Asteroid Initiative Idea Synthesis Workshop

Selected Abstracts • Sept. 30 to Oct. 2, 2013

After receiving more than 400 responses to the Asteroid Initiative **RFI**, a team of NASA scientists, engineers, and mission planners evaluated the proposed ideas. The evaluation team rated the responses for relevance to the RFI objectives, innovativeness of the idea, maturity of the development approach, and potential to improve mission affordability.

Nearly 100 respondents have been invited to present their ideas and concepts during the *Asteroid Initiative Idea Synthesis Workshop* alongside NASA personnel and members of the larger community, including virtual participants. The purpose of this workshop is to further examine and foster a broad discussion on these newest ideas and help inform NASA's planning activities.

Enclosed here is a compendium of the abstracts that were selected for presentation and discussion during the workshop. The abstracts are organized into the following topic areas:

Due to capacity constraints, onsite attendance is limited to invited, registered presenters and NASA personnel. Virtual participation is strongly encouraged. We will provide virtual participation options on the workshop Web page prior to the workshop. There is limited seating for media interested in attending; members of the media should contact Sarah Becky Ramsey at 202-358-1694 or Rachel Kraft at 202-358-1100 for additional information.

ASTEROID OBSERVATION

A PROPOSAL FOR ENGAGING MORE AMATEUR ASTRONOMERS IN MINOR PLANET LIGHTCURVE IMAGING AND ANALYSIS

Phil Beffrey

Amateur astro-imagers make a serious contribution to the observation of minor planets, and data from their observations are an important component in "determining orbits, characterizing shape, rotation state, mass, and composition" of asteroids and/or comets. A speaker at NASA's recent Asteroid Initiative RFI Google+ Hangout presentation suggested that there were, at most, a couple of hundred people/sites worldwide performing these observations.

This proposed project aims to substantially increase the number of amateur astro-imagers devoted to making these observations and, at the same time, revitalize the public's interest in space-science and all things NASA.

CHARACTERIZATION AND ORBIT DETERMINATION OF NEAR-EARTH OBJECTS WITH LASER RADAR

Jane Luu, Massachusetts Institute of Technology

Laser radar technology is now sufficiently mature to attempt active optical probing of solar system bodies beyond the Moon. We propose establishing a dedicated laser radar system at a 2m-class telescope, equipped with adaptive optics, to measure the distance to near-Earth objects (NEOs). With 10 kW average power, the system can observe NEOs as small as 30m at 10x the Earth-Moon distance (0.026 AU) if a guide star is available as the adaptive optics reference; the limiting size is 200m at the same distance if the NEO itself is used as the reference. This would complement the existing radar facilities and help build a catalog of NEOs with very accurate orbits, crucial for calculating impact probability and selecting suitable mission targets.

DEVELOPMENT OF A HIGH-PERFORMANCE, INFORMATION THEORY-BASED DATA MINING TOOL FOR ASTEROID THREAT DETERMINATION

Stephen S. Eikenberry, University of Florida

We are interested in the development of a high-performance information-theory-based data mining tool for asteroid threat determination/classification, via a collaborative effort between academic scientists specializing in astronomical studies of asteroids

(observation, classification, and orbital/dynamical modeling) and industry-based specialists at Entropy Limited. This hybrid partnership would bring together expertise in asteroids and their orbits and threat to the Earth and information theory researchers specializing in quantitative prediction, forecasting, and modeling with partially complete data sets. While NASA-based and other observational data sets have vast quantities of information on asteroids, it is often the case that the data for any given asteroid is incomplete or inconclusively matched to the asteroid identification. We can combine our skill sets to provide a tool which can fully exploit the richness of these data sets, providing probabilistic models to classify the asteroid properties, predict their complete orbital elements from partial data, and evaluate their threat likelihood and impact for the Earth.

ASTEROID OBSERVATION & CHARACTERIZATION SCOUTING MISSIONS

David Gump, Deep Space Industries, Inc.

Detection of near-Earth asteroids has far outpaced our ability to determine their nature, and thus our ability to defend Earth or find useful resources. No comprehensive method to correlate meteorite families with observed asteroid spectra exists, for example. Even the most basic asteroid characteristic – mass – is unknown for the vast majority of NEAs. For any given absolute magnitude of observed target, the mass range factor is a staggering 460 even before including uncertainties for rubble-pile structure. Missions that attempt to redirect entire uncharacterized targets with a mass range factor of 460 are unlikely to succeed. Even the alternative of selectively gathering boulders up to the return capability of the spacecraft requires sufficient advance knowledge to confirm that suitable boulders actually exist.

Scouting missions are required to provide reliable characterization of most potential NEA targets. For example, no NEAs smaller than 500 meters have been observed at close range to determine if they generally are rubble piles like their larger brethren, or if most transition to solid monoliths at some size threshold. Scouting missions that fly by (the lowest cost type of inspection) can determine volume and surface morphology; more ambitious missions that rendezvous can determine true mass (something not possible even when NEAs come close enough for radar inspection). Close-in observation also can reveal if the surface properties that sometimes can be measured from Earth's vicinity are the same as the target's more important subsurface characteristics. Example scouting missions are described that can visit potential redirection candidates sufficiently far in advance to provide this key ground-truth to enable go-no go decisions.

The data that NASA requires for planetary defense and science are highly complementary with industry's requirements for identifying resource-rich targets. Those resource-rich targets later will also benefit NASA and its need for in-space propellant and materials to reduce the cost of solar system exploration. This high correlation

between government and industry goals means that scouting missions and later redirection missions are near-perfect candidates for public-private partnerships that share costs and benefits.

LEVERAGE EXISTING 1.1M COMMERCIAL TELESCOPE FOR ASTEROID DETECTION

Gary Matthews, Exelis Geospatial Systems

Based on the time schedule defined for the program for an Orion exploratory launch in 2021, the need to find an appropriate asteroid is somewhat urgent and needs to be accomplished in the 2017 timeframe. This early detection provides the vital time required for specific training and concept of operations planning needed in order to visit or capture the asteroid. Based on this very tight time schedule, we recommend leveraging an existing system configuration for the use in the asteroid detection and observation portion of the mission. Although a 1.1 m aperture diameter commercial system is not a perfect choice, the size does provide the ability to identify the location and orbits of potential asteroids at an acceptable cost and schedule.

The other important aspect of leveraging the commercial 1.1 m optical system would be a CRADA opportunity in the form of initial cost sharing to reduce the need for early budget requirements. Exelis has been working with Goddard Space Flight Center in the development of conceptual solutions for the asteroid detection system and in the creation of potential innovative business models to augment the near term funding hurdles.

AIR FORCE SENSOR SUPPORT FOR ASTEROID OBSERVATION

John Lambert, The Boeing Company

The Boeing Company has been an active participant in near-Earth asteroid search programs for over two decades. Our initial involvement began as an outgrowth of our optical sensor development, and observational and analysis support to the Air Force Space Surveillance Network (SSN) as the prime contractor for the Air Force Maui Optical and Supercomputing (AMOS) facility on Mount Haleakala on Maui operated by the Air Force Research Laboratory (AFRL). Working closely with Air Force Space Command (AFSPC), the AFRL, and the NASA Johnson Space Center (JSC) Orbital Debris Program Office, Boeing developed and applied techniques for the optical detection, tracking, and physical characterization (size, shape, rotation, and surface properties) of “deep space” (orbital periods >225 minutes) artificial satellites and small debris objects.

Follow-up sensors are critical to successful NEA search programs since they allow the search instruments to maintain their observational cadence and achieve maximum coverage and search completeness. The NEA follow-up observations are very suitable for shared use of the Air Force optical sensors. In the past, the Air Force has been very supportive of NASA NEA observing programs and has made observing time available on its sensors. Using our detailed knowledge of both the NEA and the SSN missions, Boeing can work with NASA in requesting Air Force sensor support by helping to identify the most suitable Air Force sensors and instrumentation; estimate observing time requirements; and develop and implement hand-off, scheduling, and tracking algorithms to support newly detected NEA follow-up observations and data processing. In many cases, it would then be Boeing personnel who operate the Air Force sensors to make the observations and perform the data reduction.

USE SATELLITE STAR TRACKER SENSORS MEASURING ASTEROID ROTATION

Stephan Klene

Use star tracker from existing satellite missions to measure light variation due to rotation of asteroid. Many missions including earth observation satellites GeoEye-1, IKONOS, WorldView-1, WorldView-2, Pléiades 1A and Pléiades 1B spend over half their mission life with no operational tasks to perform. These satellites need sufficient sun illumination of the earth to perform their primary mission. During the low light and eclipse they generally have no tasks to do. During the unused times the satellite bus can be maneuvered so that a star tracker track the expected path of a known asteroid and measure the light that is being received. Star trackers are designed to measure stars move through the sensor field of view and allow measurements to be taken. This proposed solution requires some software changes to record, download and process results from measurements.

LEVERAGING PLANETARY RESOURCE'S NETWORK OF ARKYD 100 SPACE TELESCOPES TO BE LAUNCHED IN 2015

Chris Lewicki, Planetary Resources, Inc.

NASA has the opportunity to leverage innovative and low cost efforts Planetary Resources is deploying in its development of commercial robotic deep space exploration capability. In 2015, PRI will be launching and operating multiple Arkyd 100 space telescopes in Earth orbit. Given their location, they will have niche capabilities to detect and characterize Atira class near Earth asteroids, perform rapid and responsive astrometric follow-up for recently discovered objects, and characterize these objects through long duration photometric monitoring for the establishment of light curves. Basic spectroscopic capability will also be possible through utilization of bandpass filters.

Combined with PRI's internal vertically integrated development, crowd-sourcing efforts with Zooniverse and the Asteroid Zoo, the Arkyd 100 will be an ideal platform for demonstrating innovative new concepts to expand upon current NEA observation efforts.

WEB PORTAL FOR AGGREGATING, DISSEMINATING, AND STANDARDIZING OBSERVATIONS

Jeffrey L. Mitchell, Storm Bourne

I am proposing a system that allows for aggregation, dissemination and standardization of observation data. A "social research" facility that will allow researchers to collaborate and coordinate in standardized formats easily. This system would provide workflow improvements in the form of data collection and computational support for continued research on a given near earth object or minor planet. This system would provide a portal to amateur observers so that their volunteer efforts can be of maximum use. This system will be implemented as a web based portal offering a stable and easy to use user interface. The system will be developed, implemented, and maintained utilizing generally accepted software engineering techniques to deliver the type user experience that would be expected from a world class, high availability cloud based application.

MEASURING THE SIZE OF 10M NEAR EARTH ASTEROIDS WITH COHERENT DOPPLER LADAR

Bijan Nemati, Jet Propulsion Laboratory

The proposed Asteroid Redirect Robotic Mission (ARRM) hopes to nudge a small asteroid into orbit in the Earth-Moon system. Finding such small asteroids is a challenge. But finding them is only the first step. We would also need to measure the size and the mass of these asteroids. Accurate astrometry of these small objects can be used to measure the acceleration of the asteroid due to photon pressure from Sunlight. A measurement of the size then lets us derive the asteroid mass. The technique we propose to use is called ISAL, Inverse Synthetic Aperture laser detection and ranging (LADAR). Radar astronomers have been imaging near Earth Asteroids for decades using ISAR or range Doppler imaging. ISAL is the optical/laser version of ISAR or range Doppler imaging. There are two potential advantages with ISAL. One is sensitivity. A laser beam can be focused much more narrowly than a radar beam and modern high power lasers on a 4~5 m class telescope can probe the asteroid with higher power on the target than a large microwave radar. The other advantage of using optical frequencies is that the range and Doppler resolution can be orders of magnitude higher when the SNR is high. An ISAL system that could be built with current technology could measure the size of a 10 m asteroid at a distance of out to 4 lunar distances, augmenting the volume of space over which a size measurement is possible by roughly

an order of magnitude.

FREEFLYER SOFTWARE FOR ASTEROID OBSERVATION AND MISSION DESIGN

Sara Case, a.i. solutions, Inc.

As part of the Asteroid Initiative, NASA has a need for tools and concepts supporting asteroid observation, including asteroid orbit determination based on ground and space-based sensor data; modeling of each asteroid's shape, rotation state, mass, and composition; and analysis of each asteroid's overall suitability as a target for the Asteroid Redirection Mission. a.i. solutions' commercial off-the-shelf (COTS) software FreeFlyer, already widely embraced by the NASA community, offers capabilities satisfying each of these requirements. a.i. solutions recommends the use of FreeFlyer for planning, analyzing, and operationally flying this mission.

INVOLVE SMALL PRIVATE OBSERVATORIES IN ASTEROID OBSERVATIONS

Ray Pickard, Bathurst Observatory Research Facility

As a small privately operated research and educational facility, the Bathurst Observatory Research Facility in Bathurst NSW Australia relies on donations and sponsorship for its programs. The observatory undertakes research in meteorites, asteroids and provides public and school education programs. Though asteroid research is one of the observatory research goals, being donation-funded limits the work that can be undertaken. Some joint initiatives have been proposed in the past, however being reliant of private investment has proved unreliable. Asteroid research is being pursued by the observatory and suggestions of how an international approach to asteroid research are made as well as methodologies that can be utilised involving smaller observatories.

LEVERAGE ALGORITHMS DEVELOPED FOR MISSILE DEFENSE AGENCY FOR AUTOMATED NEA DETECTION

Clinton Clark, ExoAnalytic Solutions

To support the recently announced Asteroid Initiative, the National Aeronautics and Space Administration (NASA) is seeking concepts for augmenting and accelerating ground and space-based capabilities for detecting all near-Earth asteroids (NEAs) – including those less than 10 meters in size that are in retrievable orbits – determining their orbits, and characterizing their shape, rotation state, mass, and composition as accurately as possible. ExoAnalytic Solutions Inc. (ExoAnalytic) has developed algorithms and software that enables the ability to detect, track, determine orbits,

characterize and reacquire space objects in real-time – and immediately display the information in a space Common Operating Picture (COP).

ExoAnalytic is pleased to provide this white paper in response to the NASA Asteroid Initiative RFI NNH13ZCQ001L, and we welcome the opportunity to participate in the September 2013 workshop. ExoAnalytic is a small business that brings innovative technologies, approaches, and tools to the Space Situational Awareness (SSA) domain. The ExoAnalytic team has a long, successful history of support to the Space and Missile Systems Center (SMC), the Missile Defense Agency (MDA), and the Space community.

In this white paper we briefly describe our real-time processing capabilities within ESpOC, our key SSA algorithms, our recommended sensor network architecture, and we provide sample space object detection, tracking, orbit determination, and characterization results. The technologies discussed in this white paper can be used to optimize performance of current sensor networks, develop a stand-alone sensor network dedicated to NEAs, facilitate a crowd-sourced NEA solution, and rapidly (re)process and analyze historic observations to search for NEAs.

