommending another technology demonstration of the technique. The reasons include the following:

- DS1 demonstrated some aspects of Level 3 navigation autonomy during long-duration cruise. Due to a spacecraft safing event, the planned transition to a flyby did not take place onboard.
- Transitioning from one mission phase to another is an important aspect of Level 3 autonomy. Thus far, no spacecraft has demonstrated this capability completely onboard.

Since DS1 also demonstrated onboard navigation for an extended period of time, it is reasonable to ask why the technique has not been more widely adopted. The following observations address this issue:

- Perception: ground-based navigation has been used very successfully for the past 50+ years. If there's not a need to do something different, missions will invariably fall back to the tried-and-true method. Project reviews (e.g., Technical, Management, and Cost [TMC]) heavily emphasize heritage. The less heritage a technique has, the more likely the project will be seen as higher risk. Higher-risk projects are less likely to be selected.

- The landscape has changed during the past 25 years.
    - At the time DS1 flew, the Deep Space Network (DSN) wasn't oversubscribed. Fewer missions were being flown. There was not as much pressure to reduce costs during long operations phases.

Overall, the DS1 experiment provided the ability to confidently propose onboard navigation for missions that cannot be performed without it. Thus, DS1 enabled ensuing missions to use autonomous navigation for critical events when the technique was absolutely necessary.

Defining Barriers and Mitigations

As part of the ANDRAT study, a “deep dive” was made into onboard autonomous navigation barriers and mitigations. As part of this deep dive, each ANDRAT member brought their own perspective to the task, including their career experience, mission experience, and expertise along with their individual institutional knowledge (e.g., academic, corporate, NASA, Federally Funded Research and Development Center [FFRDC], University Affiliated Research Center [UARC]). Information from papers, Subject Matter Expert (SME) presentation, and weekly discussions were combined to formulate the findings in this paper and its recommendations to NASA SMD.

A detailed presentation to the ANDRAT was provided by Jason Mitchell (NASA’s Space Technology Mission Directorate [STMD]). The presentation focused on 1) the current and planned portfolio investment and adoption barriers in autonomous navigation and 2) approach to autonomous navigation hardware, software, and algorithms.

The team sought additional feedback formally and informally from their institutional subject matter experts. The team also developed, coordinated, and presented a questionnaire at the 2024 Lunar and Planetary Science Conference (LPSC) Outer Planets Assessment Group (OPAG) town hall. This purpose of this activity was to query potential planetary mission Principal Investigators (PIs) about the perceived barriers related to autonomous onboard navigation.

The overall barriers and perceptions were collected from engineers, navigation specialists, technologists, scientists, past PIs, future PIs, and Project Managers (PMs). The ANDRAT members compiled, categorized, and evaluated these barriers in addition to possible mitigations in order to address the benefit of using autonomous navigation more broadly and to assess potential risk reduction through a technology demonstration. The recurring themes of cost, people/perception, science impact, and technical issues were used to collect the key findings.

The summary of the key barriers and mitigations to onboard autonomous navigation adoption are listed here:

Table 3: Summary of the key barriers and mitigations

Barrier Type	Key Barrier to Mission Use	Mitigation
Cost	Lack of continuous funding for core capabilities	Funded demonstration and AO incentivization
	Requires additional hardware (e.g., camera) and software	
	Costs necessary to implement and perform Verification and Validation testing for each mission. Individual missions will not pay for this activity if ground-based navigation can meet their needs or if ground-based navigation costs less.	
People/Perception	Ground-based navigation can meet all requirements, is reliable and accurate, and has a long history of success.	The demonstration approach could show low-risk approach, ground interaction with autonomous navigation, and show the roles of people in the concept of operations.
	Fear: similar to autonomous cars	
	Autonomy is seen as enhancing rather than enabling or required	
	Perception of high cost and high risk, with risk-averse culture	
Science	Interference with science measurements (e.g., attitude constraints, instrument constraints, etc.)	Need to define autonomy approach to minimize additional science reduction. Need overall concept of operations scheduling approach thru Design Reference Mission execution.
Technical	Spacecraft anomalies: would need to have more ground-in-the-loop to ensure spacecraft safety	The demonstration approach could show initial autonomy. Look at standardized architecture and definitions of autonomous navigation. Note: each institution's implementation will have costs/non-recurring engineering/proprietary approach.
	Difficulty in evaluating navigation system performance and assessing risk/cost	
	Computational requirements and feasibility	
	Scalability to more complex situations/scenarios	

ANDRAT Autonomous Onboard Navigation Recommendations Details

Trades

Autonomous navigation hardware and algorithm/software approach (i.e., architectural working group) trades are needed to inform robotic science mission community of "best practices and approaches."

There are risks associated with increasing onboard autonomy. Incorrect orbit determination corrupting a designed maneuver, or a failure in the trajectory and maneuver design process itself, can end a mission by causing a substantial and unrecoverable divergence from the reference trajectory. Propellant lost to inefficiencies or imprecision in the onboard navigation can additionally cause downstream impacts to the quantity and quality of the scientific data collected by the mission. Finally, failures in other spacecraft subsystems can cause catastrophic results if not detected early and appropriately communicated to the navigation subsystem.

The ANDRAT recommends that a working group be established in parallel to a technology demonstration mission to explore how to best develop onboard navigation technology across the community. The group’s focus would be to find ways for the benefits of the demonstration mission to propagate to multiple institutions. For example, a set of agreed-upon best practices by the community, with enough room for individual institutions to innovate, will be critical in increasing the robustness of each individual implementation.

Mitigation of high-risk aspects of autonomy Level 3

The ANDRAT recommends that high-risk aspects of autonomy Level 3 in autonomous navigation be mitigated with a technology demonstration mission.

To buy down some of the risk associated with onboard autonomous navigation, the team recommends a technology demonstration mission target autonomy Level 3. Recall that the two main characteristics of autonomy Level 3 are: 1) the onboard autonomous navigation system is making “simple” automated decisions when the spacecraft is within its expected operating envelope, and 2) ground operators are otherwise engaged in more complex decision-making.

The team determined that the demonstration of “simple,” automated decision-making for onboard navigation tasks across multiple mission phases would be a meaningful and new contribution. Although DS1 has demonstrated some aspects of Level 3 autonomy over a long duration, DS1 did not perform autonomous navigation tasks onboard over multiple mission phases. A demonstration with the capability to autonomously transition between distinct phases and make successful decisions over multiple phases in different dynamical regimes or different cadences of decision-making would be a new contribution of a technology demonstration mission.

