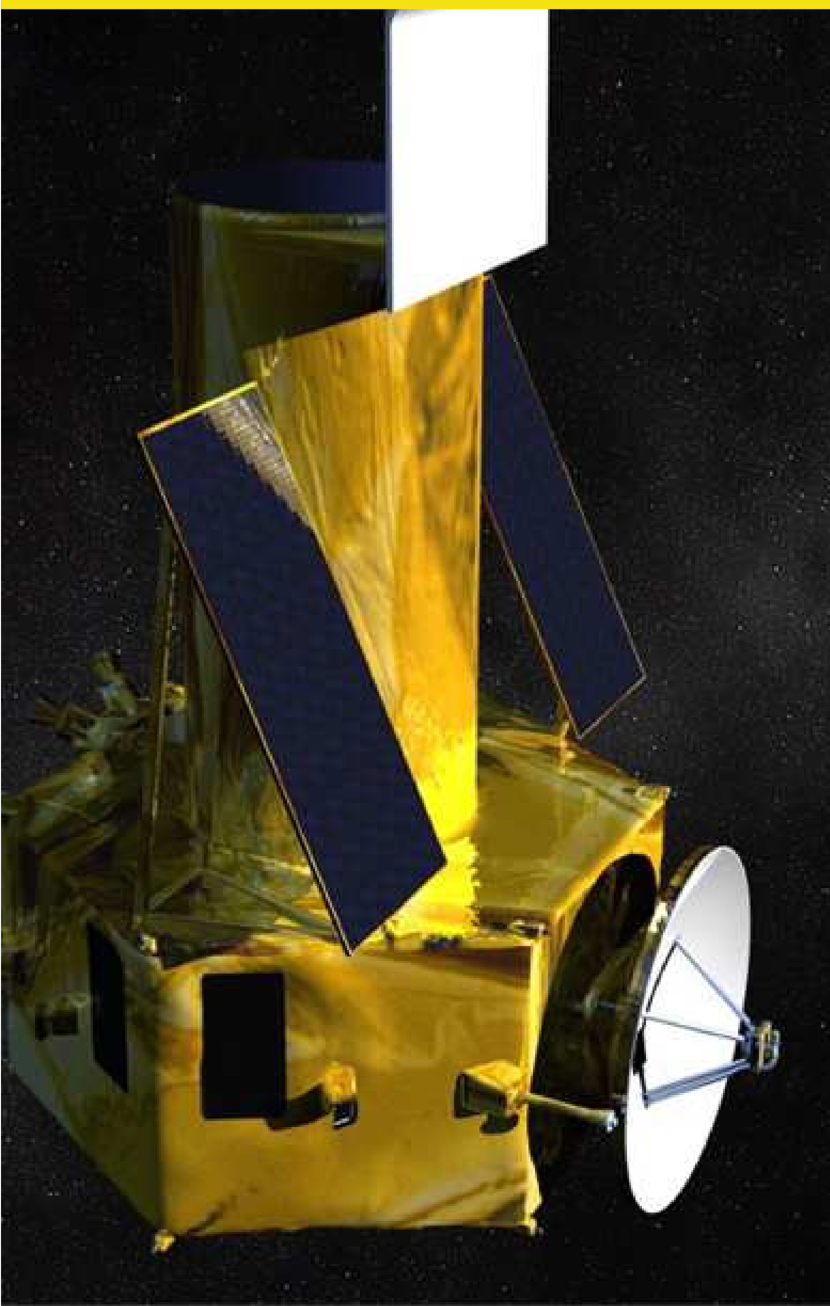
Target NEO: Open Global Community NEO Workshop Report



Target NEO: Open Global Community NEO Workshop Report

April 25, 2011

George Washington University, Washington, D.C.

February 22, 2011

Acknowledgments

The session co-chairs, who authored this report, wish to extend their gratitude to all of the workshop panelists and participants, whose willingness to share their expertise made the workshop–and this report–possible.

Introduction, Workshop Scope, Overview of Flexible Path Vision

Moderator:

John Logsdon, George Washington University

Panel:

Thomas Jones, Florida Institute for Human & Machine Cognition
Scott Pace, George Washington University
Dave Korsmeyer, NASA-ARC

The NEO Population: Knowns and Unknowns

Co-chairs:

Andy Cheng, JHUAPL
Lindley Johnson, NASA HQ

Panel:

Tim Spahr, MPC
Don Yeomans, JPL
Scott Stuart, MIT Lincoln Laboratory
Amy Mainzer, JPL
Al Harris, Consultant

Mission Design: Getting There and Back

Co-chairs:

Brent Barbee, NASA-GSFC
Dan Adamo, Astrodynamics Consultant (NASA-JSC, ret.)

Panel:

Damon Landau, JPL
Bret Drake, NASA-JSC
Ron Mink, NASA-GSFC
Josh Hopkins, Lockheed-Martin Space Systems Company
Chel Stromgren, SAIC

NEO Characteristics for Safe and Meaningful Human Exploration

Co-chairs:

Andy Rivkin, JHUAPL
Paul Abell, NASA-JSC

Panel:

Patrick Michel, CNRS, Cote d'Azur Observatory
Lance Benner, JPL
Joe Nuth, NASA-GSFC
Dan Scheeres, University of Colorado
Mike Hess, NASA-JSC

Mission Duration: Quantifying the Risks

Co-chairs:

Dan Mazanek, NASA-LaRC
Rob Landis, NASA-ARC/JSC

Panel:

Craig Kundrot, NASA-JSC
Jack Stuster, Anacapa Sciences, Inc.
Ron Turner, ANSER
Andy Thomas, NASA-JSC

Affordable Options for Increasing the Accessible NEO Catalog

Co-chairs:

Rich Dissly, Ball Aerospace
Ken Hibbard, JHUAPL

Panel:

Andy Cheng, JHUAPL
Lynne Jones, University of Washington
Ken Hibbard, JHUAPL
Amy Mainzer, JPL
Robert Arentz, Ball Aerospace

NASA HQ Feedback on Workshop Discussions

Co-chairs:

James Garvin, NASA-GSFC
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Panel:

Charles Gay, NASA HQ
Sam Scimemi, NASA HQ
Benjamin Neumann, NASA HQ

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Executive Summary

The Open Global Community NEO Workshop was held on February 22nd, 2011, at George Washington University in Washington, D.C., to bring together experts for a technical discussion of the key issues surrounding human exploration of Near Earth Objects (NEOs). The workshop addressed the following questions: Are there enough known, potentially accessible NEOs to support a robust, resilient, forward-looking, and affordable human exploration program beyond Low Earth Orbit (LEO) over the next two decades? What are the knowns and unknowns in the context of human exploration of NEOs? Is the missing information critical or optional? What is the timescale on which critical missing information must be acquired? What level of effort and what resources are necessary to resolve outstanding issues? And, finally, what is the community consensus regarding the costs and benefits of resolving these issues?

The workshop consisted of five technical sessions in which expert speakers presented the latest research and results on the relevant topics and then participated in question-and-answer sessions during panel discussions. The speakers consisted of domestically and internationally recognized small body experts in both the robotic and Human Space Flight (HSF) communities, including small body scientists and related analytical and operational experts, mission designers, systems engineers, and experts in mission operations, safety, and human health factors such as radiation. The following is a summary of those proceedings.

While ongoing ground-based surveys and data archives maintained by the NEO Program Office and the Minor Planet Center have provided a solid basis to build upon, a more complete catalog of the NEO population is required to inform a robust and sustainable HSF exploration program. The currently known low change-in-velocity (Δv), short-duration HSF mission opportunities to NEOs, with sufficient lead time to plan and launch crew toward their destinations, are few and far between.

The paucity of viable candidate destination NEOs can be attributed to the fact that NEO observing assets are currently confined to Earth's vicinity. Historical analysis of past trajectory opportunities to NEOs has shown that some were highly accessible during the timeframes of their discovery, because they had to closely approach Earth in order to be discovered.

Assuming that only a small percentage of the total NEO population potentially accessible to HSF is currently known, a better return on investment is realized by a comprehensive NEO survey based in deep space, as opposed to an augmented HSF capability providing greater NEO access, because a dedicated NEO survey will increase the number of known HSF-accessible targets by at least an order of magnitude.

To this end, there exist today multiple mature space-based survey concepts, many of which have cost estimates within the cost range of Discovery-class space missions. However, the existing survey concept capabilities and costs have had minimal intercomparison to date; they may not be using the same metrics and assumptions, especially in the area of required data processing. This disparity could be rectified through formal intercomparisons of capabilities and cost using a common set of assumptions regarding undiscovered NEO population parameters and survey completion metrics, thus providing an objective assessment of the range of available survey options.

Of course, discovery alone is insufficient; the sizes and heliocentric orbits of many known NEOs are so uncertain that they will be very difficult to find, observe, and effectively characterize to determine their suitability as targets for human exploration. Follow-up observations are needed after discovery to obtain sufficiently accurate orbit determination. Focused efforts with dedicated ground assets and future space-based assets could greatly reduce unknowns about the NEO population within 10 years.

NEOs show a wide range of diversity in their physical characteristics, and while some of this diversity is well understood from existing data, further studies are required to help constrain the envelope of NEO physical characteristics that will drive development of systems and operational concepts for future human exploration.

Characterization of candidate NEO targets should therefore include information directly relevant for human exploration needs. While some of that information can be gleaned from Earth-based techniques such as reflectance spectroscopy, radar experiments, lightcurve measurements, and so on, robotic precursor missions are required for some critical characterization details that can only be obtained *in situ*, such as the response of the NEO surface to disturbances, debris hazards in the NEO's immediate vicinity, geotechnical data, etc.

Even if a set of highly accessible, well-characterized NEOs were already known, the challenges of exploring them safely with humans must still be addressed. Mission duration is a primary factor in risk management for HSF, and mission knowledge beyond six months is limited. Acute and long-term physiological effects from radiation in interplanetary space (solar particle events and galactic cosmic rays) and crew behavioral health support are critical considerations for long-duration missions beyond LEO.