CUBESAT SWARM WITH IR SENSORS AND ONBOARD DATA PROCESSING

David Rabanus, SpaceAppsChile

Multispectral observations that allow for surface temperature determination in near IR, thermal IR (~10um), and mid-IR (18-24um). A swarm of economic cubesats, with on-board image processing capabilities that minimizes downlink bandwidth. The IR bands should allow a preliminary material determination as well. The scanning pattern of the cubesats (by spinning the space craft) allows for frequent revisiting of the same patch on the sky, allowing for signal-to-noise reduction by "image stacking".

Visible and NIR follow-up observations of space-based detections (size of object to be sufficiently large) shall be organized by a network of amateur observatories. Chile, due to its unique location, has a large number of privately organized observatories, many of which are very interested.

In general, we would like to see a better spelled-out policy for global networking of NASA with other organizations, especially amateur-based ones, for which the Space Apps Challenge already has shown to be fruitful. I think the next step would be a policy development with respect to ITAR limitations (e.g. a scientific exemption status or the like), technology transfers, and information sharing (i.e. in a virtual observatory).

ENHANCED DETECTION AND TRACKING MISSILES AND SPACE OBJECTS THROUGH GEOMETRIC NONLINEAR SIGNAL PROCESSING

Tom Burleson, Reisz Engineers

In this paper we describe the potential of an algorithm which, with minor modifications to existing radars, can greatly improve the performance of radars by increasing sensitivity without any increase in weight, power, or integration time. Our design efforts have been focused on missile defense radars and their missions, but we believe there is a role for our algorithm (GNLiSP), in enhancement of the performance of NASA radars in the mission of acquisition and tracking of asteroids.

Reisz Engineers recognizes that there are several engineering approaches that could be developed to enhance radar sensor performance. The approach selected involves the development and use of Geometric Nonlinear Signal Processing (GNLiSP) technology. This approach involves the development of an algorithm that will significantly increase the sensitivity of radar sensors as well as improve all radar functions without incurring any penalties in weight, power requirements or time. We understand that NASA has catalogued the orbits of about ten thousand asteroids that come within the region of our planet, representing potential threats. We have also been told that there is potentially ten times this number that could intersect our space. We believe that our technology could enhance the rate of search, detection and track of the remaining candidates by a half order of magnitude, and, using planned upgrades, by a full order of magnitude. The Technical Readiness Level (TRL) before Phase I would be a Level 3 (Proof of Concept) and would increase to a Level 4 (Laboratory Demonstration Validation) beginning Phase II.

DETERMINING ASTEROID ORBITS

Vadym Savanevych, Kharkiv National University, Ukraine

Developing algorithms for automatic detection of asteroids. Interested in cooperation to determine asteroid orbits.

DISCOVERY AND CATALOGING EARTH-CROSSING ASTEROIDS (ECAS) TO EXPAND AND ENHANCE FOLLOW-UP OBSERVATIONAL CAPABILITY OF ECAS IN LOW INCLINED EQUATORIAL ORBITS

Douglas Walker, University of Canterbury, Christchurch, New Zealand

Before the Earth can be successfully defended against a life-threating asteroid collision, the threat must be discovered and cataloged. It is estimated that 95 per cent of all Earth-crossing Asteroids (ECAs) larger than about 1 km in size with cis-Jovian orbits have been discovered and cataloged. However, the rates for ECAs smaller than 1 km is far worse; there is an estimated 9-10 million ECAs in the 15-20 meter size range of which only a handful are known and for sizes ranging in 40-100 meters, less than 1 percent have been found1. NASA's Asteroid Initiative mission is to find, capture and retrieve an asteroid to lunar orbit within the next 6-10 years. Prime candidates for this

mission would be asteroids in the 5-10 meter size range. In order to meet these challenges of discovering ECAs in this size range, the University of Canterbury (UofC), New Zealand, Physics/Astronomy department proposes to leverage its expertise in Difference Image Analysis (DIA) in stellar photometry in crowded fields to discovery of solar system minor bodies, specifically ECAs. In addition, it is being proposed to investigate and extend the development of image co-addition algorithms to EAC applications where the objects speed and position angle is unknown but can be bounded within certain orbital parameters. Being able to stack multiple images in combination with DIA search techniques would enable current survey systems to image several magnitudes deeper than what is currently achievable. Applying these results to the University of Canterbury's Mt John University Observatory 1-meter telescope would enable searches for extreme southern latitude ECAs ranging down into the 50-100 meter size range. A goal would be to apply the results of these DIA and stacking algorithms to imagery from currently available large optical survey systems to potentially reach asteroid discovery in the 5-10 meter size range.

A secondary proposal objective is to expand and enhance follow-up observational capability of ECAs in low inclined equatorial orbits which are only visible from the Southern Hemisphere (SH). Additional observational time at the Mt John University Observatory is being proposed for follow-up observations on asteroids in the 200+ meter size range to add to the current inventory of orbit ephemeris data for extreme southern latitude ECAs. Additional observations on asteroids in the 250 to 500 meter size range will provide light-curve data for rotation estimates and rough shape analysis. As part of this observing program, it is proposed that a Profession-Amateur (Pro-Am) program be initiated to involve serious amateur astronomers in the Australia/New Zealand region for follow-up observation work for southern latitude ECAs in the 0.5 to 1 km size range. As demonstrated by successful Pro-Am collaborations such as the Center for Backyard Astrophysics for photometry of cataclysmic variables, the American Association of Variable Star Observers for variable stars and the Planetary Society Gene Shoemaker Near Earth Object Grants, experience amateur astronomers with the right equipment and training can provide valuable scientific data and contributions to NEO research.

The principle advantage for undertaking these discovery and follow-up observations from the New Zealand location is to enable discovery and follow-up observations of ECA's which are only visible from the lower latitudes.

ASTEROID REDIRECTION SYSTEMS

EARTH'S MINIMOONS: NEW PROSPECTIVE TARGETS FOR HUMAN EXPLORATION

William Bottke, Southwest Research Institute

The population of asteroids that are temporarily captured in orbit around Earth ("minimoons") comprise heretofore uninvestigated targets for human exploration because of their proximity to the Earth and their low geocentric velocities. We believe this population can help NASA address perhaps exploration's most problematic issue: identifying a near-Earth asteroid population that astronauts and their tools can interact with within NASA's cost and scheduling constraints. These bodies may be reachable by the Orion architecture well before NASA's stated goal of visiting an NEA by 2025. They are also compelling science targets; by better understanding them, we can test theories of the creation, internal structure, and transport of small asteroids.

Here we briefly discuss what minimoons are, what their orbits may be like, their likely sizes and physical properties, and how human missions to them fit within NASA's exploration goals.

ASTEROID RETRIEVAL ALTERNATIVES FROM THE KISS STUDY

John Brophy, Jet Propulsion Laboratory

In 2011 the Keck Institute for Space Studies (KISS), along with the Jet Propulsion Laboratory sponsored a study to investigate the feasibility of identifying, capturing and returning an entire near-Earth asteroid to translunar space. This study considered a wide variety of alternatives. This RFI response describes the major alternatives considered by the KISS study. These alternatives fall into two main categories: different mission scenarios, and different spacecraft architectures.

ENABLING TECHNOLOGIES FOR ASTEROID REDIRECTION SYSTEMS

Kiel Davis, Honeybee Robotics Spacecraft Mechanisms Corporation

Honeybee Robotics (HBR) leverages its focused expertise in high reliability electromechanical and electro-optical systems, motion control, bearing design and processing, as well as AS9100 certified quality management system to ensure we offer the highest quality products possible. In response to NASA's interest in Integrated Sensing Systems we have two enabling component technologies for asteroid rendezvous, proximity operations, characterization, and capture. The Three-

Dimensional Miniature LIDAR (3DML) system can support characterization of the asteroid's size, shape, and spin state, as well as to some degree the surface properties. Combined with the Laser Induced Breakdown Spectrometer (LIBS) further information on the surface properties and composition can be obtained, thereby allowing a more accurate estimate of the mass of the asteroid. HBR technologies that can enable retrieval of a portion of the asteroid are our Touch and Go Surface Sampler that collects small and loose surface material. To collect larger specimens we can adapt our Light Adjustable Snare for Servicing & Orbital debris removal (LASSO) to capture and retrieve objects.

INTEGRATED SENSOR SYSTEMS AND APPLICATIONS OF SATELLITE SERVICING TECHNOLOGY TO ARM

John Ratti, MacDonald Dettwiler Associates (MDA) Inc.

MDA's long history developing and operating on-orbit servicing robotics, sensor suite and remote operations software provides a strong base of offerings that can be used to fully meet the objectives of the ARM Initiative. MDA's small, high TRL, integrated sensor suite can provide all of the necessary data to ensure safe asteroid rendezvous through to autonomous capture. The current mission concept can be enhanced by providing flight proven robotic technologies to progress human deep space exploration capabilities by repurposing ARV robotics and other systems to support on-orbit assembly and to act as a platform for future science. Finally, all this can be achieved through leveraging current and planned satellite servicing technologies.

LEVERAGING HERITAGE SPACECRAFT PLATFORMS AND SUBSYSTEMS TO REDUCE ARM EXECUTION RISK

Mike Elsperman, The Boeing Company

Boeing has developed an Asteroid Redirection Vehicle (ARV) concept that leverages the benefits of our commercial spacecraft portfolio, extensive Solar Electric Propulsion design, integration, and operations heritage, and successful autonomous rendezvous and capture expertise from Orbital Express. These key attributes provide an affordable flight system with the required capabilities to execute the Asteroid Redirect Mission (ARM). The ARM mission requirements result in system design based on a modified version of our 702 commercial spacecraft product line. The Boeing 702 spacecraft is a sturdy platform that can accommodate large (> 10,000 kg) propellant loads with minimal structural modifications, a key derived requirement to provide the required Delta Velocity needed to redirect the target asteroid to translunar space. The expansive payload deck can accommodate a large capture/redirect system with established interfaces for power, telemetry, and other payload services. Including a NASA Docking

System (NDS) on the ARV allows for easier crewed exploration mission integration and execution. It also enables potential reuse as a cargo tug or power/propulsion system for any translunar assets in the vicinity after the ARM is complete. The 702 can be launched on any EELV or as a dual manifest payload on an SLS. The established design and manufacturing processes, existing production and test facilities, and dependable supply chain of the 702 ensure a low risk program with minimal non-recurring engineering.

LEVERAGING HERITAGE AUTONOMOUS RENDEZVOUS AND DOCKING TECHNOLOGIES TO REDUCE ARM EXECUTION RISK

Manny Leinz, The Boeing Company

Boeing has significant experience in development of autonomous rendezvous and docking technologies for space missions. This is evidenced by our involvement with the Space Shuttle, International Space Station, and the Air Force Research Lab's Experimental Small Satellite 10 (XSS-10) program, which performed autonomous proximity operations with a Delta II upper stage in 2003. In 2007, on the DARPA Orbital Express mission, we demonstrated the ability to repeatedly rendezvous and capture a client satellite, largely through non-cooperative means, using electro-optical navigation sensors. Currently, we are developing the next generation rendezvous sensor system, known as VESTA (Vision-based Electro-optical Sensor Tracking Assembly), which will enable Boeing's CST-100 Commercial Crew Spacecraft to dock with the ISS with minimal reliance on docking aids. The VESTA system features smaller sensors and advanced processing to minimize size, weight, and power demands on the host vehicle, while increasing functionality. VESTA will fly on the first CST-100 orbital flight, which is scheduled for 2016. We have also invested in adapting the VESTA system to rendezvous and capture completely uncooperative targets, such as space debris or natural bodies such as asteroids. Electro-optical navigation sensor systems such as VESTA can perform multiple functions for an asteroid redirection mission, including star tracking, asteroid acquisition, track, and precision position / attitude determination. Determination of asteroid surface properties, 3D map generation, feature recognition and terrain relative navigation in preparation for asteroid capture are additional capabilities that these sensors can perform in support of the mission. In addition to asteroid rendezvous and capture, these sensors can support rendezvous and docking of the ARV spacecraft with other exploration elements, such as a habitation module.

COLLECTING MULTIPLE SMALL BOULDERS OR REGOLITH SAMPLES FROM RUBBLE PILE ASTEROID

David Gump, Deep Space Industries Inc.

A change to the stated target of the Asteroid Redirect Mission (ARM) could result in greatly increased scientific value without significant cost increases, and can simultaneously improve the probability of mission success. Research should be conducted to consider that if instead of targeting a single free-floating tiny but intact (monolithic) asteroid (perhaps 5 to 10 meters in diameter) or a single similar boulder retrieved from a rubble pile asteroid, the ARM should rather target the collection of multiple smaller boulders and possibly regolith or gravel. These samples would all be selected to maximize the diversity of samples collected, and all packaged, wrapped, or otherwise contained to prevent cross-contamination and to provide documentation of their source.

Mission success probability is improved by allowing an appropriate mass to be retrieved, and the maximum design payload can be returned. Gambling that the single asteroid to be returned intact (or a single boulder) is both large enough to be worth the mission cost and small enough to be successfully returned is not required: Boulders are selected and added to the payload until the desired total payload mass has been collected.

IN-SITU RADAR FOR ASTEROID CHARACTERIZATION AND ALTIMETRY

Mark Haynes, Jet Propulsion Laboratory

Radar is a fast, versatile, quantitative remote sensing tool that can uniquely aid future missions of the NASA Asteroid Initiative. Several systems are envisioned to cover the full life cycle of asteroid robotic and manned missions, redirect and deflection missions, from characterization and capture to post-scientific analysis. Multiple in-situ radar types and frequencies are suggested providing solutions to specific sensing problems in the Asteroid Initiative RFI. Applications include in-situ tomography, surface and sub-surface characterization, and real-time altimetry. Radar type and application are ultimately selected by mission-specific requirements.

MINIMOONS: DISCOVERY & RETRIEVAL MISSIONS

Robert Jedicke, University of Hawaii

As with the current ARM architecture, target discovery is a key consideration for a minimoon mission and the challenges involved in discovering minimoons are similar to those in discovering ARM targets. While minimoons are smaller than ARM targets they are typically closer to Earth - the largest minimoon in the steady-state population is about 1 to 2 meters in diameter, so detecting them requires large-aperture ground-based telescopes or a specially designed space-based system, but they are always within about 10 lunar distances and typically much closer.

