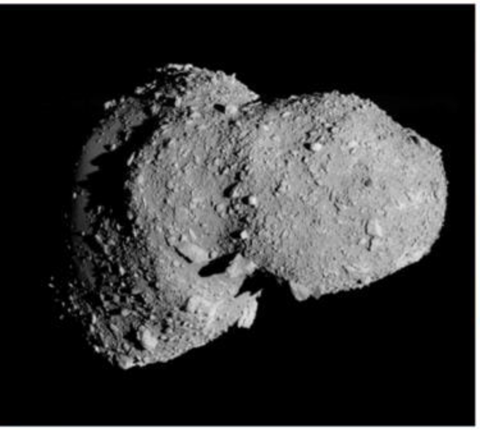
National Aeronautics and Space Administration

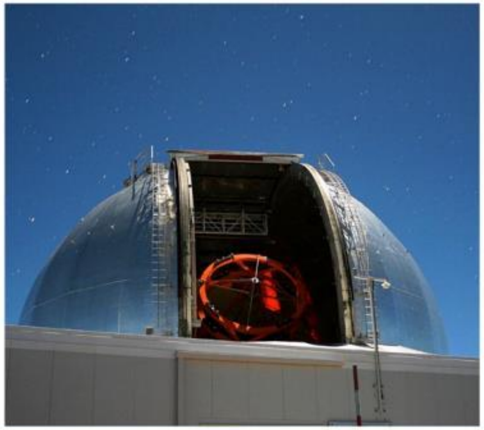
Keck Workshop: Applications of Asteroid Redirection Technology

Update on Asteroid Redirect Mission

Michele Gates, Human Explorations and Operations Mission Directorate

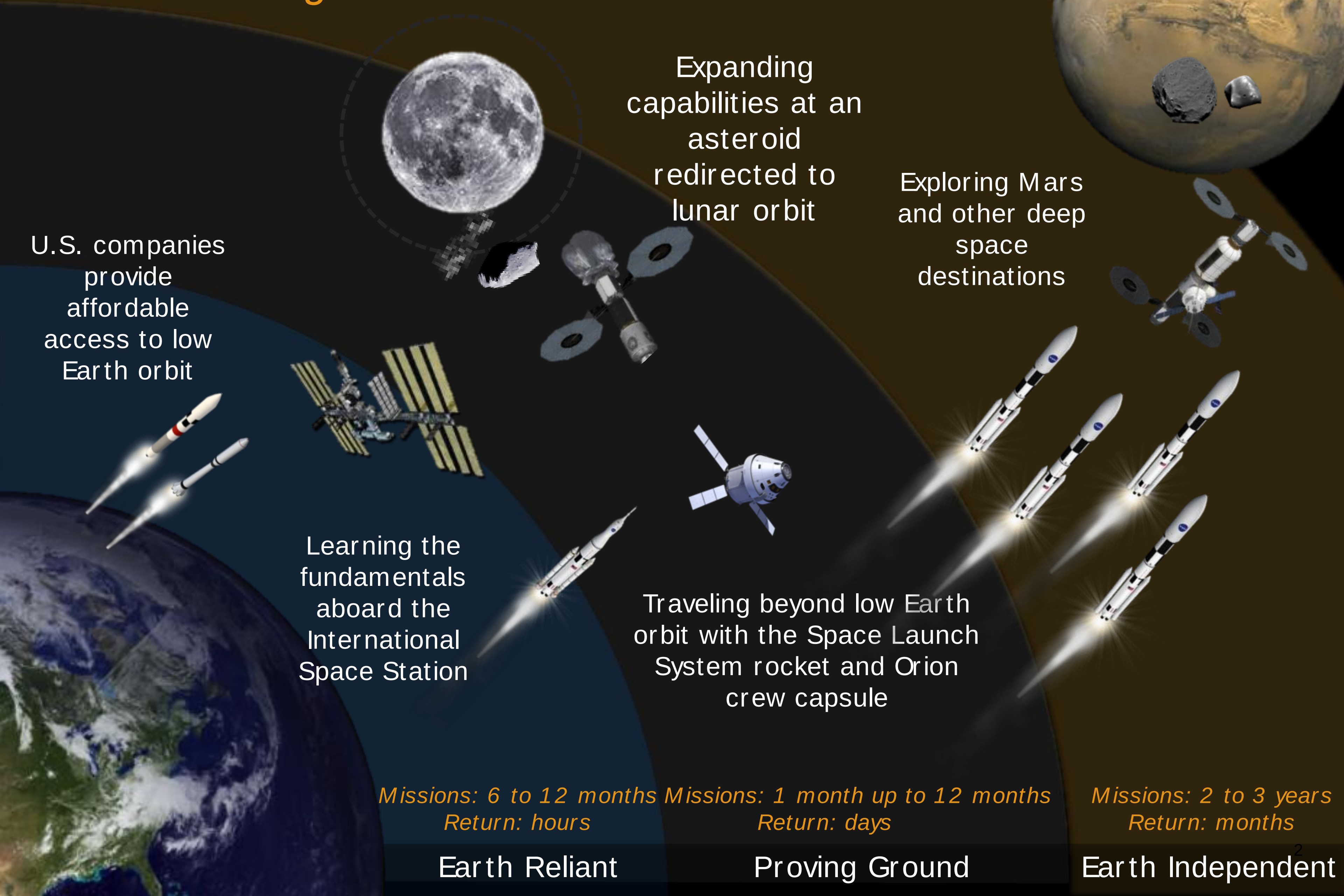
April 7, 2014





The Future of Human Space Exploration

NASA's Building Blocks to Mars

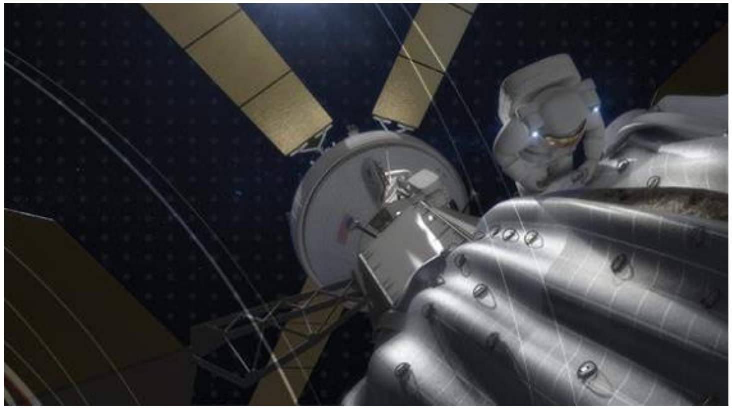


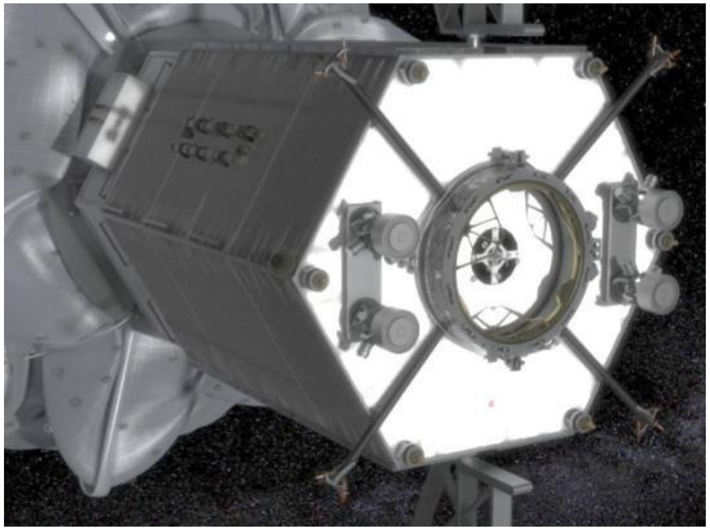
Why an Asteroid Redirect Mission?

- **Bringing an asteroid to cis-lunar space so that it could be sampled by astronauts in Orion is an excellent use of all the exploration capabilities being developed and provides a compelling early mission that advances exploration along an affordable and sustainable path.**
  - **The mission leverages the Space Technology Mission Directorate Solar Electric Propulsion (SEP) technology, including the advanced solar arrays and magnetically shielded hall thrusters, that feed forward to delivering cargo to Mars and the lunar vicinity.**
  - **The mission complements the Science Mission Directorate's Near Earth Object Observation program by expanding its capability.**
  - **The mission fully utilizes the early flights of SLS and Orion and early mission operations.**
  - **The mission also advances Exploration Extravehicular Activity, the International Docking System, Automated Rendezvous & Docking, and complex operations which all feed forward to future deep space and Mars exploration.**
  - **We also move a small planetary body from one place in the solar system to another, which is also the beginning of moving large objects around in deep space with SEP.**

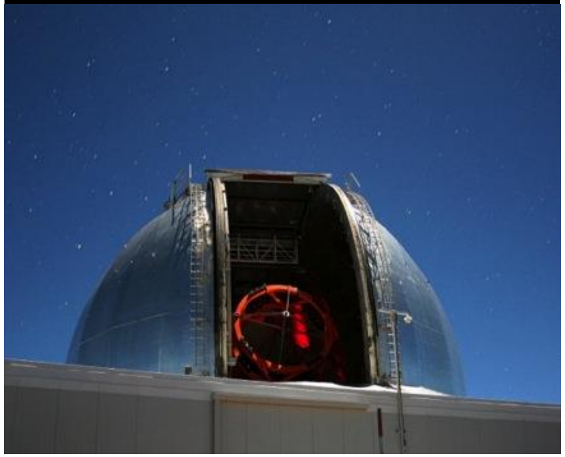
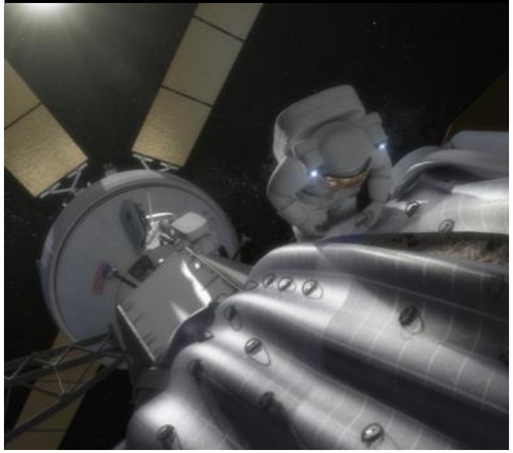
Asteroid Redirect Mission Objectives

- Conduct a human exploration mission to an asteroid in the mid-2020’s, providing systems and operational experience required for human exploration of Mars.
- Demonstrate an advanced solar electric propulsion system, enabling future deep-space human and robotic exploration with applicability to the nation’s public and private sector space needs.
- Enhance detection, tracking and characterization of Near Earth Asteroids, enabling an overall strategy to defend our home planet.
- Demonstrate basic planetary defense techniques that will inform impact threat mitigation strategies to defend our home planet.
- Pursue a target of opportunity that benefits scientific and partnership interests, expanding our knowledge of small celestial bodies and enabling the mining of asteroid resources for commercial and exploration needs.

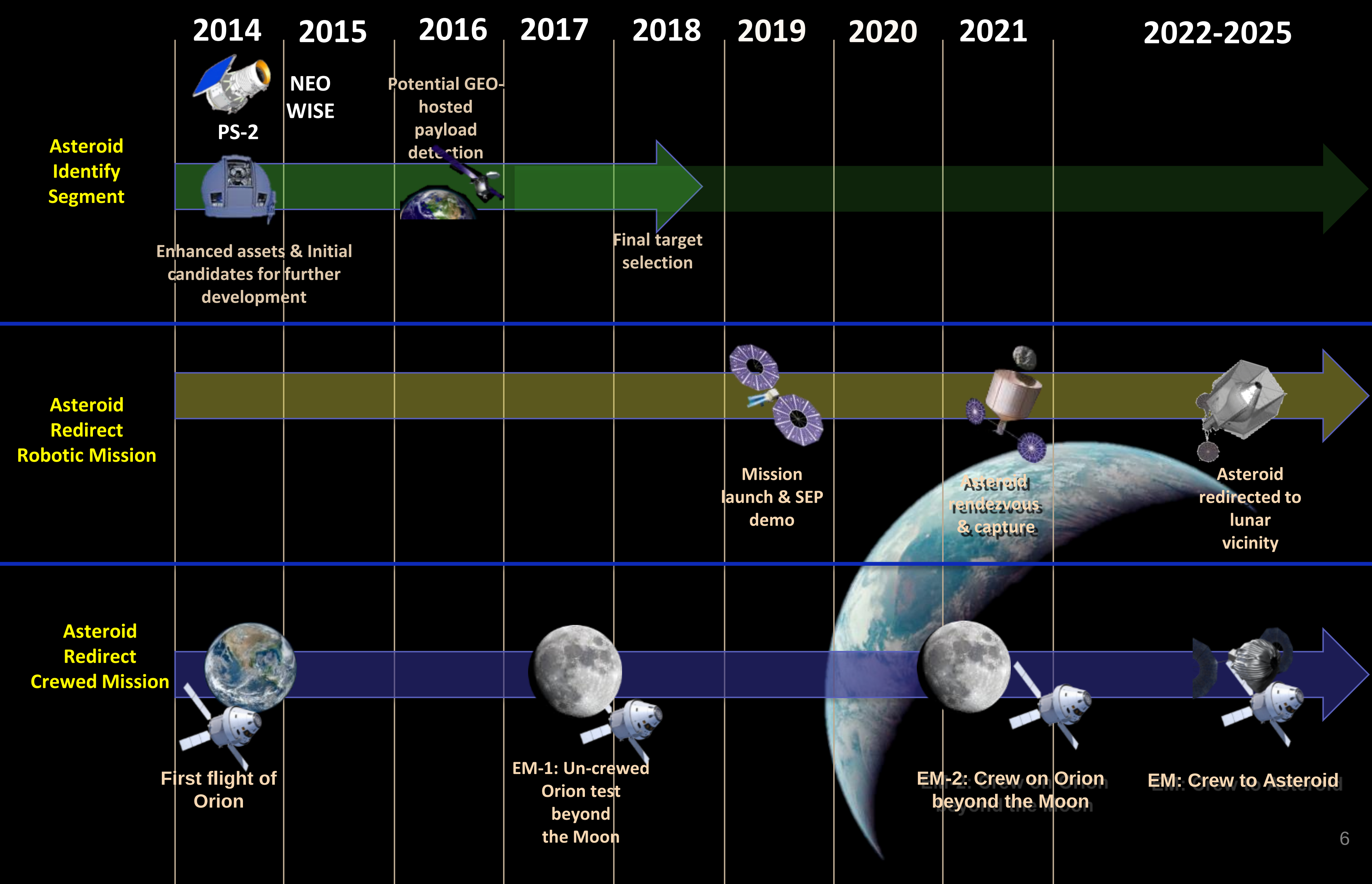




Asteroid Redirect Mission

Identify	Redirect	Explore
		
Asteroid Identification: Ground and space based near Earth asteroid (NEA) target detection, characterization and selection	**Asteroid Redirect Robotic Mission:** High power solar electric propulsion (SEP) based robotic asteroid redirect to lunar distant retrograde orbit	**Asteroid Redirect Crewed Mission:** Orion and Space Launch System based crewed rendezvous and sampling mission to the relocated asteroid

