National Aeronautics and Space Administration

Asteroid Redirect Mission (ARM)

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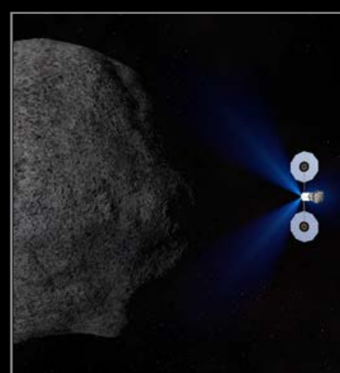
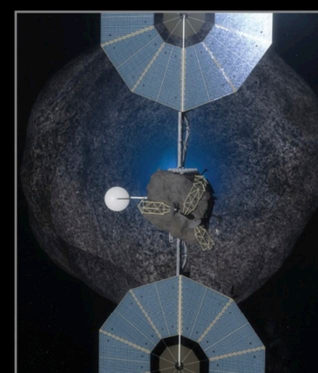
15th Meeting of the NASA Small Bodies Assessment Group – June 28, 2016


Video: ARM Robotic Segment Trajectory

Asteroid Redirect Mission: Three Main Segments

IDENTIFY

Ground and space based assets detect and characterize potential target asteroids


Pan-STARRS


NEOWISE

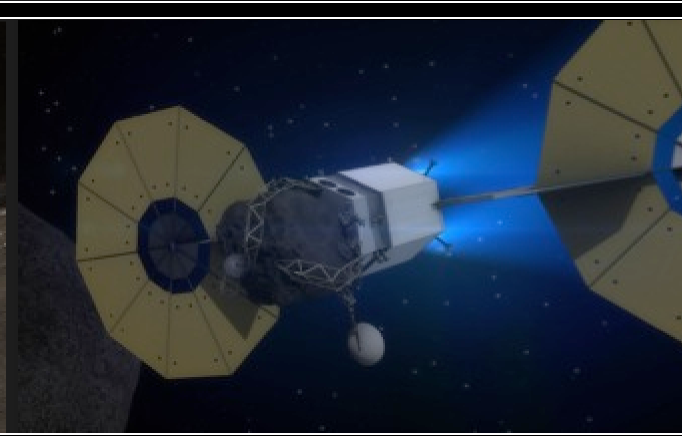

Goldstone


Arecibo


Infrared Telescope Facility

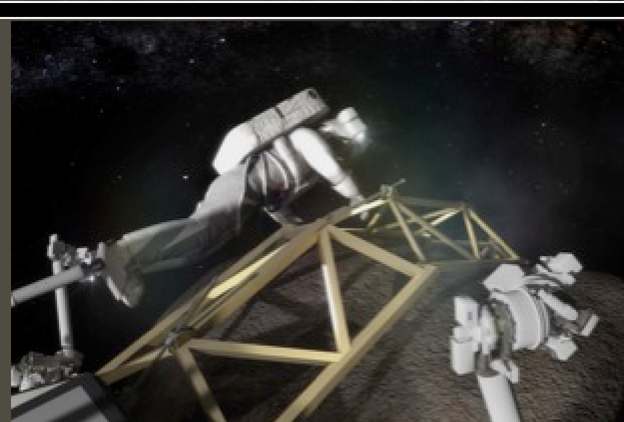
REDIRECT

Solar electric propulsion (SEP) based system redirects asteroid to cislunar space.



EXPLORE

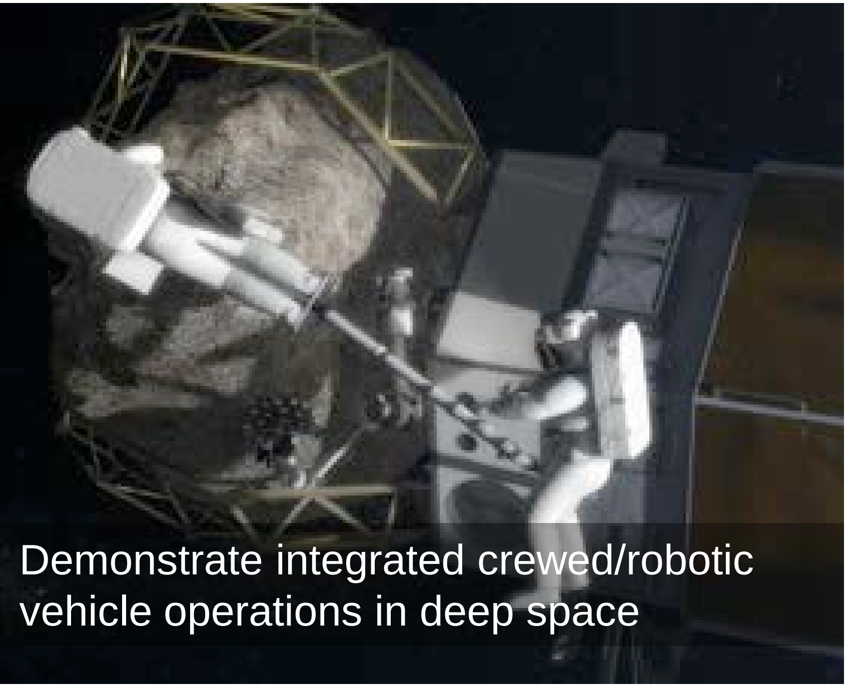
Crew launches aboard SLS rocket, travels to redirected asteroid in Orion spacecraft to rendezvous, study and returns samples to Earth