Ground-based Near Earth Object (NEO) observation facilities and detection algorithms are very mature. Indeed, there are now several complementary ground-based observing campaigns and data processing systems that discover NEOs (Pan-STARRS, Catalina Sky Survey, LINEAR). Applying these strategies to minimoon detection would require minimal modification to existing capabilities, namely the selection of a wide-band filter and tuning to the minimoons' angular rates of motion. Similarly, the NEOWISE mission has advanced NEO-detection into the space realm. A WISE-like spacecraft at the Sun-Earth L1 point would be an excellent platform for minimoon discovery.

We consider scenarios for discovering minimoons with a ground-based large-aperture optical telescope and/or a space-based IR survey. Our studies suggest that these systems can discover minimoons at rates high enough to enable mission planning. The most promising ground-based survey option is with Hyper Suprime-Cam on the 8.2 m diameter Subaru telescope for which there is at least one minimoon visible on the sky at any time. An IR survey on a space-based spacecraft from L1 with a 0.5 meter diameter mirror would be able to detect more than five minimoons on the sky visible from its location at any time.

PROPOSED DEVELOPMENT SOLUTIONS FOR ASTEROID REDIRECTION SYSTEMS

Piero Messidoro, Thales Alenia Space

Development solutions are proposed in four technology areas to support asteroid redirection systems: (1) The proposed propulsion system concept relies on a Helicon Plasma Thruster (HPT), an innovative and versatile plasma electric propulsion system. The technology is throttable and scalable, and is potentially able to use a large variety of propellants. (2) Enhancement of the capabilities of approaching and capturing asteroids is proposed by an autonomous integrated sensing system to support rendezvous, proximity operations, characterization, and capture. The specific proposal is focused on the vision based camera and image processing algorithms, which is a versatile and light equipment. (3) The proposed system concept for the capture and redirection of Near Earth Asteroids (NEAs) relies on an inflatable solution based on a high launch packaging capability and on the use of high specific strength materials which provide mass optimization in front of a huge in orbit deployable volume. In this concept an inflatable truss based on longitudinal and hoop elements has to accomplish the task of deploying a net made from the cross-stitching of high strength fabric ribbons which provides the capture volume. (4) Design of the Human Machine interaction (HMI) system is addressed to support and enhance the operator capability to command and control the involved systems during an Asteroid Redirect Mission scenario and to support EVA activities during the human mission for asteroid samples retrieval.

INTEGRATED SENSING SYSTEMS FOR ASTEROID MISSIONS

Richard Dissly, Ball Aerospace & Technologies Corp.

Integrated sensing represents a critical suite of technologies for the Asteroid Redirect Mission and other future robotic and human spaceflight programs. This paper evaluates sensing requirements from a minimal functional perspective, and presents the current state of the art components and subsystems that can be adapted to support ARM. The paper includes functionality beyond the sensor apertures because of the degree of integration, on-board processing, autonomy and fusion envisioned for ARM. Additional capabilities and concepts are investigated to enhance mission value by reducing mission risk, improving science return and enabling critical characterization to benefit planning and development for the ARM human mission.

INTEGRATED SENSING SYSTEMS TO SUPPORT ASTEROID RENDEZVOUS, PROXIMITY OPERATIONS, CHARACTERIZATION, AND CAPTURE

James Munger, Northrop Grumman Systems Corporation

Northrop Grumman offers a wide range of proven sensor products and mission components that address strategic knowledge gaps identified by the Near Earth Asteroid Working Group. Our integrated sensing systems support asteroid rendezvous, proximity operations, characterization and capture in compact packaging suitable both for robotic precursor as well as human exploration missions. We present our capabilities in hyperspectral imaging and Laser ranging for asteroid characterization from a safe distance, ground penetrating radar systems to investigate internal structure and composition of the target on closer approach, and innovative disposable CubeSat probes for close flybys and impact studies of the target asteroid, while keeping the main craft at a safe distance prior to first contact. By mapping the capabilities of our sensor packages to established mission requirements, we offer a flexible menu of solutions that support a wide range of missions**.**

ALTERNATIVE MISSION CONCEPTS AND SUMMARY OF GSFC TECHNOLOGIES AND FACILITIES RELEVANT TO ARM.

Benjamin B. Reed, NASA-GSFC

The Asteroid Redirect Mission (ARM) requires not only the expansion of industry-wide high power (25KW) solar electric power generation to a higher power range (40-50KW) and improvements to industry-standard solar electric propulsion (SEP) technologies, but also small asteroid detection systems, terrain-relative navigation sensors and

processing, autonomous tumbling target capture guidance and control, asteroid capture mechanisms, sample acquisition tools, sample storage tools, etc.

While a number of foreign-built crew and cargo vehicles (Shenzhou, Soyuz, Progress, ATV) currently in operation are capable of autonomous rendezvous and capture (AR&C), DARPA has performed an AR&C only once (Orbital Express), and does not currently have an active AR&C capable vehicle. No mission from any nation has ever performed the kind of closed-loop terrain-relative navigation and control required to capture or harvest a small asteroid.

This RFI response provides: 1) suggestions for refinement to the ARM concept of operations, including a summary of key challenges and some recommended solutions; 2) a summary of flight ready or near flight ready GSFC technologies relevant to ARM and at a state of readiness to support its aggressive 2017 launch date, and 3) a summary of unique, existing Goddard Space Flight Center (GSFC) facilities available for test of ARM technologies.

INTEGRATED SENSING SYSTEMS

John Ringelberg, Lockheed Martin

Capabilities and experience from previous and on-going programs to support a launch target of no later than 2018 is emphasized. The NASA New Frontiers OSIRIS-Rex mission will use an integrated sensor system approach to map, select a location, approach and capture a sample from an asteroid. Lockheed Martin is the mission prime contractor and is providing capabilities to support these mission operations. Experience from the AFRL XSS-11 mission is directly applicable to performing proximity operations with a non-cooperative space object, and LM has advanced these capabilities since XSS-11 through internally funded development, follow-on missions and contracted studies. The integrated sensing systems for both of these missions are presented and correlated to an asteroid redirect mission. LM has a long history of developing advanced laser transmitter, receiver, and electronics systems for space-based active and passive optical remote sensing. A concept for fusion of demonstrated sensing technologies is presented for asteroid characterization – size, shape, spin state, surface features, composition, mass, and inertia properties. These same technologies and their application to the asteroid initiative will enable future exploration missions through the technological advancement of the capabilities, and the experience gained through both human and robotic exploration.

ASTEROID REDIRECT VEHICLE WITH SOLAR ELECTRIC PROPULSION AND ROBOTIC MANIPULATOR

Adam Maher, Space Systems/Loral, LLC

An integrated Asteroid Redirect Systems solution is offered that combines state of the art Solar Electric Propulsion with flight proven bus, automated rendezvous, and dexterous robotic systems. This highly capable Asteroid Redirect Vehicle (ARV) can be deployed by 2017 and offers a wide range of scalable high power and total impulse configurations. This provides the program formulation team with mission design flexibility and the freedom to choose the right balance between technical risk and operational capability and versatility. Our scalable spacecraft comprises a large commercial bus platform using many heritage subsystems, a mix of current and next-generation Solar Electric Propulsion (SEP) hardware, a suite of already developed and largely fielded robotic and sensing technologies, and an orbit insertion strategy that enables a mission with high propulsive capacity to be staged in lunar space to begin transit to an asteroid. Our ARV provides these capabilities in synergy with other NASA and commercial space pursuits. This architectural strategy means that ARV development will spin off significant benefits for NASA objectives in space exploration and satellite servicing.

ASTEROID DEFLECTION DEMONSTRATIONS

THE SOLAR COLLECTOR OPTION FOR MANEUVERING NEAR EARTH ASTEROIDS

Robert B. Adams, NASA-MSFC

MSFC civil servants and contractors have embarked on several significant efforts over the last decade to explore options for deflecting NEO's from collision courses with earth. Two substantive documents are sampled below which discuss the solar collector option.

In our efforts the solar collector consistently came out as a strong option for deflecting asteroids smaller than 1 km with a warning period less than a decade. The solar collector, described in detail in the excerpts, is a close cousin to the solar sail. However instead of a flat sail, the reflective material is shaped into a parabolic dish. A secondary reflector allows for directing the collimated light in the direction needed for thrust.

Directing this light onto an asteroid can produce significant vaporization and resulting momentum exchange. There are several issues still to be addressed with this concept. One is the question of focus length and ability to focus over the broad spectrum of wavelengths produced by the sun. Second is the survivability of the collector over years while vaporizing material from the asteroid. Third is the ability of the secondary mirror to handle the heat loads from inevitable absorption. Finally there are issues related to the orbital mechanics of station keeping near a rotating, non-spherical, non-homogeneous asteroid for long durations.

Despite all these issues the solar collector offers great capability for asteroid deflection and retrieval. The deflection mechanism is not strongly affected by asteroid rotation and could be used to reduce rotation. It does not radioactively activate or blow holes in the asteroid, like nuclear and kinetic deflection systems. It is not constrained by asteroids with keyhole events or require 50 year deflection times like the gravity tractor. It provides its own propulsion system and is extremely lightweight, as shown in the calculations below. And it is relatively near term technology. A flight demonstration with this system could easily be produced before the 2017 target date, and using today's materials.

The following passages are excerpts from previous research done by the author and colleagues on the solar collector options. These are extensive reports that cover numerous other options for planetary defense and much of the research could be adopted for the maneuvering and capture mission. The text below has been slightly edited for readability as stand-alone passages.

PUSH-ME/PULL-YOU ASTEROID DEFLECTION DEMONSTRATION

John Brophy, Jet Propulsion Laboratory

The Asteroid Redirect Robotic Mission (ARRM) concept utilizes a 50-kW solar array (beginning of life at 1 AU) with a 40 kW electric propulsion subsystem to rendezvous with, capture, and redirect to translunar space an entire small near-Earth asteroid. This system can redirect an asteroid with a mass of up to approximately 1000 metric tons. To do so the robotic asteroid redirect robotic vehicle (ARRV) must capture, detumble and despin the asteroid before redirecting to translunar space. Depending on the density, asteroids of up to 1000 t may only be 5 to 10 m in diameter. Such small objects are typically not considered to be potentially hazardous objects. This RFI response identifies how the solar electric propulsion technology from the ARRV could be used to deflect a much larger, 50-m-class, near-Earth asteroid and how this technique could be demonstrated as part of the baseline ARRM concept.

Typical near-Earth asteroids may have densities in the range 1.9 to 3.8 g/cm3 with significant outliers beyond this range. A 50-m diameter asteroid with a density in this range would have a mass of 125,000 t to 250,000 t (1.25x108 kg to 2.50x108 kg). Assuming an albedo of 0.14, a 50-m diameter asteroid would have an absolute magnitude of about 24.3. From Fig. 1, near-Earth asteroids of this size (absolute magnitude) can have quite fast rotation rates [1]. The physical size, mass, and possible rotation rate of a 50-m diameter NEA would make it virtually impossible to despin. Therefore, a deflection technique is needed that doesn't require despinning the asteroid.

THE ISIS MISSION: AN IMPACTOR FOR SURFACE AND INTERIOR SCIENCE

Steven Chesley, Jet Propulsion Laboratory

The Impactor for Surface and Interior Science (ISIS) mission is a proposal for a low-cost kinetic asteroid impactor mission to (101955) Bennu, the target of NASA's OSIRIS-REx asteroid sample return mission. The two missions would be strong partners in this investigation, and thus the ISIS name is apt, given that Egyptian mythology tells us that Isis was the wife of Osiris. The ISIS mission concept calls for the ISIS spacecraft, an independent and autonomous smart impactor, to launch as a secondary payload with NASA's InSight mission and then guide itself to a hyper-velocity impact with Bennu while the OSIRIS-REx spacecraft observes the collision. Later the OSIRIS-REx spacecraft would descend to reconnoiter the impact site and measure the momentum imparted to the asteroid through the impact, before departing on its journey back to Earth.

TOUCH AND GO SURFACE SAMPLER, IMPACTOR PROBE, ANCHORING DEVICES

Kiel Davis, Honeybee Robotics Spacecraft Mechanisms Corporation

Honeybee Robotics (HBR) is pleased to respond to NASA's request for information for the Asteroid Initiative with a number of relevant and enabling technologies. Honeybee is interested in providing technologies and solutions for the Asteroid Deflection Demonstration (Topic Area 3) primary topic area. We are uniquely suited to provide innovative solutions and deliver qualified hardware based on our institutional history of delivering mission-critical electromechanical systems to NASA. Honeybee Robotics leverages its focused expertise in high reliability robotics, electromechanical and electro-optical systems, as well as AS9100 certified quality management system to ensure we offer the highest quality products possible. HBR has delivered critical flight hardware to Goddard Space Flight Center for the Sample Analysis at Mars (SAM) instrument and to JPL for end-of-arm tooling, each for the Mars Science Laboratory Curiosity Rover. HBR has also delivered flight hardware to Orbital Sciences Corp., Taiwan National Space Organization (NSPO), Air Force, Comtech AeroAstro, and JPL (Mars Exploration Rovers).

In the category of deployables, HBR has a number of technologies suitable to demonstrating techniques useful to planetary defense (e.g. deployment of a stand-alone transponder for continued tracking of the asteroid over a longer period of time, or the rapid evaluation of the composition of an asteroid). The Touch and Go Surface Sampler (TGSS) can facilitate rapid sample collection for return to a host craft and subsequent analysis prior to large-scale interaction with the asteroid. An alternative method for physically interrogating the target asteroid prior to large-scale interaction is using the impactor to characterize the surface properties and cohesion. Harpoon anchors allow fixturing to the asteroid prior to landing, and sample return probes provide another approach to retrieving information on the asteroid prior to large-scale interaction.

CONCEPTS FOR ASTEROID TRAJECTORY DEFLECTING USING AN ASTEROID REDIRECT VEHICLE

David B. Smith, The Boeing Company

Boeing's submittal focuses on asteroid deflection methods that are conducive to a 702 MP based Asteroid Redirect Vehicle (ARV) that would be effective against objects large enough to do significant damage to the Earth's surface.

Four deflection methods were examined, and three are considered viable. The use of a slowly applied force whether it is directly applied or indirectly applied is considered superior to the use of a Kinetic force. Each of these methods requires a substantial amount of propellant. Because of the center line, cylindrical construction, the Boeing ARV spacecraft can carry up to four (4) times its weight in Xenon. It is also modular, with common Power Management and Distribution (PMAD) systems to accommodate

various arrays and thrusters, so changes with engine configuration are possible if the deflection method requires more thrust.