In conclusion, the Open Global Community NEO Workshop has provided substantial technical review and conclusive peer support for NEO precursors, emphasizing that a NEO survey mission is necessary to realize a future human exploration mission to a NEO in the 2025-2035 timeframe. Just as launch vehicles are a critical need for access beyond LEO, so also a space-based survey mission should be considered strategic to the National Aeronautics and Space Administration (NASA), a critical infrastructure asset necessary for focused discovery, cataloging, and characterization of a more complete and robust set of targets for a more comprehensive trade-space for future human NEO missions. This asset will complete the necessary infrastructure, as begun with the available ground-based telescope systems, and is as important as other Agency-wide deep space human mission capabilities to achieve mission success.

To provide a viable, robust target set, a space-based survey system should be commissioned on-orbit approximately a decade before the planned human flight to a NEO. A system of adequate operational life (5 to 10 years) can be provided reliably, using full and open competition, for the approximate cost of a Discovery-class mission. Further, but quite notable, this affordable system could also satisfy the intent of the Congressional direction to NASA for Planetary Defense as reviewed by the National Research Council (NRC), will provide a rich data set pertinent to ground-breaking studies of solar system evolution and interaction for the broader scientific community, and is hugely relevant to the global public in providing significant return on investment for the taxpayer by providing human spaceflight capability, addressing hazards to life here on Earth, and doing more exploration for less.

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1 Introduction

The 2009 Augustine Committee reviewed the future U.S. human spaceflight program, with the ultimate goal of extending human presence into the solar system, beyond Low Earth Orbit (LEO), the Moon, and ultimately to Mars. Their report, which fed into the new Administration's vision, crafted a "flexible path approach" to achieve these goals. The flexible path includes numerous destinations, and Near Earth Objects (NEOs), in particular, have emerged as a likely first destination.

The Open Global Community NEO Workshop was held on February 22nd, 2011, at George Washington University in Washington, D.C., to bring together experts for a technical discussion of the key issues surrounding human exploration of Near Earth Objects (NEOs). The workshop addressed the following questions: Are there enough known, potentially accessible NEOs to support a robust, resilient, forward-looking, and affordable human exploration program beyond Low Earth Orbit (LEO) over the next two decades? What are the knowns and unknowns in the context of human exploration of NEOs? Is the missing information critical or optional? What is the timescale on which critical missing information must be acquired? What level of effort and what resources are necessary to resolve outstanding issues? And, finally, what is the community consensus regarding the costs and benefits of resolving these issues?

The workshop consisted of five technical sessions in which expert speakers presented the latest research and results on the relevant topics and then participated in question-and-answer sessions during panel discussions. The speakers consisted of domestically and internationally recognized small body experts in both the robotic and Human Space Flight (HSF) communities, including small body scientists and related analytical and operational experts, mission designers, systems engineers, and experts in mission operations, safety, and human health factors such as radiation.

2 The NEO Population: Knowns and Unknowns

This panel session was chaired by **Andy Cheng** (Chief Scientist in the Space Department at the The Johns Hopkins University Applied Physics Laboratory) and **Lindley Johnson** (Lead Program Executive for the Discovery Program and Program Executive for the Near Earth Object Observations Program, NASA Headquarters (HQ)) and consisted of the following members:

- **Tim Spahr**, Director of the Minor Planet Center, Smithsonian Astrophysical Observatory
- **Don Yeomans**, Program Scientist / Manager, NASA NEO Program Office, Jet Propulsion Laboratory
- **Scott Stuart**, Deputy PI, LINEAR, Massachusetts Institute of Technology Lincoln Laboratory
- **Amy Mainzer**, WISE Deputy Project Scientist, Jet Propulsion Laboratory
- **Al Harris**, NEO Population Studies, Consultant

This session reviewed the current understanding of the NEO population and the status of NEO observational programs funded by NASA. With the nation's announced goal of sending a human mission to a NEO by 2025, the population of these objects and their distribution in orbital element space has become a critical issue. Although more than 7,800 NEOs are known as of March 2011, the numbers and physical characteristics of the NEOs in extremely Earth-like orbits, which tend to be the NEOs most accessible for human exploration, are uncertain because only a small fraction of the population has been discovered and tracked.

The status of ongoing NEO observational survey programs was reviewed. These include ground-based telescopic surveys and a space-based telescopic search and characterization program. The session also presented the status of NEO database and archive facilities, as well as our present understanding of the NEO population.

2.1 NEO Monitoring and Publication of Results

The Minor Planet Center (MPC) at the Smithsonian Astrophysical Observatory (SAO) is granted authority by the International Astronomical Union (IAU) but is funded by the NASA Near Earth Object Observations Program. The MPC processes and publishes positional observations of Solar System objects from all observatories around the world. It maintains a Web-accessible orbit database that includes asteroids, comets, outer Jovian satellites, Centaurs, and Trans-Neptunian Objects (TNOs). It receives daily observations of minor planets and releases daily updates of NEO observations. It also publishes rapid alerts of interesting NEO discoveries within hours of initial observational reports. The MPC is prepared to process the data volume from next-generation NEO surveys.

The NEO Program Office at the Jet Propulsion Laboratory (JPL) coordinates the NEO observation program for NASA. It provides a precision orbit determination service, maintains a Web-accessible database on NEOs, and provides results of automated calculations of NEO close approaches to Earth. The NEO Program Office maintains a collision monitoring system, SENTRY, that examines the current asteroid and comet trajectories for objects that could impact Earth within 100 years or more, updates the orbits and uncertainties of these hazardous objects as new data arrive, and publishes this information on the Web.

2.2 The State of NEO Survey Activities

Ground-based telescopic surveys, such as the Lincoln Near-Earth Asteroid Research (LINEAR) on the White Sands Missile Range near Socorro, New Mexico, have discovered the vast majority of known NEOs. LINEAR demonstrated the application of technology for surveillance of Earth-orbiting satellites to NEO searches, using a pair of 1-m Ground-based Electro-Optical Deep Space Surveillance (GEODSS) telescopes with a limiting visual magnitude of about 20. LINEAR was the most successful search program from 1997 to 2004 and has discovered about 2,400 NEOs. The Catalina Sky Survey (CSS) currently has a higher NEO discovery rate, using a system of three telescopes at the Mt. Lemmon Observatory and the Catalina Observatory (both in Arizona) plus the Siding Spring Observatory in Australia. The Mt. Lemmon telescope is the largest of these and achieves a limiting visual magnitude of 22. With its world-wide geographic distribution, CSS can usually accomplish same-night follow up on newly discovered objects. CSS has discovered about 3,200 NEOs. An additional ground-based survey program, Panoramic Survey Telescope and Rapid

Response System (Pan-STARRS), has recently begun operations with a 1.8 m telescope in Maui, Hawai'i.

A space-based survey mission has just ended successfully, using the Wide-field Infrared Survey Explorer (WISE), a NASA Explorer mission launched in December of 2009 to conduct an all-sky survey in four IR bands (3.3, 4.7, 12, and 23 μm). To accomplish its primary astrophysics mission, WISE used a cooled 0.4-m telescope viewing 90° to the Sun. An extension to the WISE mission was funded by NASA for Solar System science, called Near Earth Object Wide-field Infrared Survey Explorer (NEOWISE), to discover and archive solar system objects in the WISE data. NEOWISE has observed hundreds of NEOs and determined their thermal emissions, which enable determinations of sizes when combined with ground-based observations of the same objects. NEOWISE as a space-based survey is not subject to the same biases as ground-based surveys and therefore provides valuable new information.

2.3 Discovery of NEOs Potentially Accessible for Human Space Flight

As will be discussed in Section 3, only a small number of the known NEOs are found in heliocentric orbits that make them potentially accessible for human exploration. A typical result of trajectory searches in the known NEO database is shown in Table 1; it is based on preliminary surveys [1], where the middle column shows the numbers of potentially accessible targets found in the known database as of mid-2009 versus size. The right column of Table 1 shows the estimated numbers of potential targets in the actual population, which are available to be discovered in a next generation NEO survey. It was noted at the workshop that the vast majority of NEOs with diameters of 150 m or smaller are fast rotators, that most known NEOs under 100 m in diameter are already lost because of their uncertain orbits, and that some objects 50 m or smaller in size may be man-made or lunar ejecta.

Table 1: Estimated Numbers of Targets Potentially Accessible* for Human Exploration

Approximate Diameter	Currently Known	Estimated Total, Actual Population
500 m	0	0
150 m	2	30
100 m	5	200
50 m	5	1500

* NEO accessibility as defined in Ref. 1.

NEOs that are potentially accessible for human exploration are difficult to detect from ground-based telescopes because they spend nearly all of the time, over the course of their orbits, close to the Sun in the sky as seen from Earth. Hence they are usually located in the daytime sky where they cannot be observed. They can be detected from Earth only when they are close to Earth and observable during twilight or night time, and this geometry occurs for any given object only at infrequent intervals, often many decades long. A space-based search would avoid this limitation and could therefore discover NEOs potentially accessible for human exploration much more rapidly.

2.4 Summary of Key Findings

1. The known NEO population is approximately complete for objects ≥ 1 km in size (nearly 90% of such objects have already been discovered). About half of the actual population larger than 400 m is already discovered. However, at smaller sizes the vast majority of NEOs remains unknown. Perhaps only a few percent of NEOs 100 m in size are currently known.

2. Ongoing ground-based surveys and data archives maintained by the NEO Program Office and the MPC provide a solid basis to build upon.

3. A more complete catalog of NEOs will expand the available NEO target catalog and help inform a robust and sustainable human exploration program. A space-based NEO search can provide such an expanded catalog far in advance of when it could be obtained by existing or planned ground-based surveys.

4. Focused efforts with dedicated space-based assets could greatly reduce unknowns about the NEO population within 10 years.

5. The sizes of known NEOs are, in the vast majority of cases, individually uncertain by about a factor of 2. This is a dominant contributor to the uncertainty in the estimated number of NEOs at a given size. NEO sizes can be measured or constrained by various techniques, including thermal infrared, radar, polarimetric, or spectral observations, but such information is unavailable for most known NEOs. Small NEOs < 150 m in size are usually fast rotators, potentially making them inappropriate targets for human missions.

