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INITIAL CONSIDERATIONS FOR NAVIGATION AND FLIGHT DYNAMICS OF A CREWED NEAR-EARTH OBJECT MISSION

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A crewed mission to a Near-Earth Object (NEO) was recently identified as a NASA Space Policy goal and priority. In support of this goal, a study was conducted to identify the initial considerations for performing the navigation and flight dynamics tasks of this mission class. Although missions to a NEO are not new, the unique factors involved in human spaceflight present challenges that warrant special examination. During the cruise phase of the mission, one of the most challenging factors is the noisy acceleration environment associated with a crewed vehicle. Additionally, the presence of a human crew necessitates a timely return trip, which may need to be expedited in an emergency situation where the mission is aborted. Tracking, navigation, and targeting results are shown for sample human-class trajectories to NEOs. Additionally, the benefit of in-situ navigation beacons on robotic precursor missions is presented. This mission class will require a longer duration flight than Apollo and, unlike previous human missions, there will likely be limited communication and tracking availability. This will necessitate the use of more onboard navigation and targeting capabilities. Finally, the rendezvous and proximity operations near an asteroid will be unlike anything previously attempted in a crewed spaceflight. The unknown gravitational environment and physical surface properties of the NEO may cause the rendezvous to behave differently than expected. Symbiosis of the human pilot and onboard navigation/targeting are presented which give additional robustness to unforeseen perturbations.

INTRODUCTION

A crewed mission to a Near-Earth Object (NEO) was recently identified as a NASA Space Policy goal and priority. In support of this goal, a study was conducted to identify the initial considerations for performing the navigation and flight dynamics tasks of this mission class. While a crewed mission presents unique challenges, previous studies have addressed general challenges of the NEO mission class. Various methods have been suggested for characterizing the irregular gravity field around a NEO, including interior solid spherical harmonics.[1] Methods have also been proposed for flexible trajectory design for beyond-Low Earth Orbit (LEO) missions using a two-level targeting scheme.[2] Several robotic missions have done extraordinary work around NEOs, for example the NEAR-Shoemaker mission to the asteroid Eros.[3] The NEAR mission to Eros culminated in a “soft” touchdown on the surface of the asteroid using an open-loop guidance method.[4] There have even been preliminary ideas of how one could use conceptual space capsule systems to visit NEOs.[5] Several studies have been conducted to identify candidate NEOs for human exploration based on geometry, composition, and orbital characteristics. Figure 1 shows a selection of these NEO orbits.

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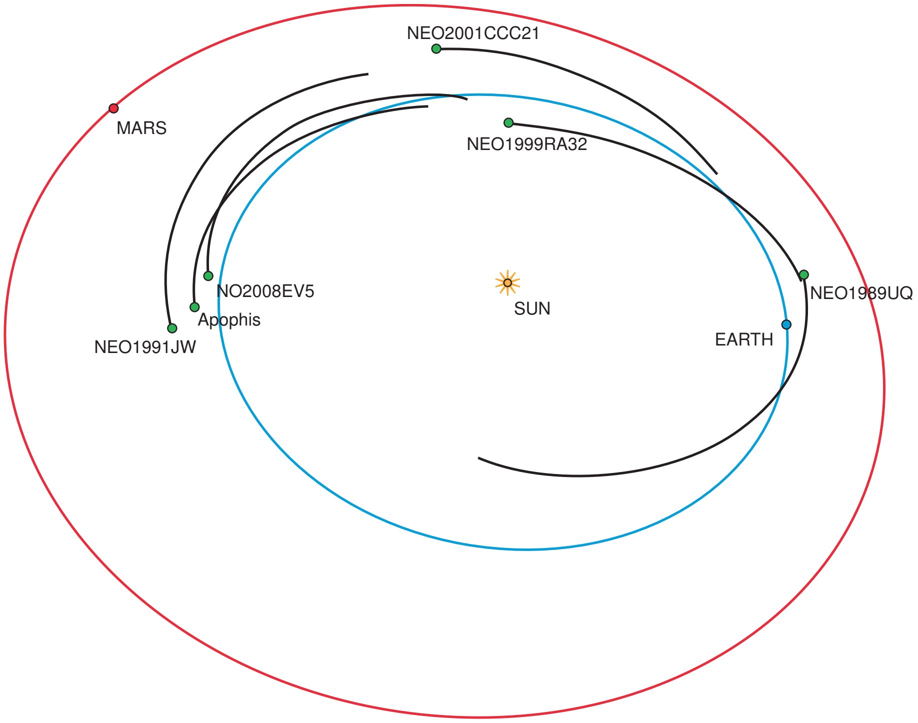

Figure 1. Several Near-Earth Objects could be candidates for human exploration

NOISY ACCELERATION ENVIRONMENT

One of more of the unique aspects for Guidance, Navigation, and Control (GN&C) in human spacecraft is the increase in non-conservative forces compared to robotic counterparts. In addition to thermal control systems, human spacecraft require systems for disposing of waste material and life support (such as atmospheric conditioning). Many of these systems require periodic venting of material out of the spacecraft. Additionally, coupled attitude jet firings to minimize translational accelerations may not always be possible due to concerns over fuel consumption. Finally, crew activity within the spacecraft has also been theorized to have unintended consequences for GN&C systems, ranging from an increased uncertainty in the location of the center of mass to induced rotation motion from activities such as exercise.

Given that the magnitude of a rotational or translational perturbation on a spacecraft from any single instance of these events is small, one may be tempted to ignore such impacts in the design of the GN&C system. However, the aggregate effects of long-term venting or multiple venting operations may have a significant impact to the performance of the GN&C system. To illustrate, consider Figure 2, which maps the change of entry flight path angle ($\Delta\gamma$) due to a 1.73m/s change in spacecraft velocity along a lunar return trajectory for an Orion-class spacecraft.

Also note that the curve in Figure 2 should scale linearly with ΔV. Thus, this curve demonstrates a high sensitivity of entry flight path angle to small perturbations when far away from the Earth. Worse, attempting to correct such a perturbation later in the trajectory results in a fuel consumption penalty if the same change in flight path angle is needed. Considering that Orion was designing to an entry fight path corridor on the order of 0.1^{o} or less,[6] the impacts of small vent forces can no longer be considered insignificant.

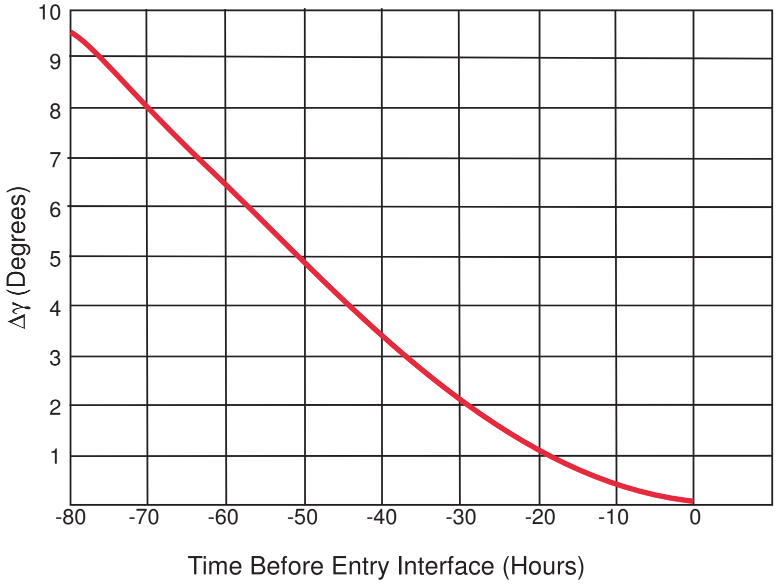

Figure 2. Entry Flight Path Angle (γ) Sensitivity to 1.73 m/s ΔV

Besides their contribution to trajectory perturbations, these small vent forces also have an impact on the quality of the navigation solution available to the spacecraft. Conceptually, more sensor measurements are required when the knowledge of dynamics is poor. Therefore, in a period of substantial venting operations, a baseline navigation plan (in terms of frequency of measurements) may be insufficient to mitigate the impacts of small force venting. Thus, if uncontrolled, small vent forces could impact navigation operations as well as cost (especially if increased ground tracking or other assets are utilized). Furthermore, independent studies conducted by various NASA centers during the Orion program confirmed that given a robust navigation architecture (in this case radiometric tracking utilizing 6 - 9 Earth-based ground stations), these small forces were the dominant sources of navigation errors.[7]

Finally, the ability to generate quick turn-around (otherwise known as "short arc") navigation solutions during periods of venting may be hindered or completely eliminated. Such short arc solutions have historically been important in assessing translational maneuver performance, during rendezvous operations, and contingency operations. Generating quality state estimates with few measurements and poor knowledge of dynamics is a navigation analyst's toughest chore.

For NEO missions, several mitigation techniques may be possible in order to lessen the impact of small vent forces on the GN&C system. First, it is highly recommended that the GN&C designers of such a spacecraft engage early and often with operations teams and with environment/life support designers. Such engagements will allow for the negotiation of items such as larger tank sizes to minimize the number of vents required and/or the ability to design venting operations to occur outside of GN&C sensitive timeframes (for example, periods where high accuracy navigation solutions are required). Additionally, the GN&C engineers may be able to negotiate venting designs such as the use of "T" nozzles which induce substantially lower rotational or translational perturbation on the spacecraft. Another little-explored option is integrating the venting operations into either the rotational or translational control system. However, this may be an overly complex solution with a relatively small benefit.

The navigation system has some additional unique options that may be considered. First, and most obvious, is to increase the fidelity of the inertial measurement unit. However, this may substantially increase system costs with minimal improvement. Sensor alignment and drift may tend to mask the actual events they are attempting to measure. Additionally, due to the low magnitude of these vents, the detection threshold may be above all but the most sensitive units.

Second, ensuring the navigation architecture is sufficient to handle such vent forces can be done by adding robustness in sensor availability. For on-board sensors, this may not be much of problem, but when considering ground-based tracking it becomes paramount. Assets must be scheduled properly and available for quick call-up to ensure that quality and timely solutions can be generated in the presence of weak knowledge of the dynamic environment.

Finally, there is historical precedent in both the Apollo and Shuttle programs for “fudge factors” in the navigation solution and trajectory prediction capabilities. These have generally manifested themselves as additional solve-for terms in the downtrack velocity or acceleration bias to improve the estimate of the state. During the Apollo program, these biases were utilized in lunar orbit where lunar gravity field uncertainty introduced a large amount of navigation uncertainty. Biases were solved-for as a function of lunar ground track and were repeatedly applied over the same lunar-fixed location. In the Shuttle program, downtrack acceleration biases were solved-for as a function of attitude and altitude. Theses biases have been shown successful in mitigating the cross-coupling of attitude thruster firings into translational perturbations.

ROBOTIC PRECURSOR MISSIONS

With so little known about general NEO composition and structure, planning a manned mission to a NEO will require specific and credible intelligence about the NEO environment before making the attempt. Since every NEO is different in terms of shape, size, and gravity, sufficient care should be taken to understand the specific environment of the NEO that is ultimately chosen to visit. In addition to knowledge gained about the environment of the NEO, identification of landmarks, and the placement of navigational aids and a structural anchor at the NEO for the manned spacecraft will be required. Landmarks will provide precise NEO orientation when future spacecraft return so a controlled descent can be initiated. Since any manned mission to a NEO will depend on a high precision approach, navigational aids that provide range and/or bearing will be critical pieces of information to the crew. Without the navigation hardware, surface contact could be made at an arbitrary and perhaps precarious location with little information available to the crew other than altitude. With such a weak gravitational field at the NEO, an anchor or docking target will need to be in place so that the spacecraft will be held in place at the NEO surface for the mission stay. Robotic precursor missions will play this critical role of determining which NEOs to explore, characterizing the NEO environment, and delivering navigational aids to the NEO surface. A sample set of NEO candidates is shown in Table 1.

