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A SIMPLIFIED, LOW RISK STRATEGY FOR THE EXPLORATION OF NEAR-EARTH OBJECTS

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ABSTRACT: The impetus for asteroid exploration is scientific, political, and pragmatic. The notion of sending human explorers to asteroids is not new. Piloted missions to these primitive bodies were first discussed in the 1960s, pairing Saturn V rockets with enhanced Apollo spacecraft to explore what were then called "Earth-approaching asteroids." Two decades ago, NASA's Space Exploration Initiative (SEI) also briefly examined the possibility of visiting these small celestial bodies. Most recently, the U.S. Human Space Flight Review Committee (the second Augustine Commission) suggested that near-Earth objects (NEOs) represent a target-rich environment for exploration via the "Flexible Path" option. However, prior to seriously considering human missions to NEOs, it has become clear that we currently lack a robust catalog of human-accessible targets. The majority of the NEOs identified by a study team across several NASA centers as "human-accessible" are probably too small and have orbits that are too uncertain to consider mounting piloted expeditions to these small worlds. The first step in developing such a catalog is, therefore, to complete a space-based NEO survey. The resulting catalog of candidate NEOs would then be transformed into a matrix of opportunities for robotic and human missions for the next several decades. This initial step of a space-based NEO survey first is the linchpin to laying the foundation of a low-risk architecture to venture out and explore these primitive bodies. We suggest such a minimalist framework architecture from 1) extensive ground-based and precursor spacecraft investigations (while applying operational knowledge from science-driven robotic missions), 2) astronaut servicing of spacecraft operating at geosynchronous Earth orbit to retain essential skills and experience, and 3) applying the sum of these skills, knowledge and experience to piloted missions to NEOs.

I. INTRODUCTION & BACKGROUND

The idea of mounting piloted missions to asteroids has been imagined for nearly half a century. The difference today, compared to 50 years ago, is that we are now much more aware of our local surroundings within the vicinity of the Earth. On 15 April 2010, the U.S. President announced a goal of manned mission to an asteroid by 2025. Prior to mounting such a mission - even a robotic precursor - there are prerequisite steps that must be taken. First and foremost is selection of a set of viable destination targets. Until a dedicated near-Earth object (NEO) survey is completed, this target set will remain far too limited to adequately plan human expeditions to these primitive bodies.

Near-Earth Object (NEO) Background

Near-Earth objects (NEOs) include both asteroids and comets whose orbits approach or intersect the Earth's orbit about the Sun. All NEOs have a perihelion of 1.3 AU or less by definition. They range in size from a few meters to as much as ~33 km across, with smaller objects greatly outnumbering the larger objects. Cometary bodies comprise <10% of the NEO population. The bulk of the NEO population originates from the inner part of the Main Belt of asteroids that reside between the orbits of Mars and Jupiter. Collisions within this source population, coupled with the gravitational influence of Jupiter, serve as the reservoir for these primitive bodies that dynamically evolve into NEOs.

Previous Studies

Under the auspices of NASA's Constellation Program (CxP), two studies to mount human missions to NEOs were completed in 2005 and 2007, respectively [1,2,3]. Both preliminary feasibility studies involved multiple launches, utilizing and adapting Cx hardware for NEO missions.

In the late 2009, the Augustine Commission concluded that the ultimate goal of human exploration is to "chart a path for human expansion into the solar system" and that "destinations should derive from goals." The destinations beyond low-Earth orbit (LEO) the Commission examined included the Moon, Mars, NEOs as well as Phobos and Deimos. The Commission's final report [4] also mentions the mining of NEOs for *in situ* resource utilization (ISRU).

A year later, in 2010, NASA's 'Human Exploration Framework Team (HEFT)' was formed. HEFT examined possible Design Reference Missions (DRMs) to NEOs. Due to the limited number of human accessible NEOs, the HEFT-designed DRMs now incorporate round-trip missions of 400+ days [5]. Such mission concept studies have so far neglected the benefit of a NEO survey in finding more accessible targets to enable mission durations on par with International Space Station (ISS) expeditions (i.e., ~180 days or less). In fact, studies led by the Exploration Systems Mission Directorate (ESMD) to date have only identified a few (maybe only one) such targets that might enable an affordable mission [6].

II. THE NEED FOR THE NEO SURVEY

NEO Target Sufficiency

As the United States embarks upon a flexible path for the expansion of manned spaceflight beyond LEO to include asteroids, it must be affordable within the increasingly constrained NASA budgets. As a result, several studies continue at various levels to identify potential NEO targets for human missions that fit within accessibility constraints. First-tier characteristics for accessibility include: short round-trip mission length (ideally <180 days), slow rotation rate (i.e., 4 to 12 hours), and large size (> 30 m diameter). Second-tier characteristics preclude binary systems or potential surface activity, and perhaps a preference for certain mineralogical composition, internal structure, etc. To date, the sundry sets of studies have identified only a few potential NEO targets, all of which are small (i.e., < 30 meters across). Hence, the most urgent, "zeroth-order" knowledge needed to prepare for any piloted missions to NEOs is to discover a sufficient number of suitable candidate targets. This knowledge need will not be met in a timely manner by existing or planned ground-based surveys [7].