As we examine the deflection methods in the following sections, we shall see the versatility of the Boeing ARV. The spacecraft's size makes it ideal for a gravity tractor, and its tank capacity makes the Ion Beam shepherding a real possibility. The bi- prop system on the ARV allows quick response necessary for close approach station keeping required for securing the asteroid and the direct application of force. Of course, all these methods require an SLS launch for the deflection of such a large asteroid.

ASTEROID REPOSITIONING FOR PLANETARY DEFENSE

Geoffrey A. Landis, NASA GRC

In recent years, it has become increasingly clear that asteroid impacts have been responsible for multiple mass extinctions on Earth, including the Chicxulub impact, which ended the age of dinosaurs. The probability of such an impact is small but the consequences would be great. Hence, there is a great interest in finding defense against such a cataclysmic impact. It is our concept to use an asteroid to defend against an asteroid. Specifically, we propose that a 7- to 10- meter diameter asteroid could be found, accessed, and brought to a position in a halo orbit around one of the stable Earth-moon LaGrange points. From this position, if a threatening asteroid is detected, the trajectory is analyzed and the defense asteroid can be ejected into a trajectory that intersects the path of the threatening object, thereby deflecting the trajectory into one that does not impact the Earth.

GRAVITY TRACTORING WITH LOCAL MASS AUGMENTATION

Tim McElrath, Jet Propulsion Laboratory

Gravity tractoring has been proposed as a means to change the orbit of an asteroid. While conveniently avoiding direct contact with an asteroid (and hence not depending on any level of cohesion or rotation state), the coupling is weak for reasonable spacecraft masses. By transferring mass from the asteroid to the spacecraft, the coupling could be increased to the point where the full Solar Electric Propulsion (SEP) of the spacecraft could be used, allowing much faster orbit change.

A large SEP spacecraft similar to the proposed Asteroid Redirect Robotic Mission spacecraft could either use something like the baseline capture system to grab a boulder, or it could use something like a brush-wheel sampler to obtain loose regolith, in both cases obtaining around 1000T of additional mass after asteroid rendezvous. With that mass, a 30m asteroid such as 2000 SG344 could be kept near the earth for 30+

years, and an asteroid similar to Apophis could be moved off of a direct Earth impact in a decade. Both of these possible missions would not be feasible using gravity tractoring without using mass augmentation.

UTILIZATION OF SURFACE MATERIAL FOR ASTEROIDAL DEFLECTION

Rob Mueller, NASA-KSC

This RFI response is targeting Area 3; Asteroid Deflection Demonstration: concepts for deflecting the trajectory of an asteroid using the robotic Asteroid Redirection Vehicle (ARV)**.** The proposed asteroid deflection can only occur with a form of momentum exchange. By using the asteroid materials themselves and ejecting them, then this momentum exchange can be provided with a very low launched mission mass. The energy for the delta velocity of the asteroid mass can be acquired by the use of solar collectors or concentrators, which convert sunlight into electrical energy or heat. A continuous stream of ejected mass will consume the asteroid over time, and deflect it via the momentum exchange causing a change in velocity and hence a change in orbit.

LOW-RISK, HIGH-HERITAGE APPROACH FOR ASTEROID DEFLECTION AND CAPTURE IMPLEMENTATION

James Munger, Northrop Grumman

Northrop Grumman's recommended Asteroid Deflection Demonstration study approach and mission concepts leverage an existing 5m diameter spacecraft bus capable of accommodating 12,000 kg of Xenon propellant in eight Dawn-derived Tanks. The system operates as a Hall-Effect driven Solar Electric Propulsion Asteroid Redirection Vehicle (ARV) with 40-50kW NG AstroMesh based solar arrays and is capable of capturing and maneuvering a large 5-13m diameter asteroid inside an AstroMesh based Asteroid capture device, called an AstroCapture into lunar orbit. Our modular ARV architecture allows integration and orientation of the sensor and characterization pallet, selectable asteroid interface modules, a fully enclosed AstroMesh based AstroCapture, a thrust or Asteroid alignment gimbal(s) and a sample selection manipulator module. This system can provide 20cm/s of Delta-V to a large 100M diameter Earth threatening Asteroid for planetary protection, assuming 30 year precision Asteroid trajectory knowledge. In addition to the Delta-V provided by the SEP based ARV, the high or low albedo AstroCapture can be separated from the ARV and provide Yarkovsky/YORP solar effects to be used to provide supplement Delta-V for up to a 30m diameter Asteroid. On-orbit deployment using either the reflective mylar or anodized sides of the AstroCapture allows Yarkovsky effects to be tailored to provide the desired and optimal trajectory whether the Asteroid is spinning, tumbling or despun. For Earth threatening Asteroids larger than 30m dia the ARV can be used to apply a long life high or low alpha surface coating to the Asteroid surface. The AstroCapture device can also potentially be

configured to thermally effect the surface albedo when used as a solar concentrator, depending on the material make-up of the Asteroid. The ARV-AsteroCapture system provides high Delta-V to maneuver small Asteroids for study, exploitation and protection while also providing the nation and the World with a flexible system for mitigating potentially cataclysmic Earth impacts. In addition the ARV provides NASA and the USG with a very high Delta-V full Earth-Moon Orbit servicing tug able to move large payloads from LEO-to-GEO and LEO-to-Lunar orbit.

MULTIPLE ATTACH VEHICLE CONCEPT FOR ASTEROID DEFLECTION

Scott Sevcik, Prospect Dynamics

Prospect Dynamics offers the Multiple Attach Vehicle concept as an alternate to the reference approach for an asteroid deflection demonstration. The concept centers on the use of a swarm of independent small satellite vehicles working in a coordinated fashion to redirect an asteroid. A larger vehicle will carry the small satellites, called Micro Attach Vehicles or MAVs, to the asteroid and handle centralized communication functions while the MAVs carry out the mission objective. They anchor across the surface of the asteroid and enable a “slow push” divert by applying coordinated thrust. Alternately, an explosive payload carried by the same MAVs would enable a high impulse divert or the planned removal of an asteroid fragment to alter the asteroid trajectory.

This approach offers inherent flexibility, scalability, and reliability at lower cost. The flexibility of the concept provides for rapid development of the MAVs based on existing CubeSat technology prior to identification of a threat asteroid. Characterization of the threat will drive quantity of the MAVs but none of the design requirements. The MAVs allow further flexibility by providing an open payload interface such that the same core bus and anchoring subsystem can enable a wide variety of mission Functionality through the use of alternate payloads enabling multiple deflection scenarios. The total impulse available to exert on the asteroid scales based on the number of MAVs. This enables a robust planetary defense system which does not require a priori threat information to define the system, only to specify the number of MAVs and the payload mix, thus shortening the timeline between threat identification and response by years.

AFFORDABLE SPACECRAFT WITH CAPABILITIES TO ENABLE MULTIPLE DEFLECTION SCHEMES

Andy Turner, Space Systems/Loral, LLC

The asteroid deflection demonstration may take many forms depending on the nature and structure of the asteroid. There will be an amazing array of possibilities described in

the RFI responses from around the world and the ARM formulation team will select a number of promising alternatives for further consideration. Using four diverse asteroid deflection techniques as design reference operations, this RFI response focuses on the definition of an affordable spacecraft with the right mix of Delta-V, control and robotic capabilities to realize a great number of those alternative deflection schemes, some traditional and reliable, some creative and risky.

SSL, the world leader in high power GEO satellites, and MDA, the world leader in advanced space robotic solutions, are pleased to present to the Asteroid Initiative a fully integrated bus with state-of-the-art Solar Electric Propulsion, autonomous rendezvous and proximity operations sensing and control, and dexterous robotic systems with performance and capabilities that enable and realize any of the asteroid deflection techniques that the Mission Formulation Team may choose.

MASS AUGMENTED GRAVITY TRACTOR

Darren Wade, Lockheed Martin Space Systems Company

An approach using in situ resources at an asteroid provides an electric propulsion vehicle with an effective method to change the asteroid's orbit, with benefits to propellant usage and time required for the deflection maneuver. This approach, which uses a 5 to 10 meter sample of a 100 m asteroid intended for return to lunar orbit to augment the tractor mass, adds little or no additional requirements on the mechanical systems above those for sample collection and return. This allows a full 1 cm/s asteroid deflection maneuver to be completed in as few as 100 days of thrusting.

ASTEROID REDIRECT VEHICLE FLIGHT DEMONSTRATION CONCEPTS FOR PLANETARY DEFENSE

Bong Wie, Iowa State University

Although a baseline 40-kW ARV is not capable of redirecting or deflecting a larger (>100 m) asteroid for any practical purpose, it can be used to redirect a small 7-m asteroid to collide with a larger (>100 m) asteroid to result in sufficiently large Earth-miss distance of a hazardous larger asteroid. Basically, a 7-m asteroid captured and redirected by a 40-kW ARV can be used as a 500-ton kinetic impactor for deflecting or disrupting a much larger asteroid. If launching of a 500-ton kinetic impactor from the Earth into an interplanetary trajectory is needed, it will require total launch energy equivalent to that of approximately 200 Delta IV Heavy launch vehicles. However, a further detailed study is needed for undertaking a technical/economic assessment of the mission feasibility of using a robotic ARV to capture and transport a small asteroid to collide with a larger hazardous asteroid for planetary defense. Other

deflection/disruption options for planetary defense will also be presented.

HONEY BEE FOR NEAR-EARTH OBJECT RETRIEVAL: SIMPLER, MORE INNOVATIVE, MORE PRACTICAL, MORE USEFUL

Joel Sercel, ICS Associates Inc.

We have developed and technically-characterized a mission-system concept and architecture we call Honey Bee for NEO object capture into high Earth Orbit. The Honey Bee mission-system architecture is radically different than the baseline NASA-JPL ARM concept. Although based entirely on technologies and components currently at TRL-4 or above, the Honey Bee system configuration uses these components in an innovative and inventive way which must remain proprietary for now. Using this radically-different system architecture, which does not include a high-powered SEP, total mission flight duration is less than five years and can be as little as two to three years depending on found-target availability for up to 1000 tonne objects. Honey Bee requires and benefits from a more extensive observation and prospecting effort which delays launch in return for much-reduced total program cost, a more programmatically-realistic budget profile, a more useful returned product, and the same or earlier final material return date. Honey Bee returns the NEO object in a form that allows immediate practical engineering application of the extraterrestrial resources contained in the NEO to potentially reduce operations costs for the International Space Station, or radically reduce the cost of other manned space ventures such as a piloted mission to Mars.

ASTEROID CAPTURE SYSTEMS

TWO CONCEPTS FOR DEPLOYABLE CAPTURE BAG USING INTEGRAL RIBS OR EXPANDING HOOPS AND TELESCOPING BOOMS

Michael McEachen, ATK

ATK is pleased to present concepts for the Asteroid Redirect Mission (ARM) Capture Bag in response to NASA RFI NNH13ZCQ001L, area 4, that leverage the broad experience and 100% flight success that ATK is proud to claim. Both concepts, the CRAW (Continuous Rod Asteroid Wrapper) and BEST (Bag Expansion Support Truss), are a natural evolution of our extensive use of elastic structures for critical in-space deployment of membranes and fabrics. Both of these options provide a compelling alternative to the reference concept inflatable Capture Bag, while avoiding the pitfalls that have plagued inflatable structures for decades. ATK understands the uncertainties and the correspondingly robust design required. These concepts achieve the required compaction, robustness, scalability, retractability, autonomous operation, and provide determinate elastic coupling between target and spacecraft until it is solidly coupled to the Asteroid Redirect Vehicle (ARV).

EXTENDABLE/RETRACTABLE BOOM CAPTURE SYSTEM

Scott Belbin, NASA-LaRC

Given the limited amount of time to develop, fabricate, test, and integrate an asteroid capture system, a high TRL design approach is desirable, if not required. Using components and materials with a TRL of 6 or higher, the concept described and illustrated herein uses reel stored extendable/retractable booms to unfurl a 20 meter capture bag with cinch lines to close the bag around the asteroid, and uses the same booms to retract the encapsulated asteroid against the spacecraft for the redirect portion of the mission.

SELF-OPPOSING MULTI-MODE ANCHOR SYSTEM AND LIGHT ADJUSTABLE SNARE FOR SERVICING AND ORBITAL DEBRIS REMOVAL

Kiel Davis, Honeybee Robotics Spacecraft Mechanisms Corporation

Honeybee Robotics (HBR) is pleased to respond to NASA's request for information for the Asteroid Initiative with a number of relevant and enabling technologies. Honeybee is interested in providing technologies and solutions for the Asteroid Capture System Technologies (Topic Area 4) primary topic area. We are uniquely suited to provide innovative solutions and deliver qualified hardware based on our institutional history of

delivering mission-critical electromechanical systems to NASA. Honeybee Robotics leverages its focused expertise in high reliability robotics, electromechanical and electro-optical systems, as well as AS9100 certified quality management system to ensure we offer the highest quality product possible. HBR has delivered critical flight hardware to Goddard Space Flight Center for the Sample Analysis at Mars (SAM) instrument and to JPL for end-of-arm tooling, each for the Mars Science Laboratory Curiosity Rover. HBR has also delivered flight hardware to Orbital Sciences Corp., Taiwan National Space Organization (NSPO), Air Force, Comtech AeroAstro, and JPL (Mars Exploration Rovers).

Honeybee Robotics has a number of technologies relevant to asteroid capture and despin. These include our Self-Opposing Multi-Mode Anchor which allows spacecraft to drill into and anchor onto asteroids with a minimum normal force. This anchoring would allow subsequent despin and maneuvering of the asteroid. Additionally, we have the Light Adjustable Snare for Servicing & Orbital debris removal (LASSO) technology that would allow a spacecraft to snare a smaller asteroid.

UTLIZING UNDER-ACTUATED LINKAGES FOR ROBOTIC GRASPING OF ASTEROID

John Ratti, MacDonald Dettwiler Associates (MDA) Inc.

As the Canadian Space Agency (CSA) Prime Contractor for robotics on the Space Shuttle and the International Space Station Programs, MDA has had the opportunity to work directly with NASA and other space agencies & commercial companies under international and bi-lateral cooperative agreements or public-private partnerships. Current budgetary pressures for space spending across the globe will make it challenging for any nation to pursue Space Exploration alone which underscores the need to share the burden with more international collaboration. MDA is ready to support the CSA and NASA for any such new Space Exploration endeavors, including NASA's Asteroid Redirect Mission (ARM).

The ARM Initiative to capture, de-tumble, and redirect a 1000 metric ton asteroid is a challenging next step in understanding the threats and opportunities in Near Earth Orbit. The mission will require the synthesis of various technologies to ensure its success, including the mechanical capture systems, software, and sensors to characterize the asteroid and enable remote retrieval and exploration operations. It will also require risk-mitigating simulation and modeling tools that can be used for mission planning and support, enabling mission operators to deal with real-time issues and off-nominal situations.