6. The heliocentric orbits of many known NEOs are so uncertain that they are effectively lost (including most known objects under 100 m in size), meaning that they will need to be independently re-discovered in order to refine their orbits. Follow-up observations are needed after NEO discoveries to ensure sufficiently accurate orbit determination in support of human and robotic mission planning.

3 Mission Design: Getting There and Back

This panel session was chaired by **Brent Barbee** (Flight Dynamics Engineer at the NASA NASA's Goddard Space Flight Center (GSFC)) and **Dan Adamo** (Astrodynamics Consultant (NASA-JSC, ret.)) and consisted of the following members:

- **Damon Landau**, Outer Planet Mission Analyst, Jet Propulsion Laboratory
- **Bret Drake**, Exploration Architect, NASA NASA's Johnson Space Center
- **Ron Mink**, Mission Systems Engineer, NASA NASA's Goddard Space Flight Center
- **Josh Hopkins**, Principal Investigator for Advanced Human Exploration Missions, Lockheed-Martin Space Systems Company
- **Chel Stromgren**, Chief Scientist for Strategic Analysis, SAIC

This session examined the current state of knowledge regarding HSF mission design for NEOs, including an overview of the potential accessibility of known NEOs and ongoing research in that regard; the range of total mission Δv, duration, and Earth departure season offered by known NEOs and how that maps to mission mass requirements; how our current understanding of astrodynamic NEO accessibility is related to NEO detection and observation constraints; and launch architecture considerations, particularly with regard to the consequences of relying on multiple launches to perform an HSF mission to a NEO. The basic profile of a round-trip mission to a NEO is shown in Figure 1, with major maneuvers and segment flight times labeled and described.

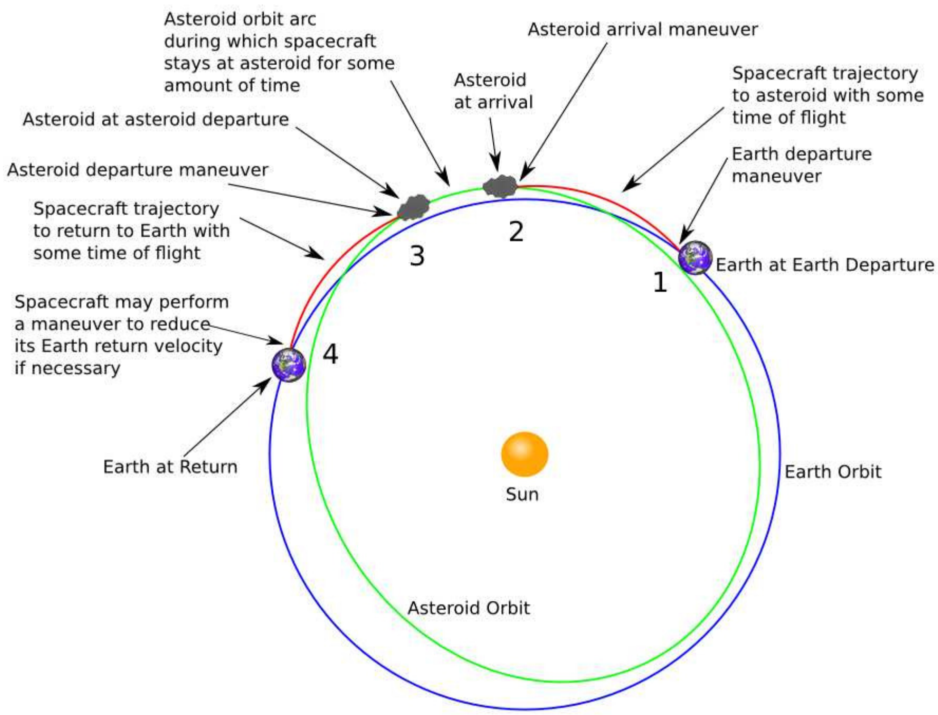


Figure 1: Profile of a Round-Trip HSF Mission to a NEO

Several independent studies have been conducted throughout the past couple of years to analyze the known NEO population in search of those which may be accessible for HSF missions, with particular emphasis on identifying NEOs that offer low Δv, short-duration mission opportunities with Earth departure dates between 2025 and 2030 [1, 2, 3]. Some studies have also explored the utilization of solar electric propulsion for missions to NEOs [4] and other destinations beyond LEO [5]. In September of 2010, NASA began a NEO accessibility survey effort known as the Near Earth Object (NEO) Human Space Flight (HSF) Accessible Targets Study (NHATS). Phase I of the NHATS was completed by the end of September 2010, and Phase II was completed by the beginning of March 2011. The entire known NEO population at the time was processed in both the Phase I and Phase II studies, though the trajectory processing parameters were revised for Phase II. Subsequent phases of the NHATS may be conducted as additional NEOs are discovered.

3.1 The Near Earth Object (NEO) Human Space Flight (HSF) Accessible Targets Study (NHATS)

The NHATS analysis process consists of a trajectory filter and a minimum maximum estimated size. The trajectory filter employs the method of embedded trajectory grids [2] to compute all possible ballistic round-trip mission trajectories to every Near Earth Asteroid (NEA) in the JPL Small-Body Database (SBDB) and stores all solutions that satisfy the trajectory filter criteria. An NEA must offer at least one qualifying trajectory solution to pass the trajectory filter.

The Phase II NHATS filter criteria were purposely chosen to be highly inclusive, requiring Earth departure date between January 1^{st}, 2015, and December 31^{st}, 2040, total round-trip flight time $\leq$ 450 days, stay time at the NEA ≥ 8 days, Earth departure $C_3 \leq 60$ km^2/s^2, total mission $\Delta v \leq 12$ km/s (including an Earth departure maneuver from a 400-km altitude circular parking orbit), and a maximum atmospheric reentry speed of 12 km/s. After determining which NEAs offer at least one trajectory solution meeting the criteria, the estimated size constraint is then imposed, whereby NEAs can be considered NHATS-qualifying NEAs only if their maximum estimated size is ≥ 30 m. This corresponds to an absolute magnitude $H \leq 26.5$ with an assumed albedo $p = 0.05$.

The following is a brief high-level summary of the Phase II study results. Of the 7,665 NEAs in the SBDB as of February 3^{rd}, 2011, 765 NEAs passed the trajectory filter and yielded a total of 79,157,604 trajectory solutions.[1] The trajectory solutions for each NEA are post-processed into Pork Chop Contour (PCC) plots that show total mission Δv as a function of Earth departure date and total mission duration. Although the PCC plots necessarily flatten a very multi-dimensional design space, they permit rapid assessment of the breadth and quality of an NEA's available Earth departure season and clearly indicate the regions of the trajectory design space that warrant further analysis and optimization. The PCC plot for the NEA with the greatest number of NHATS-qualifying trajectory solutions, 2000 SG_{344}, is shown in Figure 2.

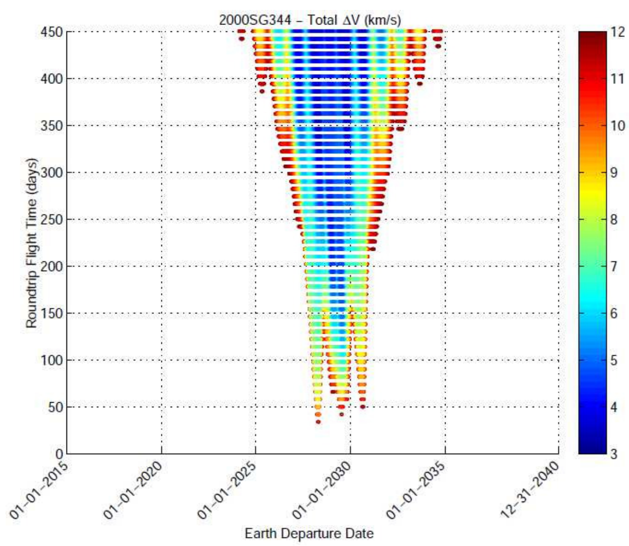
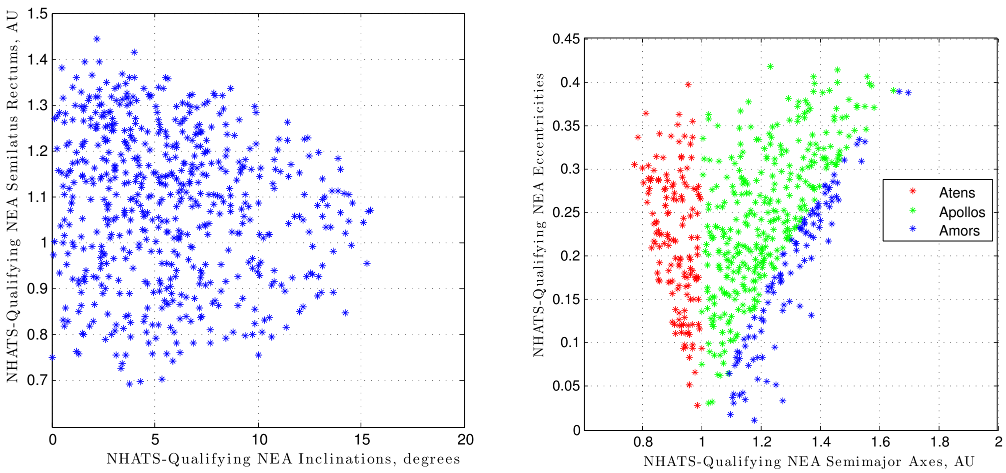


Figure 2: PCC Plot for NEA 2000 SG_{344}

[1]With a trajectory grid step size of 8 days.

