# Strengthening U.S. Exploration Policy via Human Expeditions to Near-Earth Objects


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by
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**Abstract**

By conducting a series of piloted Near-Earth Object (NEO) missions beginning about 2020, the U.S. will reinforce the scientific, economic, programmatic, operations, planetary defense, and public outreach elements of its human exploration program. Astronauts exploring a NEO would provide synergistic scientific return from a new "planetary" surface, substantially different in origin, age, and composition from those of the Moon or Mars. Explorers would assay NEO resources vital to future U.S. economic activity in space, and demonstrate extraction and utilization techniques for water, volatiles, and valuable metals. Piloted missions will also provide structural and civil engineering data needed for future deflection of hazardous NEOs. Impact prevention is a common sense, "know your enemy" mission for human explorers; the public will support space-based efforts to better understand and prevent a damaging NEO collision with Earth. Astronaut expeditions to NEOs offer dramatic, high-profile opportunities to engage the public in ground-breaking exploration more than a million miles from Earth. Finally, in the event U.S. plans for a lunar return are delayed, NEOs offer a challenging suite of alternative destinations. Easier to reach than the Moon's surface, NEOs will nevertheless broaden U.S. space capabilities, demonstrate a firm commitment to ambitious human space activities, and increase momentum toward the eventual exploration of Mars.

## Introduction

The report of the 2009 Augustine Committee, reviewing future U.S. human spaceflight plans, included Near-Earth Objects (NEOs) as high-profile destinations for astronauts in several of its options for deep space exploration (Review, 2009). A team commissioned by NASA's Constellation Program (CxP) in 2006 examined the feasibility of sending an Orion spacecraft with crew to accessible NEOs, and work continues on mission operations concepts and possible flight profiles to nearby asteroids (Abell *et al*, 2007; Korsmeyer *et al*, 2007). The team concluded in 2007 that NASA's planned Orion crew exploration vehicle can support a crew of two or three on NEO expeditions lasting several months. Upon reaching the NEO, astronauts would conduct up to two weeks of extensive surface exploration. Initial reconnaissance from orbit could be followed by a gentle "berthing" of Orion at a number of NEO surface sites. Spacewalking astronauts would emplace instrument packages, demonstrate resource extraction, and return carefully selected, pristine samples from the asteroid to the crew module. Several expeditions to different NEOs might be mounted over the course of a decade.

The Earth orbits amid a swarm of near-Earth objects, with more than 6000 cataloged by mid-2009. Most are small, rocky asteroids, but some short-period comets are also included in the NEO population. Current estimates are that there are more than 100,000

NEOs greater than 140 m in diameter (NASA JPL, 2007). Tens of thousands of such objects are at least 500 m in diameter, like the NEO Itokawa, visited in 2005 by the Japanese *Hayabusa* spacecraft. Some 540 m across, even the diminutive Itokawa has a surface area about the size of Vatican City. A sizeable fraction of the NEO population, probably exceeding 20,000, comes closer than 0.05 AU to Earth; these are termed potentially hazardous objects (PHOs). By virtue of their regular approaches to Earth, these objects represent a rich suite of exploration destinations for both robots and astronauts (Jones *et al*, 2002).

**Accessibility**

More important than close approach distance as a measure of accessibility is the total ΔV required for a round-trip mission. A small number of NEOs with Earth-like heliocentric orbits (semi-major axis near 1 AU, low eccentricity and low ecliptic inclination) offer round-trip ΔVs lower than that of a round trip to the lunar surface (~ 9 km/sec). A round-trip voyage to 1999 $AO_{10}$, for example, requires only 7.2 km/sec of velocity change in 2025/2026. The 2007 NASA study found that a handful of cataloged NEOs were within the ΔV capabilities of the Constellation vehicles between 2020-2035. Nine NEOs listed in the 2006 catalog could be reached with round-trip times anywhere from 150 to 180 days (assuming a 14-day stay at the asteroid). As ground-based NEO search capabilities increase, that potential target set should increase to several dozen objects. Because the NEO population is dominated by smaller objects, most practical targets will be just a few hundred meters in diameter.