MDA has a long history of supporting NASA in the robotic free-flyer capture of large space objects through the Shuttle and Space Station Remote Manipulator Systems. MDA's involvement in additional programs such as the Orbital Express, XSS-11 and Hubble Space Telescope Robotic Repair missions has also generated valuable

experience in capture system design, robotic operation, approach and proximity sensors and operation, and contact dynamics and mission simulations that are applicable to the ARM Initiative.

Specifically, MDA is proposing an Asteroid Capture System concept that addresses the same mission requirements that drove the KISS Study to select the Capture Bag concept, but offers advantages such as a deterministic grasping method and increased access to the asteroid surface following capture. MDA also offers space-qualified, TRL9 technologies to support the successful capture of an asteroid. This includes software that supports different levels of supervised autonomy for mission execution, based upon methods flown on the successful DARPA Orbital Express and NASA ISS Visiting Vehicle missions. As part of end-to-end pre-flight mission validation, MDA offers extensive simulation, modeling and planning tools to assure successful orbital capture operations.

ASSESSMENT OF ALTERNATIVE CAPTURE SYSTEM CONCEPTS

Carlos Enriquez, The Boeing Company

Boeing has a broad experience base with complex mechanisms for spacecraft. On the International Space Station alone, Boeing successfully led the integration of 27 complex mechanisms in a wide variety of applications. The capture mechanism for the Asteroid mission will be a challenge from any perspective. To meet this challenge, Boeing, working together with the Harris Corporation, identified hardware from previous spaceflight programs that could potentially be used to build an asteroid capture system. It is clear that any capture system must be robust and re-configurable to mitigate the uncertainty of the asteroid state. Assessment of the capture concepts appears to indicate two capture options. One set of methods rely on direct capture of the asteroid, while other methods rely initially on soft docking to the asteroid, with subsequent hard capture as the final step. The design studies of the capture systems envision a stand-alone capture pallet mated to the capture vehicle. Left attached to the asteroid and fitted with a docking or grapple interface, it would allow for future potential commercial exploitation of the asteroid after NASA's mission is complete. Boeing recognizes that all the capture methods will require close-loop control dynamic simulations that model the interaction between the capture system and the GN&C system of the capture vehicle. Lessons learned from the assembly of the ISS are extensive in this area, and are directly applicable to an asteroid capture mission. Boeing also brings experience as the integrating contractor for the NASA Docking System (NDS) which is an excel-lent candidate for consideration on the Asteroid Redirect Mission.

MOMENTUM EXCHANGE TETHER TO DE-SPIN ASTEROID

Harold Gerrish, NASA-MSFC

A spinning asteroid will have significant angular momentum and energy. A small mass can be extended from the asteroid's surface using a cable or tether to transfer the spin energy to that small mass, slowing it so that a capture can be easily affected. The law of conservation of angular momentum states that when no external torque acts on an object or a closed system of objects, no change of angular momentum can occur. Releasing a mass from the asteroid on a tether changes the total moment of inertia. The spin rate will decrease with greater tether length. Once the spin rate has slowed sufficiently, the tether and end mass can be released from the asteroid. The Asteroid Redirection Vehicle (ARV) should be able to handle it from there. Tethers have been made in the past for lengths in 10s of kilometers. Extra tether length can be added to the spool to account for greater range of spin rates of the asteroid. Tether technology for this application (deployer, tether, end mass) is very mature. The method by which the tether is attached to the asteroid is not as mature; though, in principle, it should not be difficult to engineer.

WEIGHTLESS RENDEZVOUS AND NET GRAPPLE TO LIMIT EXCESS ROTATION (WRANGLER) SYSTEM

Robert P. Hoyt, Tethers Unlimited, Inc.

To enable capture and manipulation of an asteroid while minimizing risk to the primary space-craft, Tethers Unlimited, Inc (TUI) proposes the use of a nanosatellite-scale sub-satellite, called the Weightless Rendezvous And Net Grapple to Limit Excess Rotation (WRANGLER) System, which will capture and de-spin the asteroid. WRANGLER will accomplish these functions by combining two innovative technologies that have been developed by TUI: the GRASP deployable net capture device, and the SpinCASTER tether deployer/winch mechanism. Successful testing of both technologies in a microgravity environment has established these technology components at mid-TRL maturity. The leverage offered by using a tether to extract angular momentum from a rotating asteroid enables a very small nanosatellite system to de-spin a very massive asteroid. The WRANGLER system is suitable for an incremental development program that will validate the technology through an affordable test flight in which a nanosatellite launched on a rideshare opportunity would capture and de-spin the upper state used to launch it.

DEVELOPMENT, FABRICATION, AND TEST OF AN INFLATABLE ASTEROID CAPTURE SYSTEM

Allen Lowry, Airborne Systems

This paper describes a conceptual design for the inflatable asteroid capture system (Figure 3-1) based on AirBeam technology developed by HDT/Airborne Systems and

currently used as a basis for the AirBeam shelters produced by HDT for the US Military. AirBeams are inflatable tubular textile structural elements that can be formed into a variety of shapes including; straight beams, tori, arches, and compound curves. We believe that this mature technology is uniquely suited for forming a deployable inflatable structure that has sufficient strength, rigidity, dimensional accuracy, and light weight to envelop, capture, and secure an asteroid up to 1000 metric tonnes, 5m to 13m mean diameter, with an aspect ratio of up to 2 to 1 as specified in the RFI.

NASA LaRC acknowledged the benefits of the AirBeam technology and adopted it for their Hypersonic Inflatable Aerodynamic Decelerator (HIAD) program and successfully demonstrated its performance and attributes in the IRVE-3 mission launched in July of 2012 as shown in Figure 3-2. They continue to invest in the technology and are currently funding Airborne Systems to; fabricate a second 6 meter wind tunnel test article as depicted in Figure 3-3, develop high temperature materials applications, and to produce element test articles for additional structural model validation.

The AirBeam currently forms the inflatable internal structure for lightweight deployable military shelters ranging in size from 20ft wide to 80ft wide and HDT/Airborne Systems has produced approximately 15 thousand AirBeams to date for these structures for the US military and other users. Analysis techniques are mature and models validated. Airborne Systems utilizes LS-DYNA to model the complex interstitial configuration of the braided structure and has successfully validated these models through correlation with test data.

This paper describes a conceptual design for an inflatable asteroid capture system based on a preliminary trade study and sizing analysis. This design is used to provide a basis for preliminary mass, pack volume, and performance data. A development program is described to form the basis for a future development effort leading to a flight unit.

ASTEROID REDIRECTION VEHICLE WITH SOLAR ELECTRIC PROPULSION AND ASTROMESH-BASED CAPTURE MECHANISM

James Munger, Northrop Grumman

Northrop Grumman’s recommended Asteroid Deflection Demonstration study approach and mission concepts leverage an existing 5m diameter spacecraft bus capable of accommodating 12,000 kg of Xenon propellant in eight Dawn-derived Tanks. The system operates as a Hall-Effect driven Solar Electric Propulsion Asteroid Redirection Vehicle (ARV) with 40-50kW NG AstroMesh based solar arrays and is capable of capturing and maneuvering a large 5-13m diameter asteroid inside an AstroMesh based Asteroid capture device, called an AstroCapture into lunar orbit. Our modular ARV architecture allows integration and orientation of the sensor and characterization pallet, selectable asteroid interface modules, a fully enclosed AstroMesh based AstroCapture, a thrust or Asteroid alignment gimbal(s) and a sample selection manipulator module.

This system can provide 20cm/s of Delta-V to a large 100M diameter Earth threatening Asteroid for planetary protection, assuming 30 year precision Asteroid trajectory knowledge. In addition to the Delta-V provided by the SEP based ARV, the high or low albedo AstroCapture can be separated from the ARV and provide Yarkovsky/YORP solar effects to be used to provide supplement Delta-V for up to a 30m diameter Asteroid. On-orbit deployment using either the reflective mylar or anodized sides of the AstroCapture allows Yarkovsky effects to be tailored to provide the desired and optimal trajectory whether the Asteroid is spinning, tumbling or despun. For Earth threatening Asteroids larger than 30m dia the ARV can be used to apply a long life high or low alpha surface coating to the Asteroid surface. The AstroCapture device can also potentially be configured to thermally affect the surface albedo when used as a solar concentrator, depending on the material make-up of the Asteroid. The ARV-AsteroCapture system provides high Delta-V to maneuver small Asteroids for study, exploitation and protection while also providing the nation and the World with a flexible system for mitigating potentially cataclysmic Earth impacts. In addition the ARV provides NASA and the USG with a very high Delta-V full Earth-Moon Orbit servicing tug able to move large payloads from LEO-to-GEO and LEO-to-Lunar orbit.

THE IMPORTANCE OF ASTEROID MODELING FOR SUPPORTING ASTEROID INITIATIVE ACTIVITIES

D.J. Scheeres, The University of Colorado Boulder

Underlying Areas 2-5 of the Asteroid Initiative are fundamental questions concerning what the mechanical and morphological properties of Near Earth Objects (NEO) are. Without properly understanding the physical structure of these bodies, their surface covering, their strength and possible rubble pile nature, and their overall stability to interactions it will be difficult or impossible to adequately design and develop methodologies for their surface exploration, deflection, and capture. Thus, as one element of the Asteroid Initiative it is imperative that research into the properties of small asteroids be funded at adequate levels to allow for the development of a realistic understanding of these bodies from a scientific and engineering perspective, and for these advances to be shared with the relevant technical teams working the other aspects of this problem.

This white paper's purpose is to point out the importance of studying such small asteroid properties from a scientific and engineering perspective. As such, it calls for research into these questions to improve our theoretical understanding of the physical properties of smaller asteroids, develop realistic simulations for their response to interactions, and use these results to address the existing strategic knowledge gaps associated with the small asteroid environment.

CREW SYSTEMS FOR ASTEROID EXPLORATION

THREE TECHNOLOGIES FOR HUMAN ASTEROID EXPLORATION: SMALL CAMERA AND MOBILITY PLATFORM (SCAMP), ASTEROID RESTRAINT AND MOBILITY SYSTEM (ARMS) AND SPACE UTILITY VEHICLES (SUV)

David L. Akin, University of Maryland

This document summarizes three technologies for human asteroid exploration. The Small Camera and Mobility Platform (SCAMP) is a 50-kg highly capable freeflying vehicle, which can be used for teleoperated surveys of the asteroid from the habitat, and to monitor EVA crew during human exploration. It is designed to accommodate advanced mission packages (AMPs), which can include science instruments such as magnetometers, spectrometers, and multispectral cameras, or operational packages such as miniature dexterous manipulators for sample collection and external servicing tasks to the crew vehicle. The Asteroid Restraint and Mobility System (ARMS) is a system of autonomous anchors and tether reels which provide any desired amount of down-force to an EVA crew or robotic system on the asteroid surface, and allows easy transfer between tethers for extended traverses under both positive restraint and reliable stabilization. Space Utility Vehicles (SUV) are single-person spacecraft capable of almost all EVA functions, while providing enhanced capabilities and greater crew protection against radiation, debris impact, and other environmental hazards than would be available in a pressure suit.

ANCHORING AND SAMPLE COLLECTION DEVICES

Kiel Davis, Honeybee Robotics Spacecraft Mechanisms Corporation

Honeybee Robotics (HBR) is pleased to respond to NASA's request for information for the Asteroid Initiative with a number of relevant and enabling technologies. Honeybee is interested in providing technologies and solutions for several of the primary topic areas, including: Asteroid Redirection Systems, Asteroid Deflection Demonstration, Asteroid Capture Systems, and Crew Systems for Asteroid Exploration. We are uniquely suited to provide innovative solutions and deliver qualified hardware based on our institutional history of delivering mission-critical electromechanical systems to NASA. Honeybee Robotics leverages its focused expertise in high reliability robotic, electromechanical and electro-optical systems, as well as AS9100 certified quality management system to ensure we offer the highest quality product possible. HBR has delivered critical flight hardware to Goddard Space Flight Center for the Sample Analysis at Mars (SAM) instrument and to JPL for end-of-arm tooling, each for the Mars Science Laboratory Curiosity Rover. HBR has also delivered flight hardware to Orbital Sciences Corp., Taiwan National Space Organization (NSPO), Air Force, Comtech AeroAstro, and JPL (Mars Exploration Rovers).

Honeybee Robotics has a number of technologies that support the ability of astronauts

to explore the surface of a captured asteroid, prospect for resources, and collect samples. In this micro-gravity environment anchoring of astronauts and equipment is crucial, and Honeybee has a long history and has developed a number of approaches, including Hard Rock Drilling and Hammering for setting anchors, a Fluid Anchor that allows anchoring to featured surfaces with the benefit that the anchor deployment does not exert any force that requires reaction by the spacecraft. The Self-Opposing Multi-Mode Anchor allows payloads and equipment to be securely anchored to the surface with minimal applied force.

HBR also has a long history with sample collection, and a number of our technologies are suitable to the asteroid initiative. The Pneumatic Approaches to Sample Collection is a robust method for sample collection. The Mobile In situ Water Extractor System will allow the selective collection of water. Numerous Robotic and Hand-held drills support the many tasks of astronauts and robotic systems.

ASTEROID EXPLORATION MODULE WITH AIRLOCK AND DOCKING PORTS TO AUGMENT ORION CAPABILITIES

Matthew Duggan, The Boeing Company

Crew operations at a redirected asteroid could be significantly enhanced by providing additional systems and EVA capabilities beyond those available from Orion only missions. An Asteroid Exploration Module (AEM) located with the asteroid would improve the science and technical return of the asteroid mission while also increasing Orion capability through resource provision and providing an abort location and safe haven for vehicle contingencies. Additional volume and EVA capable elements could significantly increase the effectiveness of asteroid exploration by increasing mission duration and providing more utilization options and tools for the Asteroid Redirect Mission (ARM). Orion mission capability will be stretched to the limit by asteroid missions and could be augmented by an AEM that provides re-sources such as power and atmosphere revitalization to extend mission duration and a storage location that saves launch mass by storing needed items. The AEM would also provide an abort location for an Orion mission and sustain the vehicle and crew while problems are identified and resolved. At the end of the asteroid mission, the AEM would remain a viable and extensible element that could provide translunar capabilities and services and could be reused to enhance future missions or as a building block in a new architecture. An AEM could be created using existing hardware from a number of sources. International partner space systems are well developed and ideal for these new uses, such as adapting current Russian Science Power Module (SPM) and node designs for translunar use. Study and work already done on new ISS node development could be continued. Hardware from the Space Shuttle and International Space Station (ISS) programs, such as the Orbiter Docking System (ODS) and the ISS node test article, could be combined with existing satellite hardware with a long operational history in the GEO environment. This response will discuss several options for building and

outfitting an Asteroid Exploration Module and show how this element will significantly enhance asteroid operations, Orion missions to the asteroid and new missions beyond the asteroid.