Of the 765 NEAs that passed the Phase II trajectory filter, a total of 590 NEAs also satisfied the further constraint of maximum estimated size ≥ 30 m. The distributions of osculating heliocentric orbital semi-major axis (a), eccentricity (e), and inclination (i), for those 590 NEAs are shown in Figures 3(a) and 3(b).[2]



(a) Semi-latus Rectum vs. Inclination

(b) Eccentricity vs. Semi-major Axis

Figure 3: Distribution of the 590 NHATS-Qualifying NEAs in Osculating (a, e, i) Space

To further our understanding of round-trip trajectory accessibility dynamics, it is instructive to examine the distribution of the NHATS-Qualifying NEAs according to orbit classification. NEAs are grouped into four orbit families: Atiras (aphelion $<$ 0.983 AU), Atens (aphelion $>$ 0.983 AU, $a <$ 1.0 AU), Apollos (perihelion $<$ 1.017 AU, $a >$ 1.0 AU), and Amors (1.017 $<$ perihelion $<$ 1.3 AU).

Of the 765 NEAs that satisfied the NHATS trajectory criteria, none are Atiras, 193 are Atens (31% of the known Atens), 456 are Apollos (11% of the known Apollos), and 116 are Amors (4% of the known Amors). While Apollos make up 60% of the NEAs that pass the NHATS trajectory filter and Atens make up only 25%, the percentages according to orbit family are perhaps more relevant. Note that only 11% of the known Apollos passed the trajectory filter, while 31% of the known Atens passed. These simple statistics alone strongly suggest that Aten orbits possess features that tend to enhance their round-trip trajectory accessibility as compared with Apollos or Amors. This is significant because Atens' orbits cause them to spend considerable time in Earth's daytime sky, making them difficult to discover and track using ground-based observing assets.

3.2 NEO Mission Design Challenges

It is important to note once again that the trajectory filter constraints utilized in the NHATS are ***purposely highly inclusive*** and therefore the ***NEAs that pass the NHATS filter are not necessarily accessible for HSF.*** In fact, session proceedings identified multiple technical

[2]Note that the semi-latus rectum used in Figure 3(a) is equal to $a\left(1 - e^2\right)$.

challenges associated with designing HSF missions to NEOs in the next 15 years and beyond. Mission opportunities will proliferate according to the number of known NEOs, HSF capabilities, and desirable NEO characteristics such as size. Because HSF round trips to NEOs typically span distances of ≈ 0.1 AU (≈ 15 million km) or more, mission opportunities with minimal propulsion requirements approaching those of a round trip to lunar orbit ($\Delta v \approx 5$ km/s over ≈ 10 days) are rare if mission duration is to be kept less than 180 days. For example, only four mission opportunities (two of which target the same destination) are known to meet $\Delta v < 5$ km/s and duration < 180 days criteria if Earth departure is required during the years 2025 through 2030.

Nevertheless, HSF missions to NEOs bridge a formidable Flexible Path capability gap between lunar orbit missions and those orbiting Mars ($\Delta v \approx 9$ km/s over ≈ 900 days). A carefully conceived series of progressively more challenging NEO missions to varied and interesting destinations will help bridge this gap.

3.3 Impacts of NEO Detection and Observation Methods on Human Space Flight Opportunities

Since close Earth encounters are necessary for ground-based NEO discoveries and low Δv, short-duration HSF mission opportunities, the most accessible destinations are among those posing potential threats of Earth impact. The current catalog contains 18 NEOs for which HSF mission opportunities with minimal propulsion and duration requirements coincided with their discovery. It should be noted these 18 NEOs were selected on the basis of their Earth-like orbits to serve as existence proofs of highly accessible NEOs being discovered close to their best accessibility seasons. **In practice, any of them could be found unsuitable for HSF due to size, rotation rate, or other qualities, but such physical characteristics are currently unknown for these NEOs.** If mission opportunities to the 18 NEOs had been viable with respect to HSF technology of the day, each would have required less than 200 mt Initial Mass in Low Earth Orbit (IMLEO) and duration less than 180 days using chemical propulsion.

Immature technology was not the only technical obstacle to flying missions targeting these 18 NEOs. Each of the 18 discoveries was made with a lead time thought to be insufficient for HSF mission preparations. Such preparations may entail sending a robotic precursor mission to reconnoiter the highly accessible NEO's physical characteristics. Insufficient discovery-to-mission lead time is an artifact of confining NEO observations to Earth's vicinity. If a NEO survey is performed from deep space, sufficient lead time can be provided, particularly for the most accessible HSF destinations.

3.4 Mission Architecture Considerations

Assuming chemical propulsion, multiple heavy-lift launches (≈ 100 mt IMLEO per launch) are required to enable any HSF mission opportunity to a currently known NEO. Multiple launches and orbit assembly activity prior to an HSF mission's Earth departure can incur significant loss-of-mission risk. Up to a point, this risk can be mitigated with launches planned sufficiently in advance of the mission's Earth departure season. However, additional risk can be incurred over time in orbit as systems age and humans are required to loiter in this hostile environment. Although mission risk can be reduced via more robust infrastructure, this approach is more costly than reductions realized through optimal launch timing and manifesting.

Practical, affordable HSF missions result from visiting the most accessible NEOs. These missions reduce IMLEO and the number of launches required because their short durations and minimal propulsion requirements reduce habitation, consumables, shielding, and trash masses, together with the volumes required to contain them. Due to the premium associated with NEO accessibility in near-term interplanetary HSF, a bigger return on investment is expected from better NEO surveys and tracking than from better HSF capability. In the longer term, improved HSF capability will be required to access progressively more remote (and likely more interesting) NEOs leading to Mars orbit missions.

3.5 Summary of Key Findings

1. Catalog, characterize, and track NEOs down to 100-m diameter or less as thoroughly as possible.
2. Survey NEOs, particularly those with Earth-like orbits, from a deep space vantage to find the most appropriate HSF mission opportunities sufficiently in advance of their Earth departure seasons.
3. Target initial HSF missions at the most accessible NEOs using conventional technology to the greatest extent possible.
4. Minimize the number of launches and assembly complexity leading to a HSF mission's Earth departure for interplanetary space.
5. Identify key HSF technologies and architectures relating to NEO mission opportunities.
6. Adopt objective mission design metrics, such as IMLEO reflecting performance penalties inclusive of Earth departure asymptote declination, clearly documenting their architecture dependencies and assumptions.
7. Whenever possible, plan a mission to a sequence of extended Earth departure seasons, likely targeting multiple distinct NEOs, in order to accommodate unintended departure delays.

4 NEO Characteristics for Safe and Meaningful Human Exploration

This panel session was chaired by **Andy Rivkin** (Supervisor of the Planetary Astronomy Section in the The Johns Hopkins University Applied Physics Laboratory) and **Paul Abell** (Lead Scientist for Planetary Small Bodies, NASA-JSC) and consisted of the following members:

- **Patrick Michel**, Senior Researcher, University of Nice, CNRS, Cote d'Azur Observatory
- **Lance Benner**, Research Scientist, Jet Propulsion Laboratory
- **Joe Nuth**, Senior Scientist, NASA NASA's Goddard Space Flight Center

- **Dan Scheeres**, Professor, Department of Aerospace Engineering Sciences, University of Colorado
- **Mike Hess**, Chief of the EVA, Robotics, and Crew Systems Operations Division, NASA NASA's Johnson Space Center

In this session we discussed the known physical characteristics of NEOs obtained from spacecraft and ground-based observations. Additional discussion focuses on:

- How best to determine the physical characteristics of candidate NEO targets that must be known prior to human exploration (via ground-based and/or space-based assets)
- What methods, measurements, and instruments are required to provide the necessary data for target selection and qualification
- When these data should be obtained so as to best inform scientists and engineers designing and planning future human NEO exploration missions

4.1 NEO Population Diversity and Motivations for Exploration

Our understanding of NEO physical properties has been evolving since the 1970s, via visible and infrared reflectance spectroscopy, measurements of albedos, and an increasing number of objects observed by radar. More recent work, such as the study of non-gravitational forces, binary and multiple objects, and geophysics in microgravity environments, has led to rapid and continuing progress. While there is much yet to learn, it is already clear that a wide range of diversity in physical properties is present in the NEO population.

Compositionally, we know from the meteorite collection and reflectance spectra that NEOs span a range from metallic to rocky bodies (and mixtures of metal and rock), with the rocky bodies themselves spanning a range of compositions from evolved igneous material to undifferentiated and unprocessed material including water- and organic-rich minerals [6, 7, 8, 9, 10, 11]. Material unrepresented in the meteorites is also expected to be present in the NEO population, most notably in the form of extinct comets with depleted inactive surfaces and potentially icy interiors [10, 12]. While detailed work is required to determine NEO compositions to scientifically useful precisions, it is clear that the overwhelming majority of NEOs are rocky rather than metallic, and that chondritic (unprocessed) material likely dominates the rocky bodies.

The albedos of NEOs range from roughly 4% to 30% for the most common types, but can reach higher or lower values in rare instances [13]. These albedos are directly relevant to the surface temperatures that will be found at NEOs and the operating temperatures required for spacecraft in a NEO's vicinity. Thermal inertias are typically lower than that of bare rock (and thus indicative of regolith coatings) but are higher than what is found on large asteroids and the Moon (and thus indicative of larger particle sizes than what is found in those powdery regoliths) [14]. Rotation rates vary from the order of a few minutes for some smaller (≈ 10 m) bodies to days to weeks for some objects. At sizes larger than roughly 150 m, objects are not seen to rotate with periods shorter than ≈ 2.2 hours [15, 16]. There also appears to be a correlation between rotation rate and satellite systems, with satellites found for two-thirds of NEOs 300 m and larger with rotation periods between 2.2 and 2.8 hours.

While there is much we know, there is still much to be learned about the NEO population that is directly relevant to NASA's Exploration Systems Mission Directorate (ESMD) concerns. The smaller bodies most likely to be visited by humans are not as well studied as the larger ones. We have relatively few density measurements for small asteroids. There is evidence that satellites form, evolve, and escape from NEOs, with the escaped bodies becoming independent members of the NEO population [17, 18]. The internal structure of such escapees is not obvious, however, nor is it clear how such objects might systematically differ from their parents. In addition, roughly 10% of NEOs larger than 200 m in diameter are contact binaries, another possible end state of binary evolution.