Schedule Strategy

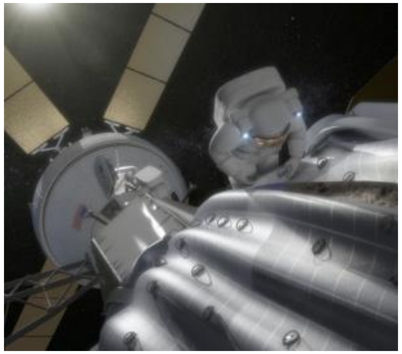


NASA Asteroid Redirect Mission Internal Studies Completed

Reference robotic mission concept
- To redirect a small near Earth asteroid and potentially demonstrate asteroid deflection
- Study led by the Jet Propulsion Laboratory

Alternate robotic mission concept
- To redirect a boulder from a larger asteroid and potentially demonstrate asteroid deflection
- Study led by the Langley Research Center

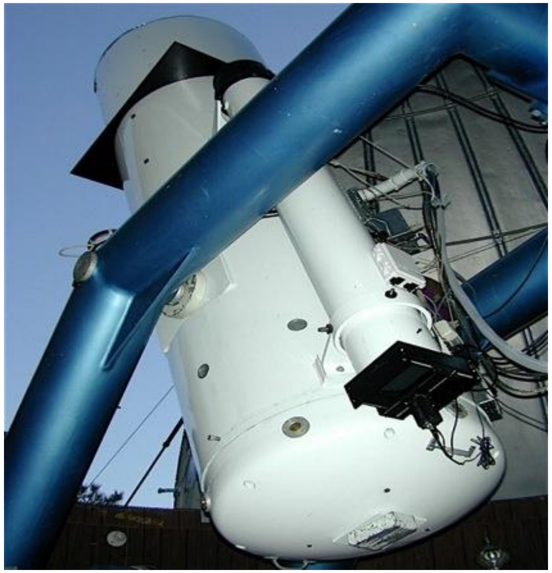
Crewed Mission
- Crew rendezvous and sampling for either concept
- Led by the Johnson Space Center



Robotic Concept Integration Team comparative assessment

Near Earth Object Identification (a few elements)

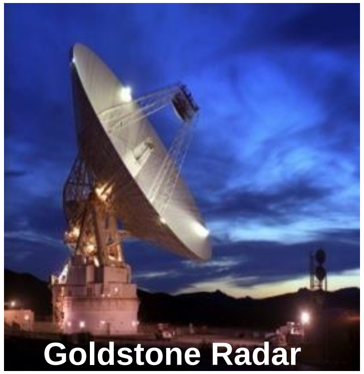
Catalina Sky Survey



University of Arizona – Tucson

NEOWISE reactivated and dedicated to NEO Search & Characterization

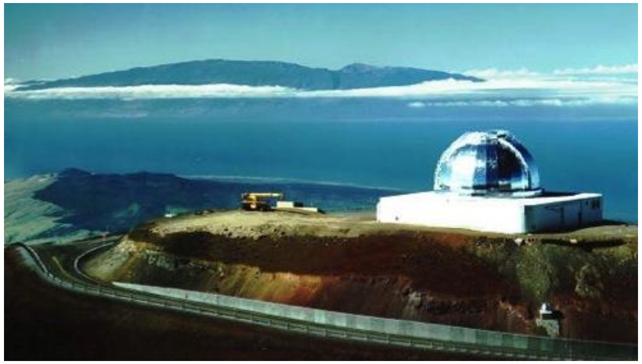
Utilize Radar (Goldstone and Arecibo) increased time for NEO observations.


Goldstone Radar


Arecibo Observatory

NASA InfraRed Telescope Facility (IRTF)

- Increase On-call for Rapid Response.
- Improve Instrumentation for Spectroscopy and Thermal Signatures.

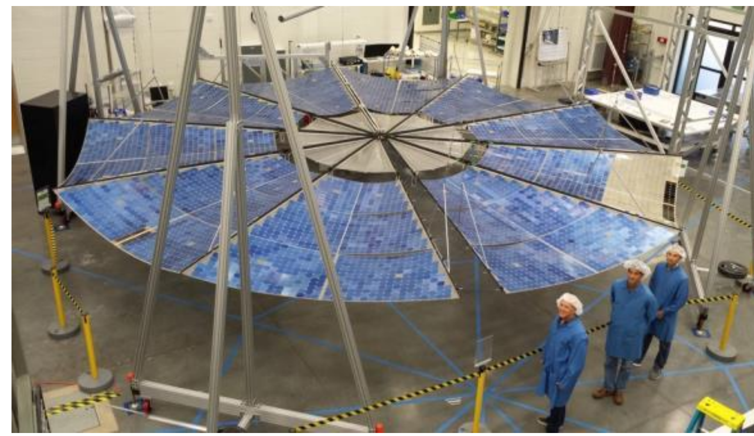


NASA Solar Array Technology Work in FY 2014

Design, Build and Test of Solar Arrays

- MegaFlex "fold out" solar array (TRL 5 by April 2014)
- Mega-ROSA "roll out" solar array (ROSA at TRL 5 by June 2014)

Each wing sized for nominally 20kW BOL



Testing includes:

- Thermal vacuum deployment
- Stowed wing vibro-acoustic exposure

Analyses and Models include:

- Design extensibility to 250kW system
- Finite element (stowed and deployed)
- CAD models (stowed and deployed)
- Structural Dynamics (stowed and deployed)
- Thermal

Design, Build and Test Solar Cell Coupons for 300V operation:

Test Power Electronics for 300V operation

- Transistors, diodes, drivers
- Destructive single event radiation testing

NASA Electric Propulsion Work in FY14

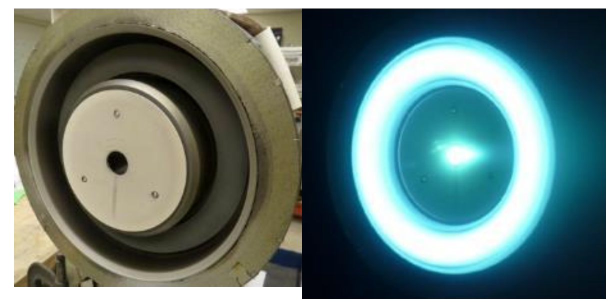
NASA's Goal

- Develop high power Hall thruster 12kW-class (2X current SOA) – changed from 15kW-class
- Developed magnetically shielded design to provide long life commensurate with mission
- Pursued high voltage (i.e. 300V input) PPU system compatible with Hall Thruster

Path Forward for Advancement

- Designing and building 12kW EDU at GRC
- Testing the magnetic shielding design now demonstrated up to 3000-sec specific impulse and 20 kW power with JPL H6 and NASA 300M thrusters.
- Designing and building high voltage PPU (300V) EDU at GRC, with option for 120V PPU
- Integrating Thruster EDU and PPU for test by end of FY14

JPL H6 with magnetic shielding



GRC 300M with magnetic shielding

Cut away of NASA 300V PPU

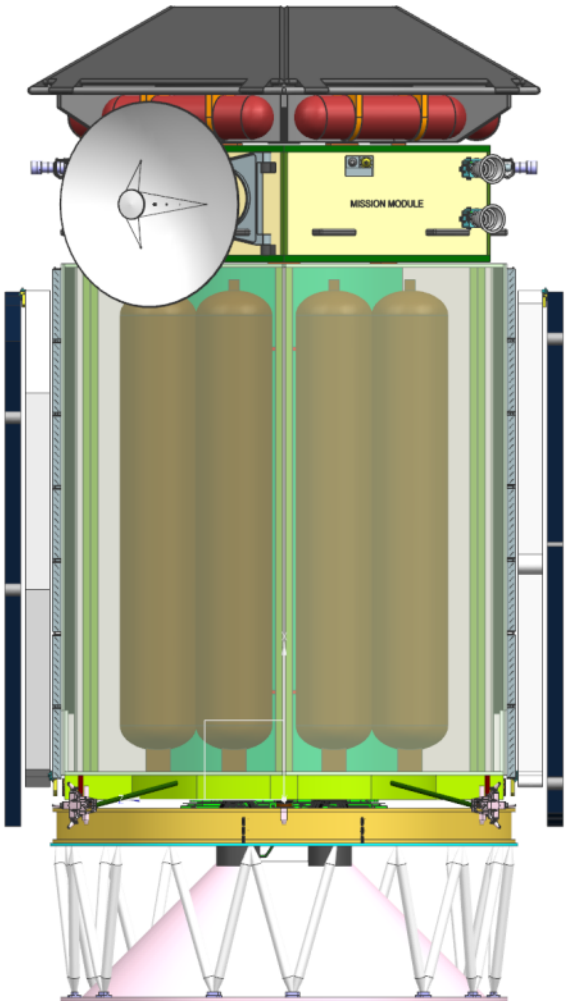
Robotic Mission Spacecraft Reference Configuration Key Features

Capture Mechanism
- Flight heritage instrumentation
- Inflatable capture bag

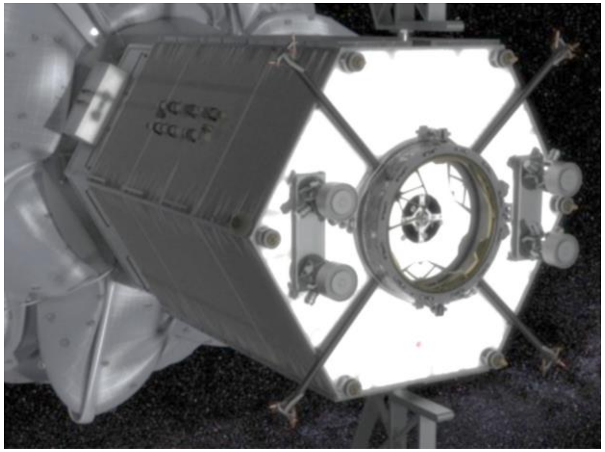
Mission Module
- Flight heritage avionics
- Simple Interface with SEPM

SEP Module
- Compatible with STMD solar array technology at 50 kW
- EP derived from STMD Hall thruster/PPU technology
- Xe tanks seamless COPV with at least 10 t capacity
- Unique structure design
- Conventional thermal control
- Conventional reaction control subsystem

Launch Vehicle I/F
- Compatible with 5m fairings
- Unique adapter depending on LV selected



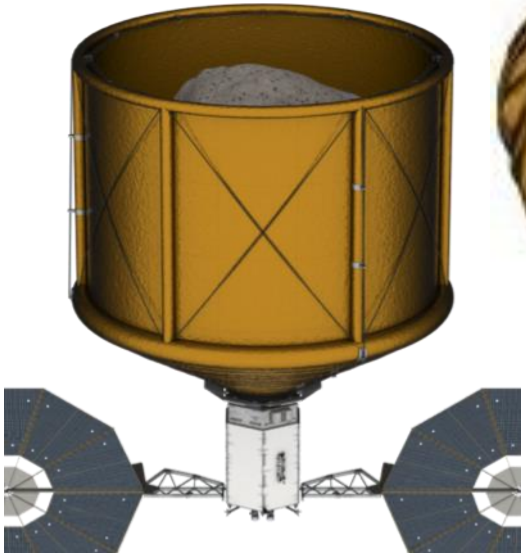
Orion docking I/F



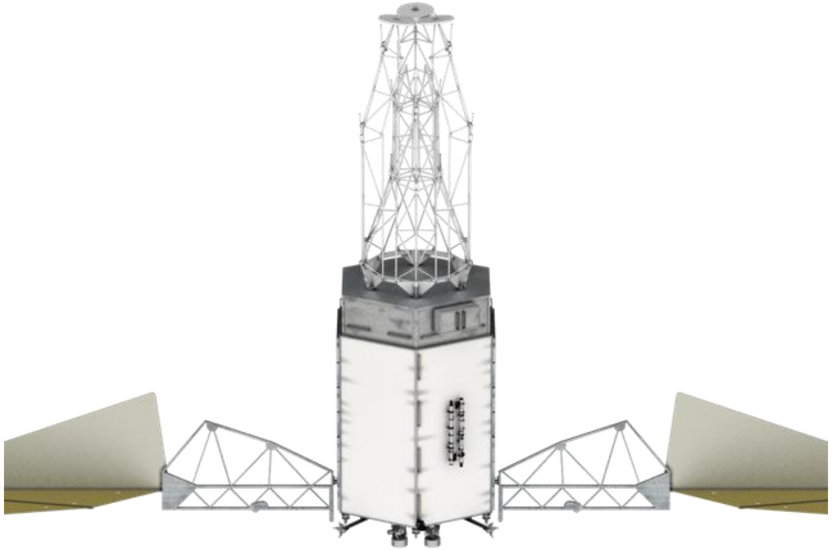
Crew access path

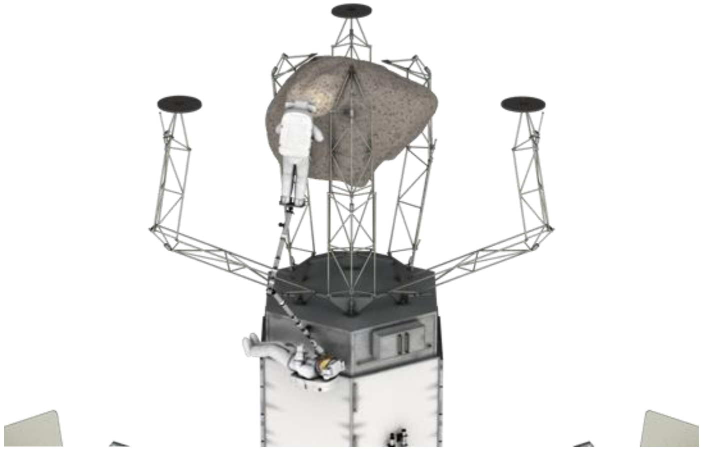
Robotic Mission Concept Options

Small Asteroid Capture: Option A



Larger Asteroid Boulder Capture: Option B





Current and Possible Future Currently Known Candidate Target Asteroids for ARM

- **Small Asteroids:**
  - Currently, 7 potential candidates
  - 1 validated candidate: **2009 BD**.
  - 1 possibly valid candidate pending Spitzer observation final results: **2011 MD**.
  - Possibly another valid candidate in 2016: **2008 HU4**.
  - Potentially future valid candidates, at a rate of a few per year.

- **Larger Asteroids:**
  - Currently, 6 potential candidates
  - Currently, 1 validated candidate: **Itokawa**.
  - 2 more valid candidates expected in 2018 (after characterization by other missions): **Bennu** and **1999 JU3**.
  - 1 possibly valid candidate with inferred boulders: **2008 EV5**.
  - Potentially future valid candidates with inferred boulders, at a rate of ~1 per year.