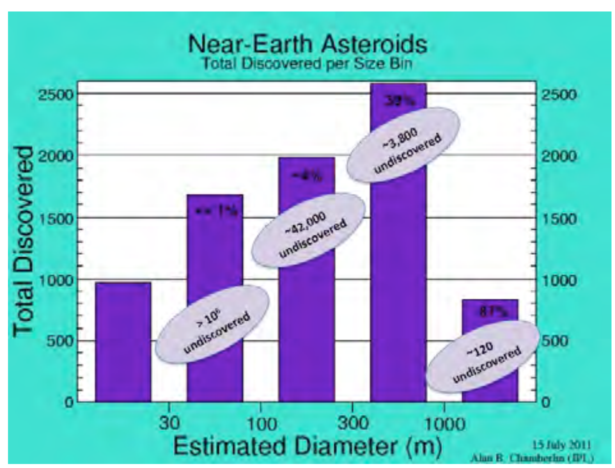

Figure 1: Near-Earth Asteroid (NEA) discoveries and estimated completeness for five size categories. Based on discovery rate statistics, and the size of asteroid to be visited by astronauts, perhaps < 3% of the NEO population [to which astronauts may venture] have been discovered (JPL).

The NEO Population

The known population of NEOs (as of 8 September 2011) is 8211 [8]. Of that figure, 1244 are potentially hazardous asteroids (PHAs). It is among the PHA population in which human-accessible targets are found, since these bodies have orbital parameters most like the earth, and are therefore energetically favourable for a round trip rendezvous mission. While Adamo *et al*., [9] describe the NEO filtering technique developed to support the Augustine Commission [4] for potential human destinations (as well as list these accessible NEOs), the total population is uncertain. Due to observational bias the distribution of the population in orbital element space is also not fully known.

NASA's NEO Observations Program is a result of the 1998 Congressional directive to begin a program to identify and catalog all NEOs down to 1-km across. The Catalina Sky Survey (CSS) and the Lincoln Near-Earth Asteroid Research (LINEAR) projects are currently conducting the ground-based survey for NEOs.

Next generation ground-based surveys for NEOs include the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) and the Large Synoptic Survey Telescope (LSST). The first Pan-STARRS telescope (PS1) is located on the summit of Haleakala on Maui, Hawaii. PS1 became operational on 13 May 2010. It has a 1.8-meter primary mirror, 3° field of view, and can cover ~6,000 square degrees per night. Exposure times are 30 – 60 seconds, allowing PS1 to reach a limiting magnitude of ~24 [10, 11].

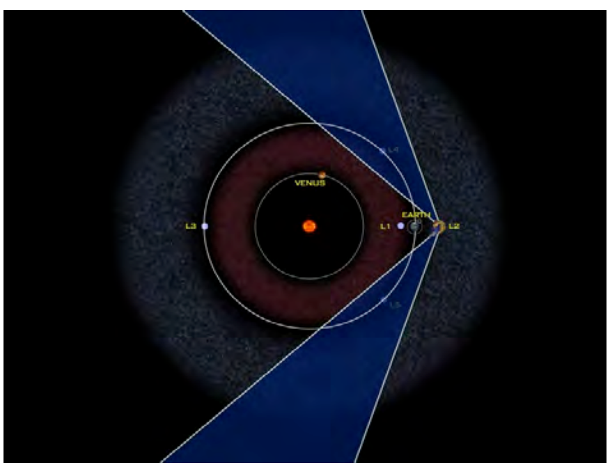

Figure 2: A depiction of the field(s)-of-regard of a space-based NEO survey telescope at SEL_2. Such a telescope looks at the 'sweet spots' to find human-accessible NEOs (NASA GSFC).

The LSST is planned wide-field survey telescope that will image the available sky ~every three nights and will be located on Cerro Pachón (atop El Peñón) in northern Chile. The LSST is comprised of an 8.4-meter primary mirror, a 3.5° field-of-view, and with a 15-second exposure has a limiting magnitude of ~25 [12]. As much promise as both the LSST and Pan-STARRS may have to detect new NEOs, neither will be able to be of much assistance to provide a robust target list for the first piloted mission by 2025.

Suitable asteroid targets for human exploration follow Earth-like orbits about the Sun and have long synodic periods; to discover them quickly requires a space-based telescopic survey [7,13]. Such a space-based NEO survey could be conducted at Sun-Earth Lagrange 1 (SEL_1) or L2 (SEL_2) or, in a trailing Venus-like orbit around the Sun [13,14]. Any of these approaches can be implemented for a low-cost, near Discovery-class mission with launch ~2015. Any space-based strategy has a high probability of discovering scores of NEOs suitable for human exploration within the first few years of operations [7].

The recent archival discovery of an Earth Trojan asteroid (2010 TK_7, oscillating at the SEL_4 point) out of the *Wide-field Infrared Survey Explorer* (*WISE*) survey efforts further underscores the fundamental need for this space-based survey. However, instead being in LEO and limiting our geometrical perspective in the search for NEOs, it is best to place that survey telescope at SEL_1 or SEL_2 or even more optimally in a Venusian orbit about the Sun. A deep space vantage point decouples the viewing geometry from the confines of earth and enables detection of those NEOs with long synodic periods (i.e., ~several decades to centuries) that are most optimal for human exploration.