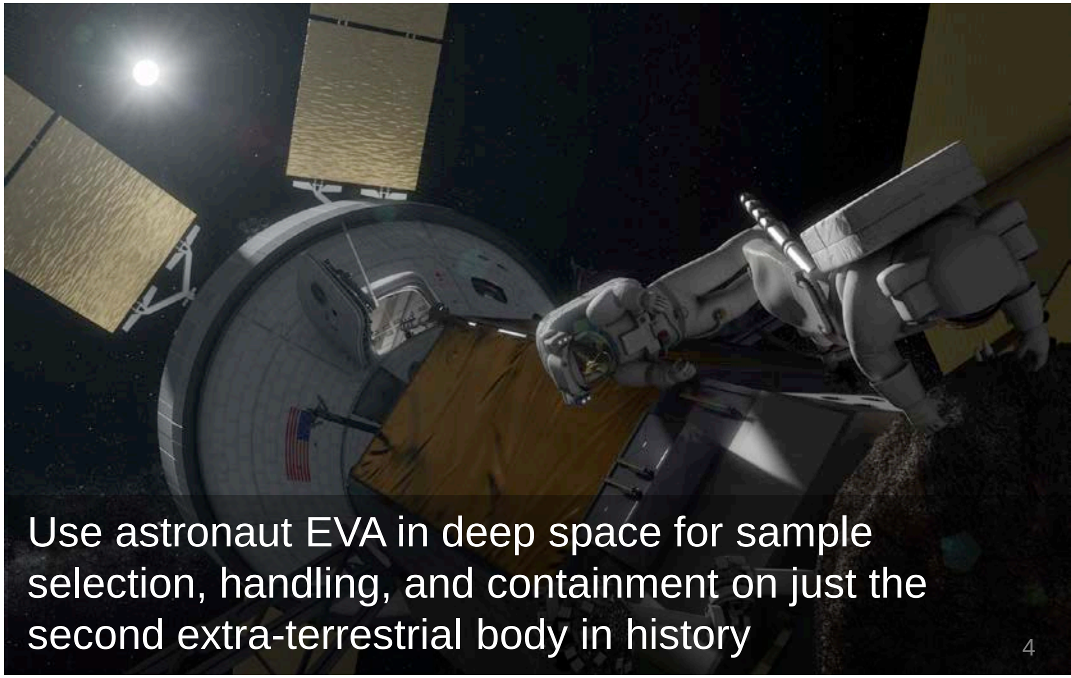
ARM Contributions to Deep Space Human Exploration

Demonstrate advanced autonomous proximity operations in deep space and with a natural body

Using high-power solar electric propulsion to transport multi-ton masses in space

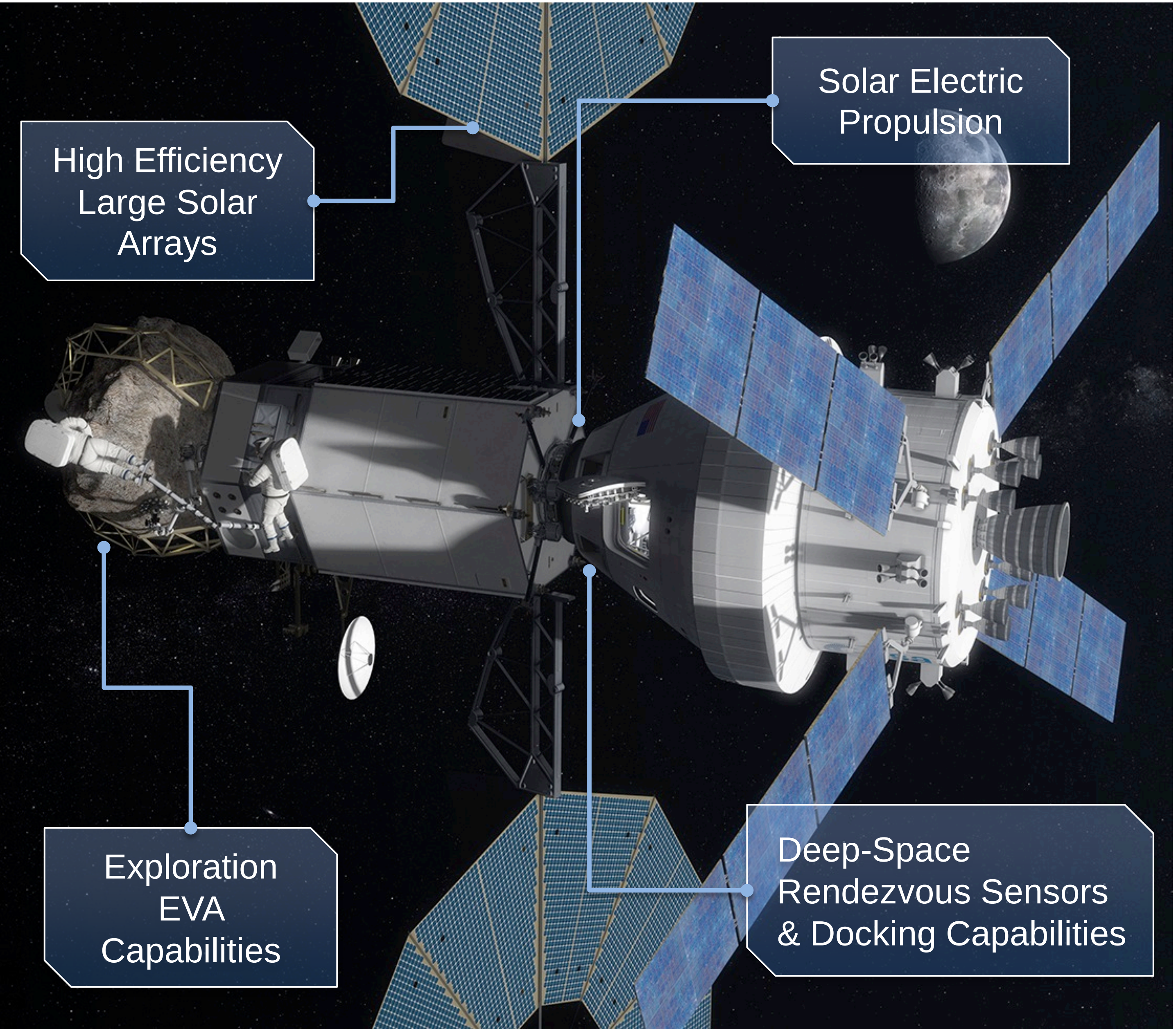


Demonstrate integrated crewed/robotic vehicle operations in deep space



Use astronaut EVA in deep space for sample selection, handling, and containment on just the second extra-terrestrial body in history

ARM: An Early Mission in the Proving Ground of Cislunar Space



IN-SPACE POWER & PROPULSION:

- High efficiency 40kW SEP extensible to Mars cargo missions
- Power enhancements feed forward to deep-space habitats and transit vehicles

EXTRAVEHICULAR ACTIVITIES:

- Two in-space EVAs of four hours each
- Primary Life Support System design accommodates Mars missions
- Sample selection, collection, containment, and return

TRANSPORTATION & OPERATIONS:

- Capture and control of non-cooperative objects
- Common rendezvous sensors and docking systems for deep space
- Cislunar operations are proving ground for deep space operations, trajectory, and navigation