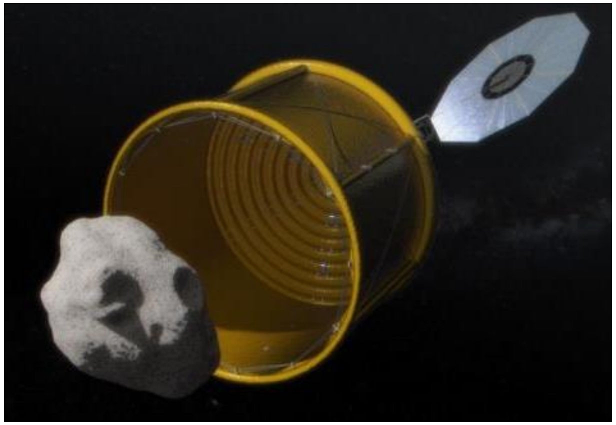
Asteroid Redirect Robotic Mission
Whole Small Near-Earth Asteroid Concept (Option A)

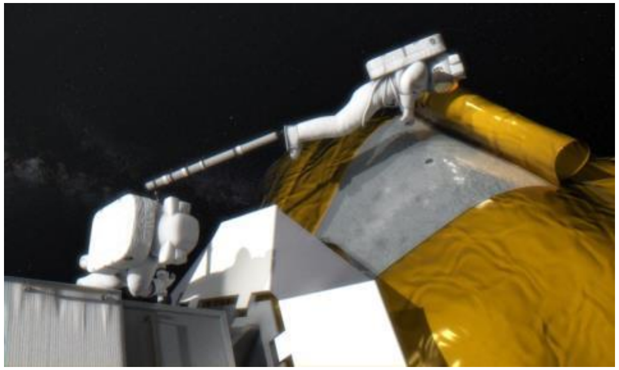
- **Rendezvous with small** less than **10 meter mean diameter Near Earth Asteroid (NEA)**
  - **Capture <1000 metric ton rotating NEA**
  - **Demonstrate planetary defense techniques**
  - **Maneuver to stable, crew accessible lunar Distant Retrograde Orbit (DRO)**

- **Candidate target is 2009 BD**
  - **5 meter mean diameter and < 145 metric tons**
  - **Launch mid-2019*; Crew accessible after 2/2024**

- **Additional candidate targets expected to be discovered and characterized at the rate of approximately 5 per year**

- Other candidates under evaluation
  - **Recent Spitzer observation of 2011 MD which is crew accessible in August 2025**
  - **2014 BA3 crew accessible in early 2025**
  - **2013 EC 20 crew accessible in late 2015**



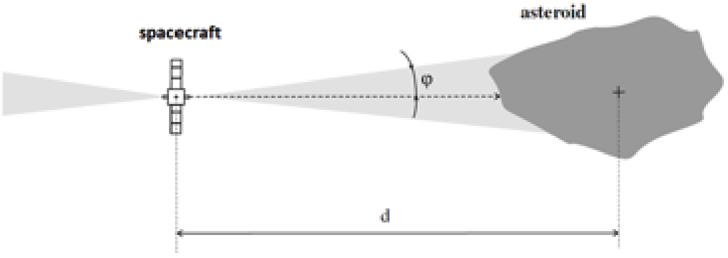


*** Launch vehicle dependent**

Planetary Defense (PD) Demonstration

- **The mission could demonstrate the gradual, precise PD approaches of Ion Beam Deflection (IBD) or Gravity Tractor (GT) on a small or large asteroid**
- **For Option A, a PD demo could be done with minimal impact to the mission design and operations**
  - No design changes, fits in existing timeline
  - IBD operations approach is independent of the size of the asteroid
- **IBD/GT relative performance on a small NEA**
  - IBD, <500 t (like 2009 BD) could impart: 1 mm/s in < 1 hour
  - GT, <500 t (like 2009 BD) could impart: 1 mm/s in < 30 hours

Ion Beam Deflector



Asteroid size-independent planetary defense demo

The Target and the Bag

- **Most large asteroids are believed to be loosely held together bodies, i.e. rubble piles. The likelihood that small bodies are fragments of large bodies implies the need for containment in a bag.**
  - Tolerant of a wide range of asteroid shapes and mechanical properties
  - Assures containment and eliminates dust as hazard for S/C
  - Local forces on asteroid due to capturing, cinching, berthing and maneuvering are estimated to be small compared to the strength of the body
- **Based on inputs from the EVA office and the strong desire to minimize complexity and risk we have limited the design space to simple spinners or slow, <0.5 rpm, tumblers, estimated to include 75% of the small asteroid population**

Rubble Pile Compressive Strength

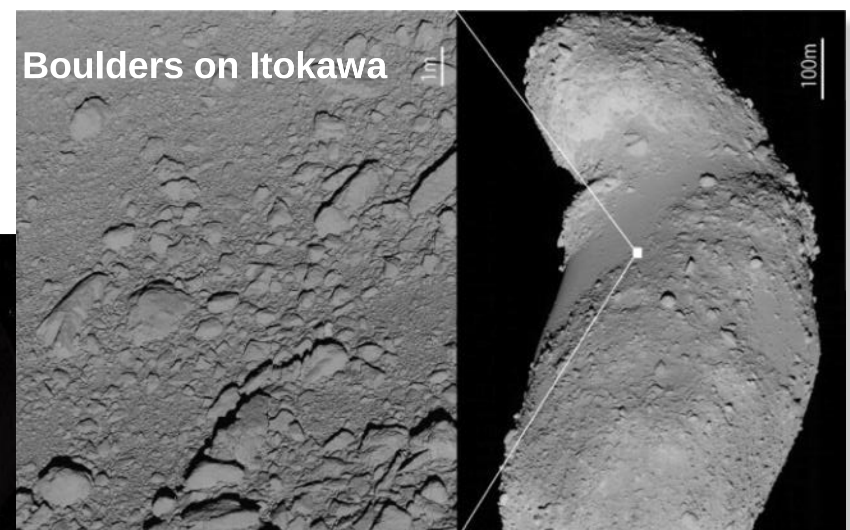
- Bolide Record: 0.1- 1.0 MPa (15-150 psi)
- "Dirt" Clod: .2-.4 MPa (30-60 psi)
- Possible lower strength <0.1MPa

Possible Spin States

- Slow (<0.5 RPM), Simple Spin
- Slow (<0.5 RPM), Tumbling
- Fast (~<2 RPM), Simple Spin
- Fast (~<2 RPM), Tumbling

Larger Asteroid Mission Concept (Option B)

- Rendezvous with a larger (~100+meter diameter) NEA
  - **Collect ~2-4 meter diameter boulder (~10-70 metric tons)**
  - **Perform deflection demonstration(s) and track to determine effect**
  - **Return boulder to same lunar orbit**
- Candidate asteroid Itokawa
  - **2-3 meter, 18 ton boulder to DRO in 2025 (2019 robotic mission launch)***
- **Other targets to be characterized by in situ observation and crew accessible in DRO in 2025**
  - **Bennu by OSIRIS-Rex**
  - **JU3 by Hayabusa 2**
  - **2008 EV5 by radar or other means**



*** Launch vehicle dependent**

Planetary Defense Demonstration at a Larger NEA

Planetary Defense Options	Capable?
Kinetic Impactor	✓
Enhanced Gravity Tractor (EGT)	✓
Gravity Tractor	✓
Ion Beam Deflection (IBD)	✓

Selected Enhanced Gravity Tractor for Itokawa Case Study

- Relevant to potentially-hazardous-size NEAs: efficiency increases as boulder and NEA masses increase.
- Leverages collected boulder mass.
- Allows spacecraft to maintain safe, constant distance from NEA.
- Demonstrates sustained operations in asteroid proximity.

Focus is on demonstrating the applicability of Enhanced Gravity Tractor on potentially-hazardous-size NEA.

Enhanced Gravity Tractor Concept of Operations for Itokawa

- Phase 1: Fly in close formation with the asteroid with collected boulder (60 days required for measurable deflection with 120 days of reserve performance).
- Phase 2: Wait for orbital alignment to become favorable to allow measurement of deflection beyond 3-σ uncertainty (~8 months from start of Phase 1).

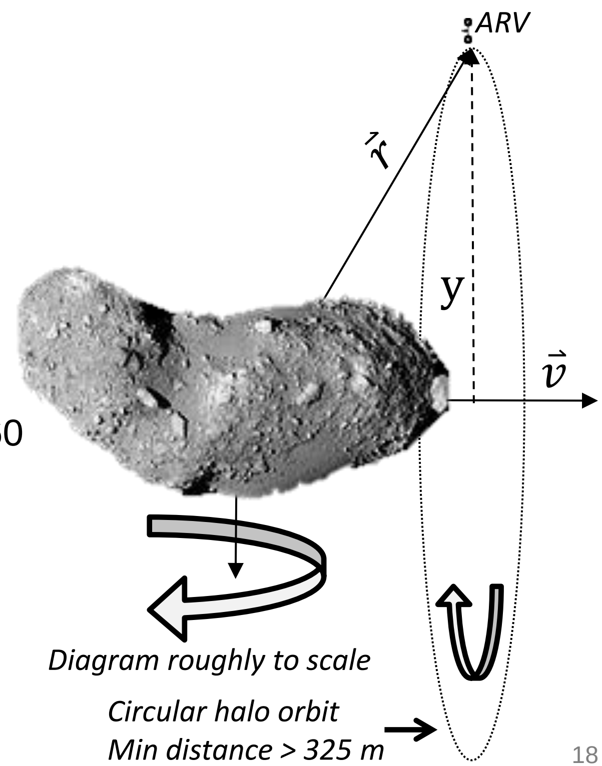
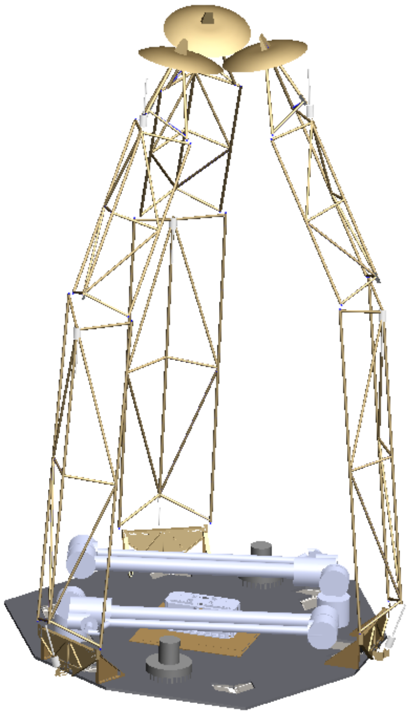


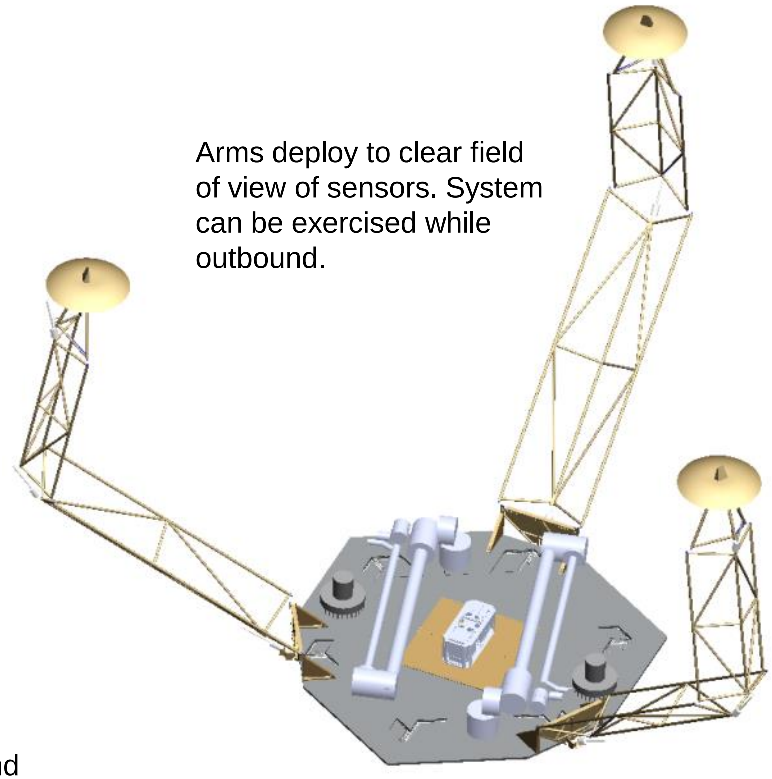
Diagram roughly to scale

Hybrid Option Design

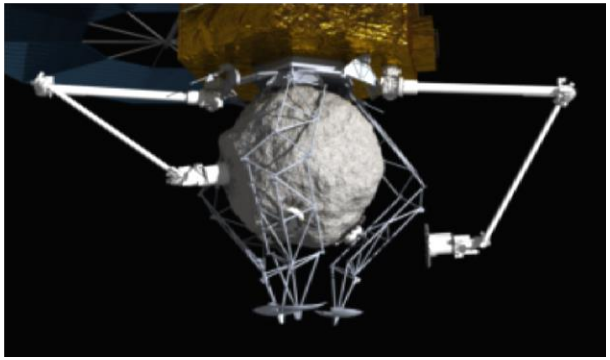
- **7-DOF Arms and microspine grippers are built and tested in parallel to Spaceframe contact arms**
- **Assembles as single module for integration with the S/C bus**



Contact Arms pinned at pads and
7 DOF arms pinned to deck for launch.



Arms deploy to clear field of view of sensors. System can be exercised while outbound.



Contact Arms with Sample Collectors and boulder constraint after capture.

Testing of microspine gripper prototype

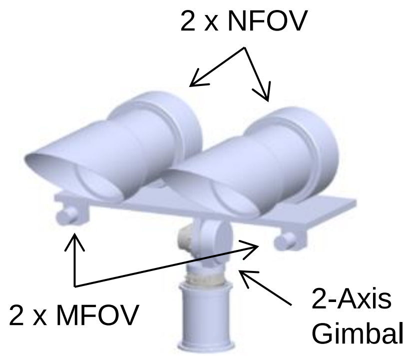
Hybrid capture system optimizes functionality and maximizes extensibility of concept.

Sensor Selection

Sensor Suite

Narrow FOV Camera
Medium FOV Camera
Wide FOV Camera
3D LIDAR
Situational Awareness Cameras

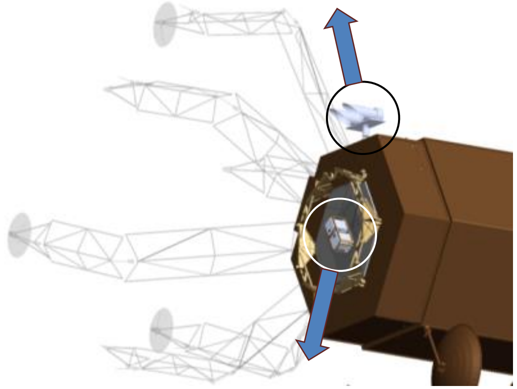
The use of multiple redundant systems enable identification and characterization of thousands of boulders in the returnable mass range, long-/close-range navigation, and execution of autonomous capture ops.



Extensibility Benefits

Validation of optical nav techniques (Exploration).
Video of ops for Exploration, Public Engagement, Science.
Enhanced surface coverage, detailed internal structure (Science, Exploration).

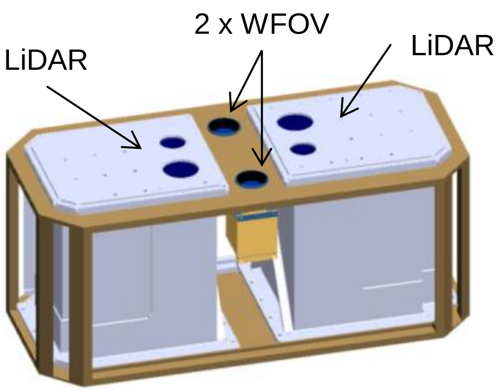
Long characterization and imaging phases collect data to meet mission needs and provides value for science, public engagement, and future exploration activities.