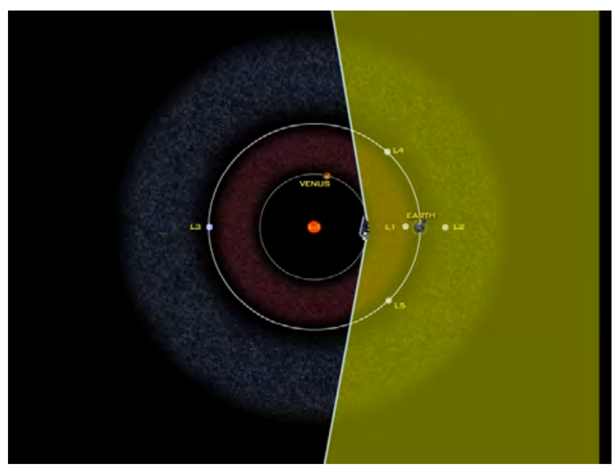

Figure 3: Field-of-regard for a space-based NEO survey in a Venus-like orbit. . Such an orbit is geometrically optimized to locate NEOs at opposition when they are brightest, even those interior to Earth's orbit. (NASA GSFC).

II. FOLLOW-UP [GROUND-BASED] CHARACTERIZATION

Upon locating potentially human-accessible targets, a detailed follow-up investigation/characterization effort should be undertaken prior to any launch of a human-led mission to a candidate NEO [3]. This can be accomplished a variety of ground-based observations and activities. Visible and infrared telescopes can refine the astrometric positions of a NEO, obtain detailed light curve information constraining NEO shapes and spin state, and collect albedo and spectral data on basic physical properties.

Figure 4: (Left-to-right) Subaru, Keck, and NASA IRTF facilities on the summit of Mauna Kea.

If a NEO has a relatively close approach to the Earth, the Arecibo and Goldstone planetary radars should be able to refine the orbit of the object and even "image" it. Radar is an uniquely powerful astronomical tool to characterize NEOs and refine their orbits [15]. These planetary radars can image these bodies with resolutions as fine as several meters (depending upon the proximity the passage to Earth) reveal the basic shape of the object and would determine its size, its spin orientation, whether it was part of a multiple system (i.e., a binary or tertiary object), and possibly its surface characteristics. This information is similar to that obtained by a spacecraft flyby mission, but provided at only a fraction of the cost.

Figure 5: Goldstone 70-m dish (DSS-14) utilized for communication and data to/from deep space robotic missions as well as radar imagery of NEOs. DSS-14 is fully steerable to 80% of the sky (NASA, JPL).

Radar observations have supported (and will continue to support) several missions and mission concept studies such as *NEAR Shoemaker, Hayabusa, Rosetta, EPOXI, Dawn, Clementine, OSIRIS REx*, etc. Forthcoming radar observations of 1999 JU_3 (target for *Hayabusa 2*) and 1996 FG_3 (target for ESA's *Marco Polo-R*) will commence in October and November 2011, respectively [15]. Such detailed preliminary investigations of potential mission targets would help constrain the pool of potential candidate NEO targets for robotic precursor missions that will prelude the ultimate human missions to these small worlds.

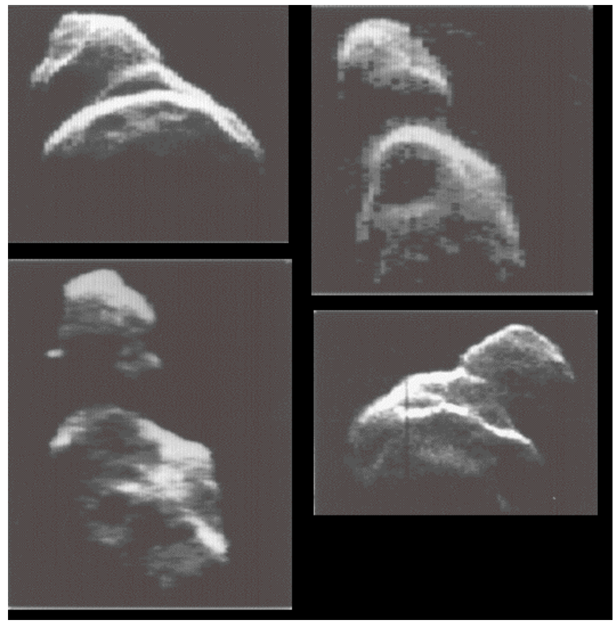

Figure 6: Radar images of 4179 Toutatis [16] obtained in late 1996, an S-type measuring 4.5 x 2.4 x 1.9 km. The next opportunity to image this NEA via planetary radar will be December 2012 (NASA, JPL).

III. ROBOTIC MISSIONS: PAST & PRESENT

In addition to ground-based efforts to characterize potential NEO mission targets described in the previous section, small precursor spacecraft should be flown to collect even higher fidelity data. The precursor spacecraft's main objective is to perform basic reconnaissance of a target NEO under consideration for the subsequent human-led mission. Such precursor missions will assess the NEO for any potential hazards and mitigate the risks that astronauts might encounter. While specific precursor missions for this purpose are still in formulation, several robotic missions to asteroids have been flown or are currently in development, both U.S.-led and internationally.