**Launch Vehicles**

The NASA study examined combinations of existing or proposed launch vehicles that could enable a piloted NEO mission. The lunar architecture comprising a paired launch of Ares I and Ares V boosters has enough performance to reach a favorable NEO target. So could a pair of Ares V boosters, one carrying an Orion vehicle and crew. Both combinations would use Earth-orbit rendezvous to mate the departure stage and crew vehicle before trans-NEO injection.

Another option is a single, human-rated Ares IV or Ares V, capable of injecting an Orion vehicle and crew directly to a NEO in one launch. For the most favorable NEO targets, a Centaur upper stage lofted by an expendable launcher (e.g. Atlas V or Delta IV) could be paired with an Ares I/Orion launch, but a heavy cargo vehicle provides the largest Earth departure stage and therefore a wider range of possible targets.

**Spacecraft**

The Orion crew exploration vehicle is capable of supporting a two- or three-person crew on a multi-month NEO mission. The 2007 NASA study examined the proposed Orion design (which passed preliminary design review in August 2009), and found that few changes would be required for Orion to perform a NEO mission profile. The Orion telecommunications system can function out to at least 6 million km from Earth. Because the Orion would target a NEO relatively close to Earth, at essentially 1 AU, the planned photovoltaic/battery power system will perform adequately. By reducing the crew size to 3 or even 2 astronauts, volume normally taken up by extra seats and spacesuits becomes available for consumable storage.

Consumables are the limiting logistical factor for a NEO mission, but because Orion has some 2.5 times the internal volume of the Apollo command module, it has much greater stowage capacity. Orion has sufficient food, water, and waste stowage volume to support two or three crewmembers for at least 90 days, and in some cases up to 150 days. Additional stowage volume for the mission could come from an inflatable or ISS-derived module launched as payload, then docked to Orion in Earth orbit or after NEO injection. Recent studies by Orion's prime contractor, Lockheed Martin, propose that two Orion spacecraft, launched separately and docked nose-to-nose, could perform a NEO mission, providing system redundancy and much added living and storage volume.

Orion life support systems, although designed for six months in orbit at Earth or Moon, will require additional qualification testing for sustained operation on long-duration NEO flights. Other upgrades include better moisture collection capacity and more consumables and spares (e.g. $CO_2$ absorption canisters or catalyst beds).

As sized for lunar missions, the Orion service module can provide about 1 km/sec $\Delta V$ for NEO missions. Augmenting the service module (by stretching or adding propellant tanks) to provide up to 3 km/sec would bring substantially more NEOs within reach.

**Mission Profile**

The typical NEO mission profile would inject an Orion spacecraft in a single or dual launch toward the target NEO. The Orion would dock with any habitation or propulsion module and pull it free from the Earth departure stage, beginning a 20- to 75-day outbound cruise phase. The crew would use the extra volume docked to Orion's nose for exercise and access to extravehicular activity (EVA) suits and supplies. This volume would also store waste and function as an airlock during the exploration phase.

The 7- to 14-day exploration phase begins with the Orion service module performing the rendezvous burn to enter an orbit around the NEO. Remote sensing using instruments carried in the Orion science bay would be followed by descent to a lower orbit, ending in proximity operations just above or on the NEO surface (Abell *et al*, 2009). After instrument placement, sample collection, and resource extraction demonstrations, the crew would depart the NEO using reaction control thrusters, then use the Orion service module engine or an added propulsion module for trans-Earth injection.

The Earth cruise phase would last about 45 days. Just before entry, the crew would jettison the Orion service module and any docked modules. Direct entry into Earth's atmosphere would be at < 12 km/sec, within Orion heat shield design margins. Parachute landing and recovery would be the same as on a lunar return.

**Feasibility of NEO Missions**

The NASA 2007 study concluded that piloted missions to a NEO are within the capability of spacecraft and launch vehicles planned for the next generation of human spaceflight. The combination of NEO accessibility (near-Earth objects are the most accessible of solar system destinations) and the planned development of a heavy-lift cargo capability creates an opportunity for these missions that has not existed since the close of the Apollo program (Smith, 1966).