The NEO Surveyor and Explorer Missions

Begun in 2010 and sponsored by a joint collaborative effort from the Jet Propulsion Lab (JPL), Glenn Research Center (GRC), and Johnson Space Center (JSC), the current framework for exploration of NEOs consists of three phases of mission classes. In chronological order, they are the NEO Surveyor mission class (launch in 2014), the NEO Explorer mission class (launch in 2018), and finally the NEO manned mission class (launch in 2025). Like the Mercury and Gemini programs leading up to the Apollo program for the first lunar exploration, the NEO Surveyor and NEO

Table 1. Select heliocentric ecliptic osculating elements of candidate NEOs for the Surveyor Missions (Courtesy NASA/JPL)

NEO	Eccentricity	Inclination (deg)	SMA (AU)
Apophis	0.19	3.33	0.92
1999 RA32	0.09	10.52	1.02
2008 EV5	0.08	7.43	0.95
2001 CC21	0.21	4.80	1.03
1991 JW	0.11	8.72	1.03
1999 AO10	0.11	2.62	0.91
2000 SG344	0.06	0.10	0.98
1989 UQ	0.26	1.29	0.91

Explorer programs will lead the way for the first manned NEO exploration. Each program will have definable goals and objectives and the knowledge gained from each of the precursor missions will lead to the greatest probability of successful manned exploration at the NEO surface. A conceptual NEO Surveyor spacecraft design in shown in Figure 3.

The NEO Surveyor missions will focus on understanding the NEO environment itself and laying the foundation for the NEO Explorer missions. The goal of the Surveyor mission is to simply gather data and examine the environment. There will be very few, if any, requirements imposed on the Surveyor missions that resemble constraints for a manned mission. For example, a Surveyor mission cruise phase to the NEO will take approximately three years - unlike a manned mission which will take only three to six months. The extended cruise time to the NEO envisioned for the Surveyor and Explorer missions is not acceptable for manned missions due to life support considerations, exposure to cosmic radiation, and crew physiology concerns. While solar electric propulsion can be used almost exclusively with unmanned spacecraft, chemical engines will be required for a manned spacecraft (perhaps in concert with solar electric propulsion) to reduce the time of the cruise phase and to account for the larger manned spacecraft mass. This increased mass is due primarily to the required consumables, radiation shielding, and increased fault tolerant spacecraft systems not typically seen on unmanned missions. Unfortunately, this has the possibility to limit the potential NEO target pool. Further, the use of chemical engines will provide the required change in velocity to return the crew to Earth, whether by nominal design or in contingency operations.

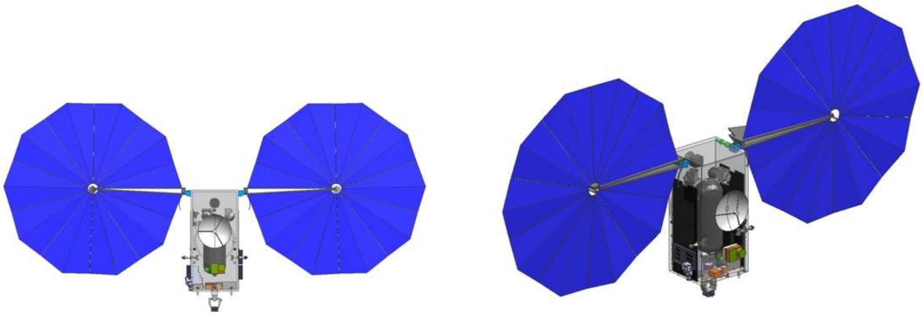

Figure 3. Conceptual NEO Surveyor Spacecraft (Courtesy NASA/JPL/GRC)

Unlike a manned mission, surface contact of a NEO by a Surveyor spacecraft is not necessarily required. Surface contact is highly desirable, but from a program cost perspective, it may be better to simply have the spacecraft survey the environment immediately surrounding the NEO rather than attempt a surface contact. This information, along with information from other NEOs that are visited by the Surveyor program, will be used to determine which NEOs are best suited for the Explorer missions and manned exploration.

Even if a surface contact by a Surveyor spacecraft is not attempted, an advantage of extended proximity operations at the NEO will be the location and identification of surface landmarks and the development of a landmark data base (much as with the NEAR-Shoemaker mission[3]). These landmarks can be used for precise determination of rotation rates of the NEOs and can be used in concert with man-made navigational aids. Indeed, when first encountering the NEO, one of the first objectives will be to determine the precise orientation of the NEO so that a high-precision approach can begin. Further, optical landmark tracking can be used in conjunction with Deep Space Network (DSN) radiometric data for high-precision navigation. Both of these sources of navigation data will be important for a successful manned landing attempt.

The Explorer missions will focus on refining the logistics and operations relevant to human exploration of NEOs. They will serve as a bridge from the more science-driven Surveyor missions to the more human-driven manned missions. Indeed, additional constraints may be imposed on the Explorer missions (i.e. cruise phase duration, approach geometery, etc.) that closely resemble constraints on manned missions. There will be fewer Explorer missions than Surveyor missions simply because the results of the Surveyor program will yield the best two or three NEOs that have the best possible chance for a successful manned mission. The constraints of the manned mission will be weighed against the intelligence gathered by the Surveyor mission. The NEOs that meet most, if not all, constraints for a manned mission will again be visited by the Explorer spacecraft.

Like the Surveyor missions, the Explorer missions will also have unique goals and objectives. The Explorer missions will focus mostly on manned surface interactions rather than immediate environmental surveys. Perhaps one of the most important aspects of the Explorer missions will be the delivery of navigation aids on the surface of the NEO. These aides (perhaps the Explorer spacecraft itself) will include such devices for future spacecraft to measure range and bearing from the proposed surface contact. Also, a secure attachment point as well as a contact target will be delivered to the surface. It is possible that the surface target will resemble the current Internation Space Station (ISS) docking target (Figure 4) that will measure approach and alignment angles between the target and the spacecraft.

The Explorer spacecraft will examine the NEO surface at close range for content, composition, structural stability, and suitability for human exploration. The results of the Explorer missions will yield detailed imagery of the surface contact location, and specific and prioritized manned exploration objectives will be determined. This information will form the basis for developing a mission timeline for the manned missions including the length of the surface stay, number of Extravehicular Activies (EVAs) required, the content of those EVAs, and hardware construction requirements.

NEO Rotation

In addition to gravity field determination, deep space radiation examination, and visible and thermal albedo characterization, one of the primary factors that the Surveyor and Explorer missions will measure is the precise rotation of the NEO. The rotation rate of the NEO is directly linked to its suitability for exploration. A NEO with high rates of rotation (perhaps in all three axes) is highly undesirable from a surface contact and controllability standpoint and will likely limit the regions on

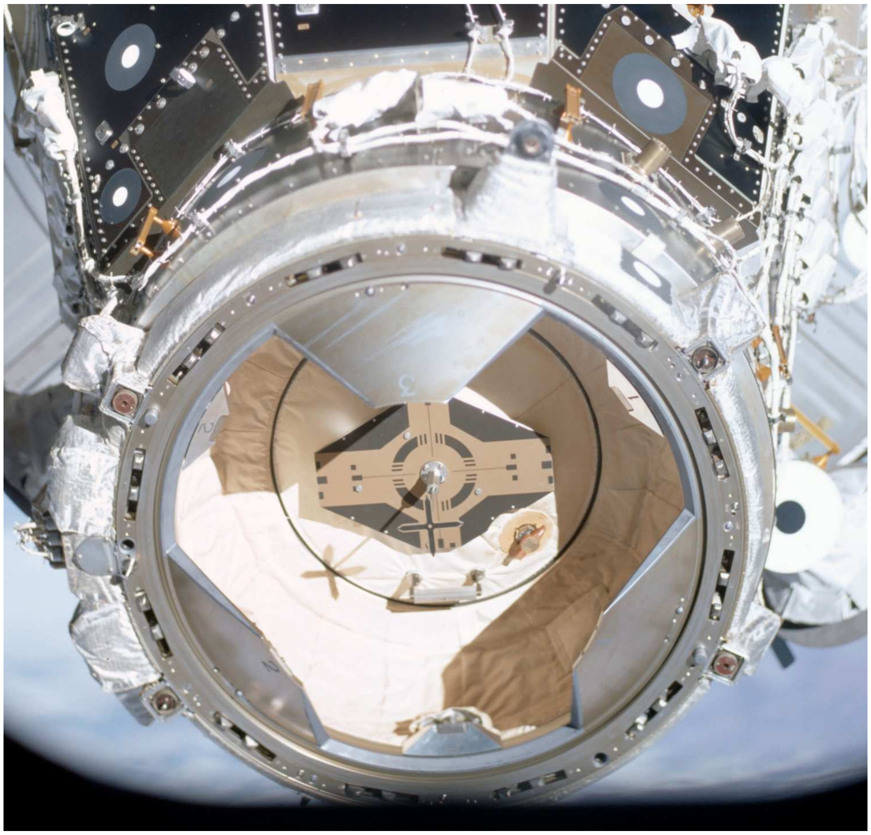

Figure 4. An optical sighting system such as the ISS docking target could prove useful for a crewed NEO mission.

the NEO where surface contact can be attempted. The maximum rate of the NEO rotation that will permit a NEO surface contact will be dictated by 1) Propellant required to match spacecraft translation and rotation, 2) Gravitational attraction of the NEO, 3) Spacecraft contact rates at surface encounter, and 4) Crew physiological adaptation.

When a spacecraft attempting a surface contact approaches a rotating NEO, the rotation and translation rates of the spacecraft with respect to the NEO surface must be eliminated. This requirement is not unique to NEOs. For Apollo missions after lunar orbit insertion (as an extreme case), the powered descent to the lunar surface performed the job of matching translational rates. For NEOs, matching rates is far less expensive as the gravity field is much weaker. For example, a JPL published white paper[8] devised a reference trajectory to a hypothetical NEO that was 760x680x500 meters in size. This object is about twice the size of asteroid Itokawa and about one third the size of asteroid Eros. It had a small mass and rotated every 3.6 hours. In summary, JPL simulations indicate it took only about 2 m/s in order to match rates and provide a near vertical landing at 0.2 m/s. This should not be surprising since orbit velocities are very small for NEOs,[3] typically on the order of 3 m/s .

If the spacecraft is not held in place by either an anchor or other docking mechanism that is permanently affixed to the NEO, the gravitational attraction of the NEO must exceed the centrifugal acceleration caused by the NEO rotation. As an example, one of the NEOs under consideration by the NEO Surveyor design team is 2001 CC21. It has a radius of $\sim$363 meters and a rotational period of 5 hours. The centrifugal acceleration at the surface is less than its gravitational attraction on some parts of the asteroid, but not all. It can be concluded, therefore, that some parts of 2001 CC21 may have rocks or boulders while other areas will be bare simply because there is insufficient gravity to hold them there. While a smooth and bare surface may seem attractive for a landing, there is very little potential for sample return unless drilling or other such destructive exploration is attempted.

If manned exploration of a NEO is considered, the Coriolis Effect upon the human explorer should be considered. While space adaption sickness has been dealt with successfully during manned missions to date, the area of "coriolis nausea" is an area that should receive further examination. With a continuously rotating central body and clear views of a fixed star field, it is likely there is some point where nausea could be induced. At what point this occurs is unknown - if it occurs at all. But obviously the minimization of rotation rates would also serve to minimize the potential for such an event.