Flyby Missions

The first few asteroid encounters were flybys and with large Main Belt asteroids. On 29 October 1991, the *Galileo* spacecraft achieved the first flyby encounter (within ~1600 km) of the asteroid 951 Gaspra. Less than two years later, on 28 August 1993, *Galileo* flew within 2400 km of 243 Ida. In so doing, a small natural satellite was discovered orbiting 243 Ida. On 27 June 1997, while en route to its primary target [433 Eros], *NEAR Shoemaker* passed within 1200 km of 253 Mathilde.

Figure 7: First asteroid flyby: a montage *Galileo* approach images of 951 Gaspra on 29 October 1991. Gaspra is in the Main Belt (NASA).

Most recently, the European Space Agency's (ESA) *Rosetta* spacecraft flew by Main Belt asteroids 2867 Šteins on 5 September 2008 and 21 Lutetia on 10 July 2010. These flybys were a dress rehearsal that exercised the spacecraft, instruments, and mission operations teams for *Rosetta*'s primary target, Comet 67P/Churyomov-Gerasimenko in mid-2014.

While flybys provide a tantalizing glimpse of these primitive worlds, such encounters are very limited in duration and spatial coverage, and yielding virtually no information about the geophysical properties of the surface, especially at the sub-meter scales needed to plan human missions.

NEO Rendezvous Missions

Rendezvous missions are defined as those missions that operate in close proximity to a body for an extended period of time. They can provide a wealth of information about the structure and composition of small bodies. To date, there have been two rendezvous missions to NEOs: NASA's *NEAR Shoemaker* mission to asteroid 433 Eros launched in 1996 and JAXA's *Hayabusa* mission to asteroid 25143 Itokawa, launched in May 2003. *NEAR* images of Eros showed a surface modified by processes unknown on larger terrestrial bodies. These unique features include global-scale fractures, suggestive of an interior structure comprised of multiple distinct blocks, to very smooth crater floors, labelled "ponds", indicative of the surface transport of small particles to local lows in the gravitational potential [17]. *NEAR* eventually landed safely on the surface, demonstrating successful proximity operations in a low gravity environment [18].

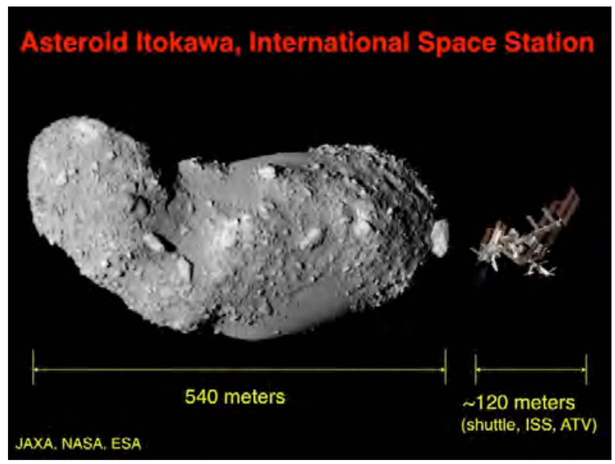

Figure 8: Comparative size of asteroid 25143 Itokawa and the ISS (with shuttle and ATV) to scale. Rendezvous and proximity operations in and about the ISS are akin to that of visiting NEOs. Due to their inconsequential gravity wells, spacecraft must station keep in proximity to the small body. Unlike flybys, it is necessary to stay at the asteroid to survey and characterize it with robotic precursors prior to human visits (JAXA, NASA, ESA).

Hayabusa was flown as a technology demonstration mission, successfully showcasing new JAXA flight elements such as ion propulsion, sample collection, and sample return to the Earth. However, the major impact of this mission arguably came from the high resolution surface imaging of the small asteroid Itokawa, showing clear evidence of a "rubble pile" body, made up of aggregates over a wide range of particle sizes (from mm to tens of meters), and loosely bound only by their very low mutual gravity. Migration of small particles to potential lows on the surface was seen on a global scale, and the absence of craters indicates a very young, dynamic surface [19, 20, 21]. Together, these missions showed small asteroids to be far from static objects, with surfaces controlled by unique physics far removed from anything we have experienced on earth, or in space.

Future Rendezvous Missions

Several international missions to NEOs are currently in development and will help determine what processes are unique, or universal, to small asteroids. JAXA is planning to launch *Hayabusa 2* in 2014 as a sample return mission to target asteroid $1999JU_3$. The mission is similar in scope to *Hayabusa*, but with the addition of a cratering experiment made by setting off an explosive charge on the surface, that will allow us to understand the geophysical response of the body to this impulse. The JAXA team will also interact with the surface of the asteroid with the MINERVA mini-lander and DLR's MASCOT. Both are surface packages, designed to interact with the surface of the asteroid and 'hop' to other locations [22].

Figure 9: Artist concept of *Hayabusa 2* and MINERVA surface package/hopper. By direct surface interation, MINERVA will enable a better and more complete understanding of the asteroid's regolith geotechnical properties (JAXA).

In November 2011, Russia plans to launch *Phobos-Grunt* towards Mars. The spacecraft will arrive in the vicinity of Mars ~late 2012, landing on the Martian moon Phobos in early 2013 [23]. While *Phobos-Grunt*'s primary objective will be to return samples from the surface of the Martian moon to the Earth, the flight techniques for rendezvous, proximity operations and anchoring to the surface are relevant to the further exploration of these small bodies.