Ground Penetrating Radar

- Not required to characterize boulders.
- Provides further risk reduction through sub-surface imaging.
- Has extensibility value to both science and exploration.

Ideal Mission of Opportunity



Mission Profile Comparison – Points of Departure

Phase/Activity	Small Asteroid (2009 BD)		Robotic Boulder (Itokawa)	
	Date/Duration	Xenon Use	Date/Duration	Xenon Use
Launch	**June 1, 2019**		**June 20, 2019**	
Outbound Leg	1.4 years	899 kg	2.2 years	4,020 kg
Asteroid Rendezvous & Proximity Ops				
Arrival	**Jan. 3, 2021**		**Sept. 11, 2021**	
Characterization & Capture	30 days		51 days	
Capture Phase Margin	30 days		18 days	
Planetary Defense Demo	1 hour		262 days	170 kg
Margin (Missed Thrust, Prox Ops)	30 days		69 days	30 kg
Departure	**Apr. 3, 2021**		**Oct. 16, 2022**	
Inbound Leg	2.2 years	858 kg	2.5 years	1,830 kg
Earth-Moon System DRO Insertion	Feb 15, 2024	127 kg	August 2025	70 kg (TBR)
Earliest ARCM Availability	**Feb-May 2024**		**Aug-Sept. 2025**	

Assumes Heavy Lift Launch Vehicle (Delta IV Heavy/Falcon Heavy) for PoD. SLS would improve performance.

Xe used: 1,884 kg
SEP Operating Time: 400 days
Asteroid Return Mass: 30-145t (2.6-7m mean diameter)

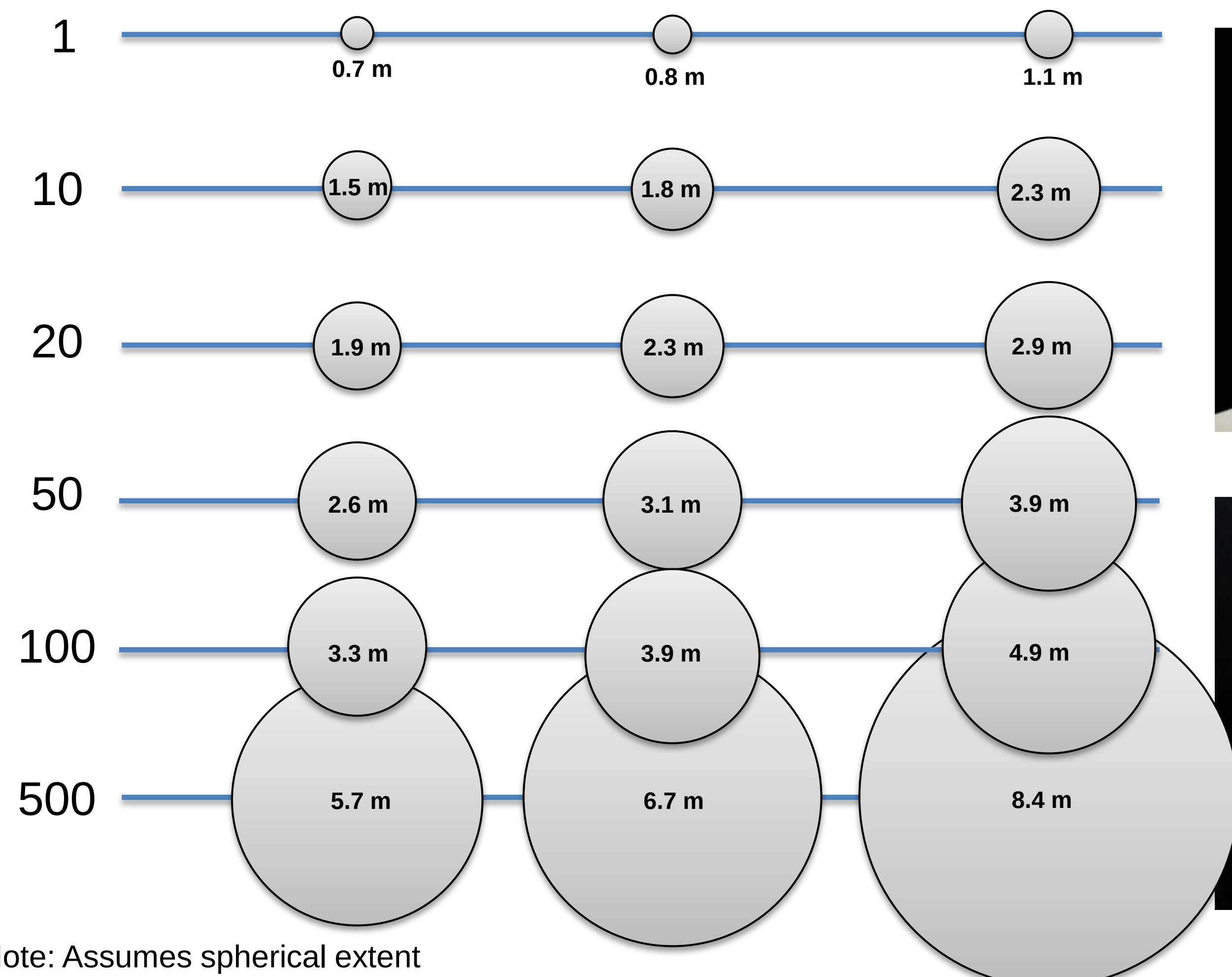
Xe used: 6,230 kg
SEP Operating Time: TBD days
Boulder Return Mass: 11 t (1.8 m spherical, 2.3 m max extent*)

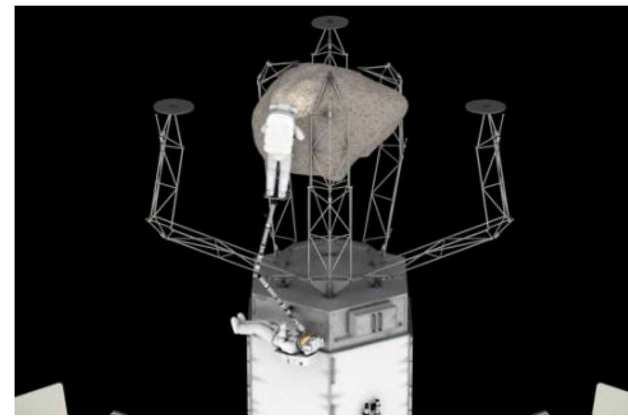
* At 2,2,1 aspect ratio

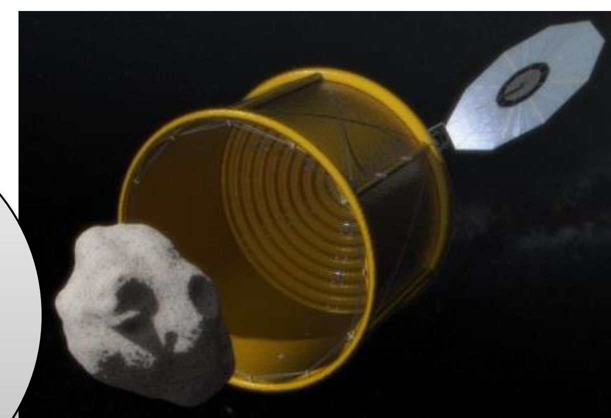
Asteroid or Boulder Mass and Size and Density

NEA Type

Mass (t) | Metallic 5.2 g/cm^3 | Stony 3.22 g/cm^3 | Carbonaceous 1.62 g/cm^3





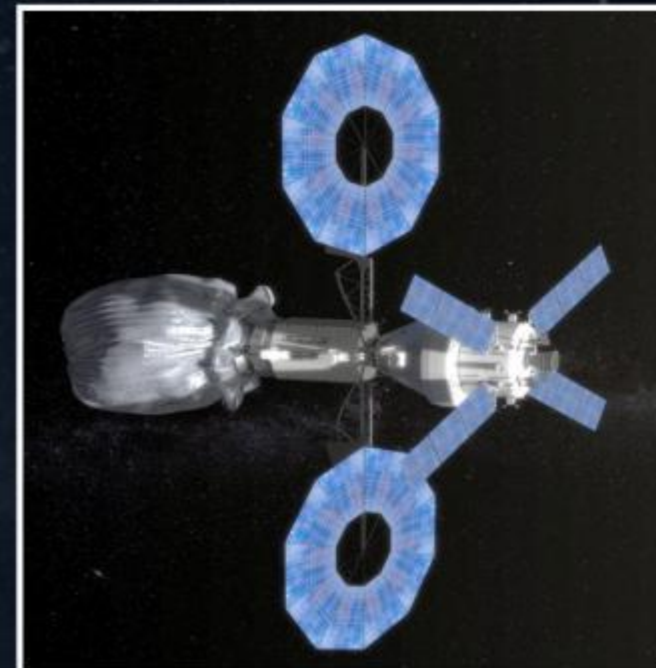


Note: Assumes spherical extent

Asteroid Redirect Crewed Mission Overview

Deliver crew
on SLS/Orion

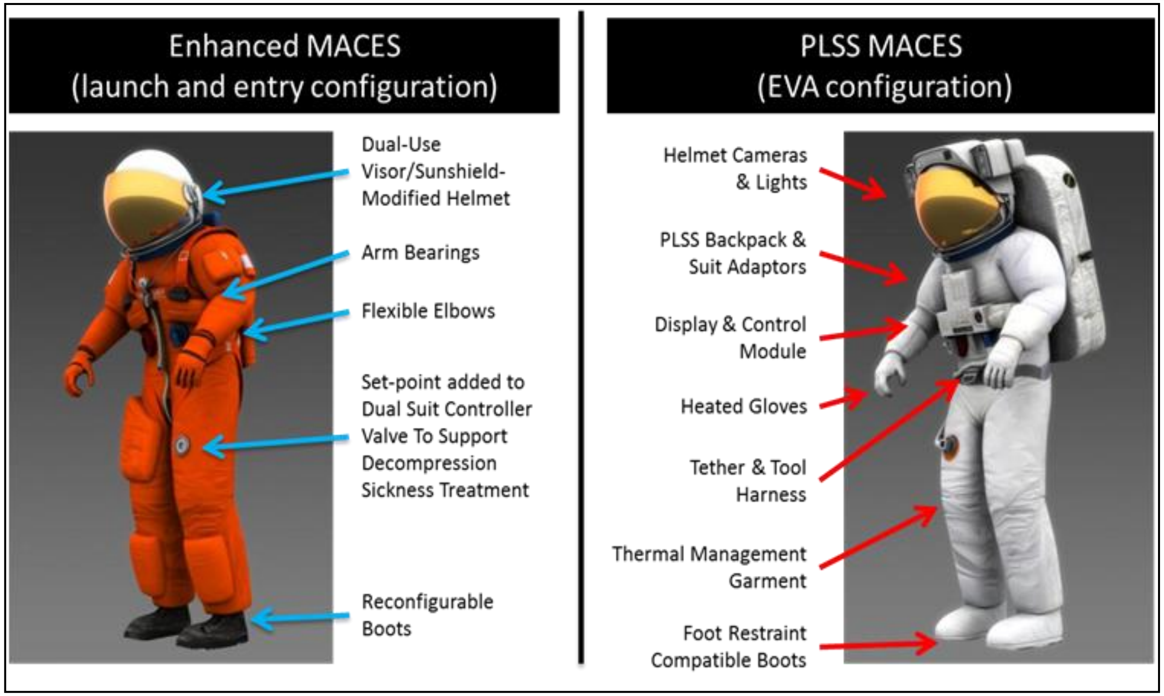
Orion Docks to Robotic Spacecraft



EVA from Orion to retrieve asteroid samples

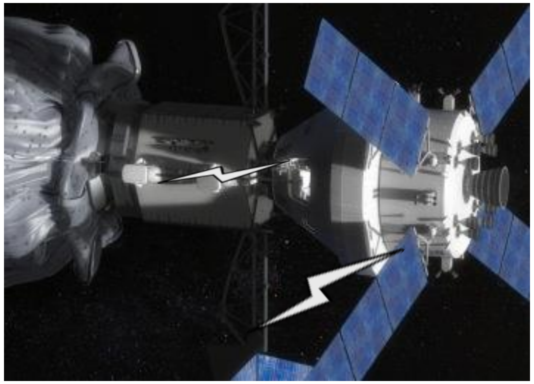
Return crew safely to Earth with
asteroid samples in Orion

Mission Kit Concept Enables Affordable Crewed Mission

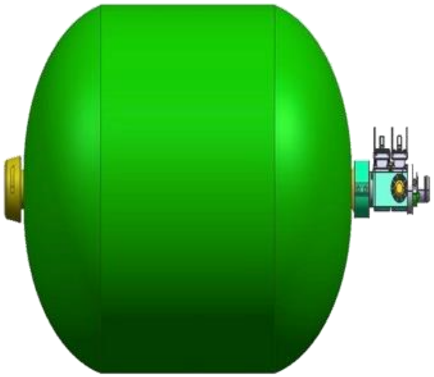


Tools & Translation Aids

Sample Container Kit



EVA Communications Kit



Repress Kit

Broad Agency Announcement (BAA) Objectives

- **Build upon RFI inputs and recommendations from the Asteroid Initiative Ideas Synthesis Workshop.**

- **Engage external community in system concept studies, technology development activities, and studies of potential future partnership opportunities to reduce mission risk.**

- **Provide alternate system concepts for consideration during ARM Mission Concept Review to be held in late 2014 or early 2015**

  – **Asteroid Capture Systems**: Concepts including using deployable structures and autonomous robotic manipulators.