ROBOTIC SYSTEMS CONCEPT SUPPORTING ASTEROID REDIRECT MISSION EVA

John Dunlop, MacDonald Dettwiler Associates, (MDA) Inc

As the Canadian Space Agency (CSA) Prime Contractor for robotics on the Space Shuttle and the International Space Station Programs, MDA has had the opportunity to work directly with NASA, other space agencies and commercial companies under international and bi-lateral cooperative agreements, or public-private partnerships. Current budgetary pressures for space spending across the globe will make it even harder for any nation to pursue Space Exploration alone, which underscores the need to share the burden with more international collaboration. MDA is ready to support the CSA and NASA for any such new Space Exploration endeavors, including NASA's Asteroid Redirect Mission (ARM).

Specifically, MDA has a wide variety of space-qualified EVA support technologies ideal for NASA's Asteroid Redirect Mission (ARM). These range from lightweight extra-vehicular robotics (EVR) to robotic and astronaut tools. Through over 30 years of strong partnership with NASA and the CSA, MDA has become a leading provider of space-qualified, reliable, safety critical robotic systems that provided NASA with complete confidence to design entire missions centered on EVA astronauts being flown on the end of an MDA robot. MDA has played a vital role in hundreds of successful space missions that involve robotics, tools, and EVA support and contingency operations. Some highlights include the Canadarms on NASA's Space Shuttle and the International Space Station (ISS) missions. Integrating this broad range of expertise for the ARM crewed mission, MDA is pleased to propose a suite of robotics and tools that not only assist the EVA crew in achieving their mission objectives, but also contribute a number of operational capabilities that are critical to ensuring crew safety and mission success, including:

- A lightweight, easily stowed robotic manipulator that supports vehicle free-flyer capture and berthing, EVA crew positioning and provides extended reach access for astronauts and/or instrument packages

- EVA tool suites developed based on MDA heritage in EVR tool-tip design and EVA-compatible tool and fixture design, and planetary technology expertise in coring, drilling, and science instruments for composition determination.

- Robotic systems that maximize EVA utility by performing the simple EVA tasks that do not absolutely require human capability either prior to the crewed mission, after the mission, or during EVA crew "off duty" time.

- Expertise required in mission planning, preparation and execution to ensure that the proposed systems are safe for manned spaceflight.

With such extensive heritage, MDA possesses the ideal combination of expertise to ensure a successful and effective ARM.

TELESCOPING BOOMS FOR ASTRONAUT TRANSLATION AND EVA TOOLS

Doyle Towles, ATK Space Systems Inc.

ATK Crew Systems technology will be supporting NASA HQ's Asteroid Human Exploration. ATK has strong EVA tool past design and development experience with numerous tools successfully flown on STS, Hubble Repair and ISS missions. ATK also has extensive past design and flight heritage with translation aids used for ISS, Shuttle and Hubble Repair, applications that can be effectively leveraged to develop an integrated EVA translation system for ARM. Along with significant expertise in EVA systems development, ATK personnel have substantial expertise in sample acquisition and handling technology development. Our expertise in extra-vehicular activity (EVA) systems, mechanism design, robotics, structural design, thermal control, electronics, and systems engineering across ATK offices will be utilized in developing concepts and later flight hardware for lightweight and low volume robotic and EVA systems, such as, tools, translation aids, stowage containers, and other equipment, that will allow astronauts to explore the surface of a captured asteroid, prospect for resources, and collect samples. ATK will use engineering experts in subsurface access technologies and sample handling, having developed several planetary drill prototypes and supporting design and development of the CheMin instrument of the Mars Science Laboratory. An envisioned, concept Crew System to support the proposed Asteroid Redirect Mission consists of: 1) a telescoping boom assembly with integrated platform structures to support astronauts accessibility to/from the Orion and work site; 2) a judiciously selected and appropriate EVA and Geological Tools Suite aligned towards specific mission goals; and 3) ergonomically designed, integrated Tool Storage and Sample containers which provide ready access, tool storage while ensuring sample integrity.

UTILIZING OCEANEERING EXPERTISE FOR DEVELOPING EVA SUITS AND TOOLS

Frank Eichstadt, Oceaneering Space Systems (OSS)

Oceaneering offers a unique combination of corporate knowledge, skills, experience and capabilities which favor the development of crew systems that enhance the overall probability of successful asteroid exploration. Oceaneering is

NASA's contractor for development of the Crew Space Suit System (CSSS), a program to design, produce and certify NASA's next generation of exploration space suits. While safety, reliability and overall functionality are the predominant drivers for space suit design, minimizing weight is always important. Oceaneering's Crew Space Suit designs already strive to achieve the lowest practical mass providing capabilities for zero-g operations to be demonstrated on ISS, as well as being upgradeable for long-duration/long range surface exploration. Oceaneering offers unparalleled experience in developing EVA equipment including robotics, tools and electromechanical equipment. Our development process ensures robust tools and equipment that are compatible with EVA environments and suited-user requirements. Oceaneering's unique combination of extensive operational and developmental experience for crew and automated systems applied in extreme environments is directly applicable to crew systems for NASA's Asteroid Exploration mission.

UTILIZING ELECTRODYNAMIC DUST SHIELD, PNEUMATIC REGOLITH RAKE, AND PERCUSSIVE EXCAVATION SHOVEL FOR ASTEROID EXPLORATION

ROB MUELLER, NASA-KSC

The NASA KSC Surface Systems Office, Granular Mechanics and Regolith Operations (GMRO) Lab and the Electrostatics & Surface Physics Lab (ESPL) are dedicated to developing technologies for operating in regolith environments on target body surfaces. We have identified two technologies in our current portfolio that are highly relevant and useful for crews that will visit a re-directed asteroid in Cis-Lunar Space: the Electrodynamic Dust Shield and the Pneumatic Regolith Rake. Both technologies are at a high TRL of 5/6 and could be rapidly implemented in time for an ARM mission in this decade.

CREW-BASED SAMPLE ACQUISITION: HOW TO DRILL IN MICROGRAVITY

Aaron Parness, Jet Propulsion Laboratory

The microgravity environment is uniquely challenging for sample acquisition, especially drilling. However drilled samples, and particularly rock cores, can provide a high science return because they contain additional information that is not present in the regolith (like grain boundaries) and because core samples are protected from surface weathering. Regolith samples from the surface will be skewed to minerals that can survive the radiation exposure and may lack soft minerals that weather faster and may only be present beneath the exterior rind of a rock. Large rocks also provide an operational asset to missions that wish to anchor and interact with the surface for sustained periods of time. These large rocks offer the most secure anchor points on the asteroids, even (especially) for so-called rubble-pile asteroids.

A crucial parameter for an extraterrestrial drill is the required weight on bit (WOB). The European Space Agency's Rosetta/Philae mission to Comet 67P/Churyumov-Gerasimenko carries a drill, SD2, with a required WOB of 100N [1]. The drill on the Curiosity rover requires a similar WOB. On the 500 meter diameter near-Earth asteroid Itokawa recently visited by the Japanese Space Agency [2], such a drill would require a lander mass of approximately 1,000,000 kg to counteract a 100 N WOB with the tiny equatorial surface gravity (0.0001 m/s2; F=ma). Similarly difficult conditions exist with respect to the torque applied to the rotating bit. A crewmember will not be able to apply these loads to the drill bit without significant anchoring to the spacecraft or the asteroid. Unrestrained, the astronaut would be just as likely to start spinning around the drill as the bit would be to spin in the borehole!

A more flexible approach is proposed where the drill self-anchors to the asteroid and redirects the forces and torques of sample acquisition back into the asteroid's surface, allowing the crewmember to sample from any location on its surface without exerting any net forces or torques. Our team has been working over the last two years to develop this type of self-anchoring microgravity drill, and have advanced the technology past proof of concept through several progressing system prototypes. The handheld instrument has been demonstrated coring into vesicular basalt in vertical, horizontal, and inverted configurations, and in harder-than-zero-g test cases where the drill is supporting a significant load in addition to those produced by drilling [3]. We would like to continue to develop the tool and begin collaboration with the crew office at JSC to get feedback from mission planners and potential crewmembers, and to transition the new technology into the mission development teams after a few years for use during future crewed missions to near-Earth asteroids.

MOBILE ROBOT WITH GRIPPING FEET FOR ASTEROID EXPLORATION

Aaron Parness, Jet Propulsion Laboratory

Leveraging technologies and strategies from climbing robots, gravity-independent anchors have been developed and demonstrated on a robot that has climbed vertical, overhanging, and inverted rock faces [1,2]. These anchors and other regolith specific anchors have been demonstrated on a variety of surface types including loose and friable materials, and would enable sustained and precise surface mobility even on the smallest of asteroids where nearly no gravitational well exists. This opens the door to multiple deflection techniques, enhanced science return, alternative capture techniques, and the placement of an anchored network of restraint cables that could be used by astronauts to safely explore the asteroid, described in detail below. A free-flier recovery behavior using small thrusters is also in development, and could provide failure recovery or allow the robot to traverse large portions of an asteroid more quickly.

EVA SYSTEMS, ROBOTIC SYSTEMS, AND SIMULATION AND TRAINING

Benjamin B. Reed, NASA-GSFC

Many astronauts have donned spacesuits since Alexey Leonov made the first Extravehicular Activity (EVA) in March 1965. And many organizations and multiple countries can claim involvement in preparing women and men to work outside the habitat environment of a spacecraft. But, today's Satellite Servicing Capabilities Office (SSCO) at NASA's Goddard Space Flight Center (GSFC) is uniquely experienced and qualified to be a member of the team that successfully plans, manages, and executes space flight missions involving EVA crews with the prime objective being the rendezvous, capture, and controlled handling and servicing of large, non-cooperative objects in space.

Our experienced team includes engineers with a history of working with astronauts to prepare for suited training tasks on the ground in neutral buoyancy facilities and for mission operations on orbit. That experience base ranges from actual suit testing and development, to participating as suited subjects for engineering evaluations of Hubble Space Telescope (HST) payloads. A strong familiarization of the capabilities of the current Extravehicular Mobility Unit has contributed to successful EVA choreography, tool design, and procedure development for our multiple EVA-dependent missions – each more challenging than the last. The SSCO has demonstrated time and again its capacity for assessment of a specialized EVA task, and has repeatedly answered the call with the design and build of tools and devices for astronauts to utilize to complete intricate operations. As more missions were completed, new lessons emerged, regarding crew body positioning and navigating EVA crewmembers safely around the carrier obstacles of the shuttle payload bay. As a result, a variety of transition and stabilization aids were designed and proven during real-time space operations. Protecting delicate science instruments through the rigor of launch, and crew handling and installation on-orbit; and safe return to Earth of crew and assets have been the top priority through every HST servicing mission. The SSCO team has designed and delivered a variety of protective enclosures that offer everything from environmental transport protection to ambient stowage capability. In addition to the evolving suite of tools designed to perform a task, the SSCO team has also developed other equipment and capabilities to aid the crew with containment of component hardware [translation bags for sharp edged electrostatic discharge (ESD) grids], lighting and inspection of the dark HST aft shroud (LED arrays on the mini power tool), and control of cables and de-mated connectors (Power Control Unity connector plate).

More recently, the SSCO team has focused on maturing robotic servicing technology that can be used to augment the EVA crewmember resulting in a substantial increase in productivity. These capabilities and concepts can be adapted to asteroid exploration and sample collection, as will be discussed in this response.

This RFI response provides: 1) a summary of flight-ready or near flight-ready GSFC technologies relevant to the Asteroid Redirect Mission (ARM) and at a state of readiness to support the aggressive 2017 ARN launch date; 2) a summary of GSFC facilities availabile for test of ARM technologies; and 3) suggestions for refinement to the ARM concept of operations, including a summary of key challenges and some recommended solutions. The key technologies and facilities are:

- EVA systems: crew aid and tools; translation aids; and stowage containers for long duration, complex-choreographed EVA

- Robotic systems: GSFC-matured robotic systems accelerate and expand EVA productivity and range from flight-ready dexterous arms to Remote Manipulator System-like systems

- Simulation and training: Advanced servicing technology and research and technology centers, which include various robotic platforms, the GSFC Freespace simulation of multiple objects in zero-g including their flexible modes, augmented by a nearby neutral buoyancy facility.

HUMAN FLEXIBLE ARV DESIGN AND ORION MISSION KIT CONSISTING OF PANTRY MODULE AND ROBOTIC ARM

Douglas G. Ross, Lockheed Martin

Both the Asteroid Redirection Vehicle (ARV) and the Orion vehicle targeted for Asteroid examination will need accommodation for the planned human interaction planned during the Orion-to-Asteroid mission. Lockheed Martin and McDonald, Dettwiler and Associates, Inc. have extensive experience developing hardware, tools and systems to support crewed space missions and designing for servicing and extravehicular activity. Human friendly features on the Asteroid Retrieval Vehicle (ARV) and up-front design for hardware flexibility will be crucial to any asteroid exploration mission to enable the range of anticipated activity that could occur at the asteroid. An Orion Mission Kit consisting of a pantry module for added stowage and a robotic arm system for exploration activity support offers a means to incorporate needed mission flexibility. The Next Generation Canadarm is a versatile robotic arm system that offers benefit to asteroid exploration and a broad range of exploration missions have been evaluated that could also use this robotic system.

USING EXISTING EQUIPMENT AND SOFTWARE, OUR ROBOTIC CAPABILITIES ENABLE AND ENHANCE CREW OPERATIONS DURING THE ASTEROID REDIRECT MISSION

John Lymer, Space Systems/Loral, LLC

SSL, the world leader in high power GEO satellites, and MDA, the world leader in advanced space robotic solutions, are pleased to present to the Asteroid Redirect Initiative a comprehensive suite of man-rated robotic technologies to aid the crew during their asteroid prospecting mission. With full access to the extensive heritage and experience of MDA, and the creation of a robotic center of excellence at our Palo Alto facility that consolidates the expertise from our robotic facilities in Canada and Pasadena, SSL offers U.S. provided and supported robotic solutions to preserve EVA timelines and maximize productivity of the crew.

ASTEROIDS: ANCHORING AND SAMPLE ACQUISITION APPROACHES IN SUPPORT OF SCIENCE, EXPLORATION, AND IN SITU RESOURCE UTILIZATION

Kris Zacny, Honeybee Robotics

The goal of this chapter is to describe technologies related to asteroid sampling and mining. In particular, the chapter discusses various methods of anchoring to a small body (a prerequisite for sampling and mining missions) as well as sample acquisition technologies and large scale mining options. These technologies are critical to enabling exploration, and utilization of asteroids by NASA and private companies.