The landing site chosen will be based on the observed rotation rate and surface features. A NEO with a larger rotation rate may indicate fewer surface sample opportunities at equatorial locations and require larger amounts of propellant to match the surface speed relative to the vehicle. At the poles, excessive dust and rocky surfaces pose exploration hazards even though less propellant would be required to attempt surface contact. It is likely that initial contact site locations will focus on mid-latitudes. Firm intelligence regarding the surface characteristics obtained from the Surveyor and Explorer phases will be critical for landing site selection.

The Explorer missions, with their preliminary surface contact and interaction information, will be able to provide an indication of the amount of dust on the NEO surface that explorers will have to endure. After surface contact has been achieved and exploration has begun, the low gravity environment will make movement on the surface challenging. Any dusty surfaces that are "stirred up" during an EVA will likely limit local visibility for extended periods - analogous to dirt and sediment being stirred up on the ocean floor. In extreme cases, an exploration site may need to be abandoned altogether because of visibility reduction. Excessively dusty surfaces will also pose problems for EVA equipment. To mitigate these concerns, thorough examination of the surface conditions during the Explorer mission phases will be necessary in order to provide adequate requirements for human-rated hardware design.

In summary, the NEO Surveyor and Explorer missions have the potential to bring back credible and specific information about NEOs that can be explored by astronauts. This information is critical in identifying not just what NEO to ultimately visit, but what environment around the NEO and on its surface should be anticipated. After gaining this information, mission timelines can be developed, system hardware on the spacracft can be designed, EVAs can be planned, and operations concepts and software can be written to maximize the success of the NEO exploration. Without this information, the prospects of a successful mission are minimal. Therefore, the use of robotic precursor missions to gain insight into the immediate environment around a candidate NEO as well as its surface is highly recommended. In addition to the scientific information gathered by the Surveyor and Explorer missions, expertise would be gained in the areas of mission design and operations. As was the case for every manned space mission, an intense flight design will be required as well as development of the infrastructure required to access, process, and utilize all the telemetry information from the spacecraft. Mission rules, procedures, and techniques of space travel in the deep-space region will be generated as well as courses of action for contingency scenarios. Software for orbit determination, maneuver targeting, and flight planning will be developed and certified for ground use. Finally, once a NEO has been chosen based on the results of the Surveyor and Explorer missions, integrated simulations involving ground controllers as well as the crew will be performed in order to fully prepare for the mission. The specific objectives of the manned mission, to some extent, depend upon what is discovered by the precursor and are beyond the flight dynamics focus of this paper.

ONBOARD NAVIGATION AND TARGETING

Navigation

Traditional onboard absolute navigation systems for human spacecraft have consisted of state propagation of ground generated solutions. These ground-generated state estimates have utilized radiometric tracking from ground stations and/or the Tracking Data Relay Satellite System (TDRSS). Recent upgrades to the Space Shuttle and current Orion design rely more on the Global Positioning System (GPS) as the primary sensor for absolute navigation. In the case of contingencies (particularly loss of communications), the Apollo and Orion programs relied on optical navigation and to a lesser extent, so did the Space Shuttle.

Obviously, the feasibility of utilizing either GPS or TDRSS is greatly constrained for a NEO mission. However, there have been studies on weak signal tracking of GPS side lobes outside of the GPS constellation shell. Unfortunately, these methods require specialized hardware for the weak signal tracking or prohibitively large antenna arrays. Additionally, little feasibility has been shown for this method outside of the range of the Earth to the Moon.

If ground based radiometric tracking is selected as the primary method of navigation for a NEO mission, it comes at a price. Previous analysis has demonstrated the ability to formulate quality navigation solutions from ground tracking measurements (range, 2-way, and 3-way Doppler) is a function of the geometry of the observing stations. Consider Figure 5 where the ability to resolve the Orion entry flight path angle (for an Earth return trajectory) is plotted for 12 station ground network.

Figure 5 illustrates that better performance is achieved when observing stations criss-cross the Northern and Southern hemisphere as well as provide a sufficient East-West baseline. The implication here is that approximately 3 stations of continuous tracking are needed to provide a robust navigation architecture. This implies a significant investment in tracking assets corresponding to a network ranging from 6 - 12 stations scattered about the Earth (depending on asset availability, redundancy requirements, and the desire to protect for short arc solutions in the case of contingencies).

It is worth noting that a ground station architecture consisting of fewer stations may be able to provide the necessary geometry to resolve the navigation solution, but it comes at a penalty of time. The relative motion of the spacecraft with respect to fixed Earth allows for stations to come in and out of view with changing geometries. As an example, 2 stations with a poor East-West baseline may obtain observeability in the East-West components due to the natural rotation of the Earth. For quiescent operations, this may be a way to mitigate the cost of maintaining a large network of stations, but it sacrifices the ability to generate short arc solutions. Additionally, the uncertainty in the spacecraft dynamics due to both noisy accelerations generated by the spacecraft and uncertainties in the gravity field of the NEO (Figure 6) may make this solution infeasible.

Considering the substantial cost of maintaining a large network of ground tracking stations, it is worth examining the feasibility of replacing the ground tracking network with onboard optical

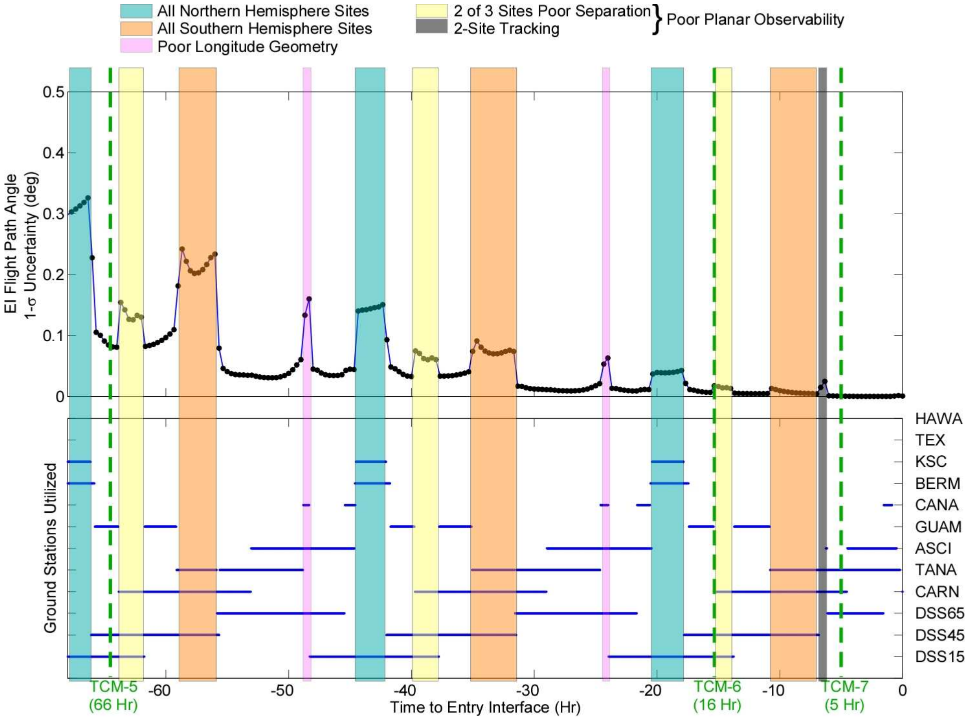

Figure 5. Ground Navigation Using the Apollo Network

navigation as the primary source of state estimates. Figure 7 illustrates the Orion optical navigation concept, which leveraged off the Apollo optical navigation system.

Obviously, there are other options with respect to optical navigation and the measurements they provide (and they should be fully explored in the design of a NEO-capabable spacecraft), but the design shown in Figure 7 suffers from the following limitations:

1. The optical navigation measurements do not change quickly in time. The consequence of this is that filtering successive measurements in time is roughly equivalent to filtering the same measurement repeatedly. Therefore, optical navigation is limited in its ability to provide short arc solution capability. This also limits the ability of filtering algorithms to map the measurement into known dynamics, thus further limiting the ability to resolve the navigation solution.

2. The limitations on short arc capability also imply a limitation on navigation accuracy in the presence of noisy accelerations or poor knowledge of the gravity field. In other words, a poor knowledge of the dynamical environment reduces the length of an arc over which a navigation solution may be generated.

3. While providing excellent geometric information, the optical navigation measurements have no direct measurement of range. The direct measurement of range is highly correlated to the spacecraft speed and therefore makes resolving important parameters such as entry conditions difficult.

Again, it is worth repeating that these observations are based on the Apollo / Orion design and

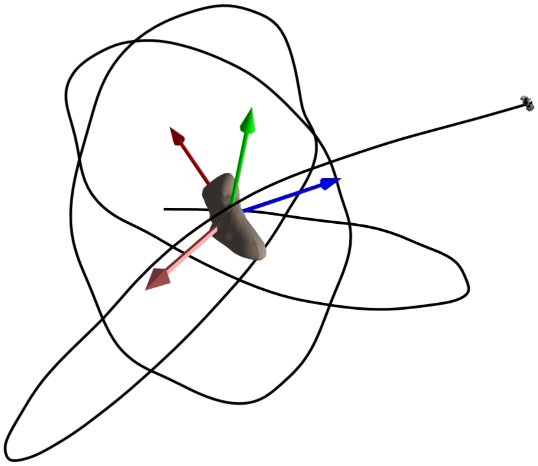

Figure 6. Gravity Field Effects on a Close-in orbit about NEO 433 Eros

may not be true for other instantiations of optical navigation. However, these limitations lead the engineers on both programs to limit the scope of optical navigation to contingency operations, specifically for the case of loss of communications and autonomous Earth return. As the utilization was limited to this scope, navigation engineers negotiated a relaxed set of entry requirements that forfeited such capabilities like precision landing in favor for items such as a larger entry flight path angle corridor. These negotiations were a direct consequence of the degraded navigation performance with optical navigation as compared to radiometric tracking. Such negotiations for a NEO mission are subject to the design and capabilities of the spacecraft.

Thus far the discussion on navigation for NEO missions has focused on either all radiometrics (with its excellent and proven performance but high lifetime costs) or all optical navigation (with its degraded performance but lower lifetime costs). However, a third "hybrid" solution may hold substantial promise. Given that the complete elimination of ground tracking is unlikely to occur for a NEO mission (if for no other reason than to maintain communication with ground operations), then it stands to reason that the simultaneous use of optical navigation and radiometrics is operationally feasible.

1. The utilization of 3 DSN stations only for radiometrics
2. Optical navigation only.
3. Optical navigation and DSN tracking.
4. Radiometric tracking from an Apollo-like network (approximately 12 tracking stations).