Asteroid Redirect Mission Progress

✓ **Robotic mission acquisition strategy decisions**	**Aug 2015**
✓ **Formulation Assessment and Support Team (FAST) established**	**Aug 2015**
✓ **Public comments due on FAST draft report**	**Dec 2015**
• https://www.nasa.gov/feature/arm-fast	
✓ **Robotic mission requirements technical interchange meeting**	**Dec 2015**
✓ **Update with Small Bodies Assessment Group**	**Jan 2016**
✓ **Robotic spacecraft early design study contracts selected**	**Jan 2016**
✓ **Formulation guidance updated for ARRM KDP-B**	**Feb 2016**
• Robotic mission launch date, readiness date for crewed mission	
✓ **Crewed segment operational requirements meetings at JSC**	**Feb 2016**
✓ **ARM leadership team strategy meeting on partnerships and** engagement	**Feb 2016**
✓ **FAST final report released**	**Feb 2016**
✓ **STMD electric propulsion development contract selection**	**Apr 2016**
✓ **Initial ARRM/ARCM safety review at JSC**	**June 22-23**
✓ **ARRM spacecraft contractor study final presentations**	**June 24**

ARM Upcoming Events

• ARRM Strategic international partner intent	early July
• ARRM KDP-B	July 15
• BAA: Investigation Team membership call	late July/early August
• BAA: Hosted Payloads	late July/early August
• ARM Community update	August

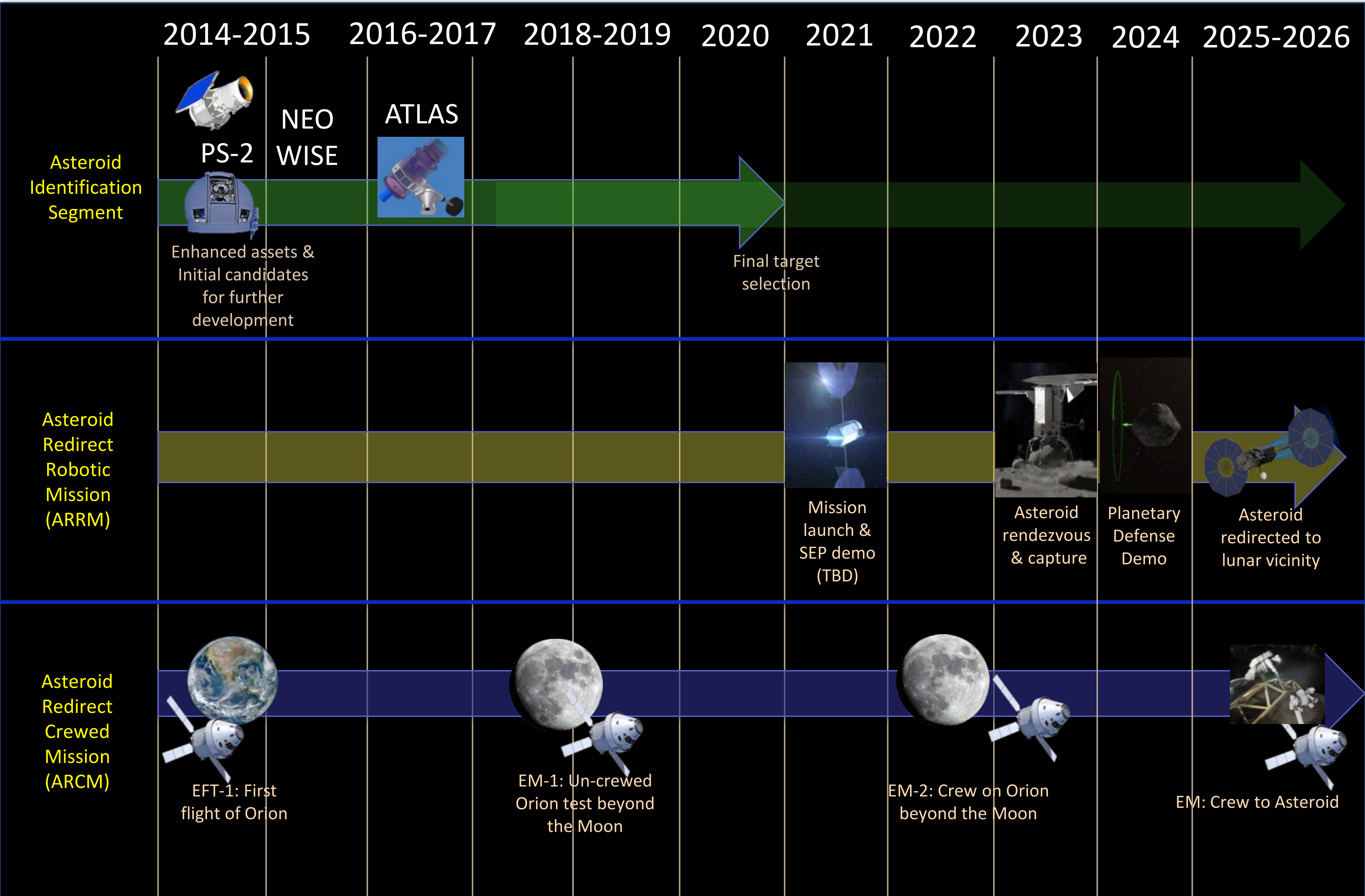
Asteroid Redirect Robotic Mission (ARRM) Formulation Guidance to KDP-B Update Feb 2016

- **Target launch date moved one year later for the KDP-B estimates and assessment.**

- **The availability of the asteroid and SEP-based spacecraft for the crewed mission moved into 2026.**

- **The viability of executing the mission within current cost cap will be evaluated at KDP-B, scheduled for July 15, 2016.**

Asteroid Redirect Mission Alignment Strategy



Human Space Exploration Phases From ISS to the Surface of Mars

Today

Phase 0: Exploration Systems ***Testing on ISS***

Ends with testing, research and demos complete*

Phase 1: ***Cislunar Flight Testing*** of Exploration Systems

Asteroid Redirect-Crewed Mission Marks Move from Phase 1 to Phase 2

Phase 2: ***Cislunar Validation*** of Exploration Capability

Ends with one year crewed Mars-class shakedown cruise

Phase 3: Crewed Missions Beyond Earth-Moon System

Phase 4a: Development and robotic preparatory missions

Phase 4b: Mars Human Landing Missions

Planning for the details and specific objectives will be needed in ~2020

Mid-2020s

2030

[* There are several other considerations for ISS end-of-life]