Restricting these decisions to be made only within the expected operating envelope of the spacecraft ensures that the onboard navigation system would only be making minor adjustments or following rules. As an example related to trajectory and maneuver design, the system would not redesign a reference trajectory but would simply design a path to follow the pre-designed reference path provided and updated by ground operators. Although simple, these decisions can increase the accuracy of navigation tasks, improve propellant usage, and reduce the potential for compounding errors. Furthermore, making these decisions onboard is likely to be feasible in the short term. Additional benefits of making these routine decisions autonomously onboard the spacecraft include reducing the workload of ground operators when performing low-level or repetitive tasks and reducing use of DSN for frequent communications.

The team expects that targeting autonomy Level 3 would 1) harness the benefits of human decision-making when the spacecraft is operating outside of expected conditions, and 2) reduce the development time for a technology demonstration mission. These complex decisions could require substantial redesign or replanning, analysis and verification of the robustness of a solution, contingency planning if a problem cannot be solved, more computationally intensive tasks, or use of techniques not available onboard. If a technology demonstration mission were to target autonomy Level 4 or above, these more complex decision-making tasks would all be performed onboard and then communicated to ground operators for verification and approval. This capability would require substantial time and investment in technology development for 1) autonomous navigation algorithms and theory for cislunar space; 2) autonomous systems, including explainable autonomy and human-machine teaming; and 3) computational hardware for spacecraft. By targeting autonomy Level 3, looping the ground into the decision-making process bypasses this substantial technology development.

Low-Earth orbit to cislunar space demonstration

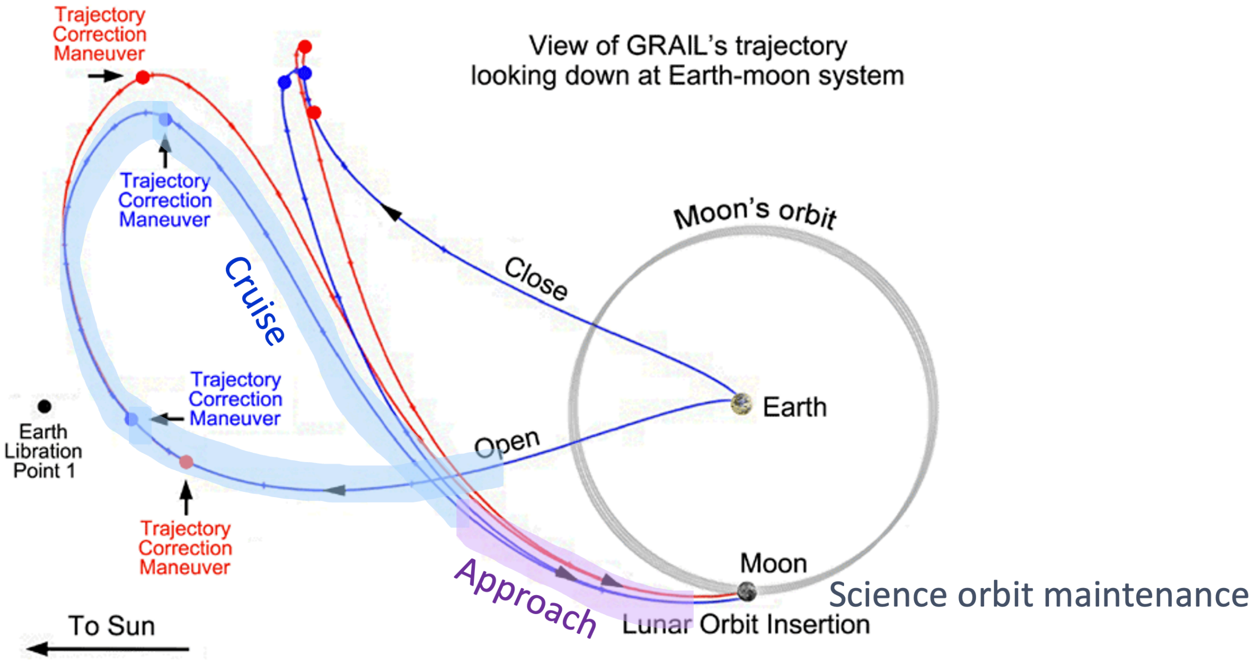
A low-Earth orbit to cislunar space demonstration would exercise autonomy during several identified mission phases. Such a demonstration has timely science applications.

Mission phases

Phases considered include quiet cruise, cruise TCMs, approach, flyby, orbit insertion, and science orbit maintenance.

The team recommends that a technology demonstration mission be designed to fly a long-duration (e.g., weeks to months) transfer from low-Earth orbit to an orbit in the lunar vicinity. Such a trajectory would exercise the most relevant mission phases for autonomous navigation technology on future NASA missions (i.e., cruise, approach, orbit insertion, and science orbit maintenance). A long quiet cruise phase that is similar to the Gravity Recovery And Interior Laboratory (GRAIL) mission would involve the spacecraft initially traveling beyond lunar orbit to be temporarily dominated by the Sun’s gravity, adjusting its path before returning to the vicinity of the Moon. This longer duration would provide the operators with the necessary time to commission the spacecraft before initiating the demonstration.

Figure 1: Recommended cislunar trajectory for technology demonstration follows GRAIL itinerary



Original image source: NASA

The cruise phase of such a trajectory is analogous to the long-duration quiet cruise phases that many missions experience on the way to their destination. The cruise phase would involve periodic orbit determination and several designed and executed trajectory correction maneuvers, all done without ground in-the-loop when within an expected operating envelope. This phase gives the autonomous navigation system the necessary time to prove that it can operate in deep space for long periods of time without assistance from the ground. This phase can also enable more experience to support characterizing the performance of the onboard navigation system. Following cruise, the spacecraft would enter an approach phase to a lunar orbit. While each individual phase has been executed onboard in previous missions, autonomously operating through a transition from a long cruise period to an approach phase has never been tested onboard a spacecraft.

The approach phase will conclude with a possible lunar flyby before an eventual orbit insertion into an orbit in the lunar vicinity. Both of these phases provide the autonomous system with the opportunity to demonstrate precise navigation relative to a celestial object. Moreover, an autonomous system has increased flexibility in these phases relative to traditional methods. For example, onboard navigation allows a significant reduction in the lag-time from generating observables to executing a TCM.

Concluding the mission with a science orbit maintenance phase would allow the spacecraft to balance the collection of science data with computation and performance of orbit maintenance maneuvers. Useful science data would increase the benefit of such a demonstration. Navigating for long periods within close proximity to a gravitational body has a different form compared to the preceding phases. This difference exists for both orbit determination and TCM design.