Table 2, adapted from the National Research Council's (NRC's) "Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies"[3] shows the characterization situation. Table 2 shows that most known NEOs have no characterization at all, while a few hundred to a few thousand have some sort of spectral data available. A handful have been characterized very well by spacecraft. The potential human spaceflight targets are most likely not yet discovered, and as more data are collected they will be better understood until they are suitably characterized or ruled out as viable targets. While observations from WISE and Spitzer have increased the number of NEOs with known albedos and sizes since Table 2 was created [13, 19], it is still true that for most objects all we know is an absolute magnitude and an orbit of varying quality.

Table 2: Characterization Levels for NEOs

	Number
NEOs larger than 50 m diameter (estimated)	≈ 500,000 - 1,000,000*
NEOs currently known (all sizes)	6,278
Rotation periods	450
Rotation pole directions	25
Detected by radar	246
Shapes estimated from radar data	25
Shapes estimated from optical data	14
Shapes estimated from spacecraft data	2
Masses estimated from spacecraft data	2
Masses estimated from radar data	4
Bulk densities estimated from all sources	10
Sizes estimated from all sources	108
Near-surface densities estimated from radar	17
Spectrally classified into taxonomic groups	489**

* Estimate based on current models.
** As of February 2011, as reported by the European Asteroid Research Node (http://earn.dlr.de).

4.2 Characterization Information Relevant to Human Exploration

Until recently, the vast majority of NEO data have been collected in support of either basic scientific research or in consideration of the general impact hazard. Much of these data, while not specifically

[3] Found at http://www.nap.edu/catalog.php?record_id=12842

collected for this purpose, bear directly on ESMD and HSF requirements. While the choice of the asteroid first visited by a human crew will be dictated by flight dynamics and human safety considerations, it will still be important to characterize the chemical composition and structure of the target as thoroughly as possible in order to ensure that the crew brings tools and experiments appropriate to the geology of the target.

First, the knowledge of orbits for NEOs varies in quality from NEOs with orbits that are well determined and can be extrapolated with high confidence to those with insecure orbits. While some of the latter may appear to be accessible, improvements in their orbits may leave them less attractive. Worse yet, many objects with insecure orbits are effectively lost, with positional uncertainties too high to allow recovery. The set of ESMD mission candidates will be drawn from objects with high-quality, secure orbits.

Lightcurve observations, commonly made for NEOs by professional and amateur astronomers using photometry, provide rotational periods and thus the angular speed of the surface. The amplitude of the lightcurve provides a measure of the axial ratios of the target body, and repeated lightcurve measurements from different viewing aspects allow the three-dimensional shape of an object to be estimated. Repeated measurements will also reveal the direction of an object's rotational pole, important for understanding the duration of daylight across its surface. Objects in non-principal axis rotation (tumbling) can also be identified by this technique.

Knowledge of the NEO's rotational characteristics will determine the overall suitability as a human destination, since objects rotating too quickly will be difficult to interact with for both engineering and human factor reasons. The majority of objects smaller than ≈ 150 m have rotation periods shorter than ≈ 2.2 hours, seen as a rough limit on suitable rotation rate [15]. However, while statistical arguments may suggest a small object will be rotating too quickly to serve as a viable mission target, measurements still must be made of specific bodies to make the actual determination. Lightcurve observations can also identify binary objects, although radar studies from Arecibo and Goldstone provide the most easily interpretable results. Roughly 15% of NEOs are found to be members of binary or multiple systems, with current models suggesting satellite formation and orbital evolution via the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) force and tidal forces [17, 18]. As mentioned above, the fraction of binary NEOs appears to be correlated with rotation rate.

It is not clear whether the presence of a satellite would disqualify an object as an HSF target or increase the risks involved in such a visit in a significant way. It is possible that the orbital dynamics in such a system would complicate operations to an intolerable extent; however, the scientific rewards for visiting such a system may justify the additional complications. Understanding the hazard posed by smaller-scale satellites (the volume density and size distribution of < 1 m size objects) will also be important before astronaut arrival, though the slow orbital speeds will likely make such debris a nuisance rather than a hazard.

Binary or multiple systems are also one of the few situations in which NEO masses can be calculated. Given a satellite system, Kepler's laws can be used to calculate a system mass. In non-multiple systems, high-precision positional measurements combined with estimates of thermal properties can be used in some cases to measure the Yarkovsky force on a NEO, which is mass dependent. In cases where neither approach is possible, an *in situ* visit is required to estimate an object's mass.

The dynamical models and observational data necessary for this understanding will also be directly applicable to any debris generated by crew or spacecraft activity at the target asteroid. We do not have a good current sense of how a NEO surface would respond to interaction (particularly in terms of dust generation), or how proximity operations might be affected. This will likely require a gravity model to be generated for the target, which will include shape, size, and density distribution as inputs.

Proximity operations and Extra-Vehicular Activity (EVAs) will also depend on the topography and overall geology of the target NEO, for both scientific and engineering reasons. The regolith properties and internal structure will have critical influence on anchoring strategies (or if alternatives to anchoring need to be developed). This, in addition to composition, will help guide sample collection plans. For example, expected variability would render samples from disparate sites desirable, while areas of different surface exposure ages would allow study of space weathering processes.

4.3 Robotic Precursor Missions

As discussed above, much work remains to be done in understanding asteroids to the degree necessary to allow safe and significant human exploration. Some of the required data can be obtained through Earth-based facilities, though the amount and kind of data will vary depending on the target, the timing of any close passes to Earth, and the part of the sky in which it appears; a close pass in the far southern part of the sky would make study by large telescopes more difficult and might preclude radar, for example. Because a human exploration target would be a very high priority target, however, we might expect a suite of ground-based and space-based facilities to be available and would likely be able to determine at least a size, composition, and axial ratios, with at least constraints on thermal properties and the presence of satellites. If the candidate target is part of a multiple system, constraints on the mass and density can be calculated, but, as noted, it is not clear that a multiple system will be judged a safe target. Figure 4 shows the type of shape models that can be generated by Earth-based data, with a combination of radar and lightcurve information used to create a shape model for Itokawa that compares very well with the *Hayabusa* approach imagery.[4]

Figure 4 demonstrates the level to which Earth-based study can reach, as an example of what might be expected before *in situ* precursor missions are launched. Before *Hayabusa* arrived at asteroid (25143) Itokawa, the shape model on the left was generated from radar and lightcurve data, and it compares well with the *Hayabusa* approach image on the right. In addition, Binzel et al. successfully predicted Itokawa's composition [8]. However, details of the asteroid's geology required *Hayabusa*'s arrival and close approaches to Itokawa, and geotechnical details such as how anchoring might work on Itokawa's surface are still unknown.

Detailed radar imaging shows that many of the NEOs with rotation periods less than 3 hours have relatively spheroidal shapes and equatorial bulges, thought likely due to transport and accumulation of regolith via YORP spin-up.

Additional information will be required, however, which can only be obtained by precursor missions designed to interact *in situ* with near-Earth asteroids. Detailed shape data, density variations and

[4] Figure courtesy of L. A. M. Benner (NASA-JPL), personal communication.

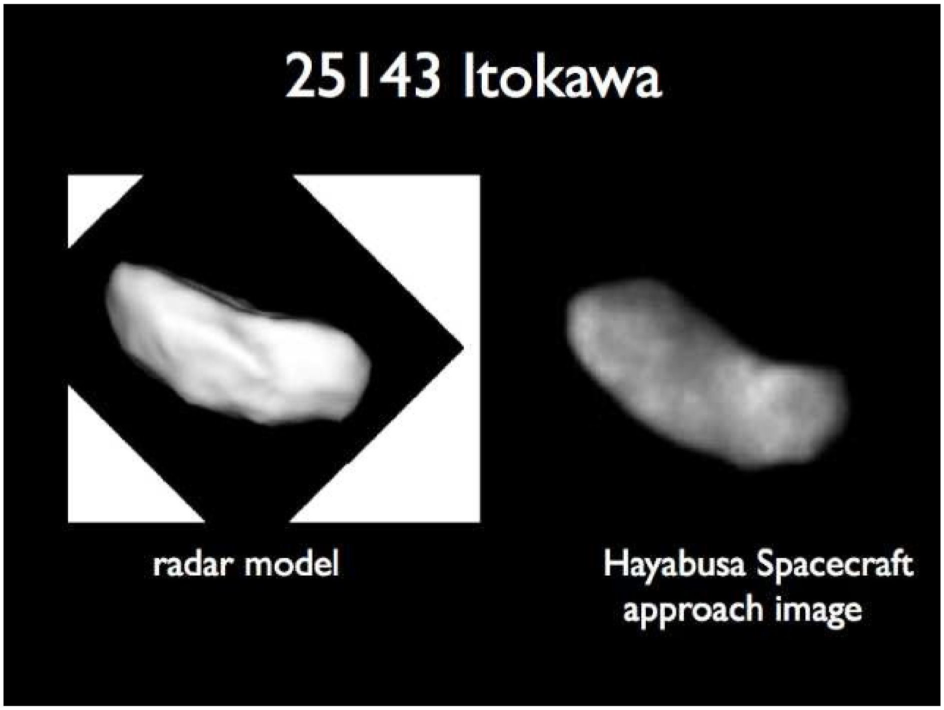


Figure 4: Comparison of Radar Model and *In Situ Hayabusa* Spacecraft Camera Imagery for NEA 25143 Itokawa

mass distribution, and surface roughness can be measured with cameras onboard a precursor, but determination of geotechnical properties and anchoring tests will likely require contact with the surface, via either a lander or a small instrument package.

We have little intuitive feel for geological processes and particle interactions in the microgravity environment of NEOs. Interparticle cohesion via Van der Waals and other forces are expected to be important, and small particles may be found largely in clumps held together by these forces [20]. Direct experience with these surfaces through precursor missions would greatly improve our expectations and ability to operate on surface materials, particularly with respect to anchoring. The internal structure of NEOs will also have a critical influence on how much force can be applied without running the risk of inadvertently disassembling a potentially very weak body.

While it is not necessarily clear that these lessons require a visit to the same object that will be visited by humans, or whether they can be derived from study of other objects deemed sufficiently similar, there is a consensus that the use of precursor missions will retire both budgetary and operational risk for human exploration at relatively modest cost. This is also true of a putative asteroid survey precursor, which could help ensure that the most rewarding, least hazardous, most accessible targets are found, rather than targets that are simply "good enough."