Strategic Principles for Sustainable Exploration

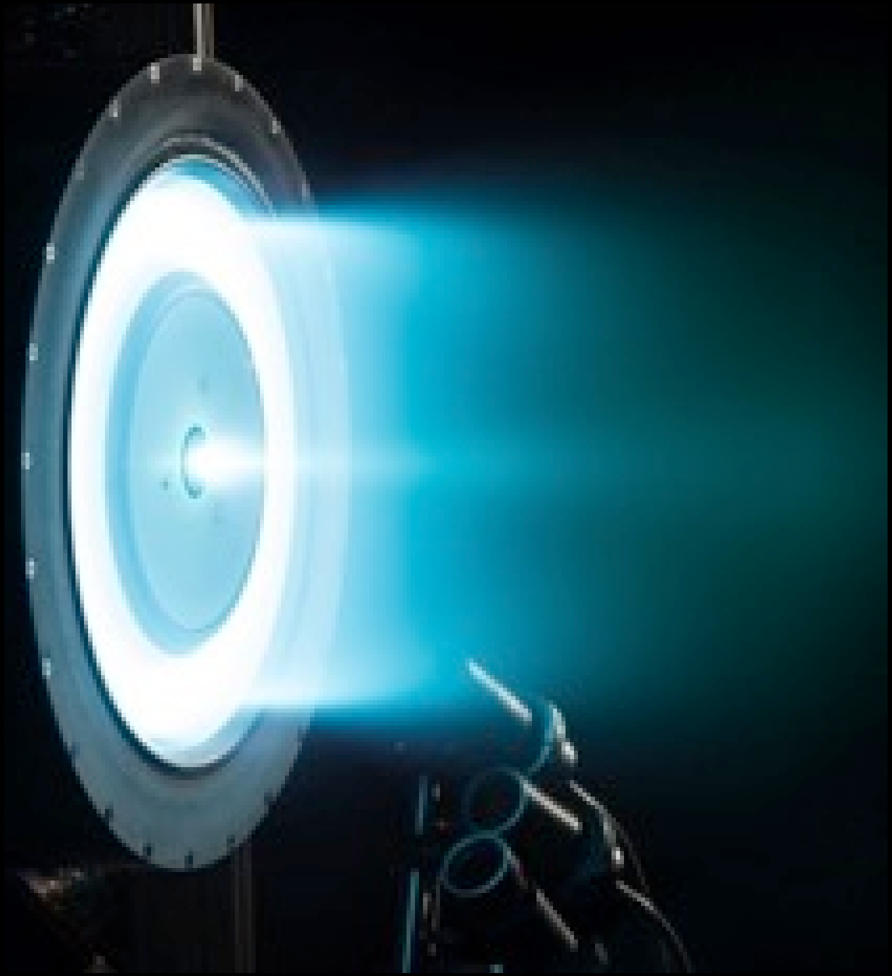
- **FISCAL REALISM: Implementable in the *near-term with the buying power of current budgets* and in the longer term with budgets commensurate with economic growth*;***
- **SCIENTIFIC EXPLORATION*: Exploration enables science and science enables exploration;* leveraging scientific expertise for human exploration of the solar system.**
- **TECHNOLOGY PULL AND PUSH: Application of high Technology Readiness Level (TRL) technologies for near term missions, while focusing sustained investments on *technologies and capabilities* to address the challenges of future missions;**
- **GRADUAL BUILD UP OF CAPABILITY: *Near-term mission opportunities* with a defined cadence of compelling and integrated human and robotic missions, providing for an incremental buildup of capabilities for more complex missions over time;**
- **ECONOMIC OPPORTUNITY: Opportunities for *U.S. commercial business* to further enhance their experience and business base;**
- **ARCHITECTURE OPENNESS AND RESILENCE: Resilient architecture featuring multi-use, evolvable space infrastructure, minimizing unique developments, with each mission leaving something behind to support subsequent missions;**
- **GLOBAL COLLABORATION AND LEADERSHIP: Substantial *new international and commercial partnerships,* leveraging current International Space Station partnerships and building new cooperative ventures for exploration; and**
- **CONTINUITY OF HUMAN SPACEFLIGHT*: Uninterrupted expansion of human presence into the solar system* by establishing a regular cadence of crewed missions to cislunar space during ISS lifetime.**

ARRM Electric Propulsion Status

Demonstrated magnetic-shielding for a long-life, high-power, high-specific impulse Hall thruster