In addition, commonly there are scientific observations taking place during the orbit phase. These observations add constraints to the onboard autonomy. Demonstrating a successful technology to perform autonomous navigation while satisfying the scientific objectives of a mission during an orbit maintenance phase would be compelling to future mission architects.

Timely science applications

Science applications considered for the technology demonstration are Decadal-level science inquiries. These inquiries include a lunar hydration cycle investigation and lunar far-side studies.

Per Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032 [11]:

> *"The Moon holds a record of volatiles obtained throughout its history. Primordial volatiles contained in the Moon's interior suggest that water was retained even through the energetic Moon-forming impact. At the surface, volatiles migrate in an active cycle and are trapped in permanently-shadowed regions near the poles, processes that occur at bodies with tenuous atmospheres across the solar system. The origin, composition, concentration, and distribution of the Moon's volatiles remain uncertain. Determining the sources(s) of the Moon's water and other volatiles may shed light on the sources(s) of Earth's water and on mechanisms that act as ongoing sources of volatiles in the present day. Lunar volatile reservoirs also have implications for in situ resource utilization by human explorers."*

If a low-Earth to cislunar space autonomous navigation demonstration is executed, there are two timely lunar investigation themes that are particularly complementary for reducing autonomous navigation risks, exercising particular mission phases and associated navigation operations, and enabling priority science as defined by the latest planetary science decadal report. These themes are studies of the lunar hydration cycle and lunar far-side studies. Science gaps still exist surrounding the lunar hydration cycle and its origin and the origin of the documented near-side and far-side asymmetry is still uncertain. Either of these scientific inquiries would benefit from the ability to observe a specific area of the lunar surface for long periods of time, i.e., orbit maintenance, and a far-side study may be communication limited and thus the incorporation of autonomy in navigation could reduce the dependence on ground communications. An autonomous navigation demonstration mission to the Moon could incorporate one or more of these scientific investigations and help to close some of the existing science knowledge gaps.

Extension to other mission types and maturation of technology

A low-Earth to cislunar space demonstration can extend to other mission types. Maturation of technology is expected to be feasible with a lower-cost SmallSat demonstration.

A demonstration mission from low-Earth orbit to a lunar-vicinity orbit involves mission phases that are analogous to those phases commonly flown on NASA missions (see Table 4).

Table 4: Mission phases and recommendations for Level 3 autonomy in tech demo

Mission Phases	**Science Discipline and Associated Mission Needs**			**Mission Phase Duration**	**ANDRAT recommendations for Autonomy Level 3 inclusion in Tech Demo**	
	Planetary science	**Helio, Astro, Earth science**	**Lunar science**			
Launch/Commissioning	✓	✓	✓	day - weeks	No	Limited benefit due to short duration of phase
Quiet Cruise	✓	✓	✓	months - years	Yes	Length of phase and repetition of tasks enables better characterization of autonomous decision-making with low risk to mission; compare to hibernation alternative
ßCruise TCMs	✓	✓	✓	hours - days	Yes	Applicability across all types of missions and disciplines
Electric Propulsion	✓	✓	✓	hours - years	No	Electric propulsion thrust arcs may be long and add unwanted layer of complexity to demo
Approach	✓	✓	✓	weeks - months	Yes	Applicability across all types of missions and disciplines, high likelihood of science observations sharing resources
Flyby (includes gravity assists and prime science target flybys)	✓	✓	✓	hours - days	No	Applicability across all types of missions, high likelihood of science observations sharing resources; however, already doing lunar orbit insertion and flyby is not necessary if it adds unnecessary orbit complexity and increased mission duration
Aerobraking	✓	✓	N/A	hours - days	No	Limited applicability and adds unwanted layer of complexity and cost to demo
Orbit Insertion	✓	✓	✓	hours - days	Yes	Applicability across many types of missions and disciplines, exercises higher complexity and smooth mission phase transition
Science Orbit Maintenance	✓	✓	✓	weeks - months	Yes	High likelihood of high-cadence primary science observations and autonomous navigation competing for time and resources; very instructive risk buy-down
Multi-moon tour	✓	N/A	N/A	weeks - months	No	Adds unwanted layer of complexity and cost to demo
Entry, Descent, and Landing (EDL)	✓	N/A	✓	hours - days	No	Limited applicability; adds unwanted layer of complexity and cost to demo (out of scope for ANDRAT)

While not as long as an outer planet transit, the cruise phase of the demonstration is sufficient to build confidence in the technology's reliability and can be constructed to include TCMs designed and executed onboard. The spacecraft can be constrained to avoid using the Earth or the Moon in its OD process for a period of time to further fit the mold of a traditional cruise phase.

While every mission is unique, the approach, flyby, and orbit insertion phases of the demonstration mission are in family with those commonly flown on NASA planetary science missions. Successfully flying a complex trajectory involving transitioning through these phases into a lunar-vicinity orbit would build significant confidence in the technology's maturity for future planetary science missions to celestial bodies.

Navigation across these mission phases is challenging due to the complexity of the cislunar gravitational environment. The technology to successfully transit to, insert into, and maintain an orbit in such a chaotic environment while additionally balancing the navigational requirements with the scientific mission objectives would extend to missions orbiting small bodies up to planets.

The mission is feasible in a SmallSat form factor, limiting the cost of the demonstration. A low-energy transfer from LEO to lunar orbit, selected to demonstrate long-duration robust autonomous navigation, is achievable with a SmallSat propulsion system. The processing needs for autonomous navigation are not extensive. These needs are met by existing processors such as the RAD750, in addition to those processors commonly used on SmallSats.

It is expected that the necessary optical navigation performance can be achieved with an imager that will fit on a SmallSat.

Offsetting risk and cost

NASA can help offset the risk and cost of a more widespread adoption of autonomous navigation by providing incentivized funding for a technology demonstration exercising Level 3 autonomy as described in this report. The ANDRAT determined that a decomposable, small-satellite scale cislunar mission is a good use case to mature several hardware components, software components, and the compatibility of concepts and fault management across platforms.

NASA should consider incentivizing the use of autonomous navigation beyond a technology demonstration for robotic planetary science missions in upcoming Announcements of Opportunity. This incentive could offset project and individual institution implementation of Level 3 (i.e., more advanced and longer duration) autonomous navigation.