4.4 NEO Proximity Operations

While operations around a given NEO will be a function of that body's specific gravity field, size, etc., dynamical modeling suggests that regardless of those parameters, a range of solutions will exist. The weak, irregular gravitational field likely presented by a NEO means that arbitrarily chosen NEO-captured orbits will not necessarily be naturally stable, and would therefore require frequent maintenance maneuvering. However, relatively stable orbits do exist, mostly within the terminator plane with orbit radii equal to a few NEO radii. Another option is for the spacecraft to stationkeep near the NEO and view its sunlit surface area over the course of the NEO's day (likely 4 to 12 hours). Stationkeeping nearby may be a particularly attractive option for NEOs with binary companions, as such companions would likely occupy the NEO's stable orbit regions. Close proximity operations can also be achieved through a series of slow hyperbolic flybys to and from a standoff position. These operations, affected by the microgravity regime, unstable orbital mechanics, and extreme NEO environments, are not like those currently used in LEO by the Shuttle relative to the International Space Station (ISS).

4.5 NEO Target Selection Considerations

Engineering, dynamical, and human factor constraints will limit the pool of viable NEOs for exploration by human crews. The size-frequency distribution of NEOs is such that as smaller object sizes are considered, the number of expected objects increases exponentially. However, smaller sizes are also much more likely to have rotation rates too fast to allow safe interaction. From a scientific point of view, in-depth exploration of any asteroid will represent a major leap in our understanding, and we are not likely to have a large enough pool of well-characterized targets to use science preferences as a discriminator between objects. Therefore, we expect non-scientific factors, such as crew safety and accessibility, to be the major criteria for target selection.

4.6 Summary of Key Findings

1. NEOs show a wide range of diversity in physical characteristics of interest for future human exploration. Some constraints are already well understood, but more data on the population as a whole is still necessary.

2. Characterization of candidate NEO targets should include information applicable for human exploration needs, including rotation period and pole direction, size, shape, presence of satellites, composition, and internal structure. In addition, an understanding of regolith properties and dynamics will be critical.

3. Robotic precursor missions are required for detailed *in situ* physical characterization of candidate human spaceflight targets to reduce operational and budgetary risk. Remote sensing observations can provide some needed data but cannot meet anticipated needs for constraints on regolith mechanical properties, internal structure, or surface particle interactions. Remote sensing opportunities are also infrequent and may not support human mission opportunities with sufficient lead time.

4. Dynamical studies suggest there is a range of proximity operation options for a variety of NEO sizes, shapes, and morphologies.

5. The selection of NEO targets for the first mission will be driven primarily by accessibility and dynamical considerations in preference to other factors. Examination of size constraints vs. rotation rate will also be a consideration.

5 Mission Duration: Quantifying the Risks

This panel session was chaired by **Dan Mazanek** (Senior Space Systems Analyst, NASA-LaRC) and **Rob Landis** (Engineer, NASA-ARC; currently assigned to NASA-JSC) and consisted of the following members:

- **Craig Kundrot**, Deputy Program Scientist, Human Research Program, NASA-JSC
- **Jack Stuster**, Vice President, Principal Scientist & Author, Anacapa Sciences, Inc.
- **Ron Turner**, Fellow, Analytical Services, Inc. (ANSER)
- **Andy Thomas**, Astronaut (STS/*Mir*/ISS), ESMD Architecture Development, NASA-JSC

This session provided a discussion of the effects and associated risks on humans and vehicle systems during long-duration interplanetary space missions to NEOs. Various concerns were discussed, including radiation exposure (cumulative dosage and episodic risks), physiological effects, psychological and social-psychological concerns, habitability issues, system redundancy, contingencies, abort scenarios, etc., along with NASA's cumulative experience to date.

5.1 Acute and Long-Term Physiological Effects from Radiation

According to Francis Cucinotta, Chief Scientist for NASA's Space Radiation Program, every review of NASA's human space exploration activities has identified space radiation effects on crew members as a top health and safety issue that must be addressed. Health risks associated with radiation exposure are the limiting factors in mission duration and crew selection. Large costs, such as those associated with advanced radiation mitigation technologies or increased mission mass, make it difficult to protect against these health risks and associated uncertainties. In addition to the long-term physiological effects from radiation exposure, the risk of acute radiation sickness, which could be lethal, increases as mission duration is extended. Carcinogenesis, chronic and degenerative tissue risks, acute radiation sickness, and acute and late central nervous system risk from galactic cosmic rays (GCRs) and the secondary radiation showers they produce is the major risk. GCRs are continuous, low flux, highly energetic, and very penetrating protons and heavy nuclei. GCR shielding options are limited. Water and hydrogen can be used for shielding, but the mass of implementing sufficient shielding is restrictive to mission duration. There are also large biological uncertainties which limit the ability to evaluate the risks and the effectiveness of mitigation approaches. Secondary particles consist largely of protons, neutrons, and heavy ions produced when GCRs contact various vehicle materials and other items brought on the mission.

Currently, the NASA exposure standard is a 3% risk of radiation exposure induced death (REID) at 95% confidence. Cancer is the primary driver of REID. This standard is subject to change, but it currently translates into approximate mission duration limits of 5-7 months for males age 45. The mission length depends on solar activity, with the shorter duration associated with solar minima due to a reduction in the heliosphere's ability to deflect GCRs coming into the Solar System. The mission durations for 45-year-old females are only approximately 3 months during solar minimum and 6 months for solar maximum. The latest NASA estimates for "Safe Days" in deep space, defined as maximum number of days with 95% confidence level to be below the 3% REID limit are shown in Table 3 (Source: "Space Radiation Cancer Risk Projections and Uncertainties - 2010," NASA). These estimates are for solar minimum with 20 g/cm^2 of aluminum shielding. These mission durations could increase by approximately 2 months if a reference population of individuals who have never smoked is considered. Reducing biological uncertainties could significantly extend mission duration, as could an increase in permissible REID. On the other hand, reductions in the uncertainties could end up reducing mission duration limits even further. Risks estimates are subject to change with new knowledge and with changes in regulatory recommendations. Increasing the permissible REID would allow longer missions, but this will likely not be in the best long-term interest of the astronauts and their families.

Table 3: "Safe Days" In Space for Deep Space Missions During Solar Minimum with 20 g/cm^2 of Aluminum Shielding

Age at Exposure	NASA 2010 US Average (days)	NASA 2010 Never Smokers (days)
MALES		
35	140	180
45	150	198
55	169	229
FEMALES		
35	88	130
45	97	150
55	113	177

Solar Particle Events (SPEs) are intense periods of high-flux, largely medium-energy protons from the Sun. Protection against SPEs represents a shielding, operational, and risk assessment challenge that is much easier to meet than protection against GCRs. Proper shielding is effective, although optimization is needed to reduce the associated mass to acceptable levels. With proper shielding, the major impacts of SPEs are confined mainly to EVAs. Typically, one or two SPEs occur during periods of high solar activity, but they can also occur around solar minima. A few SPEs during each 11-year solar cycle may be intense enough to cause acute effects to astronauts who cannot achieve access to shelter facilities within a few hours. Accurate and timely SPE alerts and operational responses are essential for crew safety.

5.2 Behavioral Health Support

Behavioral health support for crew is a critical aspect for long-duration space missions whose importance is sometimes overlooked. Stress management is a key component to keeping crew members happy and healthy. Crew stress levels may increase as the Earth recedes from view into a tiny pale blue dot and eventually fades from view and the realization sets in that the crew is committed to the entire mission duration without any attractive abort options. This stress and anxiety is similar to what is currently experienced during Antarctic winter-over expeditions or by early oceanic explorers as the land disappeared from sight. However, these terrestrial analogs still afford the possibility of contingency efforts or the ability to return to their homeland. Without significant pre-emplacement of logistics, or other contingency approaches, deep space missions will be performed without direct support from Earth or the ability to return home early. Sources of crew stress include the lack of real-time communications with family and supporting individuals, along with the psychological impact of events back on Earth (personal, local, national, and global). To reduce stress levels and maintain crew confidence and feelings of usefulness, activities to keep the crew engaged and productive during transit periods will need to be planned. Also, coping with the anticipated high-stress, short-duration activities at the NEO destination followed by the return transit period will also need to be carefully planned and monitored.

5.3 Micro-gravity Environment

Prolonged exposure to the micro-gravity environment has long been an important concern for human missions. Many aspects of this issue have been addressed through a rigorous exercise program to reduce muscle atrophy, cardiovascular atrophy, and bone mineral density loss. The issue with long-duration missions will be to provide an equivalent exercise regimen that can minimize the resources that need to be carried along. Figure 5 shows the room required for the TVIS on the International Space Station (ISS).

Another health issue associated with micro-gravity is visual impairment and increased intracranial pressure whose underlying cause(s) are currently unknown. This health problem has been experienced by seven long-duration astronauts and causes in-space and post-flight changes in vision and possibly other, as yet, unrecognized effects. Crew members experience degraded distance vision, swelling of the back of the eye, and changes in the shape of the eye. For some astronauts, increased intracranial pressure also persists post-flight.

5.4 Habitation & Life Support

Spacecraft habitability includes all aspects of an engineered environment that people need to maintain productivity and contentment, both in the short-term and over long durations. The confinement of humans for extended periods of time in relatively small volumes has historically been a limiting factor in space missions. Most people can cope with confinement in restricted quarters for some period of time, but this greatly varies among individuals and there is currently a lack of standards for long-duration habitability. One important aspect of habitability is the internal volume available to crew members. Volumetric requirements have long been a source of debate and uncertainty. While providing sufficient volume is critical, increases in volume can make missions unaffordable from mass and costs standpoints. Figure 6 shows a comparison of the amount of pressurized volume that has been available for space missions.[5]

[5] Courtesy of Marc M. Cohen, Northrop Grumman Integrated Systems.