A hybrid navigation system could deliver performance comparable to that of a large ground tracking infrastructure. Such a navigation design has the benefit of obtaining the excellent geometric information available in optical navigation while getting the direct measurement of range from radiometrics. Additionally, as the geometric information is now provided from optical navigation measurements, this hybrid solution may offer long term operational cost savings as a large network of ground stations is not required. Furthermore, it may be possible to contain the entire primary

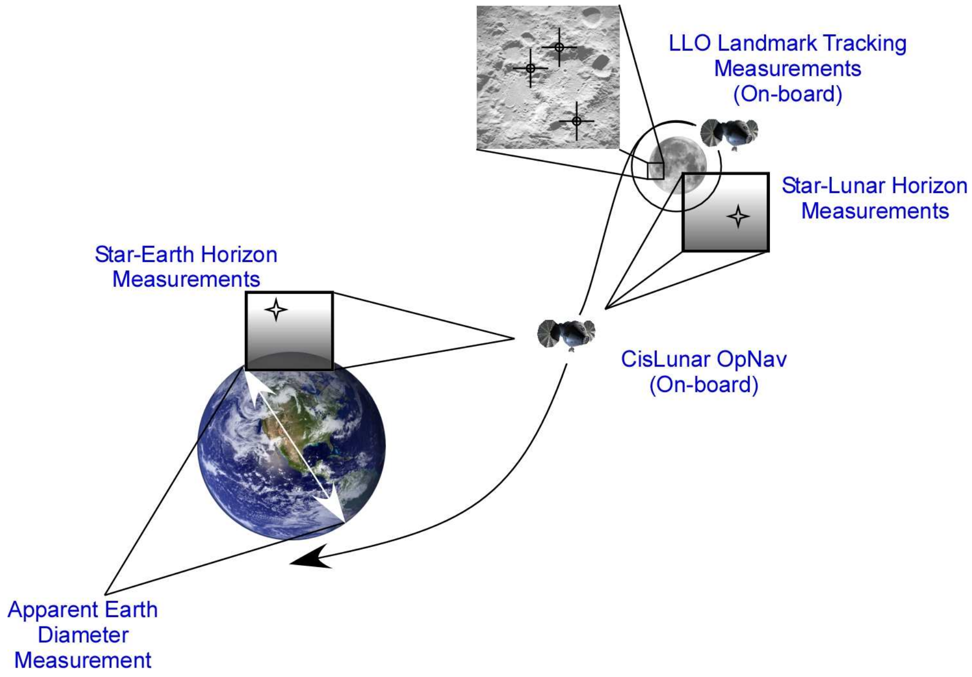

Figure 7. Sample Optical Navigation for a Lunar Mission

navigation system onboard the vehicle if a sufficient clock is provided to generate 1-way range measurements. Further study on the feasibility of such a hybrid navigation system is necessary to validate its use for NEO missions.

Maneuver Targeting

The obvious difference between a robotic mission to a NEO and a manned mission is the need to guarantee crew return and survival. Robustness and redundancy can prevent many spacecraft systems contingencies, but maneuver targeting does not lend itself to redundancy management. To carry out nominal mission objectives or to return the spacecraft and crew to Earth in the event of communication failure, careful scrutiny during the development of the operations concept of the NEO mission. For all manned missions performed from Mercury to Shuttle, most translational maneuvers (often referred to as “burns”) have been determined by ground processing and the resulting inputs to the onboard guidance system (often referred to as “targets”) have been uplinked to the spacecraft for execution. The exception to this philosophy is with respect to rendezvous and proximity operations where onboard computing resources and onboard relative state information was used to compute burn targets to achieve the proper position for the final phase of rendezvous and docking. However, even when the onboard targeting systems computed the targets, the ground was always monitoring the solution and could intervene if required.

With the exception of the Mercury program, there has always been some form of onboard targeting capability, and it is beneficial to retain this capability. This ability was necessitated by rendezvous and docking operations where external sensor data in the form of either optical or radar data was incorporated into the navigation state in order for the best possible relative motion to be used in computing the required maneuver. Cooperative rendezvous radar was available during Gemini program and the Apollo program lunar module had a cooperative rendezvous radar with a transponder on the Command Service Module. Additionally, some optical navigation inputs were possible using a sextant for angle data and Very-High Frequency (VHF) ranging for position.

For shuttle rendezvous, beginning at the Nominal Corrective Combination (NCC) burn and continuing through Midcourse Correction 4 (MC-4), a Lambert algorithm was used to provide the targeting for the burn. Beginning prior to NCC, onboard relative state information was obtained by optical navigation data obtained through star trackers (angles only) and closer in by use of the rendezvous radar (angles plus range and range rate). The burns were computed using onboard states and were closely monitored from the ground until the maneuver was executed. Rarely was a burn performed without communication capability with the ground. In fact, significant efforts were made to increase the communication coverage with the TDRSS constellation during this critical phase of the mission.

The process of computing burn targets will likely evolve considerably for NEO missions or any manned mission beyond Earth orbit where communcition with the ground cannot be assured. It is easily understood that there are two extremes for computing the targets - neither of which will be accepetable for manned missions. At one extreme, uplinking burn targets on a burn-by-burn basis can be accomplished - as was the case historically. However, this method requires communication from ground operators and does not provide any insight for the crew of future burns or other upcoming trajectory events. In this case, the crew blindly takes the targets that are provided and executes them as directed. Any complications that may occur during the preparation or execution of the burn (i.e. system failures) resulting in a delay of the burn will likely invalidate the targets forcing a ground recomputation of targets to achieve the trajectory goals. This would initiate another uplink process with the new targets and the crew would re-execute the procedure as directed. A complete loss of communication prior to the burn that would last for an extended period of time may mean that the burn may be missed altogether which could jeopardize mission objectives and/or crew safety.

At the other extreme, a trajectory optimizer application could be used onboard that will take the current navigation state along with appropriate future trajectory constraints to allow the crew to compute their own targets. The time for the burn would be at the time outlined in a flight plan or the crew's own choosing in a contingency scenario. The resultant onboard processing would optimize the burn (presumably for propellant or other such cost function) while satisfying the remainder of the trajectory constraints. This process is completely autonomous, provides the crew insight into future trajectory events, and requires little, if any, communication with the ground. However, the targeting procedures to fully utilize the optimizer application will likely be very complex as will the inputs to application. Training for the crew to perform this task will be equally complicated. If a crew size was far bigger, then it may make sense to have a dedicated trajectory expert crew member become proficient in the use of the optimizer and the many nuances that are required to determine the burn targets. More importantly, this crew member would be able to verify the solution and to resolve any issues that could arise during their computation. However, for small crew sizes (of which early NEO missions will likely have a crew compliment of four or less), providing such specific training for a function that may only be required a few times during the mission is simply not feasible. Further, the process of certifying the onboard trajectory optimizing software for use will be a lengthy endeavor and will likely be cost prohibitive as a result. Clearly, this option is just as infeasible as the burn by burn approach and again, could jeopardize mission objectives and/or crew safety.

Two-Level Targeter The use of a "two-level targeting" algorithm[9] is good medium between the two extremes of the burn-by-burn process and the fully autonomous solution offered with a trajectory optimizer. The two-level targeter uses future epoch/position points (called patch points) along a reference trajecotory and constraints that can be imposed at each patch point to achieve the desired trajectory results. Such constraints take the form of any parameter that can be derived using position and velocity vectors. The constraints can be of scalar nature (i.e. flight path angle, latitude, longitude, etc.) or vector nature (i.e. velocity continuity across patch points). During the targeting process, the patch point position vector and epoch will be adjusted in order to meet the constraints using an underdetermined minimum norm solution. While the solution cannot be considered optimum (since there is no cost function to minimize), the resultant trajectory will likely be very close to optimum if the initial patch points were determined from an optimum trajectory source.

For any manned mission beyond the Earth orbit, a more autonomous method of maneuver targeting will need to be utilized that will not require excessive interaction with the ground and be easy enough for crew execution. For a NEO mission, we propose that the two-level targeter be used as the primary means of onboard maneuver targeting once Earth escape has been achieved. The software to compute the targets is far more easily created, maintained, and executed and very little training would be required for the crew. The crew could execute the targeting procedure without ground intervention and would have complete insight into future trajectory events. The target computation process can easily be reduced to a push-button effort to arrive at quality targeting results.

It is proposed that optimum patch points (from a trajectory optimizer) be uplinked from the ground in time to perform the burn. If the burn were to be delayed, it would be an easy effort for the crew to change the time of the burn and recompute the targets based on the desired trajectory patch points. The newly generated trajectory would be very close to the original optimum solution. Further, multiple sets of patch points could be uplinked that the crew would access if needed in response to various failure scenarios. For example one set of patch points and constraints would contain the nominal mission trajectory. Another set would contain the patch points and constraints needed to return to Earth in the minimum amount of time given the current propellant availability. Still another set would contain the patch points and constraints required to return to Earth using the minimum amount of propellant given the current quantity of consumables. Of course, considerable ground operations would be needed to determine these patch points. A complex ground based trajectory optimizer would be utilized of which the resultant optimum trajectory would then be used to generate the patch points. This is a far superior method where trajectory experts that have been trained to execute and verify targeting solutions can accurately relay their optimum solutions to the spacecraft. Every scenario that was deemed necessary for mission objectives and crew safety could be generated and subsequently uplinked to the crew on a regular basis. For deep space missions with only small perturbations expected during the cruise phase, it is felt that these patch point uplinks could be made daily or even weekly to incorporate all available navigation data accumulated. Use of the two-level targeting technique is an elegant solution to a very complex problem.

In summary, the use of a two-level targeting algorithm offers a number of advantages over many methods of onboard autonomous maneuver targeting. The greatest advantage is the ease of use and the quality of results. The inputs to the algorithm are only the time, position vectors, (optional) velocity vectors, and the constraints, if any, imposed on the trajectory at each patch point. All of these can be generated on the ground and relayed to the spacecraft electronically without any action required of the crew. When the time comes for a maneuver to be executed, a few step procedure to incorporate the inputs into the algorithm can be used to compute the burn. For a loss of communication with the ground, several sets of inputs can be accessed to produce high quality trajectory results to account for a wide variety of scenarios - nominal and contingency. The crew can use this algorithm to compute quality targets for both single and multiple burns to carry out mission objectives and assure crew safety.

RENDEZVOUS AND PROXIMITY OPERATIONS

The term “rendezvous” for the duration of the space program has been to define the sequence of events and translational maneuvers required to successfully bring together two orbiting spacecraft. The term “landing”, of course, refers to a spacecraft achieving a safe condition on the surface of a planet or moon. From a NEO perspective, the term “landing” is a misnomer in the traditional sense. One cannot simply “land” on a NEO, even very large NEOs with their own definable gravity field. The “landing” is far more like a rendezvous and docking. For a manned mission to a NEO, this is a significant advantage. First, propellant requirements are substantially reduced for station keeping and movement around the NEO. The only major source of propellant usage is the initial braking performed at the NEO after the long cruise from Earth and for the initial translation required for Earth return. Second, unlike the Apollo Moon landings where successful landings occurred only six times and training environments were limited, the knowledge and experience gained throughout the ISS program related to high precision approach and docking will no doubt be of great benefit to the success of NEO surface exploration. It is clear that the technology, tools, and crew procedures of present ISS rendezvous and proximity operations are directly applicable to NEO rendezvous operations.

A NEO encounter with an unmanned probe, like the NEO Surveyor or NEO Explorer missions, will be far different than with a manned encounter. For the Surveyor and Explorer missions, there will be extended stays (perhaps months) in proximity to the NEO without actually attempting any surface contact. Indeed, this is precisely the plan for the Surveyor mission. The Explorer mission, while designed for surface contact, will likely spend considerable time close to but not necessarily in contact with the NEO. Conversely, a manned mission to a NEO will seek to minimize the amount of time in proximity operations with the NEO in order to minimize threats to the crew and enhance the chances of successful mission objectives at the NEO surface. There will not be unnecessary loitering in proximity to the NEO and once the rendezvous operations begin at the end of the cruise phase, surface contact operations will be initiated at the earliest possible time.

Like all manned missions into space, crew physiology must be accounted for in all phases of the mission and especially the rendezvous. Excessively long work days, appropriate time off for meals, personal attention, and sleeping all must be a part of the timeline and factored into the rendezvous sequence. It makes no sense to have a rendezvous profile that requires the crew to be awake for more than 12 hours. Such a long day would lead to severe degradation of crew performance and perhaps loss of mission objectives. Therefore, a rendezvous profile that fits easily into a single crew day will be a requirement for any manned mission.