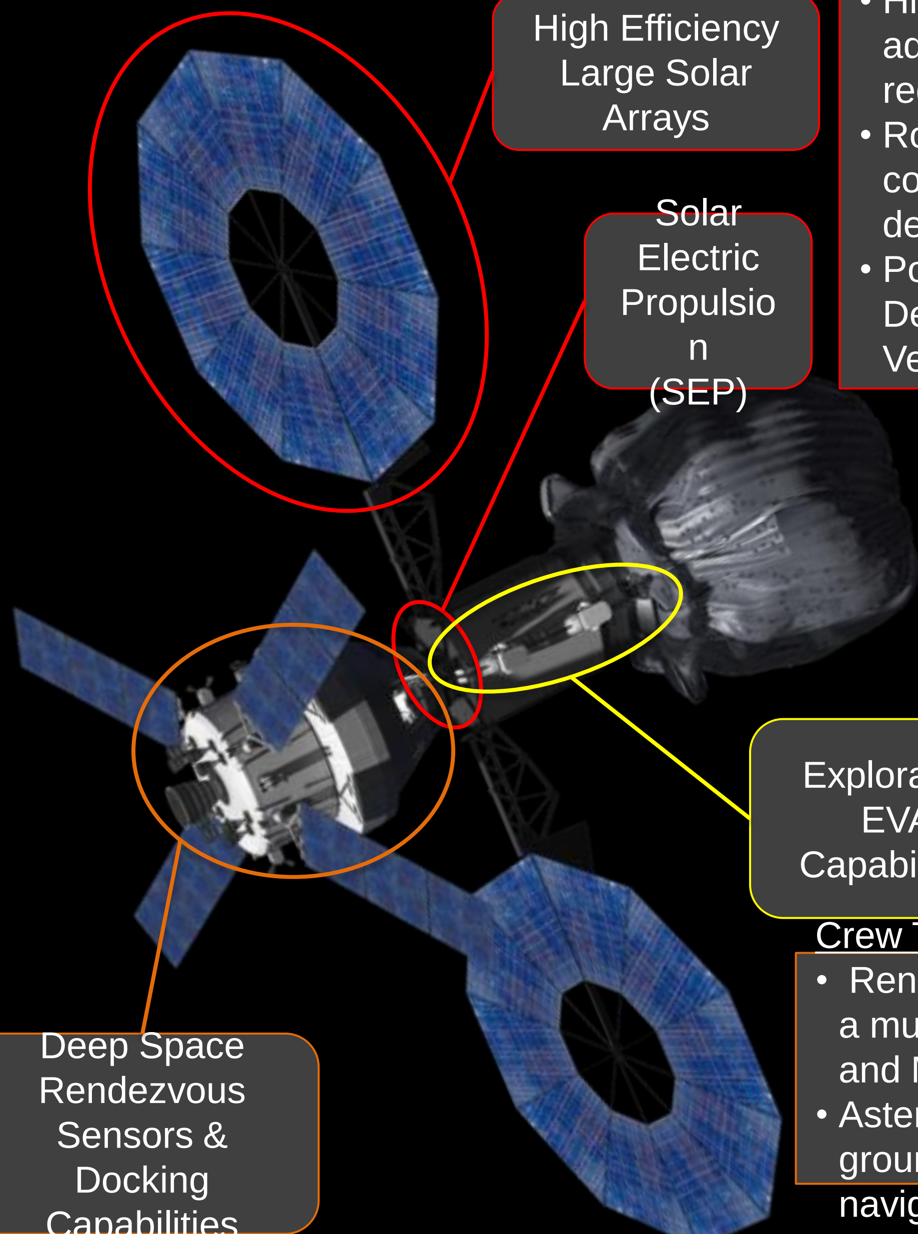
  – **Rendezvous Sensors**: Rendezvous sensors that can be used for a wide range of mission applications including automated rendezvous and docking, and asteroid characterization and proximity operations.

  – **Adapting Commercial Spacecraft for Asteroid Redirect Vehicle**: Commercial spacecraft design, manufacture, and test capabilities that could be adapted for development of Asteroid Redirect Vehicle.

  – **Studies of Potential Future Partnership Opportunities for Secondary Payloads**: Studies for secondary payloads on either Asteroid Redirect Vehicle or Space Launch System (SLS).

  – **Studies of Potential Future Partnership Opportunities for the Asteroid Redirect Crewed Mission**: Areas such as advancing science and in-situ resource utilization, enabling commercial activities, and enhancing U.S. exploration activities in cis-lunar space.

Asteroid Redirect Mission Provides Capabilities For Deep Space/Mars Missions



In-space Power and Propulsion :

- High Efficiency Solar Arrays and SEP advance state of art toward capability required for Mars
- Robotic ARM mission 40kW vehicle components prepare for Mars cargo delivery architectures
- Power enhancements feed forward to Deep Space Habitats and Transit Vehicles

EVA:

- Build capability for future exploration through Primary Life Support System Design which accommodates Mars
- Test sample collection and containment techniques including planetary protection
- Follow-on missions in DRO can provide more capable exploration suit and tools

Crew Transportation and Operations:

- Rendezvous Sensors and Docking Systems provide a multi-mission capability needed for Deep Space and Mars
- Asteroid Initiative in cis-lunar space is a proving ground for Deep Space operations, trajectory, and navigation.

ARM Near Term Schedule

• Request for Information Release	Jun 18, 2013
• NASA Internal Concepts Review	Jul 30, 2013
• Ideas Synthesis Part 1 (RFI responses)	Sep 30, 2013
• Ideas Synthesis Resumed (RFI responses)	Nov 20-22, 2013
• NASA Internal Integrated Status Review	Dec 17, 2013
• NASA Internal Mission Concept Development Review	Feb 19, 2014
• Broad Area Announcement Release	Mar 21, 2014
• Asteroid Initiative Opportunities Forum in Washington DC	Mar 26, 2014

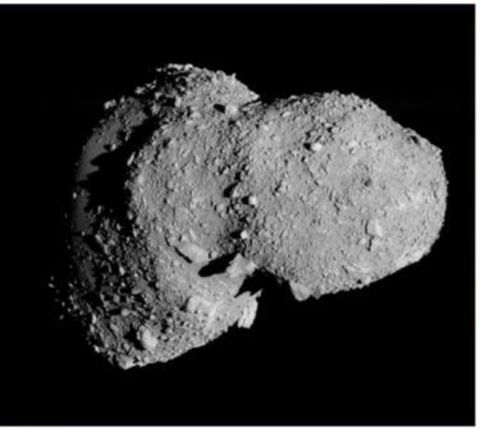
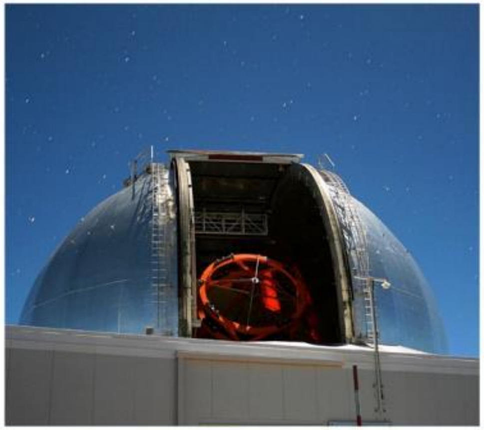
• BAA Notice of Intent Due	April 4,2014
• BAA Proposal Due Date	May 5, 2014
• BAA Awards	NET Jul 1, 2014
• BAA Kickoff Meetings	Week of Jul 7
• STMD Solar Array Systems development Phase 1 complete	June 2014
• STMD Integrated Thruster performance Test with 120V PPU	Sept 2014
• HEOMD MACES EVA end-to-end mission Sim Complete	Sept 2014
• Interim BAA Reports for Mission Concept Review	Oct 31, 2014
• HEOMD Orion Exploration Flight Test 1	Dec 2014
• BAA Period of Performance Ends	Dec 31, 2014
• Mission Concept Review	Early 2015

National Aeronautics and Space Administration

Keck Workshop: Applications of Asteroid Redirection Technology
ARM Mission Design and Solar Electric Propulsion

John Brophy
Asteroid Redirect Mission Concept Team

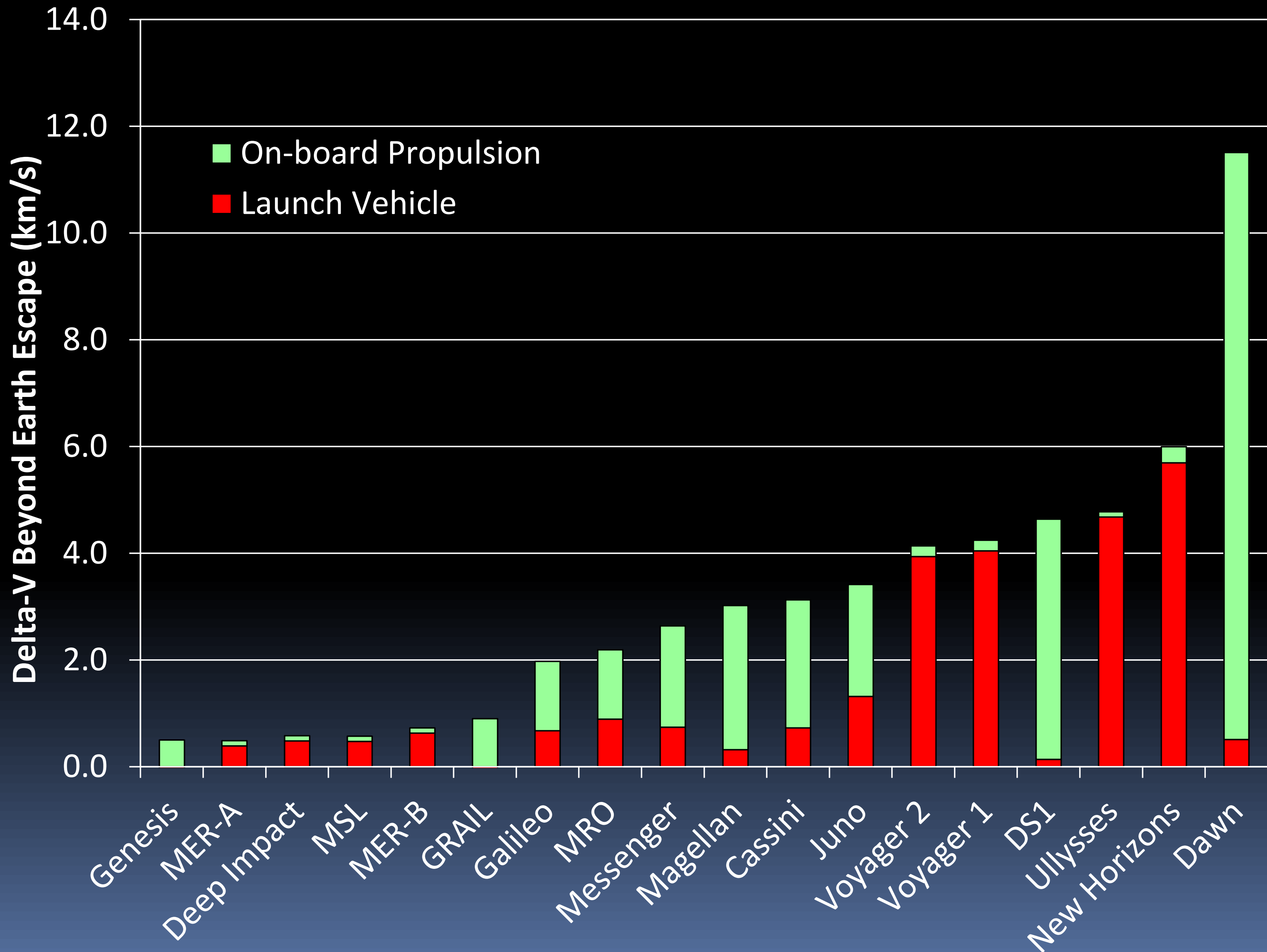
April 7, 2014

Solar Electric Propulsion (SEP) Benefits

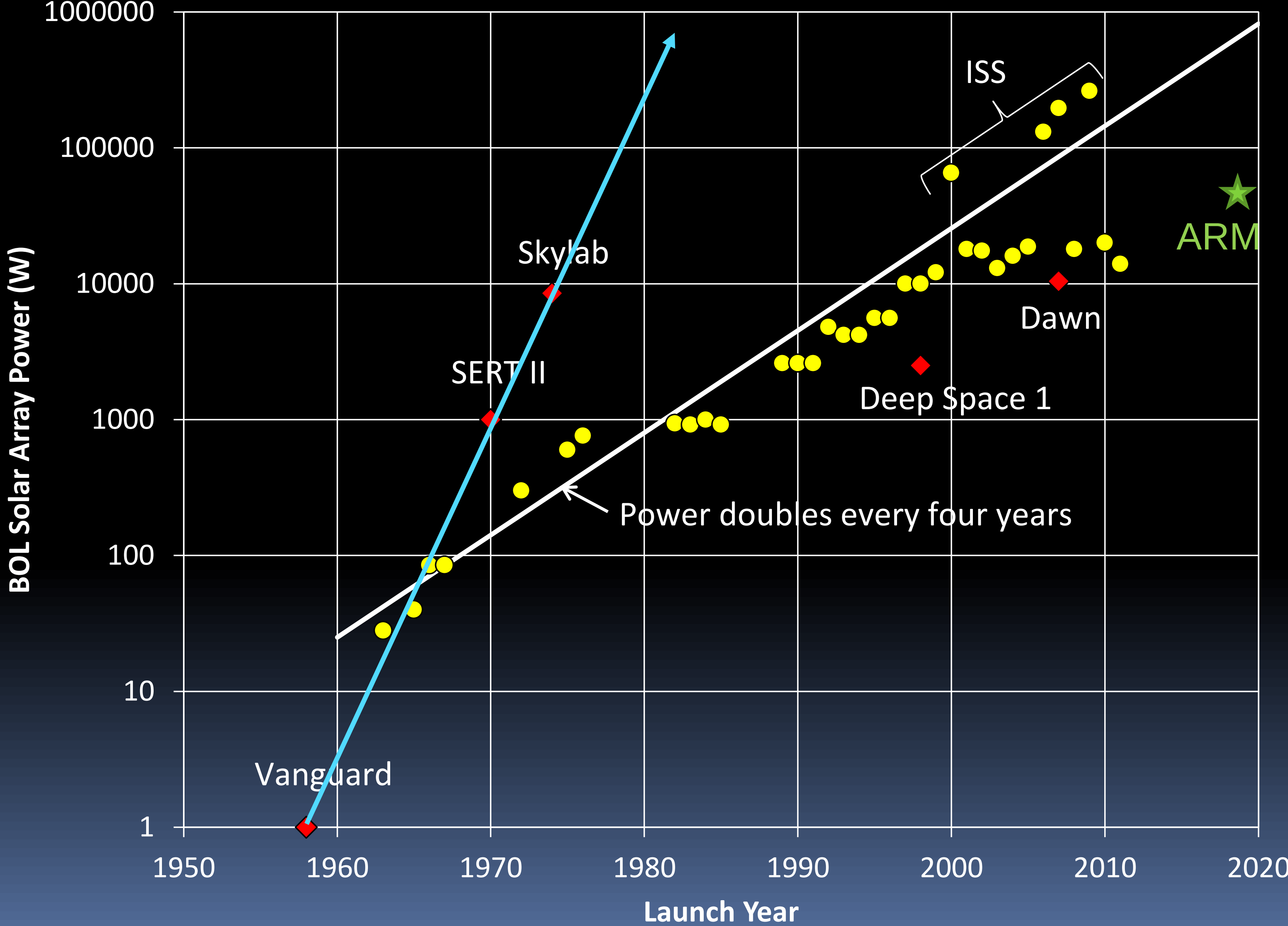
- High-power SEP provides the highest ΔV capability of any near-term, in-space propulsion technology
- It offers real time mission flexibility (e.g. launch date, trajectory)
- ARM SEP component and system technologies are extensible to multiple future applications
  - Commercial communication satellites
  - Deep space cargo, including for Mars
  - Deep space science

