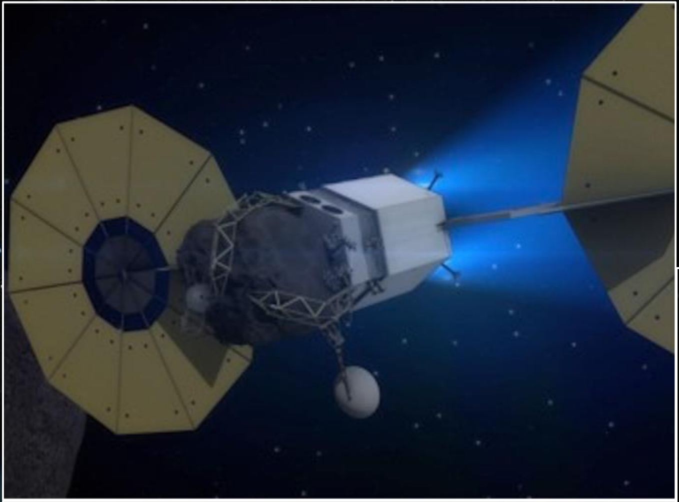
National Aeronautics and Space Administration

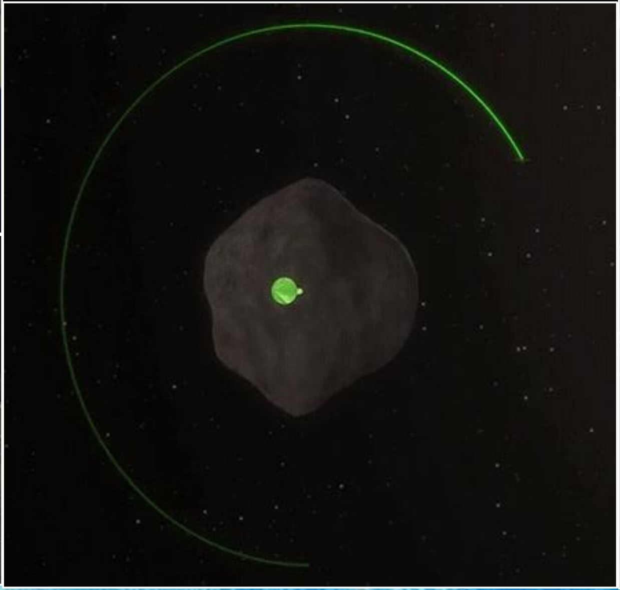
Asteroid Redirect Mission Update

NAC Human Exploration and Operations Committee

Dr. Michele Gates

March 2, 2016





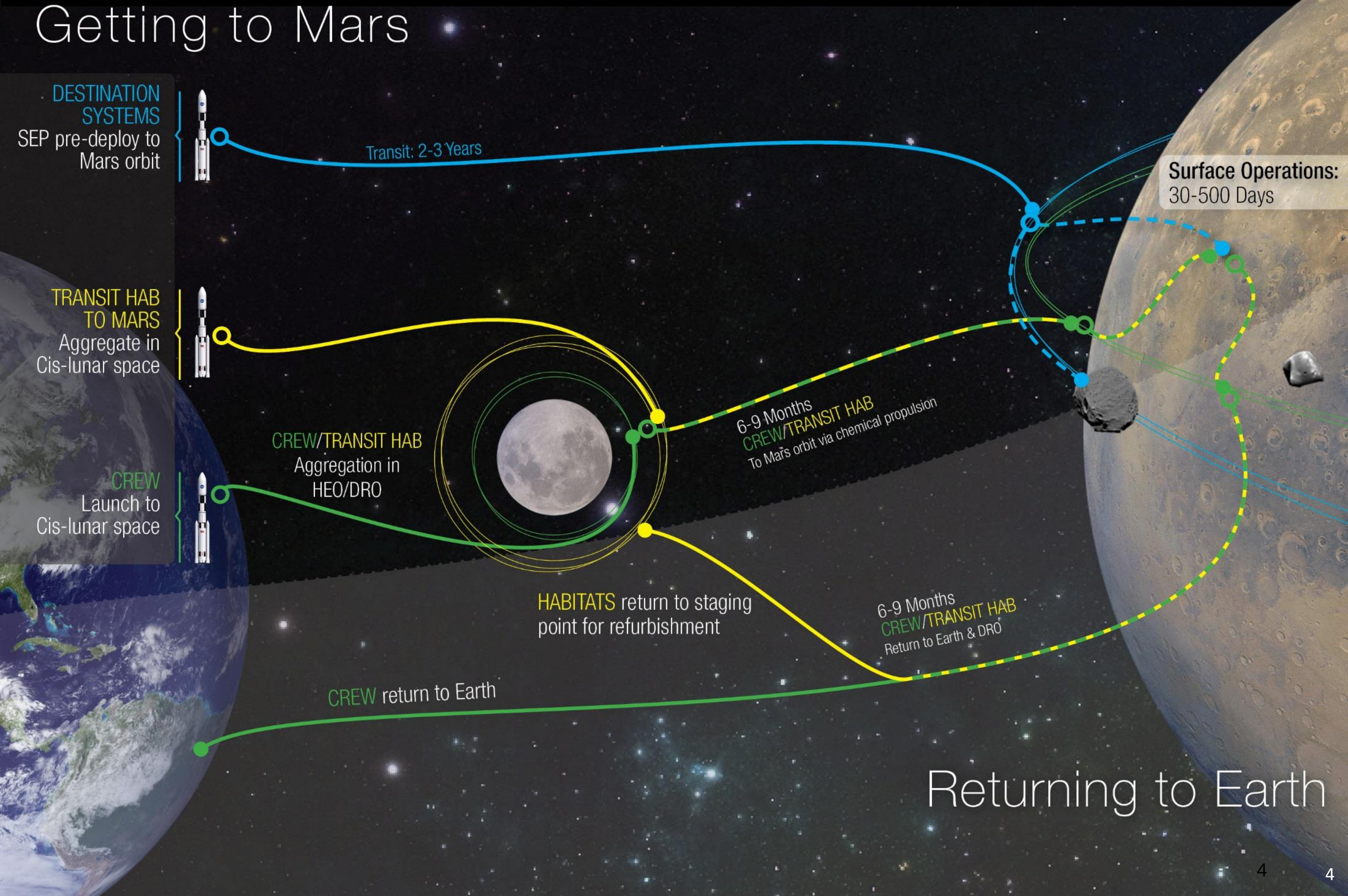
Last Update in July Included

- **Updates on contributions of the mission to exploration strategy and Journey to Mars**
- **Guidance for ARRM formulation**
- **A focus on external engagement and feedback**