Unlike the NEO Surveyor and Explorer missions, the manned NEO rendezvous would be able to utilize perhaps the most flexible and powerful of navigation aids - the crew eyes looking out of the spacecraft windows. The knowledge, judgment, and expertise of the crew piloting is what sets apart the manned from the unmanned missions. The immediate visual observation feedback to the crew, the ability to anticipate future events, and the capability to troubleshoot and correct system anomalies all assist in making a manned mission far more likely to succeed.

The Four Phases of Manned NEO Rendezvous

Although the boundaries are somewhat arbitrary at this point, there will likely be several phases of rendezvous operations required to successfully make a high precision manned surface contact with a NEO. Each phase is generally comprised of a translational maneuver, followed by a trajectory coasting arc, and finally by station keeping until conditions are appropriate to continue with the rendezvous. This is very much like shuttle rendezvous operations with ISS where there were predetermined points along the trajectory that were convenient for assessment of spacecraft health. These points are also useful positions where the rendezvous could be conveniently delayed without major impact to the mission. Such points in the shuttle rendezvous included the Initial Point, the $\vec{R}$, the $\vec{V}$, and at predetermined distances from the docking target. We propose that there be four phases of NEO rendezvous to achieve successful manned surface contact. The four phases of rendezvous, as seen in Figure 8 are the "End of Cruise" (EOC) phase, the "approach" phase, the "transition" phase, and the "final" phase.

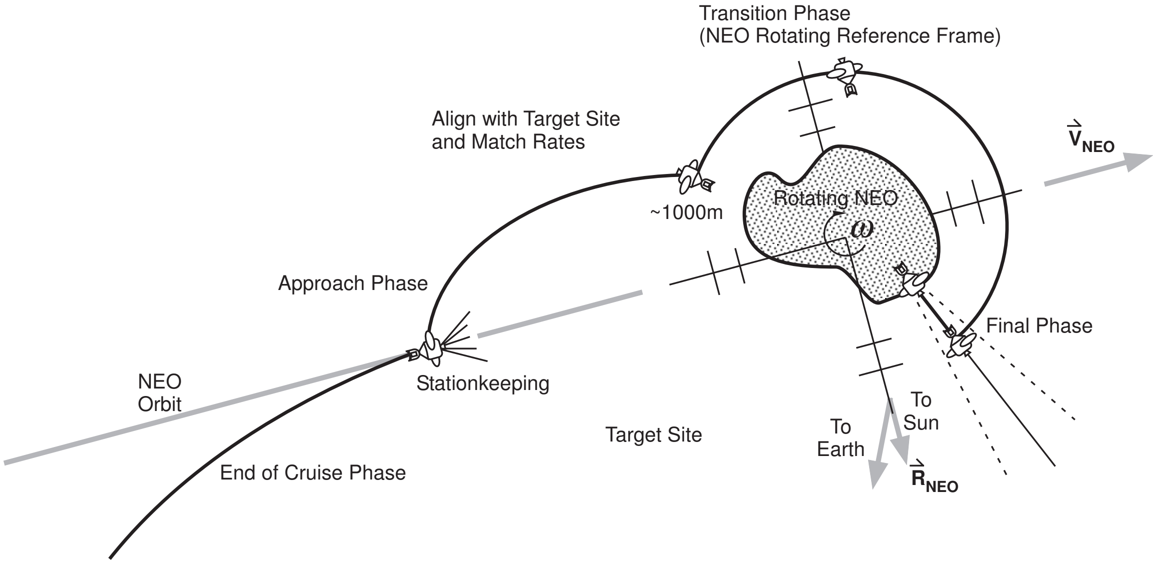

Figure 8. Sample NEO Rendezvous Profile

End-of-Cruise Phase. For much of the long outbound mission cruise, the target NEO is simply treated as a point mass in heliocentric orbit for purposes of maneuver targeting. To provide maximum protection of the spacecraft and crew, the initial approach will not be an intercept trajectory. Rather the trajectory will be constructed such that if the mission were to be aborted prior to rendezvous or if the propulsion system failed at the braking burn at the NEO, no involvement by the crew would be necessary for their safety. The spacecraft would simply fly by the NEO at a safe distance. While the mission may be lost, the crew will survive and return to Earth. When the NEO encounter begins, the spacecraft will enter into the first rendezvous phase, the EOC phase. The purpose of this phase is to demonstrate adequate propulsion system performance and to provide the first close up view of the NEO to determine its precise orientation using a landmark database and visual observations. Additionally, the EOC station keeping will allow the first attempt to contact the NEO surface navigation aids that presumably have been left behind by the preceding Explorer and Surveyor precursor missions. Station keeping at the EOC position can last for hours or even days to allow for the proper crew sleep cycles to be adjusted for surface operations over the coming days.

If there are any systems anomalies present, this would be a convenient time to resolve them before committing to further rendezvous operations.

The EOC phase will begin with a large braking burn required to match orbital rates with the NEO. Once this burn is complete, the spacecraft will be able to station keep and maintain a nearly constant distance from the NEO center of mass. Depending on the size of the NEO, this distance can range from a few thousand to tens of thousands of meters. During station keeping, the proposed location for station keeping is along the heliocentric Vbar where little input from the crew would be required to maintain a safe distance from the NEO. This is especially important if the station keeping is to be maintained during crew sleep periods or for other extended time periods where the crew may not be able to make inputs to the flight control systems.

Approach Phase. After the EOC phase, the next phase of rendezvous will be the approach phase. The purpose of the approach phase is to bring the spacecraft to a predetermined point above the surface of the NEO that is near the location of where the NEO surface contact is expected to occur. If the contact point is near the equatorial regions of the NEO, the station keeping at the end of the approach phase will be near the zero latitude position. By the same token, a polar contact attempt will dictate that the station keeping at the end of the approach phase be located near the polar region. The spacecraft will maintain position at the approach phase station keeping point until such time when NEO rotation will cause the surface contact point to pass below the spacecraft.

The approach phase begins by ending the station keeping at the EOC phase and performing a series of small translational thruster firings to bring the spacecraft to a range of approximately 1000 meters relative to the NEO surface. As with all rendezvous phases, before the approach begins, sufficient redundancy will be verified and adequate propellant will be protected in order to execute a breakout if required. From a crew standpoint, it is conceivable that a good time to begin the approach phase would be after crew wake up on that particular day. Once post sleep activities are complete, the rendezvous operations would begin. Just as is the case for the Differential Height (NH) burn on the morning of ISS rendezvous, so is the case for execution of the approach phase.

The amount of time spent at the approach phase station keeping point is dictated by the rotation rate of the NEO and where precisely the spacecraft is expected to perform station keeping. It is possible that the approach phase station keeping may last several hours or as little as a few minutes depending on where the surface contact point is located. For example, station keeping for an equatorial contact approach may take longer as the crew awaits the surface contact point to rotate underneath the spacecraft. However, station keeping for a polar contact approach will likely be very short since the polar surface region is very slow moving and would remain almost fixed with respect to the spacecraft. For this polar approach, surface translation matching would not be required and only attitude matching would be necessary. Once the surface contact point is below the spacecraft, the approach phase station keeping will end and the rendezvous will enter the next phase of approach - the transition phase.

Transition Phase. The transition phase is designed to transition from an inertial reference frame to a NEO rotating reference frame. This transition phase in a small-body fixed frame has been studied and described by Broschart.[10] The transition phase begins by performing a translational maneuver of the spacecraft such that spacecraft will match the rotational rate of the NEO to keep the surface contact point directly below the spacracft. The coast phase would be eliminated in this case and station keeping would begin immediately following the burn. The transition phase station keeping will likely be a very active phase for the crew as extensive “man in the loop” inputs to the flight control system will be required to maintain the correct orientation with respect to the NEO surface. This is similar to the True Orbital Rate Flyaround (TORF) technique accomplished today with ISS departures (Figure). During the TORF, the attitude pitch rate is chosen and a constant range is maintained as the shuttle transitions from the ISS $\vec{R}$ to ISS $\vec{V}$. The transition phase station keeping will continue until lighting and communication constraints are expected to be met at the time of expected surface contact after a controlled NEO descent.

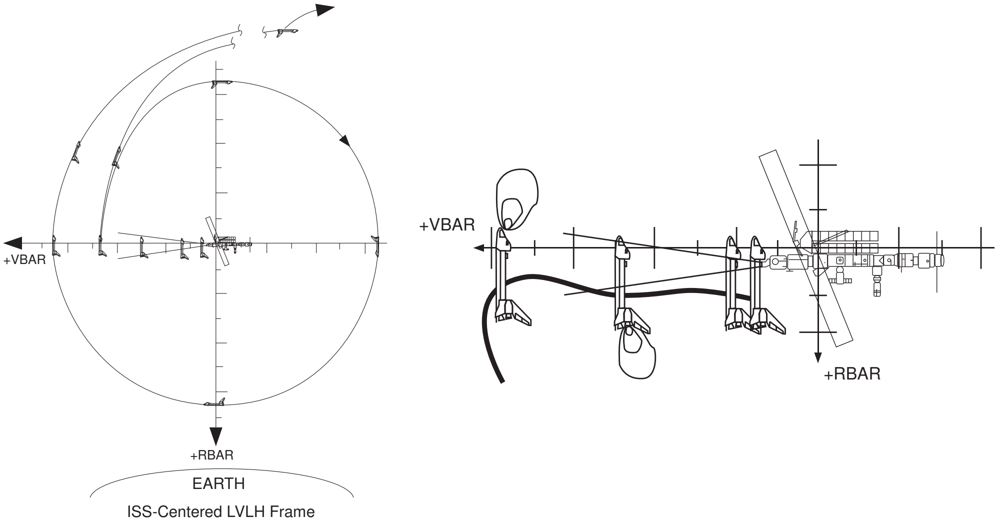

Figure 9. Rendezvous Characteristics of the Space Shuttle

Final Phase. At the completion of the transition phase, the spacecraft will begin its fourth phase of rendezvous - the final phase. The final phase will continue to match rotational rates of the NEO while still maintaining the spacecraft at a zenith location with respect to the surface contact point. However, the altitude will be decreased at a controlled rate sufficient to achieve acceptable lighting and communication conditions when the spacecraft reaches the NEO surface. To add flexibility to the final phase, a delay for any reason in the surface contact time can be made by simply nulling the range rate at any point along the descent. If an abort is declared, thruster activity will be required to not only null the range rate of the spacecraft but to provide an acceptable escape trajectory.

As the spacecraft continuously lowers its altitude with respect to the NEO surface, the use of an “approach corridor” can be used to control the approach without using excessive amounts of propellant. This “approach corridor” would rotate with the NEO as it tumbles. As the spacecraft altitude is decreased, the corridor will shrink as it approaches the surface contact target. This method has been used extensively and successfully during the shuttle/ISS rendezvous sequence where manual inputs provided by the crew maneuver the shuttle to dock with the ISS. Inputs from navigational sensors are critical in this time period that would include range to target, range rate, and a visual cue from the contact target to verify and correct spacecraft alignement. The final phase will be complete when contact and capture of the surface target is achieved, as shown in Figure 10.