NASA recently selected the *OSIRIS REx* sample return mission, planned launch in 2016, and targeting asteroid $1999RQ_{36}$. Lightcurve observations indicate a retrograde rotation rate of ~4.3 hours. Radar observations with Arecibo and Goldstone in 1999 and 2005 provided a spatial resolution of ~7.5 meters/pixel, revealing a ~575-meter body [24].

Both *OSIRIS REx* and *Hayabusa 2* will visit carbonaceous asteroids that have not been seen close-up, let alone analyzed, opening the possibility of addressing the role of the impact of such bodies on the origin of life on the Earth. While these missions, along with *Phobos-Grunt*, are sample return missions – it is not necessary to incorporate robotic sample return missions into human mission architectures to explore NEOs. However, the flight and mission operational techniques of these science-driven missions will parley into exploration-driven missions to support the piloted mission case.

IV. PILOTED MISSIONS TO NEOS

Historical Context

The challenges of getting to Mars are daunting and formidable. However, a credible intermediate stepping-stone approach for eventual manned missions to Mars and beyond includes NEOs. In the mid-1960s, after the Saturn 5 launch vehicle design had been baselined, a first step along the NEO path was taken when follow-on missions beyond the Moon were contemplated. These missions included notional concepts to what were then-called 'Earth-approaching asteroids.' [26, 26]

More than two decades later, NASA re-examined the notion of visiting NEOs [27] in greater depth as part of the Space Exploration Initiative (SEI). Over the past twenty years since SEI, a few other concept studies have examined piloted missions to NEOs [28-31].

Unfortunately, as described earlier, there is not a sufficiently robust target list of NEOs to consider mounting human missions to these small worlds. Most of the NEOs in the human accessibility filter developed by Adamo [32, 33] are, effectively, "lost." That is, they have been observed for a very short period of time (days to weeks) before being unobservable from the Earth. Since many such bodies have long synodic periods, these NEOs remain unobservable until their next apparitions -- which could be several decades into the future.

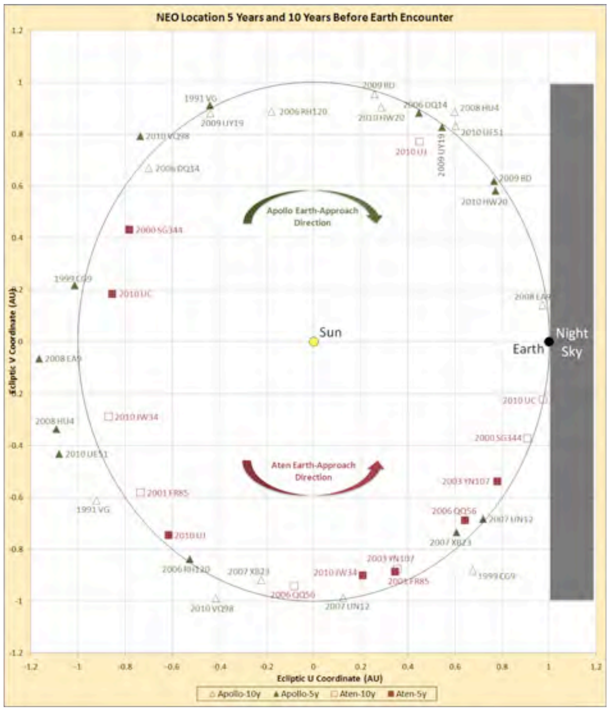

Figure 10: The plot above shows the position of 20 'affordable' NEAs 10 years before (open symbols) and 5 years before (closed symbols) Earth close approach. None of these objects is in the night sky at 10 and 5 years prior to their discovery periods. For missions in 2025 – 2030, a platform in space is needed to find the most affordable targets in a timely manner (courtesy of Dan Adamo).

Again, key is to complete the NEO survey. The advantage of a space-based survey is that it will find those NEOs with long synodic periods that are not easily visible from the Earth. While the survey is underway, alternate nearer term exploration-related development and demonstration activities can commence. First amongst these are robotic, and robot/manned missions to GEO which are a means to develop key technologies, retain critical ground support and flight skills including hard-won EVA skills and serve as the interim step to NEOs.

Manned GEO Servicing: An Initial Stepping Stone

In mid-2010, the leadership of the Space Operations Mission Directorate (SOMD) initiated an internal study with DARPA to examine the possibility of servicing high value satellites in geosynchronous orbit (GEO) [34]. The NASA Authorization Act of 2010 discusses the extension of the human presence from low-Earth orbit (LEO) to other regions of space beyond LEO, noting that the establishment of in-space capabilities, use of space resources, and the ability to repair and reuse systems in space can contribute to the overall goals of extending human presence in space. GEO is within cislunar space and represents a logical next stepping stone for human spaceflight prior to mounting missions back to the Moon or the first missions to NEOs. For nearly 40 years, NASA has demonstrated the ability to conduct spacecraft servicing and assembly operations in LEO, from the initial repair and recovery of *Skylab* to satellite repair and replace (R&R) efforts (i.e., *Solar Max, Palapa, Westar, Syncom, Intelsat VI*, etc.), to servicing of the *Hubble Space Telescope* (*HST*), and the construction and maintenance of large space structures such as the International Space Station (ISS). NASA has developed a unique repertoire of EVA techniques and experience for humans and teleoperated robotics in these areas.