Turning the NEO opportunity into a real mission depends, of course, on the actual emergence of a beyond-LEO spaceflight capability and a sufficient number of accessible NEO targets. The Obama administration will decide in the coming months whether the U.S. will develop the ability to send human explorers beyond the ISS. Ground-based NEO surveys to date have identified only a handful of asteroids that Orion can reach between 2015 and 2035, but the expansion of those programs should generate more suitable targets.

Between 2015 and 2020, the advent of the Large Synoptic Survey Telescope and the PanSTARRS NEO detection systems should increase the discovery rate by a factor of ~40. The resulting growth in numbers of accessible NEOs should enable NASA, between 2020 and 2035, to conduct 90- to 180-day Constellation-based missions. NASA's Jet Propulsion Lab is currently examining the catalog of recent NEO discoveries to search for suitable targets. Search criteria include the latest Ares V performance figures and those NEOs with round-trip mission durations up to 360 days.

## Operations

NEO missions will strengthen U.S. space policy by providing a dramatic demonstration of a robust deep-space exploration capability. By using its Constellation architecture to access NEOs, NASA will show the adaptability of its capabilities to reach not just the Moon but a variety of destinations.

NEO mission requirements are such that once the U.S. (re-)develops a piloted lunar orbit capability, it will also have in hand the capacity to access NEOs. In contrast to lunar surface exploration, NEO missions will require no expensive lander, large mobility systems, or habitation development.

Executing a series of NEO expeditions will create a wealth of deep-space operations experience at distances well beyond the Moon. Light-time communications delays of 10-20 seconds will force a high degree of autonomy in mission operations. Flight control and planning functions will operate in an entirely new regime, departing from habits developed in decades of shuttle and ISS operations in LEO. The spacecraft and crew must deal with maneuvers and acute emergencies in real-time, with the control center providing in-depth troubleshooting and analysis.

## Programmatics

Planning and executing NEO missions will require close coordination between NASA's operations, science, and exploration directorates. By engaging the full capabilities of its premier organizations, NASA will be able to sustain program momentum as it prepares for the eventual human exploration of Mars. Under this NEO stepping-stone approach, steadily increasing mission duration, distance from Earth, and science capabilities will help retire technical and operations risk. NEO missions are thus analogous to the *Apollo 8* and *Apollo 10* rehearsals for the successful *Apollo 11* lunar landing, serving as shakedown cruises for spacecraft systems like propulsion, life support, communications, EVA, and command and control.

A sustainable human exploration strategy must achieve identifiable milestones over several political administrations; a series of NEO missions will produce a steadily increasing level of scientific returns and operations experience, building toward eventual Mars exploration. Such achievements serve as a bridge between a lunar return and the much-more-difficult challenges of Mars exploration. Visiting NEOs should sustain political momentum and public engagement in the space effort during the decade or more required to mature a human Mars exploration capability.

**Science**

One of the policy benefits of undertaking piloted NEO exploration is the addition of a unique class of scientific returns to the human exploration program (Abell *et al*., 2009). NEO explorers will investigate the nature of "proto-planets" vastly different from the highly differentiated and geologically processed surfaces of the Moon or Mars. NEO surfaces consist of ancient, largely unaltered material from the era of planet formation 4.6 billion years ago. Orion crews will conduct remote sensing from NEO orbit, and deploy a telerobotic craft to reconnoiter the surface. Once on the surface, the crew would intelligently sample the surface and package ~100 kg for return to Earth, leaving behind long-lived science packages and proof-of-concept resource extraction hardware.

Robotic exploration, by contrast, is a measured process that will take decades to match the data returned from a few piloted missions. An Orion crew can accomplish rapid, in-depth exploration, from remote sensing, from telerobotic reconnaissance, and through extensive EVA sampling of the surface.