In summary, the manned NEO rendezvous sequence will likely be comprised of four phases. Each phase will consist of a translational burn, followed by a trajectory coast, followed by a period of station keeping. Each phase will bring the spacracft closer to the NEO surface contact point in a controlled manner as to maximize crew safety in the event of system failures in a minimum amount of time. There will be defined “performance gates” before the crew will be allowed to continue to

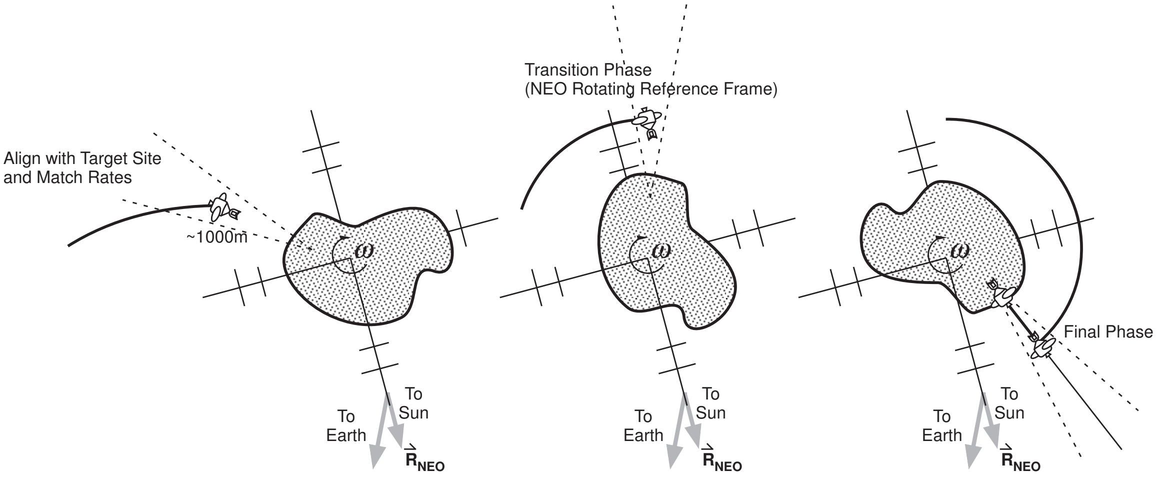

Figure 10. NEO Spacecraft Staying Within a Rotating Approach Corridor

the next phase and breakout procedures will be present if further rendezvous operations are aborted. The EOC phase will station keep at a distance from the NEO to make contact with the navigational aids on the NEO surface and to allow a convenient point to resolve any technical difficulties as well as to allow crew sleep shifting to acceptable for surface operations. The approach phase will move the spacecraft to a point above the NEO surface where the surface contact point will pass directly below the spacecraft. At that time, the transition phase will begin and the spacecraft will match rotational and translational rates with the NEO of the surface contact point. Once stable over the contact point, the final phase will begin where altitude will be decreased along an approach corridor to finally make contact with the NEO. A NEO with multi-axis tumble could use the same process, but would be much more crew-intensive. Many of the crew procedures and techniques for a successful rendezvous and docking with the ISS can directly be applied to a successful NEO surface contact. This is because landing on a NEO is far more like an ISS docking than a traditional landing. Such concepts of attitude matching, approach corridors, a controlled approach, and a docking target are all tools used today for ISS rendezvous operations and variations of these methods are clearly possible for a NEO rendezvous. The experiences gained during ISS missions will be instrumental in training future crews for their rendezvous with a NEO. The technology used to train crew members and simulate approach conditions is a capability already in use today.

ACKNOWLEDGEMENT

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Initial Considerations for Navigation and Flight Dynamics of a Crewed Near-Earth Object Mission

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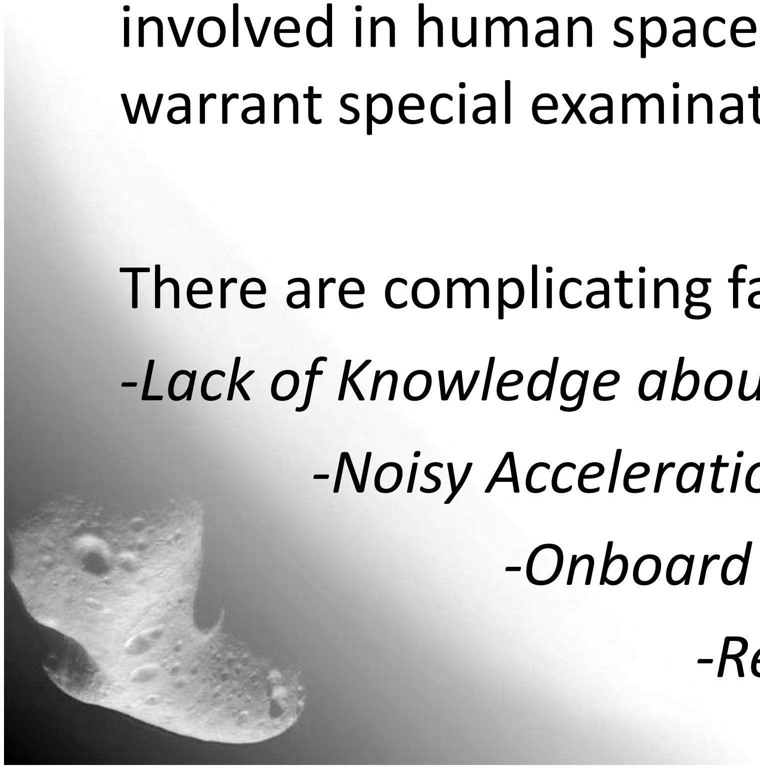
34th Annual AAS Guidance & Control Conference

A crewed NEO mission? It's never too early to start thinking.

Although missions to a NEO are not new, the unique factors involved in human spaceflight present challenges that warrant special examination.



There are complicating factors such as:

-Lack of Knowledge about the NEO Environment

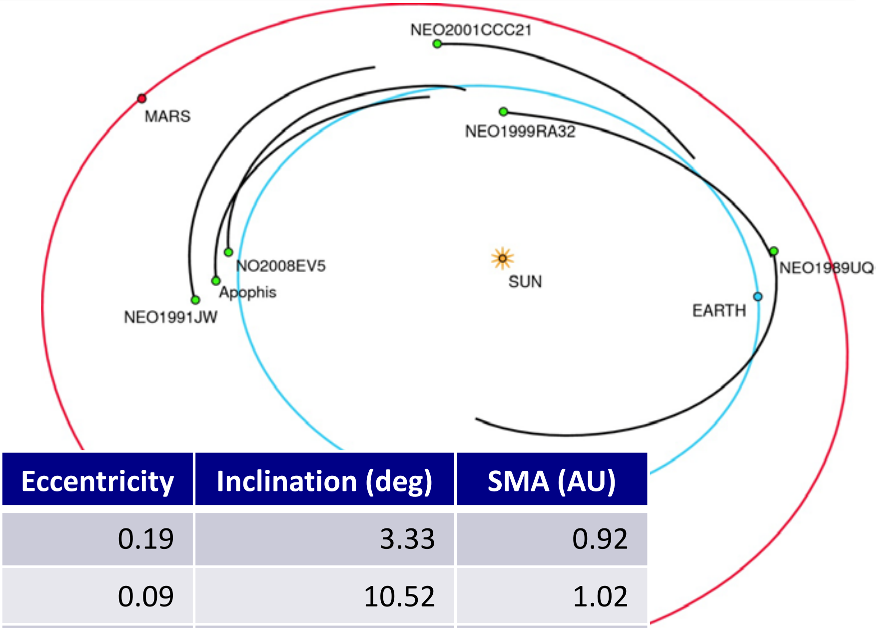
-Noisy Acceleration Conditions

-Onboard Navigation and Targeting

-Rendezvous and Proximity Operations

Many near-Earth objects present targets of opportunity.

Several studies have been conducted to identify candidate NEOs for human exploration based on geometry, composition, and orbital characteristics.

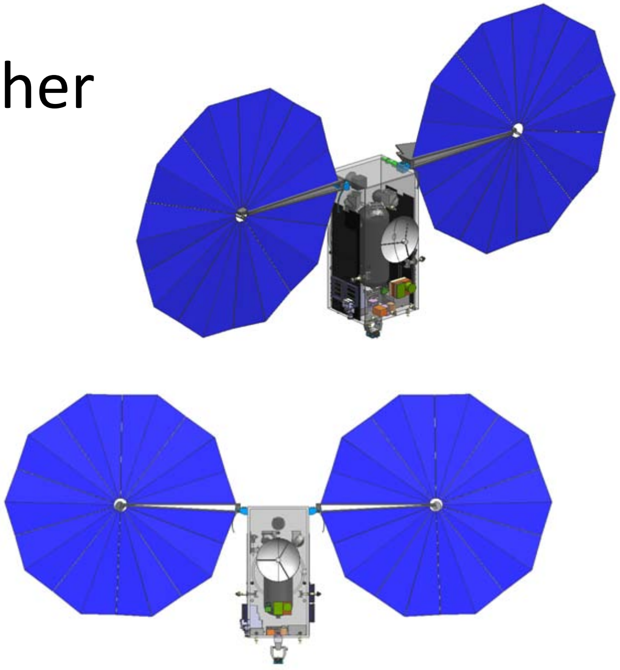


NEO	Eccentricity	Inclination (deg)	SMA (AU)
Apophis	0.19	3.33	0.92
1999 RA32	0.09	10.52	1.02
2008 EV5	0.08	7.43	0.95
2001 CC21	0.21	4.80	1.03
1991 JW	0.11	8.72	1.03
1999 AO10	0.11	2.62	0.91
2000 SG344	0.06	0.10	0.98
1989 UQ	0.26	1.29	0.91

Robotic precursors can help characterize the NEO environment.

- Gravity field, deep space radiation, temperature, minerology, landmarks, visible/thermal albedo, and more

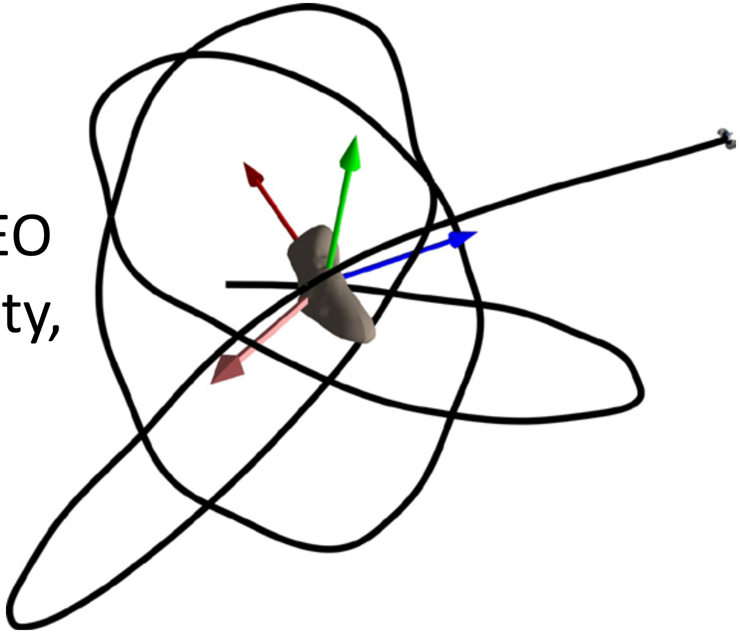
- Surveyor class – science driven, gather data and examine
- Explorer class – bridge the gap to crewed missions



Robotic precursors are invaluable preparation for a crewed mission.