Resource Savings from Onboard Navigation

A key motivator for developing an onboard navigation system is that such a system can potentially result in large resource savings. These savings could be specifically seen in the areas of the cost to perform operational navigation and the time needed on the DSN (or other) antenna for obtaining tracking data. The DSN is a particularly limited resource as more and more missions venture beyond Earth orbit, and very few antennas are currently capable of tracking these spacecraft. The scope of the ANDRAT study did not include quantifying how much of these resources would be saved by onboard navigation. Nevertheless, the team was asked to comment on the resource reduction. The team will therefore offer the following thoughts.

Reduction of cost

A major portion of the cost to navigate spacecraft is coverage of the personnel needed on the ground to perform the navigation function (e.g., analyzing the tracking data, fitting the data, evaluating the results, computing maneuver solutions, etc.). The ground navigation teams can range in size from just a few people for small and simple missions to 15-20 people for large and complex missions. Missions which have long durations incur large Phase E costs to keep the navigation team active for multiple years or even decades. If the spacecraft was performing autonomous navigation, the spacecraft could in principle substantially reduce the size of the teams. This reduction would be especially useful for reduction of costs during long missions. In order to quantify the reductions, several factors which affect navigation team size must be kept in mind. These factors include:

- The class of mission: Flagship missions will invariably have larger teams due to the complexity of the mission, compared to CubeSats or SmallSats that typically have fewer requirements on the navigation system.
- The risk tolerance of the mission: A lower risk tolerance means more personnel in order to minimize the chance of mistakes, the unavailability of someone due to vacation or illness, etc.
- Complexity of the mission and the dynamical environment in which the spacecraft operates: A tour of the Saturnian moon system is more complicated than a simple direct transfer to Mars, for example.
- The requirements on navigation accuracies specified by the science instruments, and the turnaround time needed to meet those requirements
- Spacecraft characteristics: For example, three-axis vs. spinner, balanced vs. unbalanced thrusters, the use of reaction wheels for attitude maintenance
- The phase of the mission: For example, quiet cruise vs. rapid flybys in succession for a satellite tour

Another factor is that the navigation teams perform multiple functions in addition to flying the spacecraft. These factors include:

- Attending meetings and reviews, and generally responding to questions from other subsystems
- Being trained and available in case of a mission replan using updated information based on post-launch spacecraft characteristics
- Planning for upcoming critical events or the science phase via thread tests and Operational Readiness Tests (ORTs)
- Training new members of the team as some members leave or are replaced, and as new members come on to support higher-cadence operations

The ANDRAT used a couple of case studies as examples. A real-world case is DS1, which used the onboard navigation system for a period of roughly three months without ground intervention. Effectively, there were no ground navigators flying the spacecraft. Only a skeleton team was on hand to periodically monitor DS1's performance. A more speculative example is the Mars Reconnaissance Orbiter (MRO) cruise to Mars. MRO had nine members on its navigation team. A rough estimate is that five members were actively navigating the spacecraft at any given time. If MRO had an onboard system, that team could have reduced to the 0.5 – 1.0 Full-Time Equivalent level, representing a reduction by a factor of five. Note that this observation is just a quick guess; verification of this estimate should be done more formally.

Ultimately, there is no single global answer to the question, and each mission must consider its own requirements, spacecraft characteristics, risk tolerance, etc. Missions must individually evaluate how much savings an onboard navigation system can provide.

Reduction of antenna time

In order to evaluate how much antenna time can be reduced, it is instructive to examine how tracking data is used for navigation. Standard ground navigation relies on two-way radiometric tracking data in which a coherent two-way link is established from the ground to the spacecraft transponder. For Doppler data, the data is "free" with the establishment of the link. For range data, power is required for the ranging channel. Some trade-off is therefore needed between ranging and receiving telemetry data for engineering and science. It is possible to receive one-way downlink-only Doppler and range if a highly stable clock is available onboard. This configuration is usually not the case because the clocks can add cost, mass, and power.

Any given track is often used for navigation, downlinking telemetry, and uplinking commands. Separately bookkeeping navigation needs from telemetry and commanding can therefore be difficult. However, an onboard system can shrink the antenna usage to just telemetry/commanding. The spacecraft can then take advantage of capabilities like Multiple Spacecraft per Aperture, where several spacecraft are simultaneously transmitting to a single station. Furthermore, ranging would not be needed. All power could therefore be used for telemetry in order to achieve higher data rates.

Ultimately, the exact amount of DSN time reduction must be evaluated on a case-by-case basis. ANDRAT recommends that a follow-on study tackle both resource reduction costs/benefits in a follow-on study.

ANDRAT Study: Questions and Answers

Question 1: top risks for using autonomous navigation

What are the top risks associated with using autonomous navigation for transit and orbit insertion on future NASA planetary science missions?

The team examined the challenges posed by using an onboard navigation system for the general case of a heliocentric transfer from Earth to a distant planet, and then inserting the spacecraft into orbit around that planet. Risks and barriers prevent the wider adoption of the capability. Risks and barriers were categorized as Perception, Costs, or Technical. The full list is shown in Table 5 below. The team will expand on several of the risks identified as high-level risks.

One of the largest barriers to more widespread adoption of autonomous navigation is the fact that the current state of practice on deep-space ground navigation has been extraordinarily successful. This method has been used to navigate missions to every planet in the Solar System, plus small bodies such as asteroids and comets. The technique is highly accurate, has more than 50 years of heritage, and uses well known mathematical principles. To highlight the accuracy, two-way Doppler data has a precision of better than 0.1 mm/s, with range data accurate to 2-3 m. This in turn enables delivery accuracies to the Mars atmosphere to less than 0.1 deg in flight path angle, for example.

No onboard system can currently match this level of performance. As a consequence, onboard navigation has not been viewed as necessary or even desirable. Furthermore, there is a widespread fear of introducing new technologies into one-shot individual (i.e., one-off) deep space missions. The onboard capability has therefore only been introduced in the limited situations when it is absolutely necessary for mission success (e.g., Deep Impact and DART impactors, OSIRIS-REx surface descent for sample acquisition).

A second category of barriers and risks arises because onboard navigation requires hardware on the spacecraft that the spacecraft may not ordinarily need. For optical-based systems, a camera is required. Many missions carry a camera for science purposes, and this camera can double as a navigation camera. For missions that don’t require a camera for science, the cost, mass, and power associated with adding a navigation camera is typically not perceived favorably. Other hardware that may be needed includes high-performance flight processors that are radiation hardened. However, this hardware does not represent as high of a barrier because onboard navigation systems have performed successfully using existing processors such as the RAD750.

The remainder of the risks are primarily technical and arise because onboard navigation is still relatively new with limited amounts of in-space usage. There is therefore concern about onboard navigation solutions producing incorrect answers and steering the spacecraft off course. This concern can be mitigated with extensive testing and a long-duration flight demonstration.