PARTNERSHIP & PARTICIPATORY ENGAGEMENT

CITIZEN FORUMS TO DELIBERATE ON POLICY ISSUES

Darlene Cavalier and David Guston, Expert and Citizen Assessment of Science and Technology (ECAST)

We overview ECAST's framework for citizens' deliberation forums which are the current state of the art for public engagement. These forums present an informed, safe, and empowering environment for citizens to consider the potential benefits, tradeoffs and long-term consequences of proposed policies or research directions. By tasking these citizen forums to write a report for decision makers about key principles and issues that need attention, new perspectives are brought forward that can help NASA better plan and implement missions. We believe that NASA should engage in this type of participatory forum as it establishes the Asteroid Initiative and future elements of the Capability Driven Framework.

PUBLIC-PRIVATE PARTNERSHIPS BASED ON SUNJAMMER SOLAR SAIL MISSION

Charles M. Chafer, Space Services Holdings, Inc.

Space Services Holdings, Inc. is the commercial infusion partner for the NASA-funded "Sunjammer" solar sail Technology Demonstration Mission scheduled for launch in Q1 2015. SSHI's business model and its role in the Sunjammer public-private partnership encompass many proven public participation, sponsorship, social media, and Internet monetization techniques. Asteroid Initiative missions can incorporate the Sunjammer partnership model by requiring the missions to include commercial infusion partners and granting rights, with appropriate review, to those partners. Results of such an approach include widespread education and public outreach, tangible benefits to the government, and the incorporation of innovative technologies and commercial practices into Asteroid Initiative missions.

PUBLIC - PRIVATE PARTNERSHIP TO DEVELOP AN ASTEROID DEFLECTION CAPABILITY

Joseph M. Clay, Spacedesign Corporation

Spacedesign is interested in a public-private partnership to develop an asteroid deflection capability. The asteroid deflection capability is implemented in three stages: 1) develop a Space Launch System, 2) develop a way-point between Earth and deep space, and 3) develop and test asteroid deflection.

PARTNERSHIP WITH GSFC TO LEVERAGE SATELLITE SERVICING TECHNOLOGIES

Kiel Davis, Honeybee Robotics Spacecraft Mechanisms Corporation

Honeybee Robotics (HBR) is pleased to respond to NASA's request for information for the Asteroid Initiative with a number of relevant and enabling technologies. We are uniquely suited to provide innovative solutions and deliver qualified hardware based on our institutional history of delivering mission-critical electromechanical systems to NASA. Honeybee Robotics leverages its focused expertise in high reliability robotics, electromechanical and electro-optical systems, as well as AS9100 certified quality management system to ensure we offer the highest quality product possible.

Honeybee has had an extensive and productive relationship with NASA Goddard Space Flight Center. Most notably, Honeybee provided the Sample Manipulation System as part of the Mars Science Laboratory Curiosity Rover's Sample Analysis at Mars (SAM) Instrument. SAM was provided by GSFC. Honeybee also has a long history dating back to the 1980's on collaboration with GSFC on various technology development programs ranging from instrument support, sampling mechanisms, and custom electromechanical systems.

We are pursuing a relationship with the GSFC Satellite Servicing Capabilities Office (SSCO) to leverage their expertise in robotic servicing, rendezvous, and docking as well as the Servicing Technology Center to demonstrate technologies in a relevant environment, key to risk reduction.

MAPPING THE OBJECTIVES OF THE ASTEROID INITIATIVE INTO THE ELEMENTS OF A PROGRAM

Anthony Freeman, Jet Propulsion Laboratory

NASA's recently announced Asteroid Initiative comprises an Asteroid Mission plus a Grand Challenge. The Mission itself consists of a robotic mission to capture and redirect an asteroid followed by a crewed mission to that asteroid. The Grand Challenge seeks to find all asteroid threats to human populations, via an observation and characterization campaign, and know what to do about them. The Asteroid Initiative Request for Information seeks to broaden the participation in this exciting NASA initiative through non-traditional approaches, reaching out to a broader community for ideas in the following areas related to asteroids:

(1) Asteroid Observation
(2) Asteroid Redirection Systems

(3) Asteroid Deflection Demonstration
(4) Asteroid Capture Systems
(5) Crew Systems for Asteroid Exploration
(6) Partnerships and Participatory Engagement.

NASA should be applauded for this refreshing approach to stimulate new thinking and ideas. Let's step back and consider what NASA is requesting. The time sequence of missions, the phasing of activities, the long-term nature of a planetary defense Grand Challenge, and the mix of projects and level of effort elements are quite evident. It is straightforward to map the elements of the initiative into the elements of a program, and we believe there are considerable advantages to NASA in doing so.

COMMERCIAL ASTEROID DEVELOPMENT INITIATIVE WILL LOWER COSTS TO GOVERNMENT AND EXPLOIT ASTEROID RESOURCES

David Gump, Deep Space Industries Inc.

Sustainability that reduces the cost of exploration should be the prime metric for the design of the asteroid initiative. Furthermore, intelligent structuring of the overall program to achieve sustainability must precede decisions about how to design any specific mission. It is key to anchor the initiative in the private sector from the outset, through partnerships that dramatically reduce the cost to taxpayers. If industry shares the cost of creating asteroid infrastructure, it will have a voice on crucial early decisions. These are the high-leverage choices that doom a program to failure or give it the rational underpinnings to succeed.

The current initiative has several challenges that could be solved by basing operational responsibility with industry, with NASA purchasing the agency-unique outputs that it requires. The strategy would be modeled on the Commercial Orbital Transportation Services (COTS) program and the Innovative Lunar Demonstrations Data (ILDD) program. It also would include elements of the NASA Launch Services (NLS) program – which like COTS features fixed-price milestone payments with full payment withheld until successful completion of services.

A Commercial Asteroid Development Initiative (CADI) would deliver several improvements over the current program structure. Cost to the government would be much lower, and industrial production of in-space propellant would accelerate the timetable for NASA crewed missions to Mars and other deep space destinations. Because the propellant will be produced at a profit for commercial customers as well as space agencies, CADI leads to a "virtuous circle" of growing infrastructure and declining costs over time that will greatly benefit NASA. CADI would still produce the asteroid material sought for the initial SLS/Orion test flight, with less risk of asteroid mission failure, broader public participation, and improved science.

PUBLIC-PRIVATE PARTNERSHIP WITH ARC TO TEST COMMERCIAL DEEP SPACE EXPLORATION APPROACHES

Chris Lewicki, Planetary Resources, Inc.

NASA has the opportunity to leverage innovative and low cost efforts that private companies such as Planetary Resources are deploying in their development of commercial deep space robotic exploration capability. At a cost lower than NASA's SMEX missions, the precursor mission capability through a private-public partnership can provide substantial value to NASA's ARRM/ARM mission through the significant reduction in uncertainty of physical properties for potential target asteroids that can only be obtained through close proximity characterization. Planetary Resources is fielding an asteroid exploration program of successively more capable missions to characterize near Earth asteroids of potential commercial interest. Low-cost commercial deep space exploration approaches will be tested in LEO, progress through GTO/GEO and Earth-escape opportunities to flyby Earth-crossing asteroids, with a well-tested and characterized system deployed to rendezvous with asteroids of interest. With Ames' leadership within NASA for small spacecraft systems and technology, as well as experience with low cost mission operations, a public-private partnership between NASA Ames and Planetary Resources provides an innovative, responsive and extremely cost-effective resource for near Earth asteroid observation and characterization.

OVERVIEW OF PARTNERS INVOLVED IN B612 SENTINEL MISSION

Ed Lu, B612 Foundation

There are approximately one million Near Earth Asteroids that are large enough to cause massive devastation if they impact on the Earth. After 15 years of dedicated effort, led by NASA, ground based searches have found 10,000 of these one million NEOs, approximately 1% of the total population. Continued operation of these ground surveys is expected to add 1000 new NEOs per year, falling far short of the intent to catalog a significant fraction of the potentially threatening objects and provide timely alerts that will enable missions to deflect the NEO prior to impact. B612 Foundation's Sentinel space mission, based on numerous recommendations to NASA over the past decade, is able to find 100,000 objects per year and reduce the likelihood of an unpredicted impact by over 50%.

The B612 Foundation is a non-profit organization chartered in the State of California. It was founded in 2002 by NASA astronauts and others who were concerned about the potential threat to Earth from Near Earth Asteroids (NEAs). The initial efforts of the foundation addressed technologies and methods for mitigation of threats once they

were identified. This led to detailed investigations of NEA deflection techniques and the invention of the Gravity Tractor scheme for towing a NEA out of its impacting trajectory.

LEVERAGING EXPERTISE TO INFORM ONGOING FEASIBILITY STUDIES AND DEVELOP THE TECHNOLOGIES AND SYSTEMS REQUIRED TO DETECT, CHARACTERIZE, AND RENDEZVOUS WITH NEAS

Michael O'Hara, Aerojet Rocketdyne

The Asteroid Redirect Mission and NASA's initiative to assess concepts for planetary defense against catastrophic asteroid collisions, offer unique opportunities for collaboration and partnerships between various domestic and international government agencies, industry, and academia.

Although detection of asteroids and studies of their behavior and characteristics have been ongoing for some time, no previous attempt to travel to and characterize a Near Earth Asteroid (NEA) has been undertaken. Therefore, it is important that all available expertise be leveraged to inform ongoing feasibility studies and develop the technologies and systems required to detect, characterize, and rendezvous with NEAs. The increased public awareness of the threat posed by NEAs makes for an excellent opportunity to engage the public in participatory engagement. Due to the current constrained budget environment and the ambitious schedule proposed for the Asteroid Redirect Mission, it is important that all previous and ongoing technology investments and existing system designs be exploited to the maximum extent practical to meet NASA's objectives for the asteroid initiative. Aerojet Rocketdyne has identified several high-TRL technologies that can be leveraged and used in demonstrations and near-term missions such as the 2017 Asteroid Retrieval Mission. We believe the public will be excited by these early missions. It is equally important that NASA and the agency's industry and academia partners work closely together to ensure that the public, other government agencies, and decision makers in the Administration and Congress are well informed and supportive of the asteroid initiative. Successful concept demonstrations leveraging these near-term technologies will enable the outreach necessary to solidify this support.

This knowledge collection, concept assessment, systems design, and advocacy effort can only be accomplished through the formation of partnerships and alliances across government, industry, and academia. Aerojet Rocketdyne has experience in forming the relationships and partnerships necessary to develop the technologies necessary for complex propulsion systems and has leveraged these partnerships to reduce cost and deliver propulsion solutions to government and industry customers under tight schedule constraints. Aerojet Rocketdyne also has the depth of experience in successfully engaging with the Legislative and Executive branches of government, as well as the media, that will enhance advocacy efforts with the Federal government and public.

LEARNING FROM NATURAL HAZARDS AND COMMUNICATION RESEARCH: ANTICIPATING THE FULL SPECTRUM OF COMMUNICATION NEEDS FOR ASTEROID REDIRECTION AND DEFLECTION ACTIVITIES

Margaret S. Race, Ph.D., SETI Institute-Carl Sagan Center

As NASA seeks information on system concepts and innovative approaches for its Asteroid Initiative, it has two main areas of interest: 1) the Asteroid Redirect Mission (ARM) and 2) defending our planet against the threat of catastrophic asteroid collisions. In each case, there will be need for proof of concept demonstrations to evaluate their capabilities and effectiveness. And in both cases, the public worldwide will be watching with both fascination and concern. On the one hand, these R&TD activities will mark important incremental progress on the road to further human and robotic space exploration; on the other, the public may focus on the potential for large-scale harm or societal disruption if things go amiss (even if risks may be low or safely addressed). Although the operational phases of these systems may be years away, now is the appropriate time to address important research and analysis aimed at all aspects of risk communication --whether for ARM or asteroid deflection attempts.

Thus, in considering options for new partnerships and participatory engagement in support of the overall Asteroid Initiative, NASA should be mindful of the critical need for research aimed at strengthening Earthly focused understanding and communication related to all aspects of asteroid threats— starting with detection and characterization, but also including details on decision making about asteroid capture or deflection, public understanding and perception of the threats, risk preparedness, warning systems, regional and global emergency response integration, and appropriate risk communication. Broadly speaking, these important elements fall into Primary Area #6 of the RFI, specifically items (b) through (e) and (g).

PUBLIC-PRIVATE PARTNERSHIP OPPORTUNITIES FOR ARM BASED ON APPROACH FOR RESTORE SATELLITE SERVICING MISSION

Bo Naasz, NASA-GSFC

Since 2011, the Satellite Servicing Capabilities Office (SSCO) at GSFC has been developing the Restore mission, a satellite-servicing initiative. To meet these objectives, the SSCO spent three years developing a partnership model and fostering strong relationships with industry and technology companies, resulting in an innovative public-private Partnership procurement and acquisition approach that might also meet the particular needs of the ARM mission. This response reports on potential private-public partnership opportunities for ARM identified by potential Restore partners. It also describes the Restore partnership approach, a new model that could potentially serve

as an alternative vehicle for ARM partnerships.

PARTICIPATORY ENGAGEMENT THROUGH SERIES OF COORDINATED DEMONSTRATION EVENTS

Scott Sevcik, Prospect Dynamics

Prospect Dynamics offers suggestions for questions b, c, d, e, and f. Our proposed methods to increase partnership and participatory engagement largely center around funding a coordinated series of independent demonstrations ranging from small scale events consolidated at “Demo Day” events to larger demonstrations such as Prospect Dynamic’s planned on-orbit anchoring and de-tumbling demonstration. This demonstration will also highlight how Prospect’s asteroid initiative technology is beneficial to other applications such as space debris mitigation, planetary defense, *space control, asteroid mining, and terrestrial industrial applications. Other ideas discussed in this section include Prospect Dynamic’s suggestions for facilitating participatory engagement through online collaboration tools, promoting participants on Twitter, and enabling early-stage technology developers by chartering an organization to seed promising startups.

CROWD SOURCING & CITIZEN SCIENCE

CITIZEN SCIENCE AND HUNTING COMETS USING NASA'S SOHO TELESCOPE

Peter Berrett

My experiences in hunting for a comet using the Soho telescope are informative. Briefly NASA has a website setup to encourage citizen scientists to find comets in Soho telescope images. It can be found at http://sungrazer.nrl.navy.mil/ I found out about the website 4 years ago and started hunting for a comet on and off. The following suggestions come out of that experience.