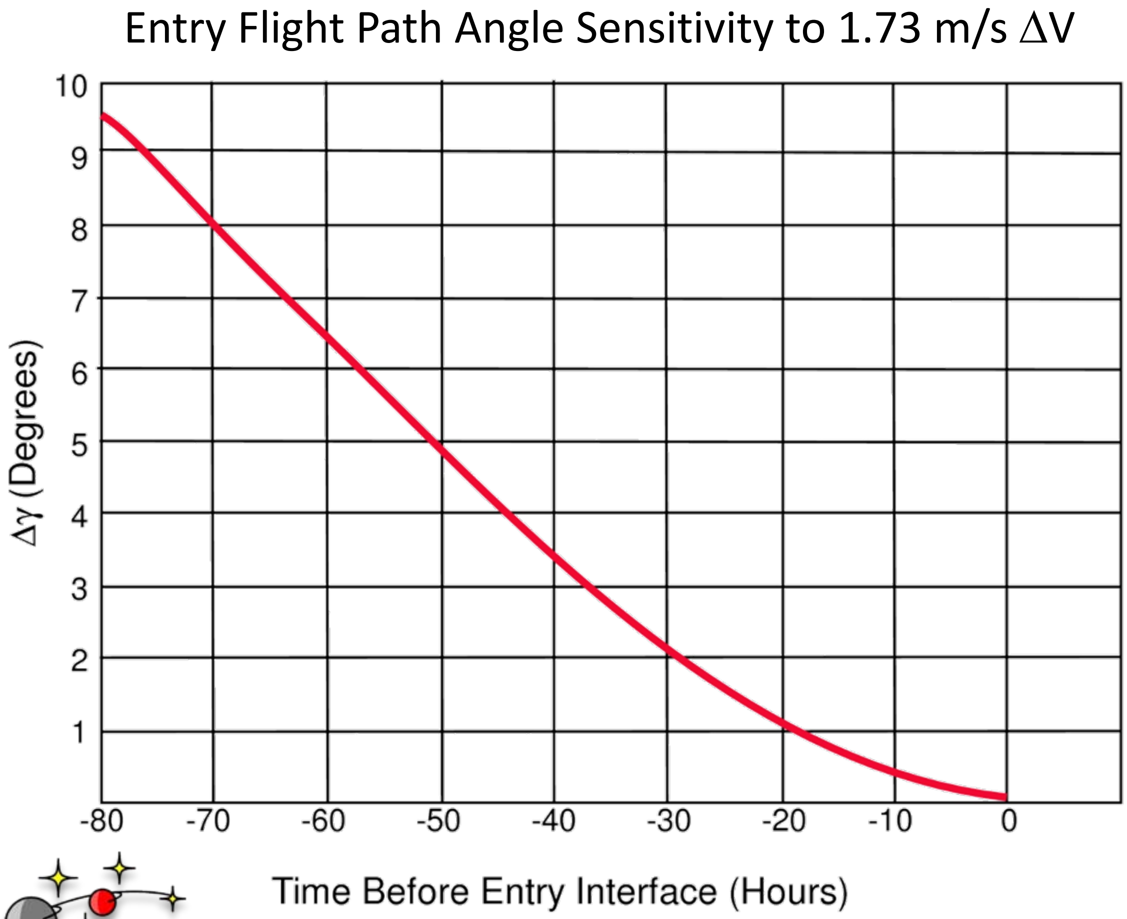
Just as *Ranger, Surveyor, Lunar Orbiter* paved the way for Apollo

Precursors can be used to study the NEO content, composition, structural stability, rotation, and suitability for human exploration - perhaps even anchor a docking target/navigation aid!



And, of course, they provide valuable preparation for ground flight controllers and mission designers.

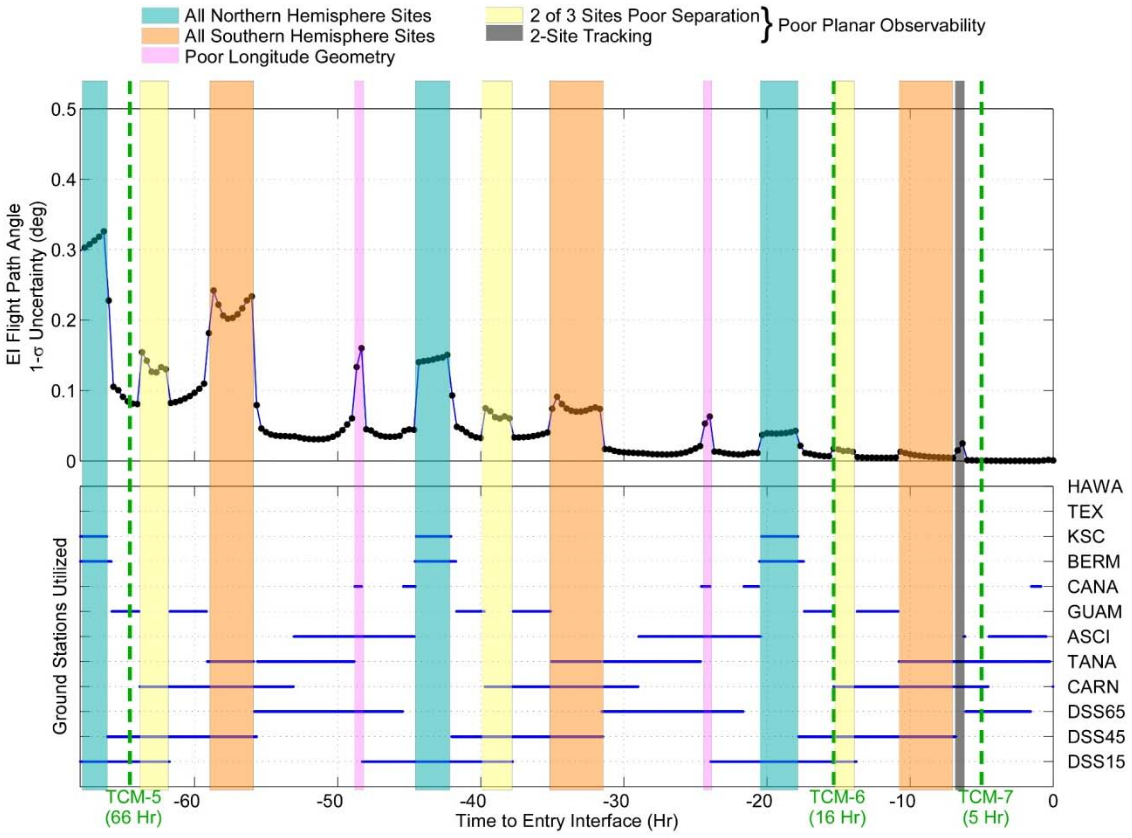
A noisy acceleration environment makes navigation challenging.



One of the more unique aspects for navigation of human spacecraft is the increase in non-conservative forces compared to robotic counterparts.

- Difficult to accurately model for orbit determination

Ground-based radiometric tracking comes at a price.

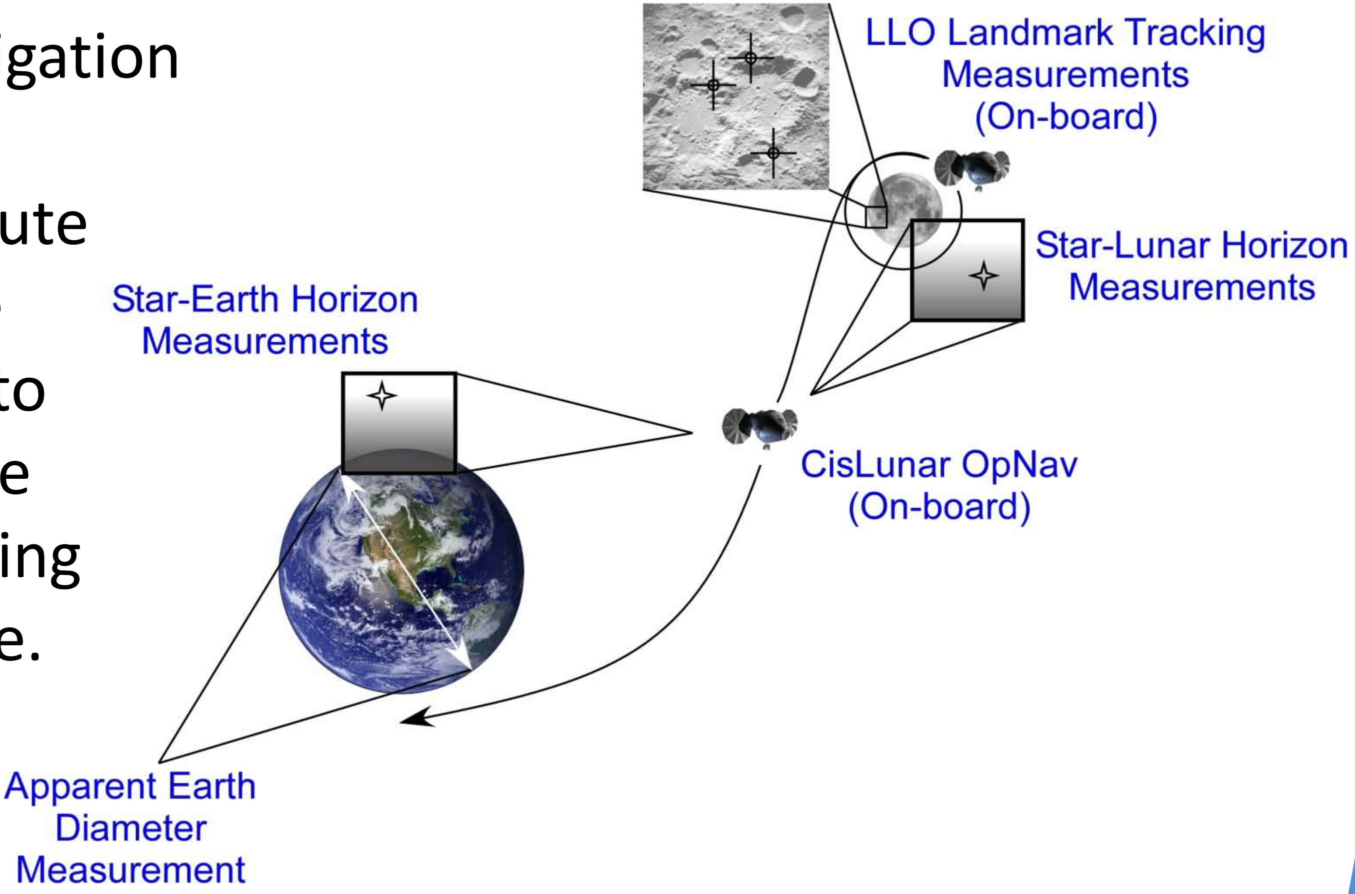


The ability to formulate quality, timely navigation solutions from ground tracking measurements is a function of the duration and geometry of the tracking passes.

Need lots of sites to be prepared for contingencies

Optical navigation reduces the need for ground-based tracking.

A hybrid navigation system could deliver absolute performance comparable to that of a large ground tracking infrastructure.



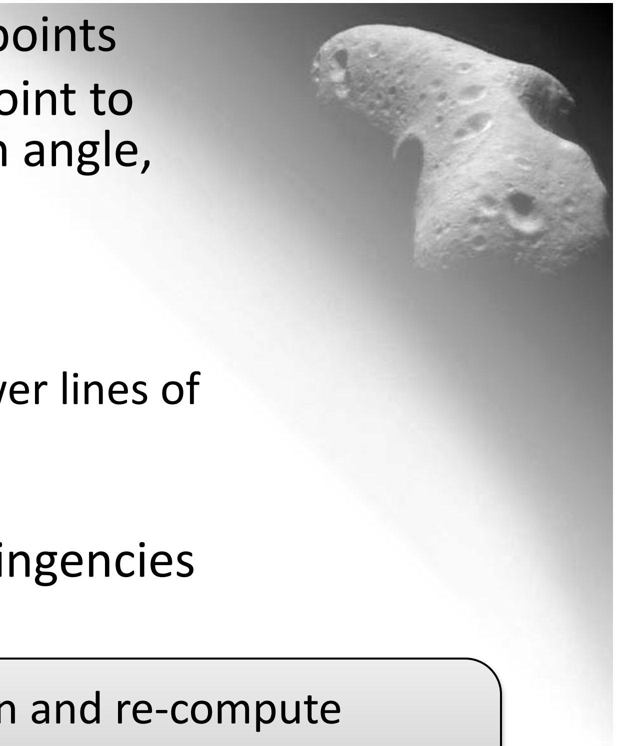
A major difference from most robotic missions is crew return and survival.