The full set of identified risks for interplanetary transit and orbit insertion are shown in the table below. Any mitigations that are highlighted by blue text are expected to be addressed by the recommended technology demonstration mission.

Table 5: Risks for interplanetary transit and orbit insertion

	Risk & Possible Mitigation	**Type**	**Level**
Risk	Current SOA of ground navigation has high heritage and reliability, so onboard capability is not necessary.	Perception	High
Mitigation	ANDRAT recommends technology demonstration mission in a relevant environment to leverage heritage.		
Risk	Fear of introducing new technologies is associated with lowering odds of passing gate reviews.	Perception	High
Mitigation	ANDRAT recommends a technology demonstration mission in a relevant environment, so that usage is no longer new technology.		
Risk	Development of onboard navigation capability causes cost/schedule overruns.	Cost	High
Mitigation	ANDRAT recommends upfront investment from funds that are separate from project. ANDRAT recommends a technology demonstration mission in a relevant environment.		
Risk	Additional hardware (e.g., camera) may be required for autonomous navigation that is not needed for the prime mission.	Cost	Medium
Mitigation	None		
Risk	There is a risk of an incorrect orbit determination solution from an onboard system due to issues such as: 1) failure to properly identify and remove bad or corrupted data, 2) systematic errors (e.g., unmodeled small forces) in the dynamics or measurement, 3) filter divergence, resulting in degraded or catastrophic navigation performance.	Technical	Medium
Mitigation	Rigorous ground testing is necessary. A high degree of in-flight testing prior to operational use is recommended.		
Risk	There is a risk of incorrect and/or failed computation of trajectory and/or maneuver design.	Technical	Medium
Mitigation	Rigorous ground testing is necessary. A high degree of in-flight testing prior to operational use is recommended.		
Risk	Competition for onboard computational resources from other subsystems results in delays in computing navigation solutions.	Technical	Low
Mitigation	Rigorous ground testing is necessary. Development of radiation-hardened advanced flight processors is recommended.		
Risk	Corruption of onboard memory (e.g., from cosmic ray Single-Event Upset [SEU]) may lead to faults in onboard processing.	Technical	Low
Mitigation	Develop radiation-hardened advanced flight processors.		
Risk	Accuracy that is currently available from sensors may not be sufficient to meet performance requirements.	Technical	Medium
Mitigation	Add capability to use other sensors (e.g., one-way Doppler).		
Risk	There is a lack of maturity of fault responses in case of anomalies.	Technical	Medium
Mitigation	Invest in development of advanced fault response software and capabilities.		
Risk	There is a lack of sufficient in-flight testing to demonstrate performance.	Technical	Medium
Mitigation	Invest in an ANDRAT-recommended technology demonstration flight in a relevant environment.		

Question 2: top risks for missions that cannot use GPS

What are the top risks associated with using autonomous navigation for future NASA Astrophysics, Earth science, and Heliophysics science missions that cannot use GPS?

The risks associated with using autonomous navigation without GPS for Astrophysics, Earth science, and Heliophysics missions are not fundamentally different than those risks described above for NASA planetary science missions. Transiting to a heliocentric or Lagrange point orbit involves the same navigational processes as those necessary for planetary science transfer and insertion phases. In fact, the necessary navigation precision is commonly less stringent on these missions when compared to planetary science missions.

However, the risk of a need for additional hardware for autonomous navigation is much higher. The most mature technology for onboard navigation is optical navigation. This maturity is partly due to many planetary science missions carrying high fidelity imaging instruments for scientific observations that have been dual-purposed for navigation. Astrophysics and Heliophysics missions rarely have such navigation-grade cameras onboard for scientific purposes. Adding an optical navigation system to these missions would potentially involve significant additional cost. High-performance space imagers, on the other hand, are continuing to advance. Dependent on the specific mission constraints, it may be possible to achieve the necessary navigation performance with a low-cost (or even Commercial Off-The-Shelf [COTS]) camera in the near-term.

Question 3: top risks for autonomous transfer from LEO to lunar

What are the top risks for future low-cost NASA missions that autonomously transfer from low Earth orbit (LEO) to a lunar orbit?

The team examined the risks and barriers for using a low-cost mission to demonstrate onboard autonomous navigation specifically in cislunar space. The team assumed that a low-cost mission would involve a small satellite (i.e., SmallSat). These spacecraft possess a low mass and small form factor, but an increasing number of SmallSat and CubeSat missions are indicating their potential to perform valuable science, exploration, and technology demonstration tasks. The risks and barriers for using a SmallSat mission for the technology demonstration are listed in Table 6, followed by a mitigation suggested by the team. These risks and barriers are categorized by their type and criticality. Any mitigations that are highlighted by blue text are expected to be addressed by the recommended technology demonstration mission in cislunar space.

The most significant risks to the success of a technology demonstration mission are cost-related. Because a low-cost mission typically doesn’t get priority for substantial DSN time, it may not be able to frequently communicate with the ground to support verification and characterization of the autonomous navigation system or communicate unexpectedly when veering outside of the operating envelope. Furthermore, the mission likely cannot support a dedicated technology demonstration. Thus, the team recommends that NASA invest and lead in the technology demonstration mission while also arranging for sufficient DSN access.

To buy down multiple technical risks, the team recommends investment from NASA, government, industry, and academic institutions for substantial technology development. Autonomous navigation technologies must be able to make robust, safe, and accurate decisions in more complex dynamical environments with uncertain information and across multiple operating modes. The hardware used to sense or implement these tasks must also be reliable, produce accurate data, and support computations. Substantial development will be needed across various sectors, missions, and technical disciplines to develop new algorithms, develop new hardware, and validate these technologies across various space environments.

The team recommends that a low-cost technology demonstration mission uses a larger SmallSat, as opposed to a smaller CubeSat. Despite the low-cost benefit that a small spacecraft mission provides, its form factor introduces risk to the success of a technology demonstration mission. Because the hardware onboard a SmallSat must be miniaturized, power, propulsion systems, and propellant margins may be limited. As a result, onboard computations may need to compete with other resources or science tasks. Furthermore, poor performance of an onboard navigation system or departure from expected conditions may make it difficult for the spacecraft to reach its planned orbit. Increasing the size of the recommended spacecraft from a CubeSat to a SmallSat means that these power and propulsion systems will be more capable, thereby reducing these risks.