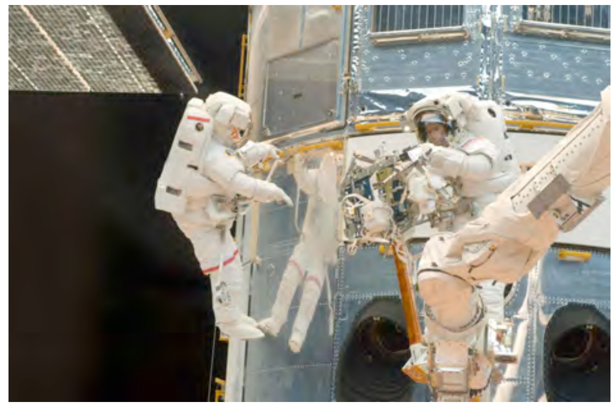

Figure 11: Space shuttle missions to *Hubble* have demonstrated the value of astronauts servicing priceless assets. NASA has developed a unique repertoire of capabilities in EVA techniques from the hypogravity environment of the Moon to the microgravity environment to service *HST* and construct the ISS. A future logical step is servicing satellites at GEO, followed by piloted missions of exploration to NEOs (NASA).

Servicing in GEO represents a uniquely stressful environment due to: 1) EVA limitations in GEO driven by electron radiation dose and electron charging (see Figure 12) (GCRs and solar particle events (SPE) are similar to deep space) and 2) grappling and securing non-cooperative satellites. GEO missions are of sufficient duration, distance and complexity to provide a viable demonstration of autonomous combined human and robotic operation in space, a key operational concept for the exploration of NEOs.

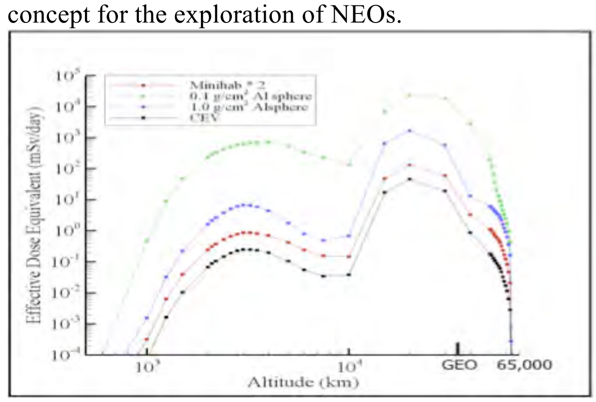

Figure 12: Effective Electron Dose vs. Altitude (DARPA-NASA Manned Geosynchronous Servicing Study).

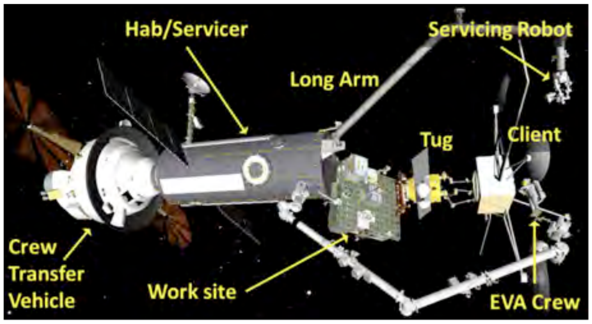

Figure 13: (from left to right) Crewed vehicle, Hab/servicing module with attached worksite, and space tug/grapple. Servicing in GEO may very well be the key stepping stone to planetary deep space destinations such as NEOs (NASA JSC).

Therefore, development of the vehicles, systems, technologies and operational techniques to accomplish GEO satellite servicing represent a core human space flight (HSF) functionality that is synergistic with the exploration of NEOs and the subsequent first human missions to Mars. While HSF vehicle, systems and technologies development is underway, the NEO target list can be matured.

An NEO Target List with High Relative Accessibility

Numerous factors influence NEO accessibility in the context of human spaceflight. Many of these factors depend on evolving HSF capability and are beyond the scope of this paper. Until piloted mission capabilities relating to propulsive velocity change and mission duration are better defined, the concept of *relative* NEO accessibility has proven useful. Given a certain minimal level of interplanetary human spaceflight capability, NEOs in more accessible orbits will be those considered for initial human missions beyond the Earth-Moon system [36].

In late 2010, the NEO HSF Accessible Targets Study (NHATS, pronounced as "gnats") was initiated under NASA auspices. In association with NHATS, a set of HSF mission design compliance criteria and constraints is evolving. Values assigned to this parameter set are intentionally optimistic with respect to current HSF capabilities. Of the 7665 NEOs catalogued in the Jet Propulsion Laboratory's (JPL's) Small Bodies Database (SBDB) as of 2011 February 3.76 UTC, NHATS has identified 765, or 10.0%, with at least a single compliant mission design solution [37].