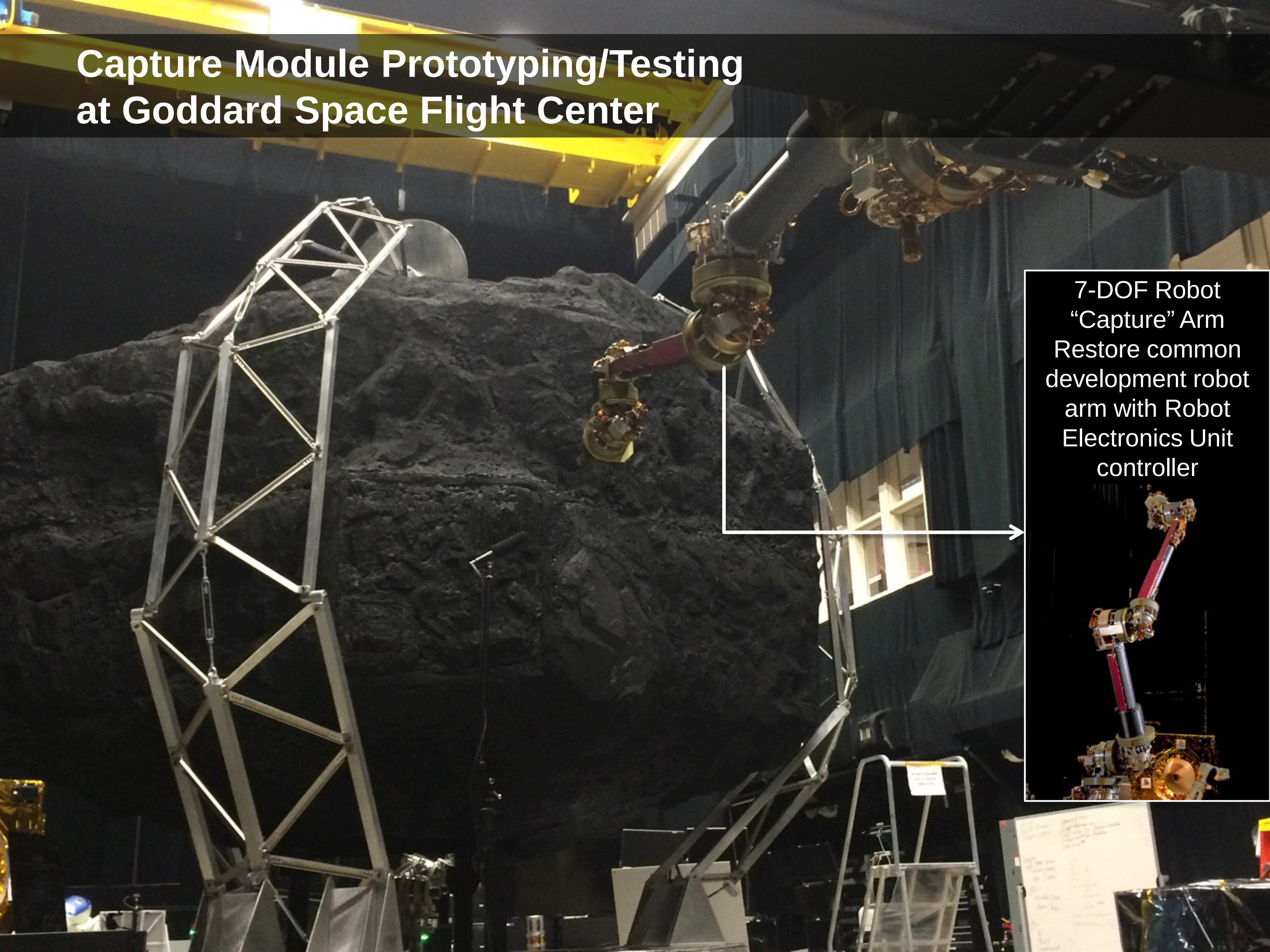
Electric Propulsion Subsystem Procurement

- **Contract awarded April 2016**
- **2,000 hours of planned wear testing on the technology development unit underway.**



12.5 kW, 3,000 s hot-fire thruster test at GRC

Capture Module Prototyping/Testing at Goddard Space Flight Center



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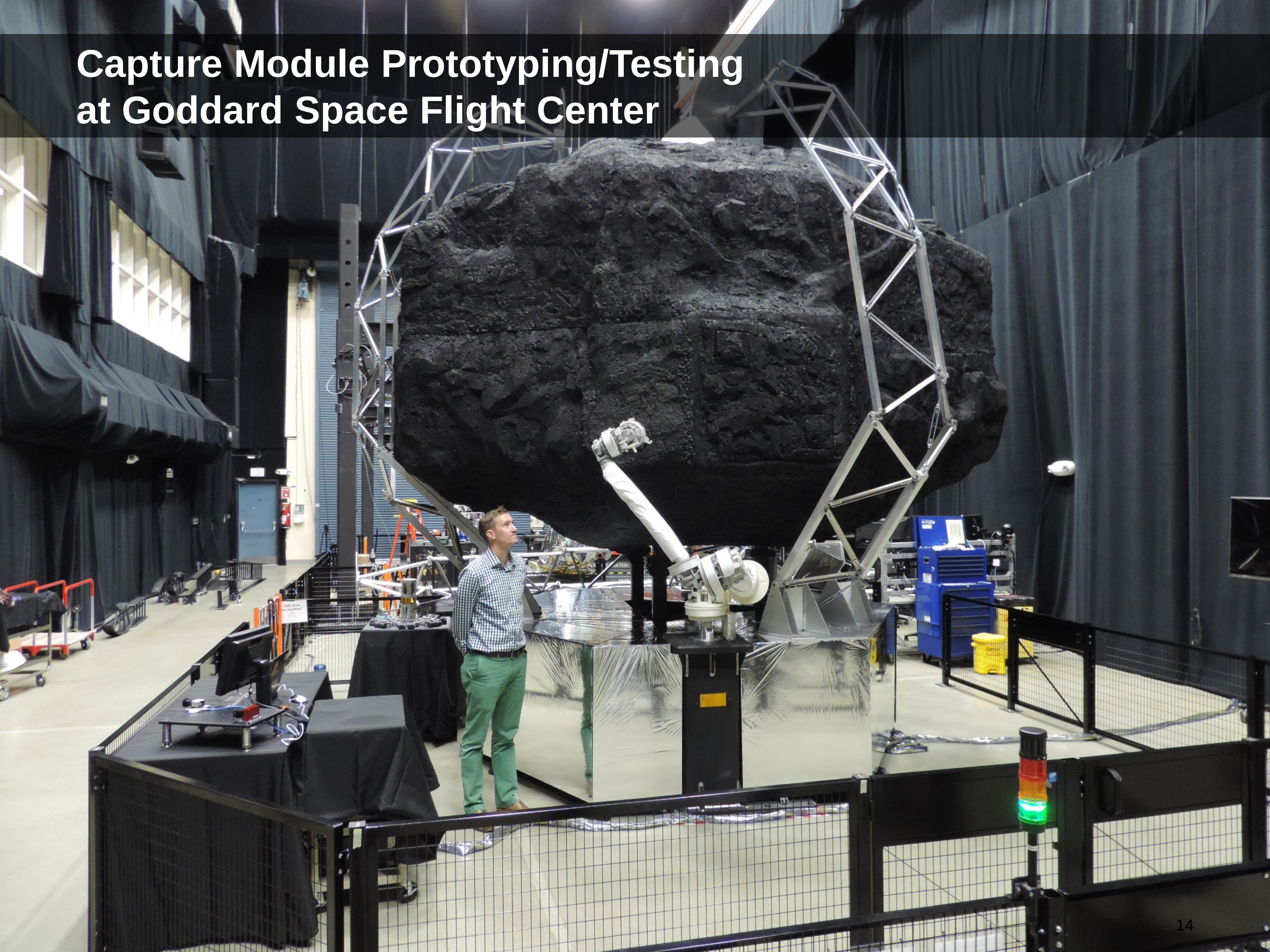


Capture Module – Restraint System
Langley Research Center

- Full scale welded metal prototype delivered
- Flat-floor testing of landing, extraction, and ascent underway