SEP Enables High ΔV Missions

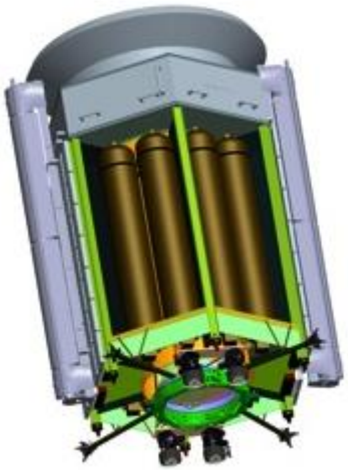


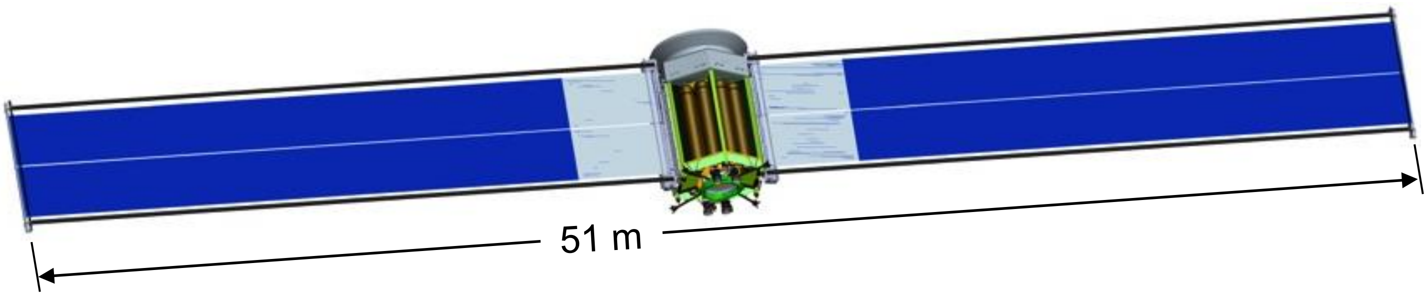
It's All About Power

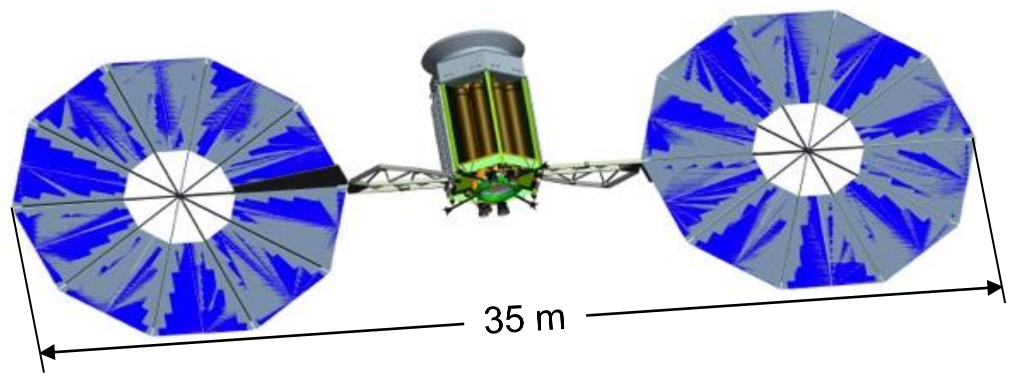
Space Solar Power History



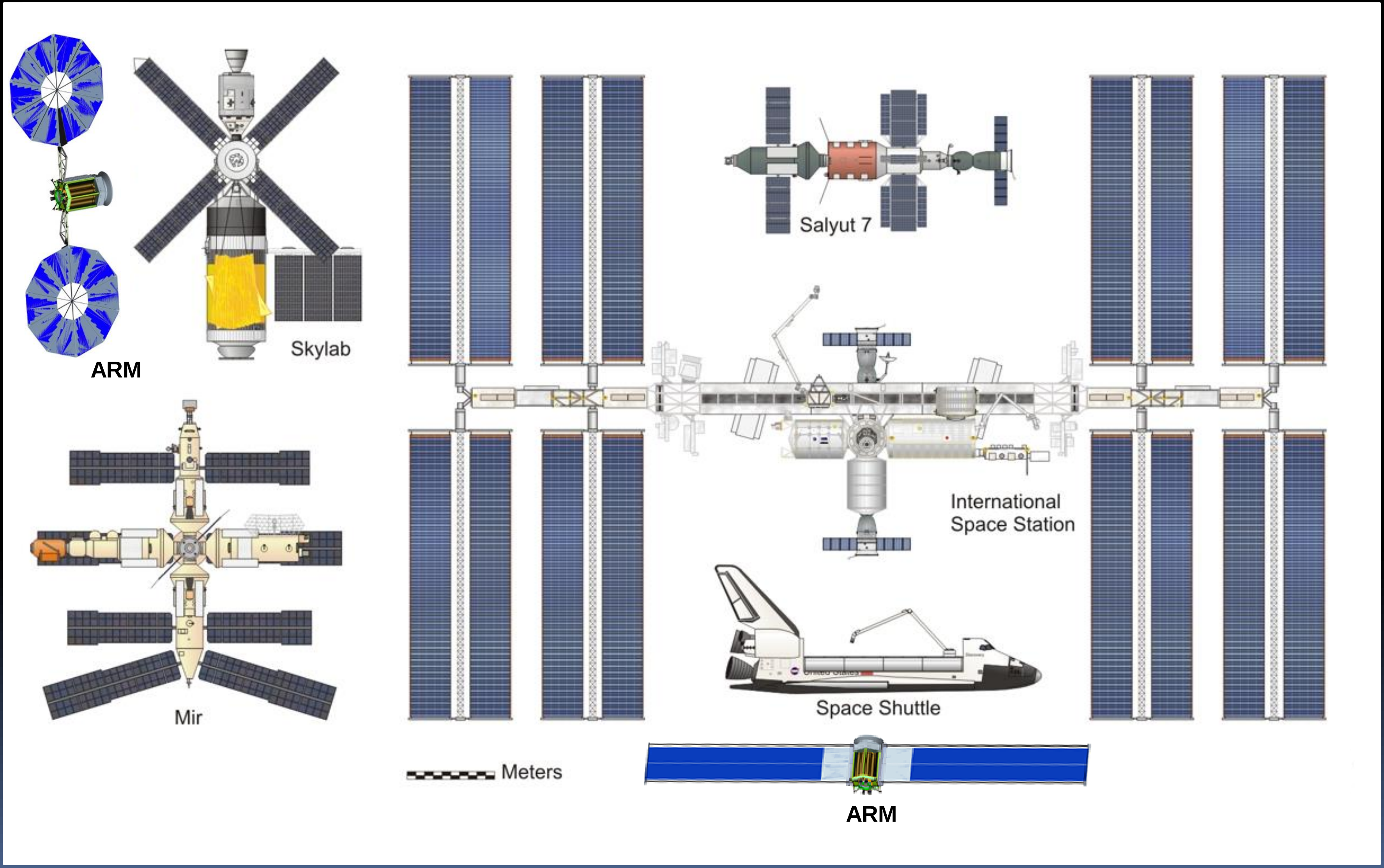
Representative Flight System Deployed Configurations



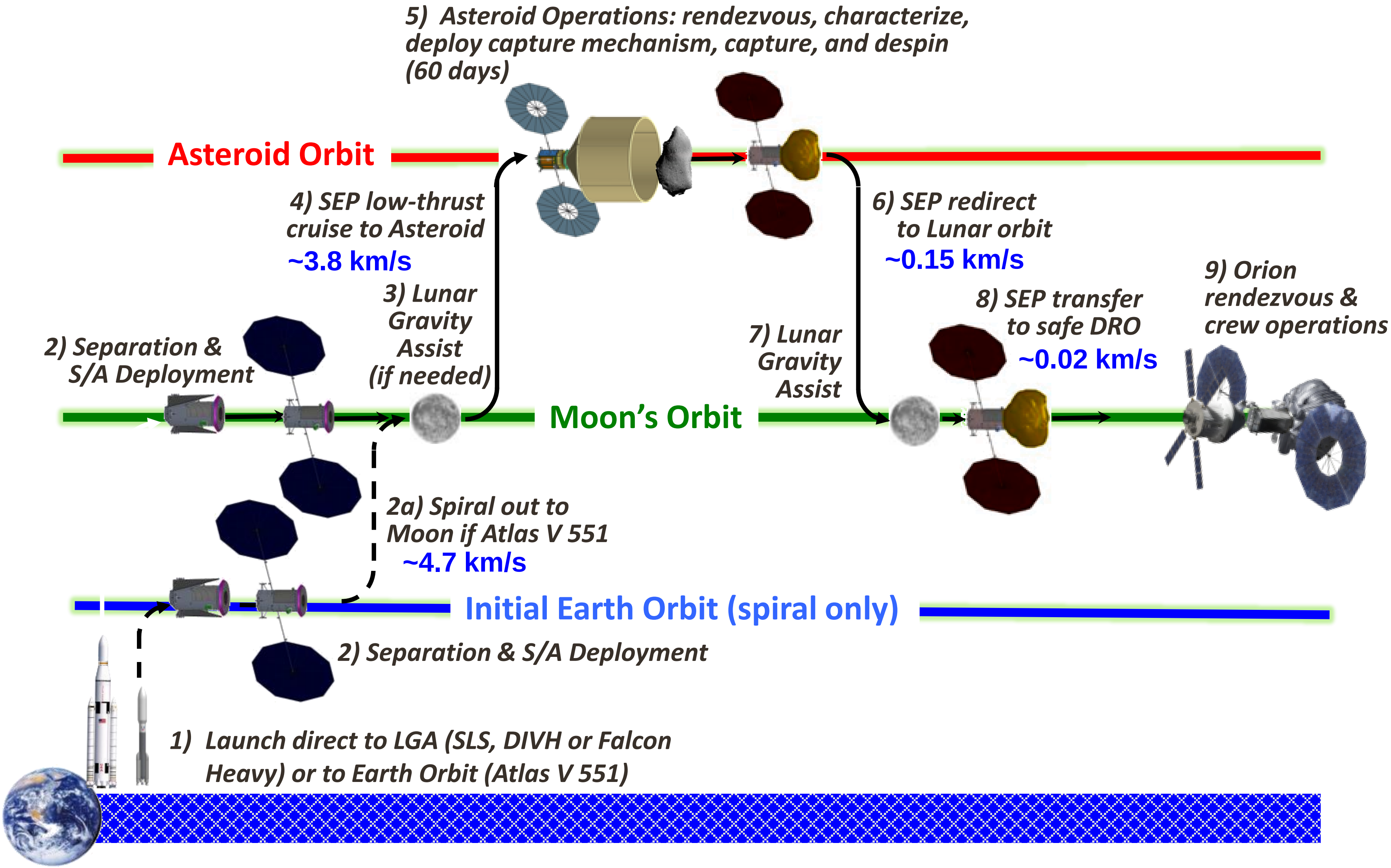




ARV Size Comparison



Mission Option A Overview



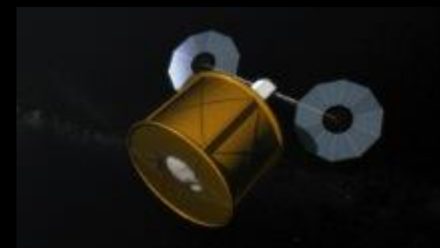
Option A: Proximity Operations Overview

Orbit Refinement and Rendezvous
(Radio and Optical)

Pre-Capture
Capture System Deploy

Final Approach

Capture



Capture Bag Retraction

Characterize, Spin down, and Detumble

Option B: Mission Timeline

Day 0 — Day 14 — Day 51

1. Approach (14 Days)

1,000 km to 100 km. Refine shape model, acquire landmarks, and update spin state.

2. Characterization (37 days)

Four fly-bys (~7.5 days each) with a week reserved for processing and gathering additional images as needed

3-4. Dry-Runs and Boulder Collection (18 days)

Dry-Runs (x2): ~5.3 days each. ~6 hours to complete dry-run with 5 days of coast in-between for downlink and processing.

Boulder Collection Attempt: ~7.4 days with ~0.5 day for collection and 7 days for ascent and coast to allow for downlink and processing

Day 69 — Day 120

3-4. Contingency Dry-Run and Boulder Collection Attempts (51 days)

Reserve for complete dry-run sequences at two additional sites and four additional boulder collection attempts between the three sites to protect against failed collection due to boulder properties, system anomalies or other contingencies.

5. Orbit Determination (21 Days)

Hold for precise orbit determination prior to gravity tractor demonstration.

Day 141 — Day 231 — Day 360 — Day 381 — Day 400

6. Gravity Tractor (90 Days)

Maintain orbit for at least 90 days. Resources reserved for 180 days.

6. Hold for Alignment (129 days)

Hold for to allow deflection to propagate and to achieve favorable orbital alignment for deflection verification.

7. Deflection Verification (21 Days)

Hold for precise orbit determination to verify orbit deflection.

Margin (19 days)

Unused margin in the 400 day stay-time allocation.

Operations heritage to prior robotic missions

Mission unique operations

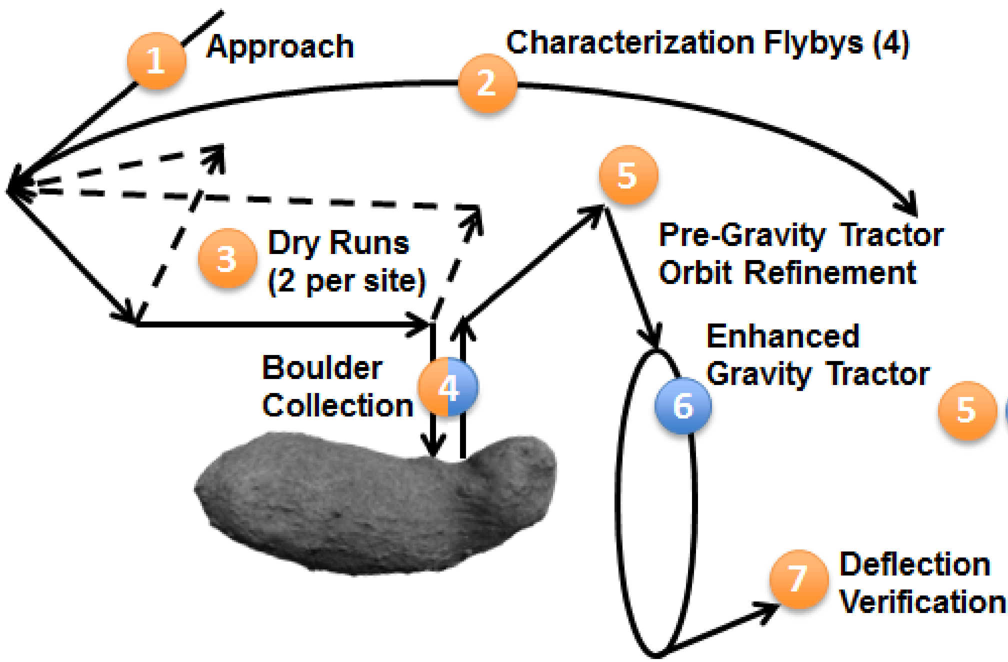
Option B: Proximity Operations Overview

Proximity Operations Timeline (400 days)

1	2	3	4	Reserve (3 & 4)	5	6	Reserve (6) & Wait	7	Margin

\# Operations heritage to prior robotic missions

\# Mission unique operations



Proximity operations having a high heritage, along with a conservative operations strategy.

1 2 **Approach, Flybys, & Characterization:** 37 days to verify and refine shape, spin, and gravity models, and obtain ~cm imagery for majority of the surface.

3 **Dry Runs:** 2 dry runs at up to 3 sites refine local gravity, provide sub-cm imagery, and verify navigation performance.