Figure 5: Astronaut Sunita L. Williams, ISS Expedition 14 Flight Engineer, Exercises on the Treadmill Vibration Isolation System (TVIS) in the *Zvezda* Service Module

The logarithmic scales on both axes emphasize the growing volume requirements as mission duration is increased. However, it should be pointed out that these data represent vehicles that were sized primarily for engineering reasons, and not specifically for habitability. Proper and rigorous standards for minimum acceptable volume are much more complex and must take into account crew size, mission length, expected tasks, how the volume is apportioned, etc. Such standards do not presently exist.

For example, segmentation, privacy, and personal space are essential for long-duration missions. The ability to maintain sufficient sleep duration and proper sleep/wake cycles is one critical need that is dependent on a successful habitability design. Aesthetics of the living environment and other factors (e.g., acoustic environment, odors, plants, etc.) are also essential aspects of habitability that require careful consideration and innovative approaches in order to keep spacecraft masses at acceptable levels. Major improvements in the reliability, mass, and volume of life support systems (closed or nearly closed) are also enabling for future long-duration space missions. Figures 7 and 8 show maintenance and repairs being performed on the ISS. These pictures highlight the size and reliability needs for deep space missions beyond LEO. Space will be at a premium for NEO missions. Figure 9 shows ISS Expedition 24 crew members in the ISS Tranquility Node, which has approximately two-thirds of the pressurized volume provided by the National Aeronautics and Space Administration (NASA) deep space habitat designs currently being considered, and highlights the level of crowding that will be prevalent in small volumes when including the logistics needed for

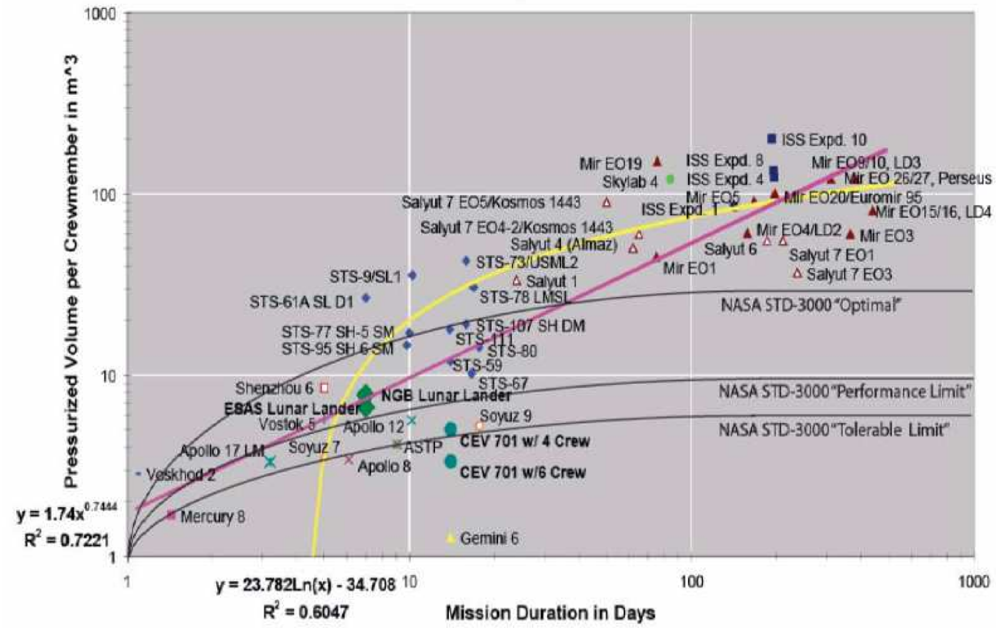


Figure 6: Comparison of Pressurized Volume Available for Space Missions and Terrestrial Analogs

long duration deep space missions.

5.5 Human Factors and Group Interaction Considerations

The famous Antarctic explorer Roald Amundsen is quoted as saying, "The human factor is three quarters of any expedition." The purpose of human exploration is to explore *with* humans, and although this seems like an obvious statement, it is often overlooked when designing systems and architectures. Human factors and group interactions are critical aspects of long-duration missions, whether they are performed on Earth or in space. The aggregate workload and the proper mix of work-related activities and recreational opportunities are important to maintaining crew morale and keeping crew members feeling productive and useful. Personal hygiene, clothing, and food preparation are some examples of the day-to-day aspects of living that need to be addressed to ensure the happiness of the individuals and the crew as a whole. Detailed, comprehensive selection criteria need to be utilized to determine the suitability of crew members, as well as to help predict their compatibility with one another. Leadership qualities, as well as the willingness to be led, are important considerations in developing proper crew composition. NEO missions will very likely be composed of both males and females and will be multi-national. Panel members suggested that modifications to future crew selection criteria may be needed before missions to NEOs, or other deep space destinations, are undertaken. Additionally, remote monitoring of human performance and adjustments during the mission will be important to mitigate issues and conflicts that will arise. Almost as important as the relationships among crew members is the relationship of the crew with mission control operators and mission management. Mutual trust and respect among all

Figure 7: Astronaut Peggy Whitson on ISS Expedition 16 Performing In-flight Maintenance on the Carbon Dioxide Removal Assembly

segments of the mission team are critical for mission success.

5.6 Mission Support/Operations Considerations and Abort Options

Human missions outside of cislunar space have extremely limited abort capabilities, particularly if Earth return is time-critical. Shortly after the Earth-departure propulsive maneuver, the crew will likely be committed to an Earth return not very different from that in the nominal mission plan. Reliable propulsion systems will be required to allow the completion of mission-critical deep space maneuvers. Equally important, the lack of abort options will require sufficient onboard medical capabilities and careful management of logistics and consumables. An acceptable, stable food supply and effective waste handling are critical considerations. The storage of food, water, and other consumables directly affect the overall volumetric mission requirements. Additionally, the serviceability of subsystems and the availability of adequate spares are vital for the proper, long-term operations of the spacecraft. Traditional approaches, such as the replacement of modular subassemblies called Orbital Replacement Units (ORUs), as is used on the ISS, incur a significant mass penalty. The ability to make component-level or board-level swap-outs can substantially reduce the number of spare parts and their associated mass.

The mission approach and support for EVA are important from a risk standpoint, but are not directly dependent on total mission duration. However, the probability of loss of mission or loss

Figure 8: Astronaut John Phillips on ISS Expedition 11 Performing Repairs on the Russian ELEKTRON O_2 Generation System

of crew due to Extra-Vehicular Activity (EVA) hazards such as exposure to dust, volatiles, and sharp edges, which compromise suit integrity, are amplified as mission duration is increased. Suits damaged during operations at the NEO may be rendered non-operational and impact crew safety if a critical EVA is required during the return trip to Earth.

The effects of the space environment on spacecraft materials and electronics also carry a certain amount of mission risk. Just as with humans, the effects of radiation on the spacecraft (e.g., data corruption, system shutdown, etc.), must be addressed. Additionally, micrometeoroid impacts can result in damage to the spacecraft and possible decompression, and although such an impact is a lower probability event than an impact by the orbital debris associated with LEO missions, such an impact is still a risk that can have a catastrophic effect on the mission.

Finally, the synergistic effects of multiple environmental factors must be considered due to our lack of experience in missions beyond cislunar space. For example, the combined effects of stress and radiation on the brain and endocrine system could act together and result in long-term physiological or psychological effects. As an additional example, the combined habitability effects of environmental and social monotony, communications delay, and the confines of limited living space and long-duration mission or abort scenarios could jeopardize the mission in a variety of known and possibly unknown ways.

Figure 9: ISS Expedition 24 Crew Members in the ISS Tranquility Node

5.7 Summary of Key Findings

1. The major finding of the panel was that the duration of the mission is the primary factor in risk management, and that the cumulative experience and knowledge base for human space missions beyond 6 months is severely limited at this time. This is all the more crucial for human missions outside of the Earth's protective magnetosphere, where we have no long-duration experience.

2. The acute and long-term physiological effects from space radiation are the primary physiological risk to humans.

3. Behavioral health support and the psychological and sociological issues associated with extended confinement in relatively small volumes are also significant concerns that increase the risk to the mission.

4. The micro-gravity environment offers physiological challenges that have been largely eliminated through effective exercise programs, but some issues, such as the risk of visual impairment from increased intracranial pressure, are still being researched.

5. Additional issues that affect the risk to the mission and crew include: habitability; human factors and group interactions; life support system reliability; medical support; logistics and waste management; subsystem serviceability and the presence of adequate spares; and the synergistic effects of multiple environmental factors.

6. Deep space missions do not afford the abort opportunities and psychological comfort provided by rapid return to Earth that is a hallmark of missions in cislunar space, particularly LEO missions.
7. The panel cited public understanding and acceptance of mission risk, along with the risk/benefit relationship, as an important consideration in establishing sustained human presence beyond LEO.
8. NASA's Office of the Chief Health and Medical Officer currently tracks about 60 risks for HSF, and the Human Research Program has been working on 28 risks for missions to the Moon, Mars, and now NEOs. Additional information about these risks can be found at the following website: `http://humanresearchroadmap.nasa.gov/`.

6 Affordable Options for Increasing the Accessible NEO Catalog

This panel session was chaired by **Rich Dissly** (Senior Manager, Ball Aerospace & Technologies Corporation) and **Ken Hibbard** (Senior Spacecraft Systems & Operations Engineer, The Johns Hopkins University Applied Physics Laboratory) and consisted of the following members:

- **Andy Cheng**, Chief Scientist, Space Department, The Johns Hopkins University Applied Physics Laboratory
- **Lynne Jones**, LSST Solar System Project Scientist, University of Washington
- **Ken Hibbard**, Senior Spacecraft Systems & Operations Engineer, The Johns Hopkins University Applied Physics Laboratory
- **Amy Mainzer**, WISE Deputy Project Scientist, Jet Propulsion Laboratory
- **Robert Arentz**, Advanced Systems Manager, Ball Aerospace & Technologies Corporation

As discussed in the previous sessions, the current set of viable mission targets for HSF is very small; however, to date we have discovered only a small percentage of the reasonable HSF targets that exist in the NEO population. Early identification of a far larger catalog of suitable targets for HSF will enable NASA to optimally plan for human exploration missions to these bodies beyond the Earth-Moon system. There are several viable options for rapidly increasing the catalog of good HSF targets, with existing concepts or capabilities at varying degrees of maturity. This session discussed several of these options, and explored their relative effectiveness and costs.