- **Maneuver targeting** should strive to achieve crew autonomy for mission success and allow safe return in the event of communication or other failures.

- *Trajectory optimizers* achieve this goal but have disadvantages.
  - Difficult to use, far too many input parameters for efficient crew interaction
  - Difficult and expensive to test and certify (ground or onboard)

- *Ground uplink* of maneuver targets on a burn-by-burn basis offers no autonomy.
  - No reliable targeting if communication is lost
  - No insight to the crew of upcoming trajectory events

The two-level targeting algorithm offers a medium between those extremes.



- Uplink a reference trajectory defined by patch points
- Update the epoch and position of each patch point to meet constraints (velocity continuity, flight path angle, altitude, etc.)

- Not an optimizer, but…
  - quality solutions, easy to use, requires much fewer lines of code, easily implemented (even onboard)

- Additional trajectories can be uplinked for contingencies

Easy for the crew to change the time of the burn and re-compute targets based on the patch points (push button). The newly generated trajectory would be very close to the original optimum solution.

A NEO “landing” is far more like a rendezvous and docking.

The technology, tools, and crew procedures of present ISS rendezvous and proximity operations are directly applicable to NEO rendezvous operations.

A phased "approach" can be used to "approach" the NEO.

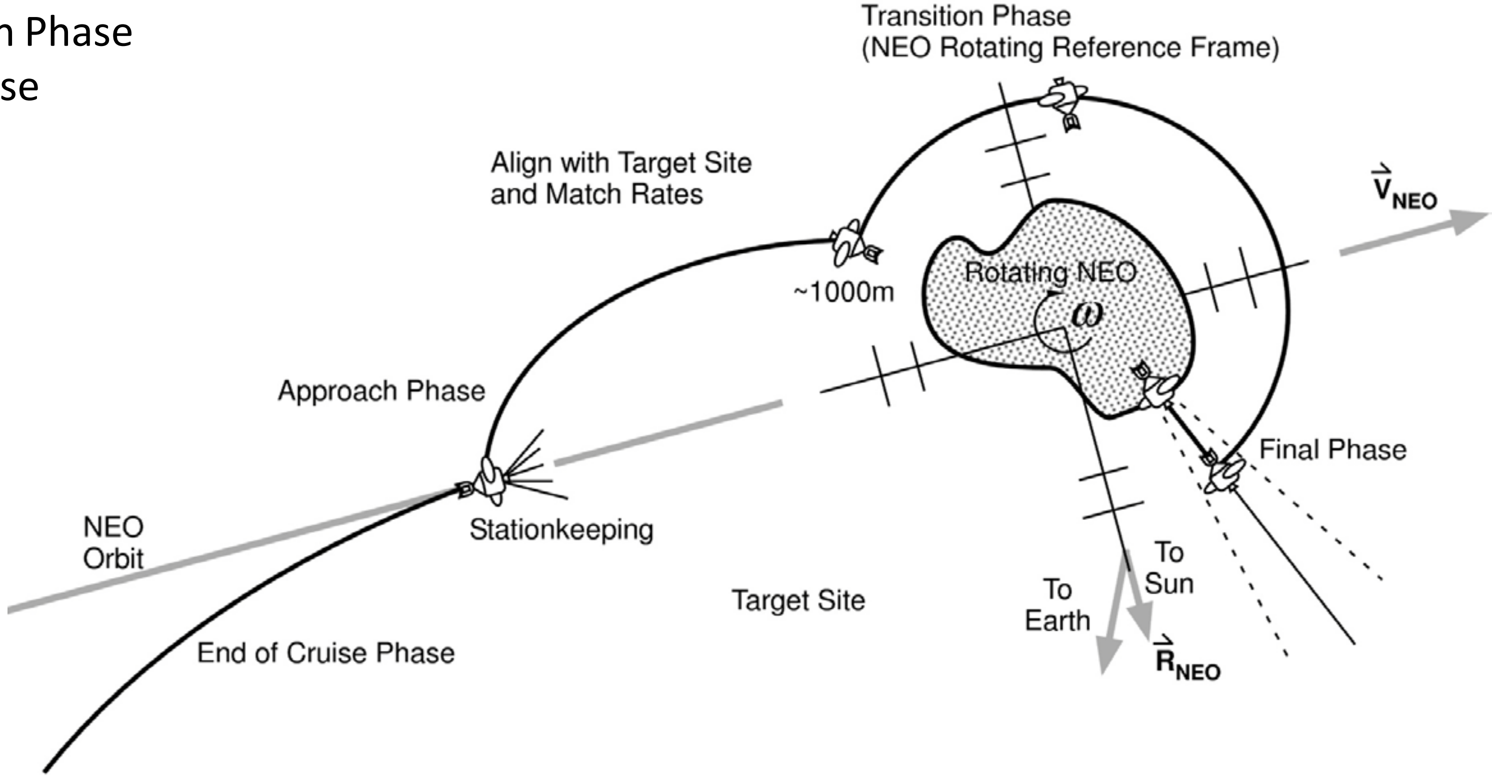
A four-phase manned NEO rendezvous offers a high-precision and stable approach.

-End of Cruise Phase

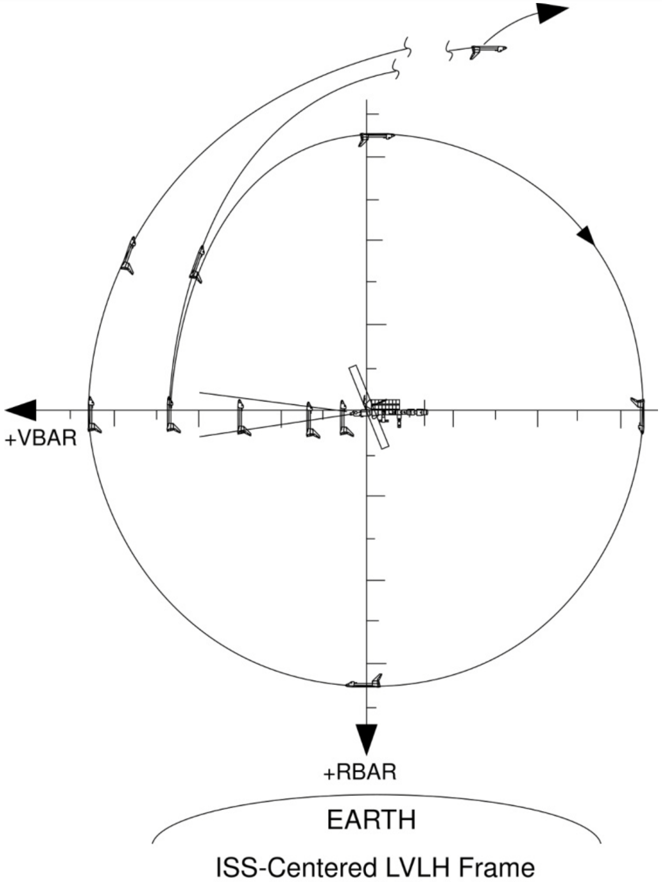
-Approach Phase

-Transition Phase

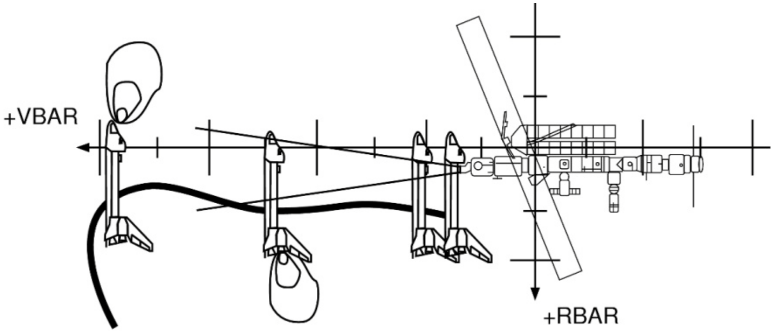
-Final Phase



Maintaining correct orientation with respect to the NEO is challenging.

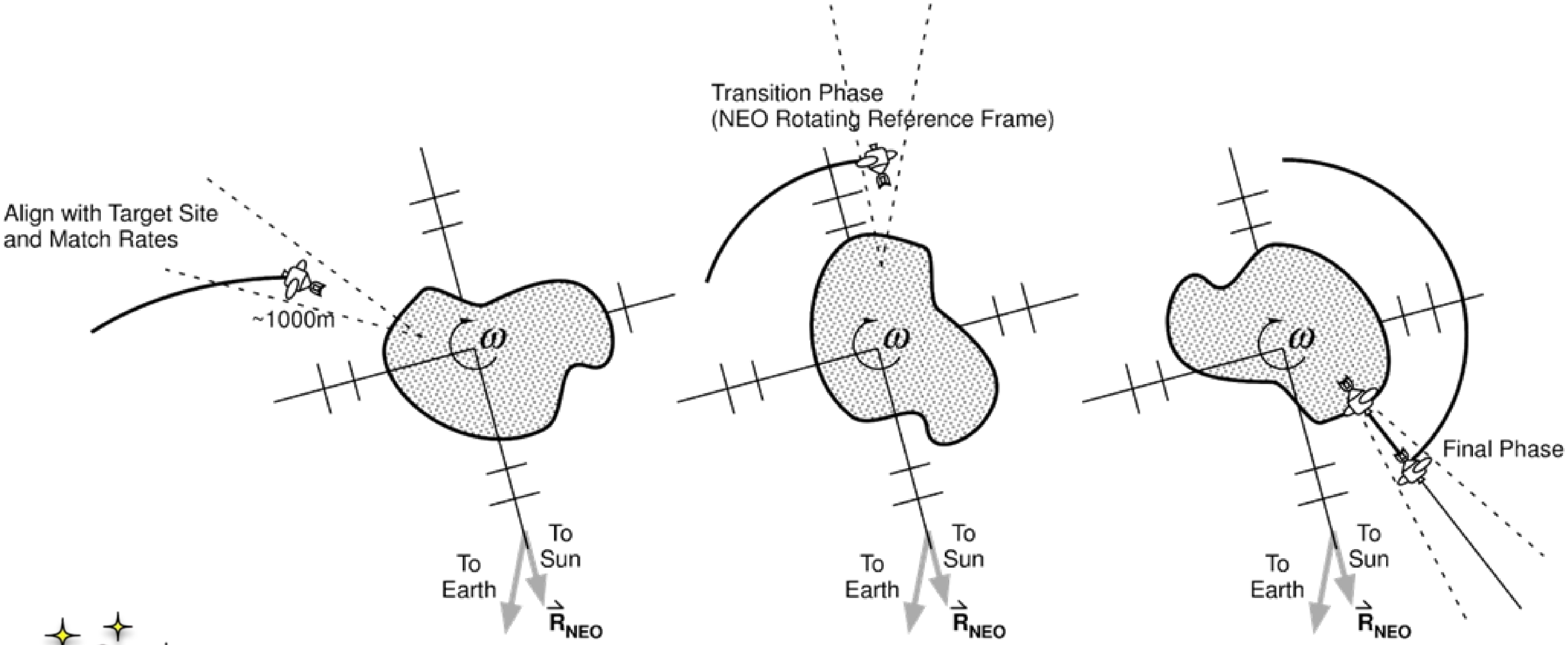


But it is similar to the Twice Orbital Rate Flyaround technique accomplished today with the ISS.



Each phase brings the spacecraft closer to the NEO contact point.

The approach occurs in a controlled manner so as to maximize crew safety in the event of system failures.



Many aspects of NEO rendezvous are already familiar.

Attitude matching, approach corridors, controlled approaches, and docking targets are all in use today.

The experiences gained during ISS missions will be instrumental in training future crews for their rendezvous with a NEO.