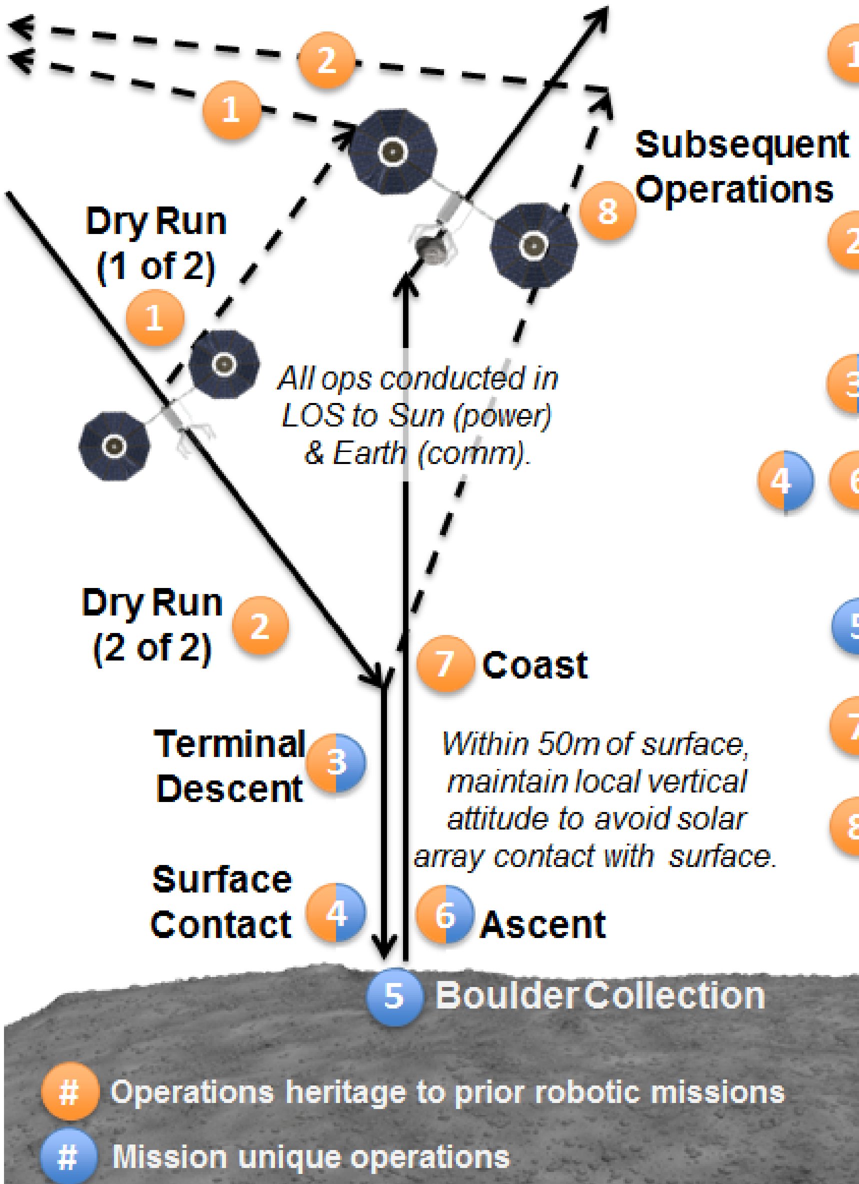
4 **Boulder Collection:** Reserving for up to 5 boulder collection attempts provides contingency against surface and boulder anomalies.

5 6 7 **Enhanced GT Demonstration:** 260 days allows for operations and proper Earth-Itokawa alignment to verify deflection.

6 **Enhanced Gravity Tractor (EGT):** 180 days reserved for EGT operations, 60 days required for measurable deflection.

Operations Margin: In addition to conservative operations profile, 19 days of unencumbered operations schedule reserve is provided in mission plan.

Option B: Boulder Collection



1. **Dry Run (1 of 2):** *Refine local gravity* and increase *boulder characterization* while in *passively safe* trajectory. Sufficient time allocated between dry runs to downlink data, process data, and update spacecraft.
2. **Dry Run (2 of 2):** System verifies *closed-loop* Terrain Relative Navigation acquisition of landmarks for descent navigation by while in *passively safe* trajectory.
3. **Terminal Descent:** No nominal thrusting toward asteroid to *limit debris*.

4, 6. **Surface Contact/Ascent:** Contact arms allow *controlled contact/ascent*, provide stability, and limit debris. Thrusters provide attitude control and contingency ascent.

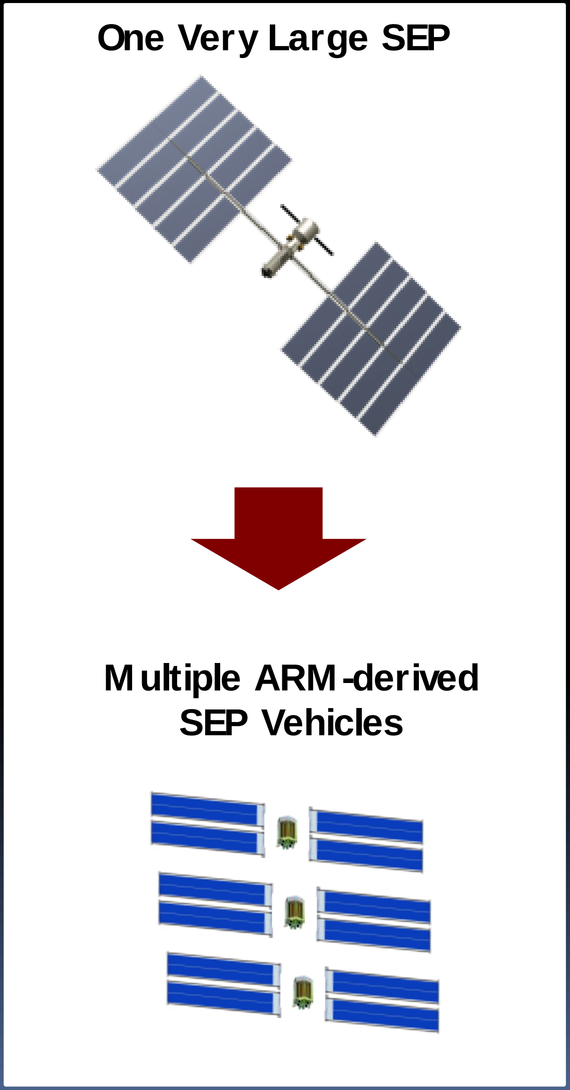
5. **Boulder Collection:** *Conservative* 120 minutes reserved, nominal ops estimated at 30 minutes.
7. **Coast:** Slow drift escape provides time to *establish mass properties* of the combined spacecraft/boulder system.
8. **Subsequent Operations:** As appropriate, transition to performing gravity tractor or subsequent capture attempt.

Conservative, high-heritage operations mitigate risks during boulder collection operations to increase probability of successful boulder capture.

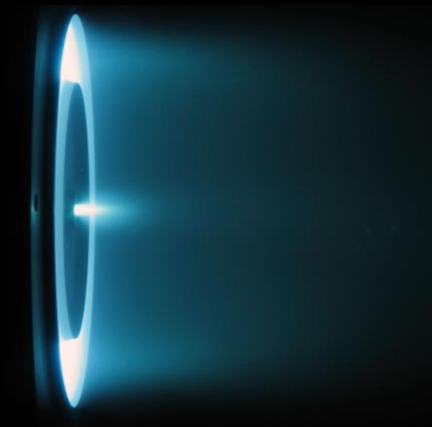
Future Use of ARM Robotic Spacecraft and Solar Electric Propulsion

- Some assessments have shown that human Mars missions utilizing a single round-trip monolithic habitat + Orion requires a very high power SEP vehicle
  - Approaches 1 MW total power
  - An engineering and operational challenge

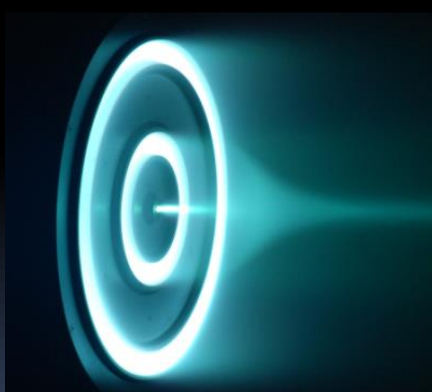
- Alternate architecture concepts enable ARM derived SEP to be used. As an example:
  - Pre-deploy crew mission assets to Mars utilizing high efficient SEP, such as
    - Orbit habitats: Supports crew while at Mars
    - Return Propulsion Stages or return habitats
    - Exploration equipment: Unique systems required for exploration at Mars.
  - High thrust chemical propulsion for crew
    - Low-thrust SEP too slow for crew missions
    - Crew travels on faster-transit, minimum energy missions: 1000-day class round-trip (all zero-g)



High-Power Hall Thrusters



Hall Thruster

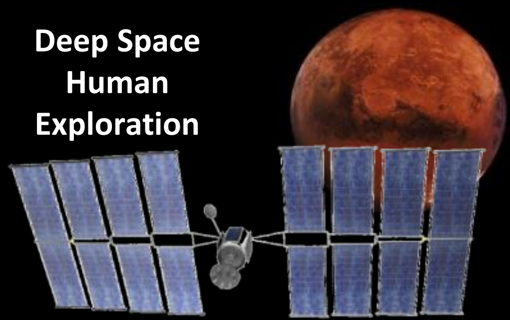


Nested Hall Thruster

- Hall thrusters have extraordinary performance and are extremely scalable
  - Isp’s from 1000 to 8000 s
  - Power levels from 200 W to >100 kW
- Magnetic shielding enables huge advances in the technology
- Nested Hall Thrusters may facilitate high-power operation and a very large throttle dynamic range

High-powered SEP Enables Multiple Applications

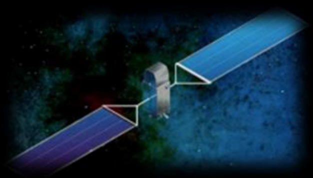
Deep Space Human Exploration



Satellite Servicing

Payload Delivery

Commercial Space Applications

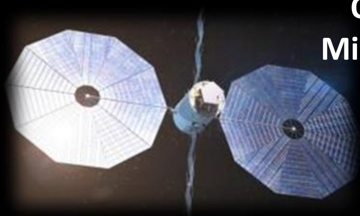


ISS Utilization

Orbital Debris Removal

Space Science Missions

OGA Missions




A DEEPER VISION, **A BOLDER MISSION,** ONE STEP AT A TIME
Step One:
2014

Back-Up

Future Use of ARM Robotic Spacecraft and Solar Electric Propulsion

- **Some assessments have shown that human Mars missions utilizing a single round-trip monolithic habitat + Orion requires very high power SEP**
  - Approaches 1 MW total power
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  - Pre-deploy crew mission assets to Mars utilizing high efficient SEP, such as
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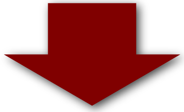
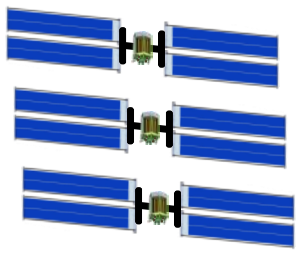
    - Exploration equipment: Unique systems required for exploration at Mars.
  - High thrust chemical propulsion for crew
    - Low-thrust SEP too slow for crew missions
    - Crew travels on faster-transit, minimum energy missions: 1000-day class round-trip (all zero-g)

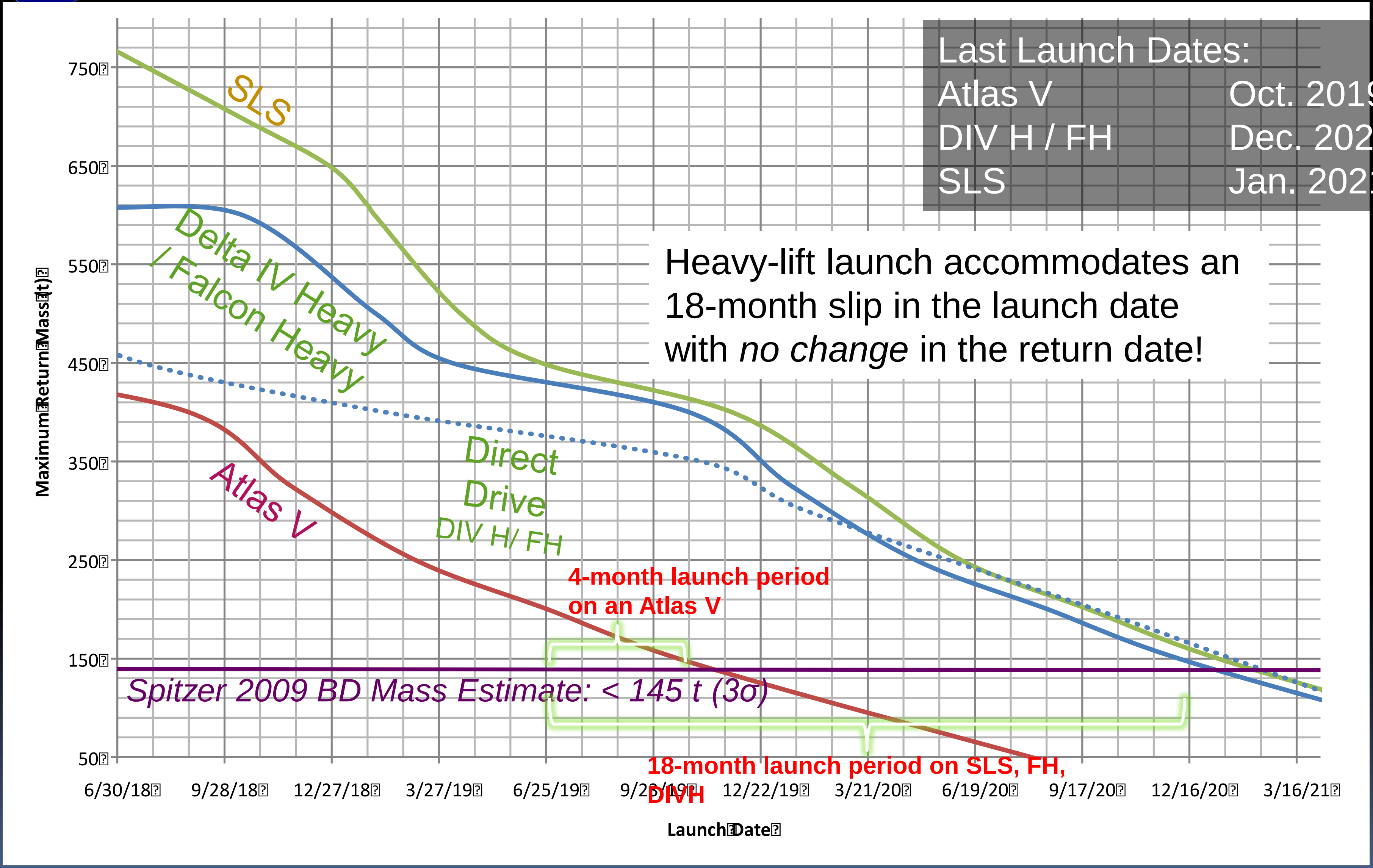
One Very Large SEP



Multiple ARM-derived SEPs



2009 BD: Max Return Mass vs. Launch Date



Option A: Candidate Asteroids for Mission Design

- Each asteroid's return date is fixed & dictated by natural close approach times
- Lower V_∞ allows return of larger objects
- Assuming mid-2019 nominal launch