6.1 Survey Options

The survey options discussed covered a wide range of vantage points (both ground-based and space-based), spectral band passes, and observing strategies. These are summarized in Table 4.

Each of the options described is established, meaning that no technology development is needed for implementation, although the levels of concept maturity vary. A brief description of each follows.

Table 4: NEO Survey Options

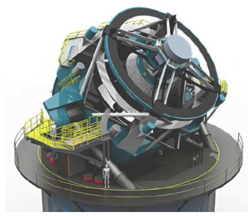
Option	Observing Location	Lead/Concept	Bandpass
1	Ground	LSST	VIS-NIR
2	L_1	JPL/NEOCam	Mid-IR
3	L_2	APL/NEST	VIS
4	Heliocentric @ 0.7 AU	APL/NEST	VIS
5	Heliocentric @ 0.7 AU	Ball/NEO Survey	Mid-IR

- **Large Synoptic Survey Telescope (LSST)** - A 6.4-m optical, ground-based telescope with a 10 sq deg field of view. LSST, shown in Figure 10(a), will survey the entire visible sky every 3-4 days in two filters for at least 10 years. LSST is on schedule for full science operations in 2019.
- **Near Earth Object Camera (NEOCam)** - A space-based mid Mid Infrared (Mid-IR) observatory concept, shown in Figure 10(b), that is stationed at Sun-Earth L_1, where it observes over a wide range of solar elongation angles. Uses a 50-cm-aperture primary mirror. Both optics and detector are passively cooled. Nominal 4-year mission life.
- **Near Earth Survey Telescope (NEST)** - A space-based visible observatory concept, shown in Figure 10(c) with two mission options: observing from Sun-Earth L_2 or from a heliocentric orbit at approximately 0.7 AU. The L_2 option would observe a "sweet spot" centered latitudinally on the ecliptic, with a solar elongation from 40° to 70°. The heliocentric option observes in opposition. Nominal 2-year mission life.
- **NEO Survey** - A space-based Mid-IR observatory concept, shown in Figure 10(d), located in heliocentric orbit at approximately 0.7 Astronomical Unit (AU), observing in opposition. Uses a 50-cm-aperture primary mirror. Telescope is passively cooled, and detector is actively cooled. Nominal 2.5-year mission life.

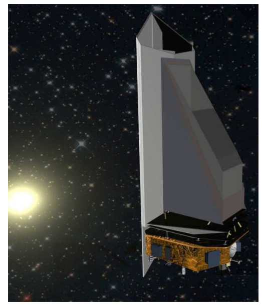
6.2 Survey Simulation Results

To understand the effectiveness of these options for discovering new NEOs, each has been subjected to a range of survey simulations using models that include observatory performance parameters, a simulated population of target objects extrapolated from the known population, and appropriate noise sources (e.g., zodiacal light and realistic background confusion limits). Each of these simulations has been calibrated statistically against the known NEO population, so we would expect the simulation extrapolation to finding undiscovered objects to be robust; overall results presented in the workshop are shown in Table 5.

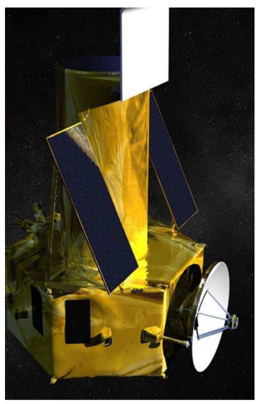
The simulations of each of the survey options reveal that ***a dedicated NEO survey will increase the number of HSF accessible targets by at least an order of magnitude*** [21]. But as a caveat, each of these simulations was produced independently by different institutions, so they have not been cross-checked to determine if they give similar results for a common set of survey specifications.



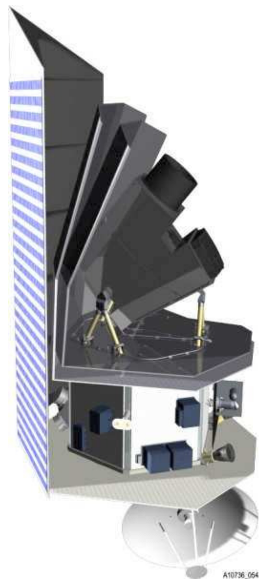
(a) The Large Synoptic Survey Telescope



(b) The Near Earth Object Camera



(c) The Near Earth Survey Telescope



(d) The NEO Survey

Figure 10: NEO Survey Telescope Concepts

6.3 Survey Operations Considerations

Any future survey mission must provide follow-up characterization of all discovered objects, at a minimum, providing observation arcs sufficient to reliably locate the object again, and ideally also providing some measure of object size. It is essential that the observation cadence be designed to provide proper data to support the MPC and to ensure easy integration with other (existing) data sets. The science data processing software, both onboard and ground pipeline, is critical for accurate NEO detection. Mission effectiveness (discoveries as a function of time) and cost for survey concepts vary primarily as a function of observing location, bandpass, and cadence. Some highlights from the session:

- Observing from the ground is the least expensive option (with respect to new/add on costs), but also the least effective (with respect to time efficiency); the additional costs to existing (or planned) ground assets is $\approx 25\%$ of the costs of a new space-based platform, but requires

≈ 2-5 times more observation time.

- Observing from the first or second Sun-Earth libration points is an effective option for Discovery-class cost.
- Observing from a Venus-like heliocentric (≈ 0.7 AU) orbit is the most effective option, but is more expensive than observing from one of the aforementioned Sun-Earth libration points.
- Visible systems are less expensive than thermal infrared (IR), but the latter may enable better characterization of target size.

Table 5: NEO Survey Simulation Results

Concept	% Completion	Duration	Comments
LSST	80% complete after 10 years; 90% after 12 years for all NEOs, diameter > 140 m	10-year nominal LSST mission with 2-year extension	2-year extension to existing LSST design would include optimization for NEO science
NEOCam	≈ 70% for PHOs, diameter > 140 m	4 years	PHOs are Potentially Hazardous Objects, a subset of the NEO population
NEST	40% for full NEO population, diameter > 140 m	2 years	The L_2 "sweet spot" survey is more efficient for larger objects (> 140 m), the 0.7 AU opposition survey is more efficient for smaller (> 50 m) objects
NEO Survey	≈ 70% for NEO population subset of interest for HSF (diameter > 60 m); 90% completion for full NEO population, diameter > 140 m, in 7 years	2.5 years	In 2.5 years this concept will discover > 50 objects with diameter > 60 m; Statistics only considered targets with probable one-way rendezvous $\Delta v < 5$ km/s; Additional cost required to satisfy George E. Brown goal, primarily in longer operational costs

The details of the individual survey concept presentations highlight the fact that completion metrics for the concepts are not identical, and that capabilities and costs have had minimal inter-comparison to date. It would be prudent to conduct some form of inter-comparison, preferably sanctioned by NASA, of effectiveness and cost among available concepts using a predefined, common set of assumptions on undiscovered target population parameters and completion metrics to objectively assess the range of survey options. It is also essential that the requirements for an HSF target survey are well constrained in terms of time, minimum size, desired characterization, and necessary data processing (end-to-end).

6.4 Summary of Key Findings

1. Dedicated, affordable, highly capable survey concepts exist at varying degrees of maturity.
2. Each of these concepts would dramatically increase the number of suitable NEO targets for future human exploration by at least on order of magnitude.
3. Many of the cost estimates (i.e., the space-based solutions) fall within the current Discovery mission-class cost range.
4. The panel recommends additional study of these potential concepts to objectively analyze them against a common set of requirements and in a manner that permits direct cost comparison.

Acronyms and Abbreviations

ANSER Analytical Services, Inc.

APL The Johns Hopkins University Applied Physics Laboratory

ARC NASA's Ames Research Center

AU Astronomical Unit

Ball Ball Aerospace & Technologies Corporation

C_3 Characteristic Earth Departure Energy

CNRS Centre National de la Recherche Scientifique

CSS Catalina Sky Survey

ESMD NASA's Exploration Systems Mission Directorate

EVA Extra-Vehicular Activity

GCR galactic cosmic ray

GEODSS Ground-based Electro-Optical Deep Space Surveillance

GSFC NASA's Goddard Space Flight Center

H Absolute Magnitude

HQ NASA Headquarters

HSF Human Space Flight

IAU International Astronomical Union

IMLEO Initial Mass in Low Earth Orbit

IR infrared

ISS International Space Station

JPL Jet Propulsion Laboratory

JSC NASA's Johnson Space Center

L_1 Sun-Earth Libration Point 1

L_2 Sun-Earth Libration Point 2

LaRC NASA's Langley Research Center

LEO Low Earth Orbit

LINEAR Lincoln Near-Earth Asteroid Research

LSST Large Synoptic Survey Telescope

Mid-IR Mid Infrared

MPC Minor Planet Center

mt Metric Ton (1,000 kg)

NASA National Aeronautics and Space Administration

NEA Near Earth Asteroid

NEO Near Earth Object

NEOCam Near Earth Object Camera

NEOWISE Near Earth Object Wide-field Infrared Survey Explorer

NEST Near Earth Survey Telescope

NHATS Near Earth Object (NEO) Human Space Flight (HSF) Accessible Targets Study

NRC National Research Council

ORU Orbital Replacement Unit

p Albedo

Pan-STARRS Panoramic Survey Telescope and Rapid Response System

PCC Pork Chop Contour

PHO Potentially Hazardous Object

REID radiation exposure induced death

SAIC Science Applications International Corporation

SAO Smithsonian Astrophysical Observatory

SBDB Small-Body Database

SPE Solar Particle Event

STS Space Transportation System

TNO Trans-Neptunian Object

TVIS Treadmill Vibration Isolation System

VIS-NIR Visible to Near-Infrared

VIS Visible

WISE Wide-field Infrared Survey Explorer

YORP Yarkovsky-O'Keefe-Radzievskii-Paddack

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