Rank	Designation	*n*	*d* (m)
1	2000 SG_{344}	3,302,638	29 - 66
2	2006 BZ_{147}	1,674,416	22 - 49
3	2001 FR_{85}	1,618,888	33 - 75
4	2010 UJ	1,082,350	15 - 34
5	2009 HE_{60}	970,582	20 - 44
6	2007 YF	791,134	30 - 66
7	2010 JK_1	773,964	35 - 78
8	2004 VJ_1	679,319	37 - 83
9	2009 YF	663,423	31 - 69
10	1993 HD	656,700	20 - 44
11	2001 QJ_{142}	638,089	55 - 123
12	2006 FH_{36}	630,084	69 - 155
13	2009 HC	555,180	30 - 66
14	2011 AA_{37}	546,096	74 - 165
15	1999 CG_9	541,015	24 - 53
16	2007 UY_1	537,599	71 - 158
17	2005 QP_{11}	491,888	14 - 31
18	2009 OS_5	478,949	51 - 115
19	2009 DB_{43}	477,581	14 - 30
20	2001 CQ_{36}	473,574	77 - 171
21	2004 JN1	465,681	54 - 121
22	1999 AO_{10}	462,650	45 - 101
23	2003 SM_{84}	445,022	76 - 169
24	2009 CV	434,988	37 - 84
25	2009 TP	433,374	52 - 117

Table 1: The top 25 accessible NEOs ranked according to *n*, a tally of NHATS-compliant mission solutions associated with each NEO. Maximum estimated diameter *d* must exceed 30 m for each NEO listed.

To reiterate, a particular NEO's NHATS compliance is pre-decisional with respect to interplanetary HSF architecture capabilities NASA has yet to specify or bring to operational readiness. Nevertheless, it is meaningful to list the more accessible NEOs NHATS has identified, ranking them using a straightforward, if somewhat subjective, metric. This metric is *n*, the tally of NHATS-compliant mission solutions associated with a specific NEO. Table 1 identifies the "top 25" NEOs, listing them in order of descending *n*.

In NEO exploration, size *does* matter, so Table 1 also contains an estimate of the likely diameter range *d* for each NEO. Values of *d* associated with a specific NEO are computed from its SBDB absolute magnitude, together with plausible albedo values of 25% (corresponding to minimum value in Table 1, column *d*) and 5% (corresponding to maximum value in Table 1, column *d*). Regardless of its associated *n* value, a NEO must have a maximum estimated *d* exceeding 30 meters to be included in Table 1.

A useful tool in visualizing NEO-specific accessibility is the "pork chop" plot. Figure 14 is an example of such a plot for the highest *n*-ranked NEO, 2000 SG_{344}. The horizontal axis in this plot spans a subset of the NHATS-permissible Earth departure dates extending from 2015 January 1.0 UTC to 2040 December 31.0 UTC. The Figure 14 vertical axis measures round-trip mission duration, its maximum permissible NHATS value being 450 days. Hue in the chart indicates the sum of all propulsive impulse magnitudes Δv_{TOT} required to depart a 400 km Earth parking orbit targeting NEO intercept, null NEO relative motion at NEO arrival, target Earth intercept following a finite NEO loiter period, and achieve atmospheric entry speed no more than 12.0 km/s upon Earth return. Blue hues correspond to the smallest Δv_{TOT} values, red hues correspond to the largest, and 12.0 km/s is the maximum NHATS-permissible Δv_{TOT} value.

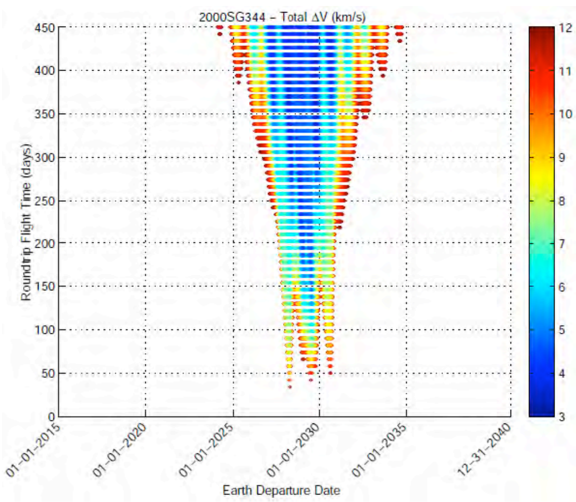

Figure 14: Pork chop plot of the n = 3,302,638 NHATS-compliant mission solutions pertaining to 2000 SG_{344}.

Intentionally optimistic NHATS human spaceflight mission design criteria help inform ongoing astrodynamics studies of NEA accessibility mechanics [38]. However, when more realistic human spaceflight capabilities are reflected by values assigned to the NHATS mission design parameter set, the number of compliant NEOs is dramatically reduced to three: 2000 SG_{344}, 2007 XB_{23}, and 2006 RH_{120}. These are the only NEOs offering at least one mission opportunity departing Earth between 2025 and 2030 with Δv_{TOT} less than 5.0 km/s and round-trip mission duration less than 180 days. However, none of these opportunities enjoys Δv_{TOT} less than 4.5 km/s or duration less than 170 days. According to notional parametric mission analysis, compliance with these more restrictive criteria requires only two heavy-lift launches, each placing 100 metric tons of payload mass in low Earth orbit, while permitting use of conventional chemical propulsion throughout.

The three more realistic NEO destinations would therefore seem to be feasible targets, but two of them are likely very small in size, perhaps too small to justify a piloted mission. As shown in Table 1, 2000 SG_{344} may be up to 66 m in diameter, but 2007 XB_{23} and 2006 RH_{120} have maximum estimated diameters of only 23 m and 7 m, respectively. Both are therefore too small to appear in Table 1. This dearth of viable human destination targets clarifies the need to discover additional highly accessible NEOs within the next several years if any HSF missions to NEOs are to be planned for and executed within the 2025 – 2030 time frame.