Robot Subsystem - Microspine Gripper
Jet Propulsion Laboratory

- Uses ~2000 independent hooks to opportunistically grip the surface
- Fast release capability
- Integrated rotary-percussive anchoring drill augments Microspine grip capability
- Design update from risk reduction

Technology Update
- Updated design of gripper, drill, drivetrain, and anchor
- Prototypes completed and tested with surrogate asteroid material

Leveraging Commercially Available Spacecraft Bus Capabilities

- **The acquisition strategy for the ARRM spacecraft leverages existing commercially available U.S. industry capabilities for a high power solar-electric-propulsion (SEP) based spacecraft for the agency's Asteroid Redirect Robotic Mission.**
  - Align with U.S. commercial spacecraft industry plans for future use of SEP
  - Reduce costs and cost risk to ARRM

- **Strategy includes procurement of the ARRM spacecraft bus through a two-phase competitive process:**
  - Phase 1 four spacecraft design studies in progress
  - Phase 2 competition for development and implementation of the flight spacecraft bus by one of the study participants

- **JPL selected four companies to conduct Phase 1: Lockheed Martin Space Systems, Littleton, Colorado; Boeing Phantom Works, Huntington Beach, California; Orbital ATK, Dulles, Virginia; and Space Systems/Loral, Palo Alto, California.**

Procurement Process for ARRM Spacecraft

NASA Acquisition Strategy Meeting (August 2015) designated JPL as the lead for the Asteroid Redirect Robotic Mission (ARRM) and concurred with JPL's plan to utilize its proposed two-step acquisition of a commercially-derived spacecraft.

Step 1 study contracts:

- ***Goals:***
  1. ***To determine the current capability of commercial spacecraft providers as they apply to the ARRM mission.***
  2. ***To influence the ARRM mission design based upon these capabilities such that the spacecraft can be procured at minimum risk and cost.***
  3. ***To investigate how ARRM can align with and enhance future industry needs/opportunities.***
- Vendors needed to have relevant capabilities:
  - Experience with large Geosynchronous or Deep Space vehicles
  - Experience with moderate-to-large Solar Electric Propulsion systems

Reduced Spacecraft Bus Implementation Risk

- **The study phase of this two-step procurement has allowed for a far greater level of interaction with the potential spacecraft vendors than is possible via the normal acquisition process.**
- **The vendors have responded to the limited set of requirements they were given (a six-page spacecraft specification of functional requirements instead of the typical 100-page set).**
  - This approach has not over-constrained their designs or unintentionally disallowed their heritage
  - Vendors are able to apply heritage (sometimes from multiple product lines) to address issues
- **In turn, vendors have asked for more information in the areas where they need it.**
  - In response, the ARRM project team has responded with additional documentation and changed some requirements
- **The vendors have a much better understanding of what JPL is asking for and the result should be a much better proposal in Step 2**
  - The typical scope revision that occurs shortly after issuance of a contract should be eliminated
  - Cost risk should be greatly reduced through this process

Progress on Spacecraft Studies

- **Step 1 studies are underway**
- **Mid-term briefings completed**
- **There are significantly different designs from the different vendors**
  - ARRM requirements and mission design allow adequate design flexibility **(Goal 2)**
- **Vendors possess and are clearly applying significant commercial heritage (Goal 1)**
  - Structures, Attitude Control, Computing, Power Distribution, Deployment Mechanisms, Propulsion
- **Vendors are prepared to bring contributions (Goal 1,3)**
  - New capabilities in electronics, fuel tanks, data interfaces, and solar arrays that were developed with internal corporate funds
- **ARRM-derived designs are compatible with future commercial and Government applications (Goal 3)**
  - Electric Propulsion Space Tug, Satellite Servicing/Refueling, Next-Gen Communication Satellites, and Deep Space Habitat and Cargo transportation

Two Upcoming Opportunities

- **An announcement of payload opportunities for <u>PARTNER-PROVIDED SYSTEMS</u> to be hosted on the robotic ARM spacecraft.**
  - Following a successful KDP-B, issue a broad solicitation as early as July 2016 for partner-provided payloads.
  - Intent is to provide the resources for payload accommodation with partners providing systems or instruments for investigations or experiments toward partner goals and awarded through no-cost contracts.

- **An opportunity for <u>PARTICIPATION IN THE ARM INVESTIGATION TEAM</u> (IT), which will be a multidisciplinary group of U.S. industry, academia, and government, and international members.**
  - With an initial term of 3-5 years, the IT will assist with the definition and support of investigations for the robotic and crew segments of the ARM in the science, planetary defense, in-situ resource utilization, and capability and technology demonstration domains, as well as provide Program-level and Project-level support.

Call for Partner Provided Payloads

- **Following a successful KDP-B, NASA plans to issue a call for partner provided payloads to fly on the ARM Robotic Segment**
  - NASA will provide accommodations including integration with ARM robotic spacecraft
    - Expected total allocations of 50 Kg mass, 200 W operational/50 W keep-alive power plus 32 GB data storage and downlink
  - Partner provides payload consistent with ARM goals, objectives, robotic mission implementation schedules, interfaces and operations
    - Payloads assumed non-mission critical and may include remote sensing or deployable systems
    - Priority to payloads which may help characterize asteroid or otherwise reduce mission operations risks
  - Successful proposers will be offered representation on ARM IT

- **Open to US Industry, academia, Government agencies, NASA Centers and International participation**

Formulation and Support Team (FAST)

- **The FAST final report and complete set of public inputs was released on February 18, 2016 and can be found at:** https://www.nasa.gov/feature/arm-fast

- **Report provides:**
  - Overview of the FAST effort.
  - Responses to a set of high-priority questions that were derived from the ARRM engineering team's risk analysis and needed to help design and develop the ARRM mission, spacecraft, and capture system.
  - An initial list of potential investigations which could be performed by ARM (ARRM and/or ARCM).
  - List of additional findings by the FAST in combination with public input.
  - A summary of relevant public inputs and comments received by the deadline of December 4, 2015.
  - Appendices with more detailed responses to each of the ARRM Project questions.

The Formulation Assessment and Support Team (FAST) identified ARM as a unique opportunity to gain a wide range of valuable knowledge beyond other asteroid missions or from what is available in current meteorite collections.