Table 6: Risks and barriers of a relevant, low-cost technology demonstration

	Risk/Barrier & Possible Mitigation	**Type**	**Level**
Barrier	Low-cost missions have lower priority for DSN time, reducing 1) communication with ground operators at lower autonomy levels, and 2) regular data download for verification during demonstration.	Cost	High
Mitigation	The mission team should coordinate with DSN to have sufficient access during a demonstration mission.		
Barrier	There is limited capability for a low-cost mission to invest in targeted technology development.	Cost	High
Mitigation	• Investment is needed in autonomous navigation technology development. • NASA should invest in and lead the demonstration mission, then incentivize future demonstrations. • Use COTS hardware during demonstration where possible.		
Risk	A processor that isn't radiation-hardened on a SmallSat may reduce the reliability of computations that are critical for autonomous navigation.	Technical	Medium
Mitigation	Investment is needed in technology development for radiation-hardened processors for small form factors. Use redundancy on a demonstration mission.		
Barrier	Autonomous trajectory and maneuver design in chaotic cislunar space is complex outside of a narrow operating envelope and currently low TRL.	Technical	Medium
Mitigation	• Investment is needed in technology development for autonomous trajectory and maneuver design. • For a demonstration mission, use a lower Level of Autonomy (<= 3) with ground support.		
Risk	• Cislunar image processing is more complicated and has more failure modes than image processing during cruise with unresolved bodies.	Technical	Medium
Mitigation	• Investment is needed in image processing and technology development. • For demonstration mission, rely upon simpler image processing techniques that have lower accuracy.		

Table 6 (continued): Risks and barriers of a low-cost technology demonstration mission for onboard autonomous navigation in cislunar space

	Risk/Barrier & Possible Mitigation	**Type**	**Level**
Barrier	• Autonomous navigation in a more populated cislunar region would need development of autonomous collision detection and capabilities for avoidance decision-making.	Technical	Medium
Mitigation	• Investment is needed in technology development. • Select a lower Level of Autonomy (<= 3) for technology demonstration in order to engage ground operators in collision-avoidance tasks.		
Barrier	Limited power on smaller spacecraft form factors might require tradeoff between onboard computations and other operational tasks, increasing the complexity of implementation and creating competition for resources with scientific instruments.	Technical	Low
Mitigation	Use the SmallSat form factor (rather than CubeSat) for a technology demonstration mission in order to potentially improve processing and power capabilities.		
Risk	The propulsion system and propellant margin may limit the capability to reach science orbit due to onboard navigation system failure or poor performance, resulting in increasing risk of mission failure and becoming space debris.	Technical	Low
Mitigation	Use the larger SmallSat for a technology demonstration mission with the SmallSat's higher-capability propulsion system and increased propellant margin.		
Barrier	Limitations in accuracy of a passive onboard navigation system (e.g., optical) may not be sufficient to meet the performance requirements of a mission.	Technical	Medium
Mitigation	Add active data types (e.g., one-way radiometric Doppler and/or ranging) to onboard system for a technology demonstration mission.		

Question 4: architecture and requirements for a technology demonstration

What architecture(s) and requirements are necessary for a tech demo to retire the risks identified above?

The team recommends that a technology demonstration mission should aim for Level 3 automation as described in Table 6 above. The team also expects that a demonstration in the next two-to-three years would not allow enough time for maturing low-TRL technologies needed for Level 4 automation. Level 2 has been sufficiently demonstrated and would not benefit from the demonstration. The team asserts that Level 3 has the greatest benefit for the cost and is feasible to achieve in the near future. The following requirements would also need to be met for a meaningful demonstration:

- Operate at Level 3 for a period of at least one month without requiring ground intervention within the operating envelope. The key here is showing continual "hands-off" operations while maintaining the spacecraft's course.
- The mission plan should include insertion into orbit (e.g., low-lunar orbit, Earth-moon Lagrange point).
- Demonstrate onboard OD, maneuver computation, and execution of the maneuver. This activity exercises the major computational elements of navigation. It is assumed that the processing of raw navigation data (e.g., images, one-way radiometric tracking data) will also be done onboard as it makes little sense to process the data on the ground and then uplink it.
- Have capability available to compare onboard OD and maneuver solutions against ground-computed results. An important consideration is that the ground computations verify the onboard computations in order to fully assess performance.
- Transition from one mission phase to another onboard (e.g., cislunar cruise to lunar approach). An important step toward confidence in autonomous navigation is seeing that the onboard system can successfully execute a transition from one mission phase to the next without ground assistance.
- Demonstrate the ability to (1) autonomously detect errors in the OD or maneuver design/execution, and (2) gracefully recover from faults, whether unplanned or deliberately injected into system. This step is crucial because faults are always a consideration. A well-designed onboard system must be able to respond properly. Deliberate injection of faults can be done if the system is performing smoothly in order to further demonstrate the response for a wide variety of faults.

The overall architecture of the onboard navigation system, the manner in which the system is hosted, and how the system interfaces with the rest of the flight system should be studied in preparation for a technology demonstration. It is outside the ANDRAT's scope to define this architecture, but the team has identified some of the issues that must be addressed with related recommendations. The recommendations are primarily to scope what is feasible in the near future and still remain within reasonable budgets. The following are a few key items:

- The autonomous navigation software can be hosted onboard the primary flight computer or on a separate processor or co-processor. The main advantage to the latter approach is that any faults within the navigation system can be isolated and will not cause a ripple effect that impacts all of the other subsystems. The only disadvantage is that the additional processor has cost, mass, and power implications.

- The navigation software is driven by a simple time-driven and/or event-driven sequence. In principle (and if available), the navigation system can interface with a higher-functioning executive (e.g., Task Networks) including Artificial Intelligence (AI)-driven systems. In the near-term, it is expected that simple sequences will keep the costs of designing the system to a minimum. However, the software should be architected to accommodate future capabilities including interfaces that would allow the system to grow to more powerful executives in an extended mission or in a follow-on mission.
- The interfaces of the navigation subsystem with other spacecraft subsystems (e.g., Attitude Control System [ACS], propulsion) is the minimum necessary for performance. This interface ensures that the navigation system can easily be ported from spacecraft to spacecraft with minimal modifications, and thus minimizes the overall development and recurring costs.
- The primary sensor for navigation is a camera operating in the visible light spectrum, potentially augmented with one-way uplinked radiometric data. The optical system is currently the most mature option, requiring no further advances in technology. The one-way radiometric technique has some development still remaining. More exotic options such as pulsar-based navigation require more hardware development for fitting into a form factor that is suitable for small spacecraft.

It is recommended that a follow-on study look at these issues in more detail.