V. SUMMARY

The space between Earth and Mars swarms with near-Earth asteroids and comets. It is a considerable amount of jetsam and flotsam left over from the formation of our solar system that contains valuable remnants of this early formation process. These NEOs are the most easily accessible bodies in interplanetary space. The known population of NEOs is expected to grow exponentially in the coming decade, offering many more potential target asteroids. Therefore, as we look beyond the ISS program, NEOs offer invaluable deep-space experience and a logical, attractive stepping stone to Mars and beyond. Piloted visits to NEOs before more extensive lunar exploration or Mars expeditions can demonstrate the interplanetary capability of the next generation piloted spacecraft, thus opening up the frontiers of the solar system to the unique capabilities and talents of human explorers.

Survey First

The current dearth of viable candidate NEOs as potential destinations for human exploration is due to the fact that the world's NEO observing assets are currently confined to the vicinity of the Earth. Analyses of past trajectory opportunities to NEOs have shown that some were highly accessible during the timeframes of their discovery, because they had to closely approach Earth in order to be detected. Due to their long synodic periods of several decades and longer, the work-around to this geometric observing handicap is a deep-space telescopic NEO survey mission whether that asset is placed at SEL_1 (or SEL_2) to look at the 'sweet spots' as depicted in Figure 2; or, in a Venus-like orbit about the Sun looking outward as described in Figure 3.

If this crucial first step proceeds to implementation, the complete catalog of candidate NEOs could then be transformed into a matrix of opportunities for robotic and human missions for the next several decades. This matrix would include critical mission parameters (e.g., required Δv, mission durations, departure opportunities, etc.) and shared with the international community. This matrix would not drive architectures or schedules, but would illustrate windows of opportunity that could be exploited by the respective agencies based on their capabilities and budgets. The overall return to the NEO community in terms of science, flight techniques and technology/instrument demonstration would be increased by this collaboration more than the contribution of any single agency, and would provide many more well-characterized targets for piloted missions. Meanwhile, an extensive ground-based campaign would be undertaken to better characterize these potential mission targets [3, 13].

Science-Driven to Exploration-Driven Missions

There are currently a couple science-driven missions to NEOs that will proceed to launch: *Hayabusa 2* and *OSIRIS REx*.[†] Already underway, *Rosetta* is en route to Comet 67P/Churyumov-Gerasimenko and carries the *Philae* lander. While 67P is not an asteroid, the anchoring techniques employed by *Philae* are absolutely relevant to understanding how to anchor to other small bodies such as asteroids. The same holds true for the *Phobos-Grunt* mission to be launched later this year in the effort to land/anchor on Phobos.

Exploration-driven robotic precursor missions on the other hand, would serve a slightly different purpose. Prior to mounting piloted missions to NEOs, basic characterization of the target asteroid is required. These precursor missions will act much like the pathfinder robotic missions of *Ranger*, *Lunar Orbiter*, and *Surveyor* to the Moon that preceded the Apollo missions there. This basic characterization of the target NEO will identify potential hazards that may pose a risk to both the crew and their spacecraft and would determine whether the asteroid was multiple-body system, spin state, potential surface activity, internal structure on a global scale, surface stability, geotechnical properties of the regolith, etc. While these are primarily engineering requirements and measurements in preparation for the human missions, a great deal of science will also be gleaned from such measurements.

[†] *Marco Polo-R* is one of four medium class missions selected by ESA's Cosmic Visions Program for further study. If selected, it will launch to 1999 FG3 in 2020.

ISS as a Testbed to NEO Exploration

The micro-gravity environment of the ISS provides a highly useful facility to investigate a wide array of issues that are key to long duration space missions in general and to NEOs, specifically. Most notably, these include ISRU, EVA and ECLSS systems, as well as long-term habitation and radiation mitigation. Although current terrestrial ISRU techniques are still being matured, both JAXA and NASA have significant amounts of extraterrestrial materials [water-, metal-, and volatile-rich meteorites] that could be utilized in a glove box or ISRU lab rack experiment on the ISS. If water, carbon, and precious metals are extracted in minute quantities, it is a valid first step and proof-of-concept in the direction towards NEO exploitation. Considering that there are three research laboratories available on the ISS (*Destiny, Kibo*, and *Columbus*), there is the potential to run parallel technology demonstrations with multiple international partners, each participating in their own way to achieve a common goal. Such international experiments may be manifested to fly on JAXA's H-2 Transfer Vehicle (HTV) or ESA's Automated Transfer Vehicle (ATV), Russia's Progress or any of the potential COTS cargo carriers to that are scheduled to service the ISS in the coming years, furthering international engagement in this endeavor.

The collective experience of Apollo, Space Shuttle, Salyut, Mir and ISS programs underscores the world's space agencies capabilities to meet operational challenges and solve problems in the space environment. Despite the current uncertainty for the future of human exploration beyond ISS, humanity could be poised to execute historic missions of exploration and discovery, by reaching for the resources and knowledge at these nearest waypoints in interplanetary space. The key is to complete the NEO survey first.

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