Asteroid	Asteroid Mass Est.	Asteroid V-infinity	Earth Return Date	Crew Accessible	Notes
2009 BD*	30-145 t (returnable)	1.2 km/s	Jun 2023	Mar 2024 or earlier	Valid mission candidate, rotation period > 2 hrs, Spitzer-based upper bound on mass
2011 MD*	TBD (max 620 t)**	1.0 km/s	Jul 2024	Aug 2025	Spitzer obs. successful final characterization results pending Rotation period 0.2 hrs
2014 BA3	TBD (max 500 t)**	1.8 km/s	Jan 2024	Early 2025	Discovered Jan 2014, not detected by Radar Optical characterization pending
2013 EC20	4-43 t (returnable)	2.6 km/s	Sept 2024	Late 2025	Discovered March 2013, Radar characterized rotation period ~ 2 min 2024 return requires DIV H or FH launch 2020 return possible with Feb 2018 launch
2008 HU4	TBD (max 700 t)**	0.5 km/s	Apr 2026	Mid 2027	Close Earth flyby in April 2016

* High-fidelity trajectory analysis performed for 2009 BD and 2011 MD
** Max returnable mass using a Delta IV Heavy or Falcon Heavy

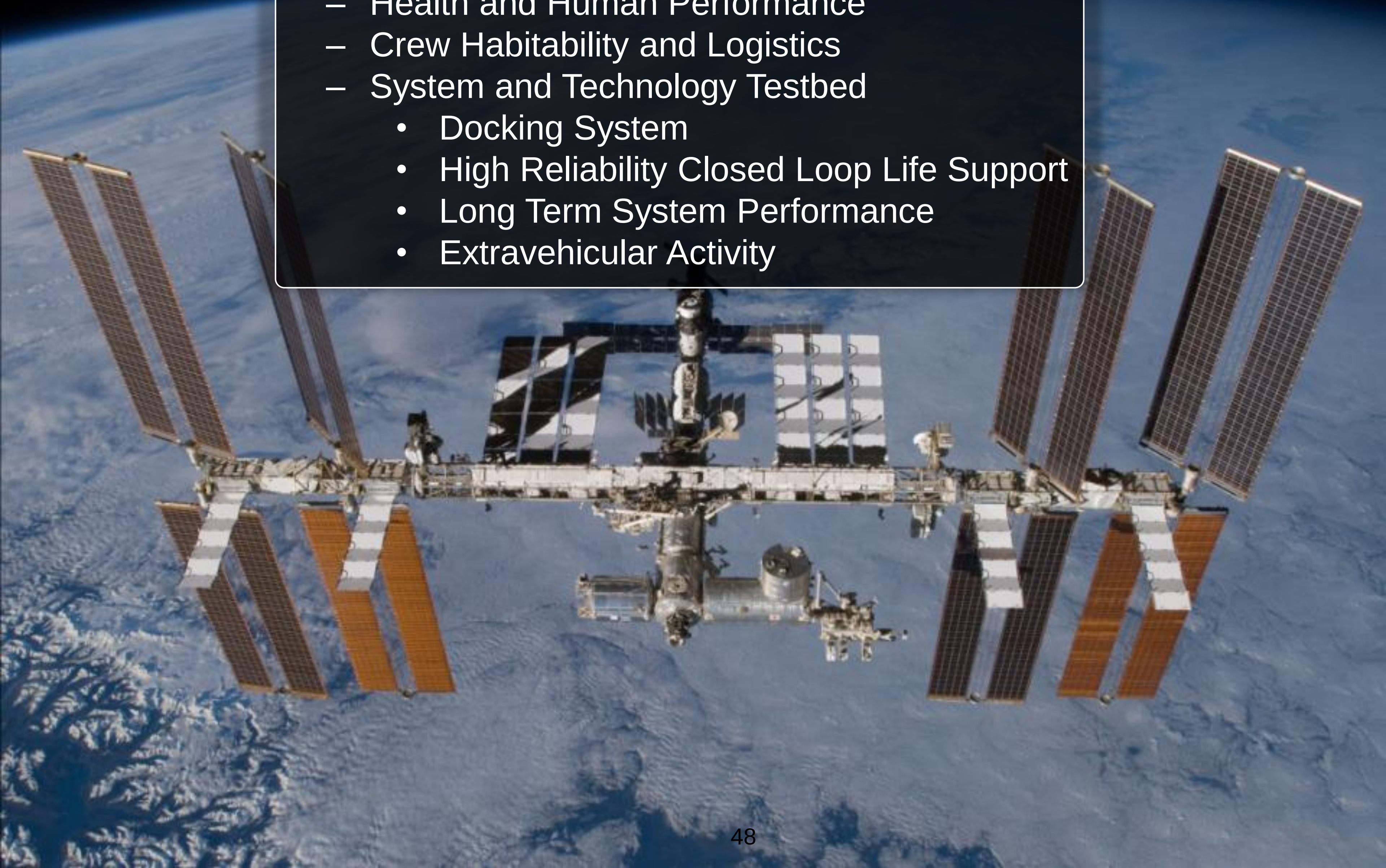
Summary of NEA Targets Analyzed: Option B

Configuration and operations are robust to a wide range of NEA sizes, masses, and rotation rates beyond Itokawa.

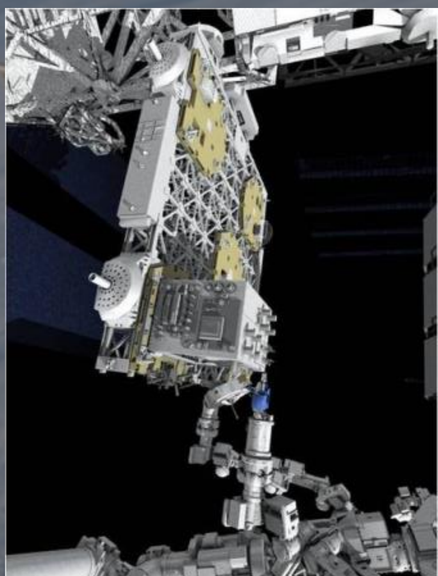
	Itokawa	Bennu	1999 JU_3	2008 EV_5
Mass	3.15×10^{11} kg	7.79×10^{10} kg	1.55×10^{12} kg	1.05×10^{11} kg
Dimensions	535 x 294 x 309 m	Mean Dia.: 492 m	Eff. Dia.: 870 m	420 x 410 x 390 m
Rotation Period	12.132 hours	4.297 hours	7.627 hours	3.725 hours
50 m Sun Angle	45 degrees	60 degrees	37.5 degrees	60 degrees
Contact Sun Angle	30 degrees	15 degrees	15 degrees	15 degrees
Dry-Run 1 Dur.	5.25 days	5.13 days	5.25 days	5.13 days
Dry-Run 2 Dur.	5.28 days	5.26 days	5.28 days	5.26 days
20 m Descent Dur.	12.73 min	11.37 min	4.51 min	7.96 min
Contact Velocity from 20 m	5.237 cm/s	5.861 cm/s	14.788 cm/s	8.371 cm/s

ISS Enables Long Duration Exploration For Mars

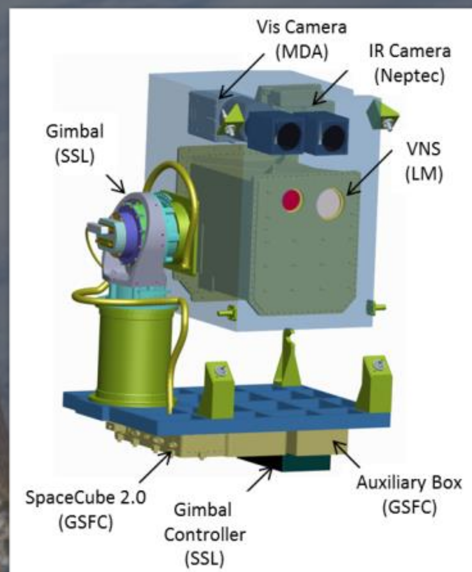
- Health and Human Performance
- Crew Habitability and Logistics
- System and Technology Testbed
  - Docking System
  - High Reliability Closed Loop Life Support
  - Long Term System Performance
  - Extravehicular Activity



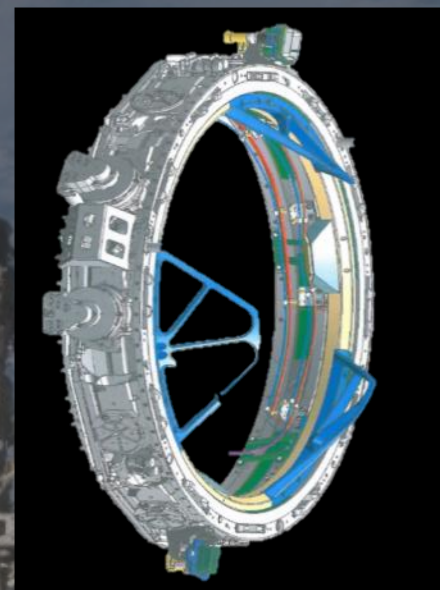
International Space Station: Exploration Platform



In-Space Robotic Servicing



Automated Rendezvous & Docking Sensors



International Docking System

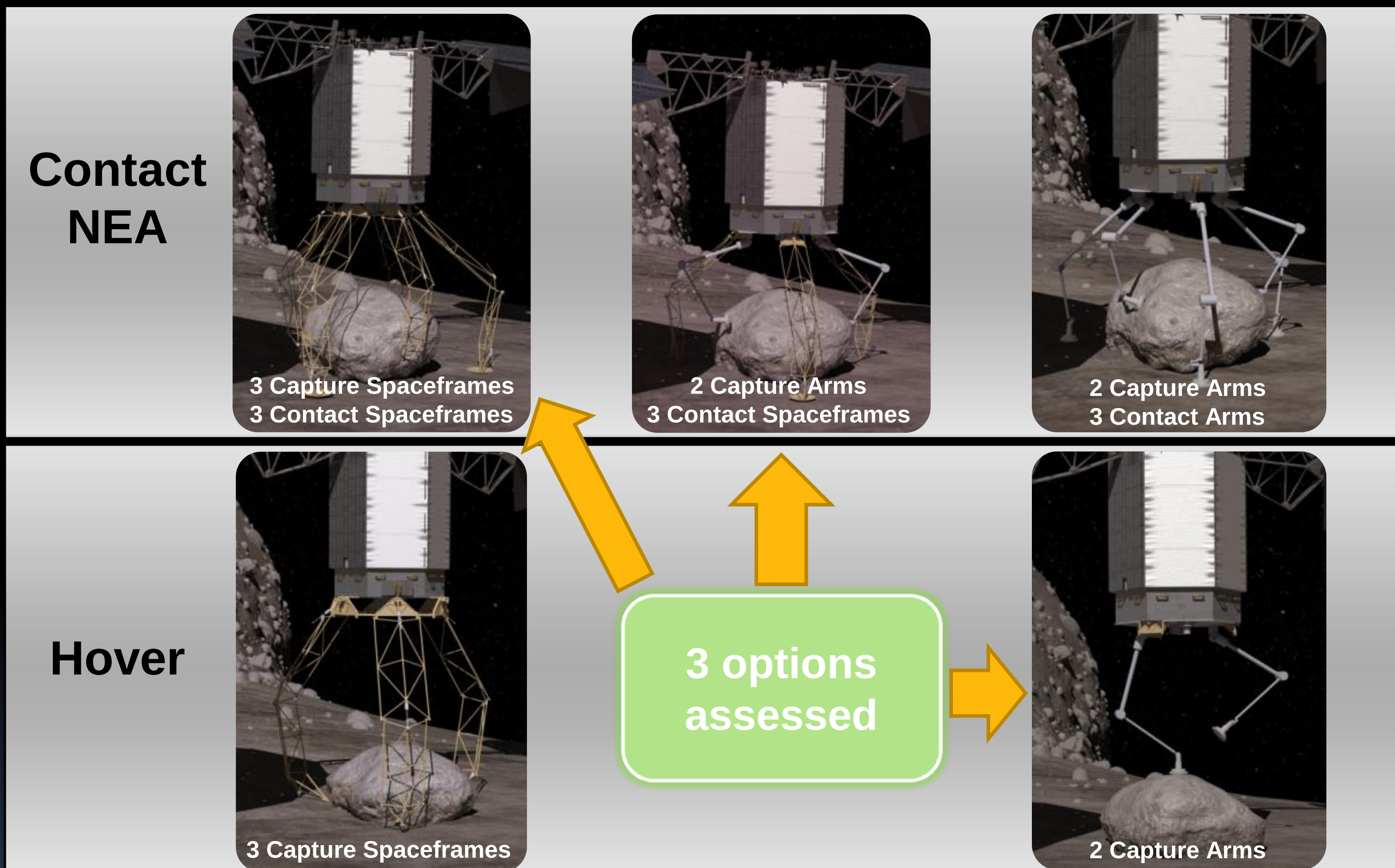
ECLSS/Amine Swingbed

Human and Health and Performance

- **Increased radiation**
  immunology, carcinogenesis, behavior/performance, tissue degeneration, pharmaceutical stability…
- **Distance from Earth**
  behavior/performance, autonomy, food systems, clinical medicine

Note that effect severity generally increases with mission duration.

Proximity Operations and Capture System Options



Award Information

Solicitation Topic	Total Available Funding	Anticipated Number of Awards	Maximum Individual Award
Asteroid Capture Systems	$2M	4-5	$500,000
Rendezvous Sensors	$1.8M	4-6	$450,000
Adapting Commercial Spacecraft for the Asteroid Redirect Vehicle	$1.8M	4-6	$450,000
Studies of Potential Future Partnership Opportunities for Secondary Payloads	$0.2M	4	$50,000
Studies of Potential Future Partnership Opportunities for the Asteroid Redirect Crewed Mission	$0.2M	4	$50,000

Notices of Intent

- NASA strongly encourages, but does not require, the submission of a Notice of Intent (NOI) to propose by all prospective offerors.
- The NOI should contain the following information:
  - Name, address, telephone number, email address, and institutional affiliation of the offeror.
  - The solicitation topic in which you intend to propose.
- The NOI should be submitted by email to the Point of Contact listed in the BAA.

Proposals

- Proposal Content:
  - Title Page
  - Section I: Executive Summary
  - Section II: System Concept
  - Section III: Technical Approach
  - Section IV: Capabilities
  - Section V: Data Rights
  - Section VI: Price Proposal
  - Section VII: Draft Statement-of-Work
- Proposals are limited to 20 pages (page limits for each section are specified in the BAA).
- Proposals should be submitted by email in Adobe PDF format to the Point of Contact listed in the BAA.

Evaluation Criteria

1. **Relevance** – The Government will evaluate the relevance of the proposal to the objectives of the Asteroid Initiative and the system requirements specified in the BAA.

2. **Technical Merit** – The Government will evaluate the quality, depth, and thoroughness of the proposed technical approach, and the organization's capabilities and the qualifications of key personnel.

3. **Cost** – The Government will evaluate the overall cost reasonableness of the firm fixed price to the Government, and the extent to which the offeror complied with the specified dollar limits in the BAA. The Government will evaluate the total direct labor hours by skill mix, travel, and subcontracts.

BAA Schedule

- Mar. 6 Synopsis Release
- Mar. 21 BAA Release
- Mar. 26 Asteroid Initiative Opportunities Forum
- Apr. 4 Notices of Intent due
- May 5 Proposals due (45 days)
- Jul. 1 Contracts Begin
- Oct. 31 Interim Reports to support Mission Concept Review
- Dec. 31 Contracts Complete (180 days period of performance)

Questions

- Please address questions by email to:

Chris Moore
NASA Headquarters
Email: HQ-Asteroid-BAA@mail.nasa.gov

- BAA website for reference information:

http://www.nasa.gov/asteroidinitiative