Question 5: demonstration using small spacecraft

Would a demonstration of autonomous navigation using a small spacecraft to autonomously navigate from LEO to a lunar orbit buy down any of those risks? If so, which navigation technologies would be most useful to demonstrate and what data would be most beneficial to collect? Specifically comment on the readiness and usefulness of navigation tools such as pulsar navigation, atomic clocks, fault management, and validation/verification technologies.

A demonstration of an autonomous navigation system using a small spacecraft to navigate from LEO to a lunar orbit would buy down many of the risks identified above. A well-designed, documented, and successful demonstration mission will reduce the perception, cost, and technical risks associated with introducing a new technology onboard a future NASA spacecraft.

The team recommends onboard optical navigation as the primary technology for a demonstration mission. Optical navigation is mature and applicable to a wide class of NASA missions outside of Earth orbit across most mission phases. Optical navigation observables are already commonly captured as part of the traditional navigation process such as in the approach phase to a celestial body. However, outside of limited windows during NASA missions such as DS1, Deep Impact, OSIRIS-REx, and DART, these observables are traditionally processed on the ground by engineers with complementary radiometric observables. A long-duration demonstration mission navigating primarily using optical navigation across several mission phases is a necessary condition for future NASA missions to select onboard optical navigation rather than relying on ground navigation.

Complementary one-way radiometric navigation would add value as a secondary technology to demonstrate on such a mission and should be considered. Such a technology would add flexibility to future systems and would allow autonomously navigated spacecraft to take additional advantage of the immense resource in DSN. However, the capability to process one-way radiometric data onboard requires a high-fidelity onboard clock such as the Deep Space Atomic Clock (DSAC). This inclusion increases the Size, Weight, and Power (SWaP) and the cost of the demonstration mission. In addition, one-way radiometric navigation is less mature than optical navigation. This technique may require additional techonology development.

Pulsar-based navigation technology is not expected to be a broadly applicable near-term solution for autonomous navigation and is not recommended for the demonstration mission. This technology is much less mature than optical navigation and requires additional hardware development to fit within the constraints of a small satellite form factor.

In addition to processing observables, a robust onboard navigation system also requires an advanced fault management system in order to detect and respond appropriately to unforeseen issues without compromising the mission. The team recommends the exploration and inclusion of fault management technologies beyond the standard spacecraft safing approaches on the demonstration mission.

The team also discussed architecting the demonstration mission to provide the ability to upload and test additional capabilities. These capabilities include providing stubs for additional software that would move the autonomy toward Level 4. This additional software includes smart executives that confirm successful execution of commands, planners/schedulers that could work around faults detected in flight by advanced fault management software, resource management software to balance goals against limited and expendable resources onboard, and onboard data processing such as filtering and prioritizing data prior to downlink. These software packages would more fully exercise new processors such as the High-Performance Spaceflight Computing (HPSC) processor and would be flown in shadow mode initially to verify correct behavior.

The demonstration spacecraft could support new approaches to test and defend against cybersecurity attacks. Additional science could be explored, such as flying radiation detectors that would map the currently unexplored environment in cislunar space. Pending the expected lifetime of the spacecraft hardware upon completion of the autonomous navigation demonstration, the flight system could provide an in-flight testbed for additional flight algorithms. This use could break the lack-of-heritage barrier that is currently encountered for new flight software.

Question 6: what science might be accomplished?

Beyond the demonstration of needed technologies to buy down the identified risks, what science might be accomplished on an autonomous navigation technology demonstration from LEO to lunar orbit?

The team identified potential opportunistic science cases that might be accomplished on an autonomous navigation technology demonstration from low-Earth orbit to lunar orbit. Two investigations are particularly complementary for reducing autonomous navigation risks and enabling priority science as defined by the latest planetary science decadal report: studying the lunar hydration cycle and conducting lunar far-side studies. The recent Decadal Survey has identified science knowledge gaps in both of these cases that such a mission could augment.

The origin of lunar hydration is still unknown. Placing a spacecraft into a lunar-synchronous orbit (i.e., an orbit with the same period as the period of lunar rotation) from which to observe variability in surface hydration in the same spot of lunar landscape over the course of a lunar day would help disentangle some parameters (e.g., composition and viewing geometry) in the hydration studies. With observations of hydration or proxies of hydration and simultaneous surface temperature measurements, the daily cycle of hydration would be better constrained and understood. A lunar-synchronous orbit could enable these measurements, requiring orbit maintenance over a specific lunar latitude and longitude for a month or more at a time. This orbit would exercise some aspects of the autonomous navigation technology highlighted elsewhere in this report.

Another synergistic science case with an autonomous navigation demonstration relates to lunar far-side studies. The origin of the near-side and far-side asymmetry is still uncertain. Small spacecraft can provide observations of lunar impacts and evolution or context images for future far-side sample return, especially in geological transition regions (e.g., between low and high heat flow regions) to better constrain characteristics related to the asymmetry. Typical far-side lunar studies can suffer from a lack of communication with the Earth. Autonomous navigation and science sequences could enable unique investigations, especially if longer periods of communication outages are anticipated during science data collection.

Question 7: demonstration other than from LEO to lunar

Would a demonstration other than from LEO to lunar orbit be more effective in reducing the risks identified in questions 1-3? If so, what would that demonstration be? What science (if any) might it accomplish as a secondary goal? What technology gaps exist?

The team also examined other mission types to determine which are best suited for an autonomous navigation technology demonstration and risk reduction. Increased duration for the quiet cruise phase and little risk of collisions were identified for missions to the vicinity of the Sun-Earth L1 or L2 Lagrange points, Near-Earth Object (NEO) or asteroid belt tours, or a Phobos and Deimos mission. A heliophysics-focused or astrophysics-focused study could be justified at the Sun-Earth Lagrange points, in addition to studying the Earth as an exoplanet at low spatial resolution. Asteroid family population studies, transient monitoring, and phase curve data collection could be achieved during asteroid tours. Insight could be gleaned on the Martian moon origin by comparative planetology and extended studies of surface landscapes on Phobos and Deimos.

Risks of these alternative trajectories and targets include but are not limited to risk to exiting observatories if failure occurs, the need for additional hardware (e.g., camera on a heliophysics mission), longer lifetimes for small-form hardware components, small errors accumulating over long time spans threatening subsequent tour visits, increased propellant mass pushing a mission into a larger form factor, and a need for fault management to coordinate with science (see Table 7).