Formulation Assessment and Support Team (FAST)

Organization
NASA Langley Research Center (Mission Investigator)
NASA Johnson Space Center (Deputy Investigator)
NASA Langley Research Center (IT Analysis and Integration Lead)
Arizona State University
Penn State University
Arizona State University
Southwest Research Institute
University of Central Florida
University of Central Florida
Jet Propulsion Laboratory
John Hopkins University-Applied Physics Laboratory
NASA Johnson Space Center
Missouri University of Science and Technology
NASA Goddard Space Flight Center
University of Maryland
Planetary Science Institute
NASA Goddard Space Flight Center
University of Colorado
TransAstra
United States Geological Survey
Honeybee Robotics

- Provided information on the nature of the asteroid target and boulders.
- Provided ideas and recommendations to enhance the scientific return, including a wide range of observations and instruments.

FAST Leadership

FAST Participants

Preliminary Prioritization for Hosted Payloads from FAST Findings:

- **The following is a preliminary ARRM prioritization for hosted payloads based on inputs from the FAST.**
  1. Thermal imager for basic boulder/regolith thermal inertia properties
  2. Multispectral imaging (broad-band filters) for morphology/composition
  3. Visible-near infrared spectrometer (~0.4-4 micron) to assess hydration
  4. Regolith geotechnical property estimation via surface interaction
  5. Acoustic/ultrasonic sensors to provide boulder characterization during and/or after collection during the ARRM
  6. Free-flyer camera and/or orbit determination asset
  7. Surface interaction deployable payloads
  8. In Situ Resource Utilization deployable assets/experiments
  9. Small carry-on impactor
  10. Global radar tomography and near-surface structure characterization with Ground Penetrating Radar

- **Payloads that can perform multiple investigations and reduce risk for the ARRM are preferable.**

ARM Investigation Team (IT)

- **Two-phase solicitation for IT membership planned in coordination with call for hosted payloads on the ARRM.**
  - Phase I solicitation planned for this July/August with announcements in March/April 2017 in coordination with selection of contributed payloads.
  - Phase II solicitation after selection of additional payloads and 6-month integration study.
- **IT will participate in the definition, design, development, and operations phases of the ARRM with the goal of maximizing the probability of mission success and the knowledge return from the mission.**
- **IT will lead or assist in the implementation of mission investigations focused on the following four main areas as they support the robotic and crewed segment objectives:**
  - Science
  - Planetary defense
  - Asteroidal resources and in-situ resource utilization (ISRU)
  - Capability and technology demonstrations
- **NOIs and proposals will be submitted electronically via NSPIRES.**

ARM Investigation Team (IT)

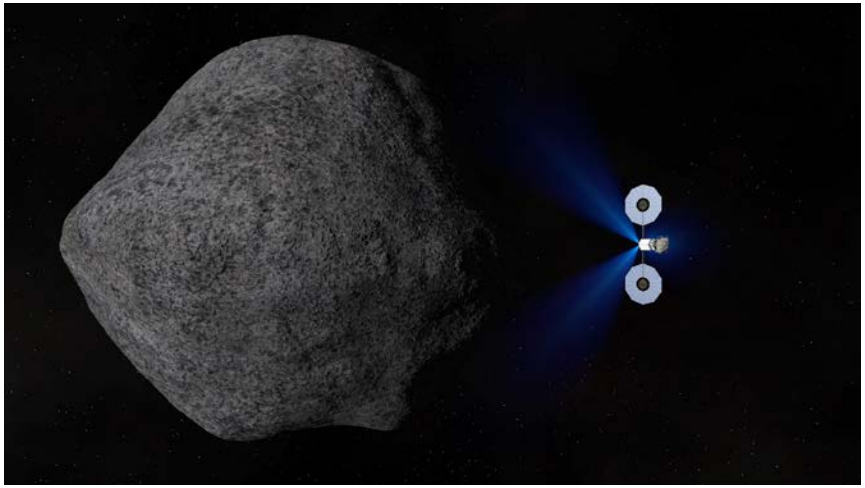
- **The IT will support ARM Program-level and Project-level functions, provide technical expertise, and support NASA Headquarters interactions with the technical communities.**

- **Some examples of duties of the selected members:**
  - Provide technical expertise to ARRM and ARCM project teams to assist in the mission operations and vehicle development (e.g., NEA/surface/boulder properties estimates, test suites, support engineering, etc.) and extensibility/technology opportunities.
  - Perform analyses to support spacecraft and mission design.
  - Support concept of operations development for the mission and hosted payload suite, including characterization and boulder collection phases.
  - Provide input into asteroid target selection.
  - Provide inputs to planning and implementation of planetary defense demonstration.
  - Provide inputs into post-capture characterization and EVA sampling and investigation sites (e.g., planning and procedures).
  - Provide input for curation, contamination control, and the types of samples to be obtained.
  - Support education and public outreach efforts.

- **Support for post-docs, research, travel planned.**

Planetary Defense Demonstration

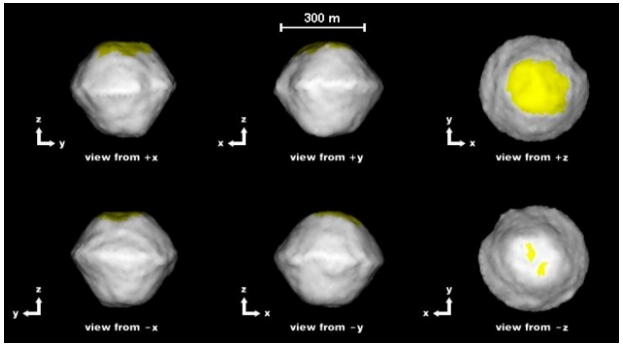
- **Enhanced Gravity Tractor (EGT)**
  - Uses the mass of the collected boulder to augment the mass of the spacecraft and increase the gravitational attraction.
  - ARRM PD demo is moving toward a stationary in-line mode (vs. halo orbit) to decrease GN&C complexity and provide better range of mass applicability (boulder and asteroid) with the planned Ion Propulsion System (IPS) thruster throttle range.
  - Low IPS throttling requires additional thruster validation and verification and also adversely impacts the cathode lifetime.
  - In-line GN&C is simpler to implement, but will require large IPS gimbal range-of-motion.
- **Small, but measurable deflection will be imparted on hazardous size asteroid**
  - 2008 EV_5 deflection can be verified using ground-based radar
  - Other targets may require the Asteroid Redirect Vehicle (ARV) to loiter near the asteroid for deflection verification via differential ranging to the ARV