- Utilise existing Soho comet hunters and the general public to find asteroids
- Provide them with images from ground based telescopes suitable for asteroid hunting
- Provide them with a simple suite of tools
- Target areas of the sky where at that time, no known asteroids or near earth objects should be
- Use a similar reporting regime as exists at the above website
- Let them name what they find (or at least suggest names to the International Astronomical Union) and be credited as the discoverer

CREATE AN ASTEROID INITIATIVE COMMUNITY SCIENCE PORTAL FOR GLOBAL CROWDSOURCING

Andy LaMora, TopCoder, Inc.

NASA seeks to use innovative methods such as crowd sourcing, prizes and challenges in order to support the Asteroid Initiative. NASA can create an Asteroid Initiative Community Science portal as a way to inspire and to engage the general population to become part of the overall initiative. TopCoder's expertise and experience in developing and operating a global crowdsourcing community can help NASA to build the necessary community and crowd sourcing infrastructure, and to seed the community with TopCoder's existing global community of nearly 500,000 members. TopCoder specializes in crowd sourcing. Competitions, activities, and games that tie into the overall goals of the Asteroid Initiative can be used to leverage the natural inspiration that space related exploration and science generates.

THE LARGE SYNOPTIC SURVEY TELESCOPE (LSST) PROJECT PLANS TO CONDUCT CITIZEN SCIENCE ACTIVITIES

Tim Axelrod, Large Synoptic Survey Telescope

The Large Synoptic Survey Telescope (LSST) is currently by far the most ambitious proposed survey of the sky. This wide-field, ground-based optical telescope, which has been designed to image a substantial fraction of the sky every few nights, is scheduled to begin operation in 2021. One of its four main science drivers is exploration of our Solar System, and LSST will provide astrometric, photometric, and orbital data for millions of small bodies. LSST is the only upcoming ground-based survey capable of reaching the 90% completeness limit for 140 m or larger NEAs, and it will detect objects as small as 10 m at distances as large as 0.1 AU (15 million km), as well as 100 m objects in orbits similar to that of Venus.

Thanks to these performance characteristics, LSST is capable of significantly contributing to the asteroid observations described in this RFI. The LSST Education and Public Outreach (EPO) program is fully integrated with the science mission and emphasizes engaging a large, diverse audience of non-specialists with LSST data products through Citizen Science.
We first briefly overview the LSST system, and then discuss how Citizen Science activities can improve the NEO detection efficiency.

CROWD-SOURCED ASTEROID DATA ANALYSES AND ALGORITHM DEVELOPMENT

Chris Lewicki, Planetary Resources, Inc.

Planetary Resources is leading a multi-phase open innovation activity that enlists members of the public to assist in the identification of moving objects not identified by automated pipelines, as well as the notation of associated image artifacts and features. This data corpus can facilitate the structured training of advanced machine-learning algorithms to be developed through follow-on incentive prize competitions. The Catalina Sky Survey is generously providing its entire survey dataset for the project, consisting of approximately 25 telescope years of observations providing 3 million individual images or about 750,000 image stacks. Planetary Resources and The Zooniverse project are collaborating on a citizen-scientist activity to provide context to this data, and the NASA Open Innovation lab has confirmed strong interest in facilitating algorithm challenges following this work to establish new and improved capability in the areas of moving object pipelines. We anticipate results from these activities within 6 months from start, and to be able to support algorithm development challenges shortly thereafter as follow-on work. The “Asteroid Zoo” project has direct applicability to future minor planet survey activities, by both improving the existing machine algorithms, as well as facilitating new methods for rapid identification of candidate new objects. Several opportunities for leveraging and extending this work exist. Through Planetary Resources’ successful ARKYD Kickstarter campaign, a 17,000 member community has already demonstrated strong interest in enabling and contributing to this and future projects.

A CROWD SOURCED SOLUTION FOR DETECTION AND MONITORING OF NEAS

Michael Paolucci, Slooh LLC

Slooh's will leverage its expertise, software infrastructure, intellectual property (U.S. Patent 7,194,146 B2), media partnerships, worldwide land based telescope network and team of amatuer astronomers to detect and monitor for NEA, as well as build general awareness and education of NEA and NASA's related activities in the broader public.

PROVIDE GRANTS TO SMALL OBSERVATORIES; UNITE SMALL ORGANIZATIONS AND INDIVIDUALS IN ASTEROID RESEARCH

Ray Pickard, Bathurst Observatory Research Facility

A multifaceted approach of asteroid search programs needs to be implemented that include partnerships with private organizations and individuals willing to participate in research. It would be imperative that encouragement is offered to those willing to participate with follow up correspondence and feedback. There are individuals with knowledge of aspects of asteroids, meteorites, imaging technology, and willingness to become involved that collectively add a larger knowledge base to such a project. In addition, small organisations do not attract the funding that a united approach could achieve. There is also the encouragement offered to participants of working with an internationally recognised agency on a real project that has ultimate benefits for human existence.

LARGE-SCALE CAMPAIGN THAT INVOLVES THE PUBLIC TO DISCOVER FAST MOVING NEOS

Carl Hergenrother, University of Arizona

A successful large-scale campaign that allowed members of the general public to discover fast-moving Near-Earth Objects (NEOs) in their close passages by the Earth is relevant to NASA's Grand Challenge. The method, results, experience, and lessons learned are summarized to aid the future engagement of citizen volunteers in similar efforts. The "Fast-Moving Object (FMO) Project" was part of the University of Arizona's Spacewatch Project from 2003-2006 and resulted in many discoveries of FMOs. Users were given exclusive access to freshly taken images of the sky in near real time *via* the web and were provided credit for their discoveries as the objects were confirmed and followed by the international community of asteroid astrometrists. The objects found by

the volunteers tended to move too fast for Spacewatch's software to detect automatically, so the FMO Project provided a unique service to science while also engaging the general public in front-line research. The results and the limitations of the FMO Project are summarized along with advice for the future.

CITIZEN SCIENCE AND THE MINOR PLANET CENTER

J.L. Galache, IAU Minor Planet Center

Light curves are a useful method of obtaining the spin periods and even shapes of asteroids, and an important part of the asteroid characterization process. The drawback is they require long observation times, often several nights; this makes them unlikely projects for professional astronomers, whose time on large telescopes is limited. Amateur observers are better suited for this task as they are more likely to have entire nights available for observing. We propose to set up a hub at the Minor Planet Center (MPC) that will coordinate amateur observers around the world to take light curves of NEAs (Near Earth Asteroids) as soon as they are discovered, while also observing already known NEAs. Despite the limitations of amateur observing equipment, we estimate that a total of ~130 NEAs could be observed each year, of which ~90 would be new discoveries. The project website would offer video and written tutorials explaining the complete process from start to finish, including analysis of the acquired data, which would be stored in the MPC's already existing asteroid light curve database (currently housing over 200 NEA light curves).

NEXT GENERATION ENGAGEMENT

ASSEMBLE A TEAM OF FILMMAKERS AND SOCIAL ACTION CAMPAIGNERS TO CREATE A FILM TO EDUCATE THE PUBLIC ABOUT THE ASTEROID THREAT

Erik Andreasen and Alden Stoner, Participant Media

Participant Media could assemble a talented team of filmmakers, marketing executives and social action campaigners to create a film with the intent of entertaining and educating a vast, global audience as to the potential threat of an asteroid striking the earth and our need for global cooperation to organize planetary defense. The film would aim to inspire viewers to subsequently engage with the issue and take specific actions outlined by our social action campaign after the seeing the film. Participant aims to pull together an experienced team of producers, writers, a director, and actors to help develop a script, and then ultimately finance and produce a feature film highlighting the potentially existential threat of a large asteroid colliding with earth.

The Social Action department works alongside the production team to help ensure the applicability of the story to what's happening in the world at large, and how it might motivate people to action. The Social Action department works with best in class foundations and non-profits to identify the tipping point and unmet needs around a selected issue. From there, the strategy develops based on the theory of change to target the most influential audience around making sustainable social change. In tandem with the release of the film, the social action campaign commences, pulling together a number of media channels and activations to accelerate the identified change.

ASTEROID OBSERVATION AND MISSION SIMULATION AUTOMATED MOVIE PRODUCTION (ASTEROID-AMP)

Eric M. De Jong, Jet Propulsion Lab

Create a knowledge-driven asteroid observation and mission simulation automated movie production pipeline. Create and distribute asteroid movies to museums, planetariums, movie theaters and the web using CineGrid, Internet2 and the resources of the museum alliance partners. Asteroid-AMP movies will engage the public, press and film industry in the Asteroid Initiative.

Successful Asteroid observation and mission plans require the collection, organization review and edit of a complex set of mission parameters. The analysis of this data is greatly enhanced through the creation of "movies." Asteroid observation movies visualize an asteroid's trajectory, spin rate, shape, albedo, bi-directional reflection, texture, roughness, strength and composition. Asteroid mission simulation movies visualize mission spacecraft, trajectories, position, orientation, instruments, internal

elements and operations.

The Asteroid-AMP knowledge driven automated movie production environment distribution and display pipeline provides efficient visualization of asteroid observations and asteroid mission simulations. The Asteroid-AMP pipeline is a paradigm shift in asteroid observation knowledge extraction, movie production, distribution and display. Current methods for asteroid observation analysis, movie production and distribution are labor-intensive and expensive. Asteroid-AMP shifts visualization control from Hollywood style production teams to algorithms and automated procedures.

The Asteroid-AMP pipeline automates the creation, distribution and display of time, feature and event driven asteroid movies. The Asteroid-AMP pipeline uses asteroid observation experiment data records (EDR) and meta-data from the small body archive data system. Asteroid-AMP relies on new data flow, event and feature detection code, meta-data driven procedures and custom search and pattern recognition algorithms. Asteroid-AMP creates 3D stereoscopic movies from asteroid observations and mission simulations.

ASTEROID INITIATIVE SPECIFIC MODULE WITH ENHANCEMENTS FOR EYES ON THE SOLAR SYSTEM AND ASTEROID WATCH

David J. Delgado, Jet Propulsion Laboratory

JPL has a robust and proven set of Public Engagement platforms upon which to build new and imaginative ways to bring public enthusiasm to understanding Asteroid research. Creating an Asteroid specific module that integrates the visualization and simulation capabilities of the Eyes on the Solar System platform with the highly visible Asteroid Watch Twitter feed has great potential to expand public interest in the NASA asteroid initiative:

Eyes On The Solar System: A 3D visualization and simulation tool, most of a decade in the making, is a vibrant living cyber catalogue and calendar of all of the Sun's planets, most of it's moons and presently almost 100 major asteroids. More than 300,000 downloads have been logged every month over the past two years. Born from Eyes on the Earth and recently begetting Eyes on Exo-Planets, Eyes on the Solar System is the "space scape" of objects in our Sun's influence. Eyes on the Earth plots surface data of dozens of NASA earth observing missions. Eyes on Exo-Planets is what's known and being discovered, about planets rotating around Stars in the immediate neighborhood of our Milky Way galaxy.

LARGE-SCALE, GLOBAL INCENTIVE PRIZE COMPETITIONS

Alex Hall, XPrize Foundation

XPRIZE is the global leader in the creation of incentivized prize competitions. Our mission is to bring about radical breakthroughs for the benefit of humanity, thereby inspiring the formation of new industries and the revitalization of markets. XPRIZE works to accelerate the pace of innovation across sectors with prizes that are audacious, yet achievable.

XPRIZE undertakes detailed market, stakeholder and risk analyses to inform both the design of the competition, as well as the associated marketing and media plans. These analyses create the foundation for a sound competition structure and the detailed set of competition guidelines and judging criteria. Part of this design is based on a technical Visioneering Workshop to define and refine the specific technical details of the top prize concept(s).

Once competition guidelines are established, XPRIZE works to announce the competition at a high profile forum, and works to recruit a solver community. In addition, XPRIZE works to ensure that we support the solver community by hosting annual mandatory team summits; providing a robust online system for teams to gather and share information; ensuring that teams are meeting competition milestones; and establishing that all teams, regardless of their place in leaderboard standings, are considered heroes and innovators through XPRIZE's marketing and media efforts.

Founded in 1995, XPRIZE is the recognized world leader for creating and managing large-scale, global incentive prize competitions that stimulate investment in research and development worth far more than the prize itself. To date, XPRIZE has successfully awarded four prizes with combined purses of over $23 million, including the Ansari XPRIZE, a space competition in which we offered a $10 million prize for the first non-government organization to launch a reusable manned spacecraft into suborbital space twice within two weeks. XPRIZE currently has four active prizes with combined purses of over $44 million, including the $30 million Google Lunar XPRIZE (GLXP), a breakthrough space competition to land a privately funded robotic spacecraft on the Lunar surface. GLXP is the largest incentive competition in history.

PUBLIC ENGAGEMENT THROUGH MOVIES, GAMING, COMPETITIONS, AND NASA-SPONSORED EVENTS LIKE FIRST ROBOTICS

Eric Klien, Lifeboat Foundation Response

The Lifeboat Foundation is responding to item 6) Partnerships and Participatory Engagement.

The Lifeboat Foundation is a nonprofit nongovernmental organization dedicated to encouraging scientific advancements while helping humanity survive existential risks

and possible misuse of increasingly powerful technologies, including genetic engineering, nanotechnology, and robotics/AI, as we move into a very complex future.

The Foundation is pursuing a variety of options, including helping to accelerate the development of technologies to defend humanity and improve its prospects, new methods to combat viruses (such as RNA interference and new vaccine methods), effective nanotechnological defensive strategies, and self-sustaining space colonies in case the other defensive strategies fail and for their contribution to the future of humanity.

We propose three project concepts as our part of this information gathering request.

The first is a joint NASA/Lifeboat Foundation media venture, beginning with public awareness through historical cinema; moving to a video/cinema competition format; concluding with a major effort to create a near-real-time, online gaming effort fed by actual tracking data, while including components of science fiction and competition.

The second is a new competition venue similar to other current NASA efforts. This would be targeted at garage innovators, the Hackerspace/Maker community, and universities. A tiered set of goals would challenge participants to begin with simulated asteroid ore, and eventually produce finished components.

The third activity would leverage many existing NASA pathways into the public, by adding Asteroid Initiative goals into currently sponsored events such as Odyssey Of The Mind; FIRST Robotics, and Lunabotics.

In addition, our members provide overarching comments to the mission as relates to larger societal goals.

This discussion covers aspects of multi-purpose, cooperative missions within and without NASA with the unmanned asteroid retrieval mission as the initiator, with a focus on the later use of the retrieved asteroidal materials as radiation shielding for crew habitats at proposed EM-L1 or L2 logistics stations.