Although several science cases are identified along with some autonomous navigation benefits, the ANDRAT asserts that the possible advantages do not outweigh the risks over the more simplistic and shorter duration low-Earth orbit to lunar orbit as recommended in this report. Therefore, ANDRAT concludes and recommends that executing an autonomous navigation demonstration from low-Earth orbit to cislunar space and lunar orbit insertion at an autonomy level of 3 remains the most effective demonstration.

Table 7: Risks and benefits of types of science by target

Target	Science	Benefits	Risks and Gaps
Sun-Earth L1/L2	Heliophysics or astrophysics focus Planetary science: 1. Low spatial resolution study of Earth as an exoplanet	• Incorporates long, quiet cruise with lunar flyby • Slower modes of instability reduce complexity of autonomous navigation • Lower orbit insertion costs • Little risk of collisions	• Risk to existing observatories if failure occurs • Addition of camera hardware adds cost and mass to mission • Use of continuous thrust might increase lifetime, fault management, need to coordinate with science
Tour of NEOs or asteroid belt	Planetary science: 1. Asteroid family population studies and statistics 2. Transient monitoring and phase curve data collection	• Increased duration of quiet cruise phase • Little risk of collisions	• Longer mission requires longer lifetimes for low-cost hardware • Small errors accumulate over long times, potentially threatening subsequent small-body visits during tour • TCM design faults may be mission-threatening • Might not insert into orbit around small body • Use of continuous thrust might increase lifetime, fault management, and the need to coordinate with science
Phobos and Deimos	Planetary science: 1. Martian moon origin insight by extended studies of surface landscape 2. Comparative planetology between Phobos and Deimos	• Increased duration of quiet cruise phase • Little risk of collisions • Includes two orbit insertion phases: 1. After interplanetary arrival 2. After Mars orbit insertion	• Increased propellant mass budget for orbit insertion after interplanetary transfer • Risk to existing Mars missions • Communications delay may impede lower autonomy levels • Small errors accumulate over long times • Longer mission requires longer lifetimes for low-cost hardware • TCM design faults may be mission-threatening • Use of continuous thrust might increase lifetime, fault management, need to coordinate with science

Question 8: onboard autonomous science data processing

How might the inclusion of a demonstration of onboard autonomous science data processing augment an autonomous navigation demonstration mission? For instance, using science obtained in-transit to modify the navigation goals?

The team also considered whether a demonstration of autonomous onboard science data processing could be useful in determining scientifically interesting data or could be used in modifying the navigation goals. Autonomous data processing could identify and flag transient activity, alert onboard data storage to save images near a tagged event and prioritize data to be downlinked, enable the collection of high-cadence data in data-storage-limited scenarios, and determine appropriate windowing of high science value frames.

If science or navigation instruments "monitor" a body or system as a targeting tool and onboard science processing makes a discovery (e.g., new binary, moon, ring, outburst, transient event), navigation goals may need to be augmented for spacecraft safety, object avoidance, or increased science acquisition and return. Operating at Level 3 autonomy for science data processing and navigation will keep the ground in the loop if outside of the expected operating envelope before altering trajectories or the timing of nominal navigational operations and using spacecraft resources. This approach may be especially important since project management may require that primary science or technology demonstration objectives are successfully achieved before modifying navigation goals.

Conclusions

The ANDRAT study examined the relevance of a demonstration mission to help reduce risk and enable further adoption of onboard autonomous navigation for NASA SMD missions. The following are the conclusions of the team relative to this assigned study:

- Over all options considered, ANDRAT concludes that the barriers and identified risks would be substantially mitigated by a low-Earth to cislunar demonstration with Level 3 autonomy.
- A low cost, low-Earth-to-cislunar autonomous onboard navigation demonstration would be applicable to planetary, Astrophysics, Heliophysics, Earth, and lunar science missions. This demonstration would reduce risk, help enable priority science, and improve mission adoption.
- Technologies like atomic clocks would enable precision one-way radiometric navigation along with COTS imaging sensors. Advanced algorithms, fault management, smart executive, planning, and scheduling technologies would benefit onboard autonomous navigation.
- Efforts to remove gaps in technical maturity would be further aided by technology development for autonomous navigation, autonomous systems, and computational hardware, as well as by testing in a stressing and relevant environment.
- Incentivizing future AOs for incorporation of autonomous navigation would help enable implementation of autonomous navigation on a larger scale.
- ANDRAT asserts that NASA investment in an autonomous navigation demonstration mission would result in lower mission costs and lower DSN demand.

ANDRAT concludes that NASA investment in autonomous navigation technologies and approaches, demonstrations, and incentivizing future missions of opportunity will help lower mission costs (especially longer-duration missions), lower DSN demand, increase science potential, and increase mission robustness. The technology has the potential to enable exciting new science missions that are not possible with traditional ground-based navigation.

Appendix 1: Acronyms and Abbreviations

ACS: Attitude Control System
AI: Artificial Intelligence
ANDRAT: Autonomous Navigation Demonstration Relevance Assessment Team
AO: Announcement of Opportunity
COTS: Commercial Off-The-Shelf
CTS: Cornell Technical Services
CU: University of Colorado
DART: Double Asteroid Redirection Test
DDOR: Delta Differential One-way Range
delta-V: delta-Velocity
demo: demonstration
DS1: Deep Space 1
DSAC: Deep Space Atomic Clock
DSN: Deep Space Network
FFRDC: Federally Funded Research and Development Center
GNC: Guidance, Navigation, and Control
GPS: Global Positioning System
HPSC: High-Performance Spaceflight Computing
IMU: Inertial Measurement Unit
JPL: Jet Propulsion Laboratory
JSR: Journal of Spacecraft and Rockets
L1: Lagrange 1
LEO: Low-Earth Orbit
LPSC: Lunar and Planetary Science Conference
max: maximum
MD: Maryland
min: minimum
MRO: Mars Reconnaissance Orbiter
NEO: Near-Earth Object
OD: Orbit Determination
OPAG: Outer Planets Assessment Group
ORT: Operational Readiness Test
OSIRIS-REx: Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer
PI: Principal Investigators
PM: Project Manager
SAE: Society of Automotive Engineers
SEU: Single-Event Upset
SMD: Science Mission Directorate
SME: Subject Matter Expert
STMD: Space Technology Mission Directorate

SWaP: Size, Weight, and Power
TCM: Trajectory Correction Maneuver
tech demo: technology demonstration
TMC: Technical, Management, and Cost
TRL: Technology Readiness Level
UARC: University Affiliated Research Center

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Appendix 3: Final Briefing charts

Please refer to the slide package named Appendix_3-ANDRAT_Final_Briefing.pdf.