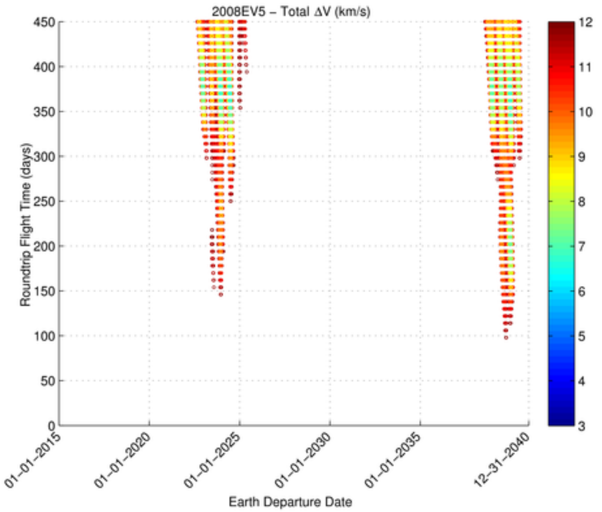
- **Actual EGT planetary defense mission could collect much more mass, increasing the effectiveness of this technique.**

Community Interest in Reference Target 2008 EV_5

- **Significant interest from the science and small bodies communities with well-documented investigation opportunities.**
  - Primitive, C-type (carbonaceous) believed to be rich in volatiles (water and organics).
  - Target of ESA's Marco Polo-R candidate sample return mission (not selected by ESA).
- **Largest asteroid with lowest mission ΔV (6.3 km/s) of the 1756 objects (as of 6/17/16) in the Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) list.**
  - Potential human mission target in late 2030s.
  - Possible target for resource collection.
- **Large, hazardous-size asteroid provides a representative target for a planetary defense demonstration.**



2008 EV_5 shape model from radar observations.



2008 EV_5 Minimum Mission ΔV for 2015-2040.

Enabling In-Space Resource Utilization

- **Multiple tons of material collected by the ARM provides:**
  - Large quantities of valuable, pristine water-rich C-type material (limited primitive meteorite collection on Earth)
  - Ability to understand for the very first time, the water and volatile content as a function of depth (core sample from a multi-meter boulder)
  - Enables in-situ, industrial-scale material extraction and processing (many kilograms to multiple tons)
  - ~100 kg returned to Earth by astronauts during crewed segment
- **Delivering the material to a stable lunar orbit provides:**
  - Orbital laboratory facility near Earth
  - Easily accessible by asteroid mining companies and NASA partners
  - Short communication delay allows testing of telerobotic mining techniques
  - Permits human repair and servicing of mining equipment and for the collection/return of products and equipment for evaluation

Enabling In-Space Resource Utilization

- **Characterization and proximity operations with a human-class spacecraft provides relevant experience for future mining operations**
- **Collection of surface regolith samples provides geological context of the boulder and allows correlation with Earth-based observations**
- **Examples of opportunities for contributed payloads at the target asteroid:**
  - CubeSat prospector technology demonstration
  - Material extraction or processing demonstrations

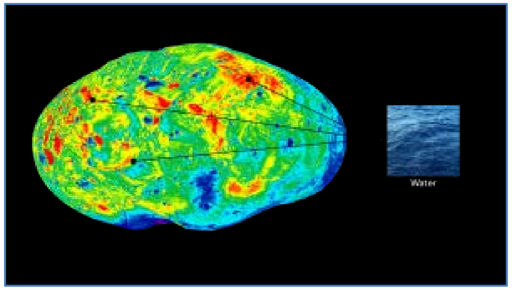


Image Credits: Planetary Resources

- **The evolving asteroid mining community expects that material and operations provided by ARM will accelerate commercial asteroid mining efforts**

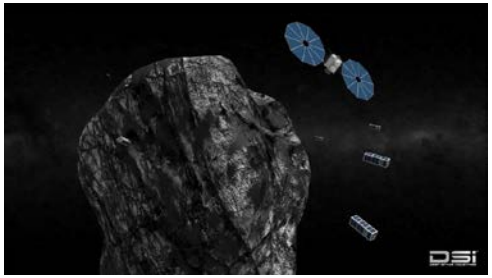


Image Credits: Deep Space Industries

Scientific Characteristics of ARM Targets

- **Preferred target asteroids are primitive C-type (carbonaceous) asteroids. The ARM reference target 2008 EV_5 is a C-type asteroid.**
  - Primitive, C-type (carbonaceous) asteroids are believed to be rich in volatiles (water and organics). Carbonaceous meteorites found on Earth have up 20% water by weight and are thought to be from C-type asteroids.
  - The study of these asteroids and their associated meteorites has the potential to further understanding of early Solar System evolution (volatile content, thermal history, etc.).
  - Carbonaceous asteroids may have played a key role in the formation of Earth's atmosphere and oceans via delivery of volatiles. They may also have delivered key ingredients for the formation of life (astrobiology).
- **The ARM reference target 2008 EV_5 appears to be representative of a distinct population of carbonaceous asteroids unlike other sample return targets**
  - Opportunity to obtain a large multi-ton sample from a completely different parent carbonaceous asteroid (new world).
  - Furthers understanding of the variety of conditions and materials that existed among carbonaceous parent asteroids.

Science of ARM samples

- **ARM samples will consist of materials collected from the boulder and those obtained from the surface of the parent asteroid (regolith) around the boulder.**
  - The “landing” pads of the spacecraft will collect regolith particles of the surface, which will be analyzed for space weathering effects and help place the boulder samples into context.
  - The boulder will be sampled via a variety of methods by taking materials from its outer surface, chipping off sections to expose its interior, and obtaining cores of its deep interior.
- **The large amount of samples (~100 kg) returned via the crew will allow a much more intensive study of the asteroid materials.**
  - Bringing samples to Earth laboratories allows for a more coordinated approach to sample analyses and experimentation. Several techniques can be used on similar samples all within the same laboratory (NASA Astromaterials Research Laboratory).
  - The abundance of samples allows for destructive investigations (or innovative methods) to be performed that would otherwise be discouraged.
- **Obtaining deep core samples (~1 meter) will allow the pristine nature of asteroid volatiles to be more thoroughly investigated as a function of depth.**
  - Volatile material (organics and water) near the surface can be degraded or destroyed by thermal or radiation effects. The rock of the boulder shields the volatiles from heat and radiation, thus preserving their pristine nature. The deeper the sample the more pristine it is likely to be.

www.nasa.gov/arm