Sending astronauts to asteroids would showcase the capabilities of humans as field explorers: physical dexterity, problem-solving capacity, and ability to react in real-time to changing circumstances. A piloted Orion would enable rapid access to multiple sites on the asteroid, using multiple spacewalks for high-value field investigation. The crew could quickly select the best sampling technique to collect a macroscopic suite of materials, each documented in "NEO-logical" context. Compared to the pace and returned data from robotic missions, piloted NEO expeditions would represent a large, rapid increase in our understanding of these enigmatic, ancient objects. A combined robotic and human NEO exploration campaign would be a model for future investigations of Phobos, Deimos, Mars, and eventually Main Belt asteroids. Although human NEO exploration is not justified solely by scientific benefits, inclusion of several well-chosen asteroids as human spaceflight destinations will dramatically increase its overall science return. Astronaut exploration of one or more NEOs is certain to deliver surprising discoveries.

**Cooperation**

The technological, scientific and operations challenges of NEO expeditions will provide opportunities for NASA to collaborate with its international partners and/or commercial providers of hardware and logistical services. As in the International Space

Station program, international partners could augment the size and capabilities of NASA's Orion crew exploration vehicle. For example, Ariane V could boost an Earth departure stage to LEO, or Japan could supply an ISS-derived habitat module for the mission's cruise phase. Partner agencies could design, test, and launch robotic precursors for the exploration campaign, or deliver scientific or resource extraction packages for emplacement on a NEO. Commercial firms could launch propellant tankers for Earth departure, or adapt inflatable habitat technologies to provide Orion with an airlock or added living space. In return, NASA could offer to an international partner an astronaut assignment on one or more NEO expeditions, adding a highly visible international dimension to the flight.

**Planetary Defense**

Investigation of the interior structure of a variety of NEOs will build the physical properties and civil engineering knowledge required for a future deflection campaign. Just as valuable will be acquisition of extensive operations experience around NEOs of varying size, density, rotation state, and mechanical properties. To prevent a future impact, we should determine to know our "enemy," employing our best explorers – human beings – to prepare us for the inevitable NEO collision threat. Recognizing that survival is a simple but powerful motivator of human endeavor, the space program could provide few greater legacies than the prevention of a future cosmic catastrophe.

**Public Engagement**

NEO missions add new and dramatic exploration opportunities to our program of deep-space exploration. Modern communications will enable the public to join astronauts in the exploration of an exotic asteroid surface, millions of km from Earth. The alien NEO surface and striking views of our distant home will combine to create a powerful visual impact. For most of the world's population, that experience will be reinforced by their first experience at seeing humans visit another celestial body.

**Conclusions**

Piloted Near-Earth Object expeditions, beginning in about 2020, represent major advantages to the U.S. human spaceflight program. Such missions will reinforce the scientific, operational, programmatic, planetary defense, collaborative, and public outreach strengths of the program.

Sending Orion crews to several NEOs would take advantage of the unique flexibility and adaptability of human explorers. Astronaut explorers would provide synergistic scientific return from a “new” planetary surface, substantially different in origin, age, and composition from those of the Moon or Mars. Explorers would assay a variety of NEO resources vital to future U.S. economic activity in space. Crews could also emplace and demonstrate key technologies for recovering water, other volatiles, and valuable metals from NEOs.

Piloted missions will provide data on the physical properties, interior structure, and civil engineering aspects of NEOs, preparing us for a future deflection of a hazardous NEO. The application of our spaceflight technology to a potential Earth impactor is a common-sense, "know your enemy" mission for our exploration program, one strongly supported by the public.

NEO missions will result in steady growth in our operations experience, with each NEO visited adding to our deep-space abilities and reducing the technical and biomedical risks of future long-duration voyages. A sequence of missions of steadily increasing duration and difficulty will also demonstrate solid progress over a decade or more, sustaining public, executive, and legislative support across many political cycles.

The Augustine Committee was attracted to the affordability and practicality of using NEOs as part of a "flexible path" to beyond-LEO exploration. If the present administration directs NASA to defer a lunar return, NEOs provide the U.S. with an accessible but exciting set of alternative destinations. More accessible than the Moon, NEOs will nevertheless stretch our capabilities and demonstrate a firm U.S. commitment to ambitious human space exploration. Experience gained near and on the Moon, complemented by true deep-space expeditions to NEOs, will serve the U.S. and its partners well as we plan for the eventual exploration of Mars.

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