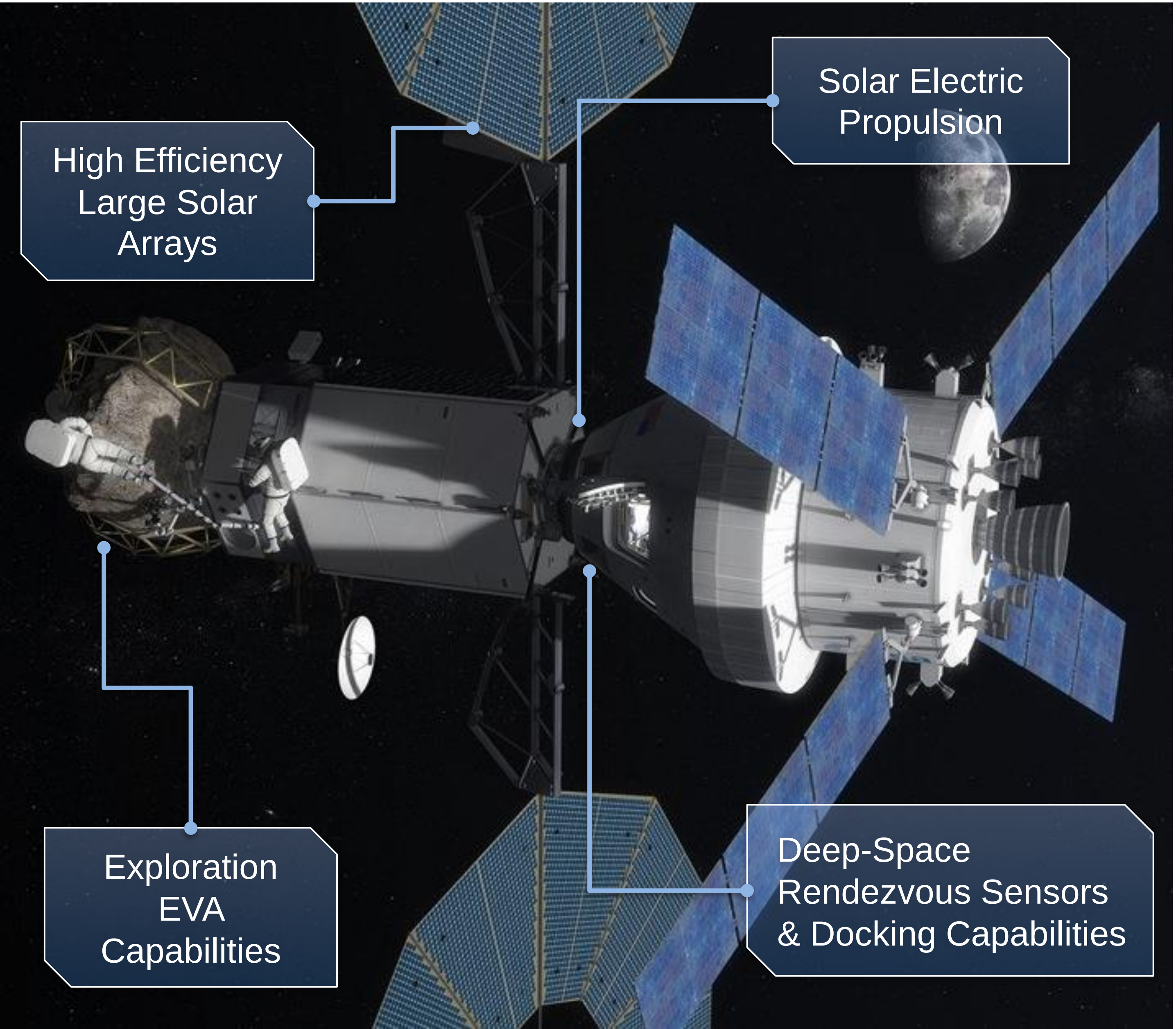
Asteroid Redirect Mission Progress

✓Robotic Mission Concept Review and Formulation Authorization	Mar 2015
✓Acquisition Strategy Decisions for Robotic Mission	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
✓Robotic spacecraft early design study contracts selected	Jan 2016
✓Update with Small Bodies Assessment Group	Jan 2016
✓Complete 6th of 6 total Peer Reviews for Restore-L Synergy Subsystems	Jan 2016
✓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

A Sustainable Exploration Approach
Mars Split Mission Concept



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:

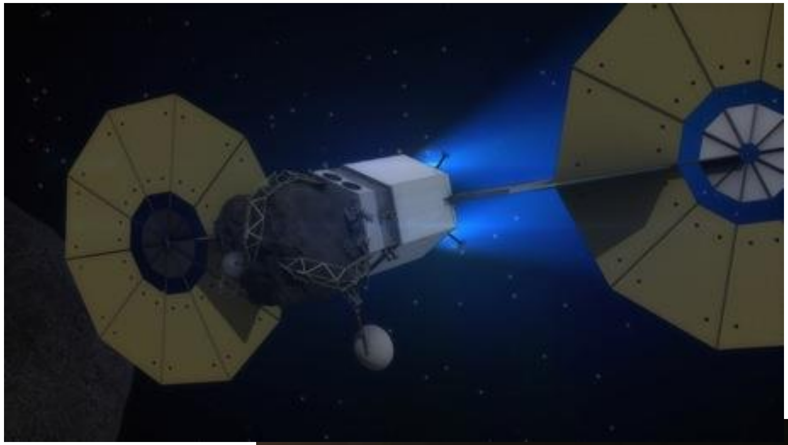
- Two in space EVAs of four hours each
- Primary Life Support System design accommodates Mars
- Sample selection, collection, containment, and return

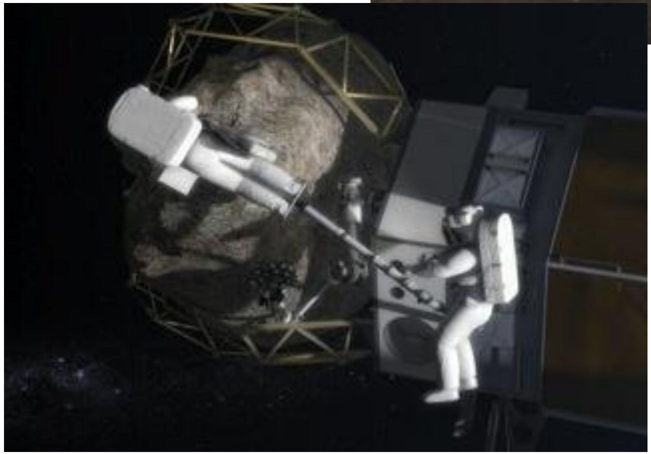
TRANSPORTATION & OPERATIONS:

- 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

ARM Objectives in Support of Human Exploration

- Transporting multi-ton objects with advanced solar electric propulsion
- Integrated crewed/robotic vehicle operations in deep space staging orbits
- Advanced autonomous proximity operations in deep space and with a natural body
- Astronaut EVA for sample selection, handling, and containment





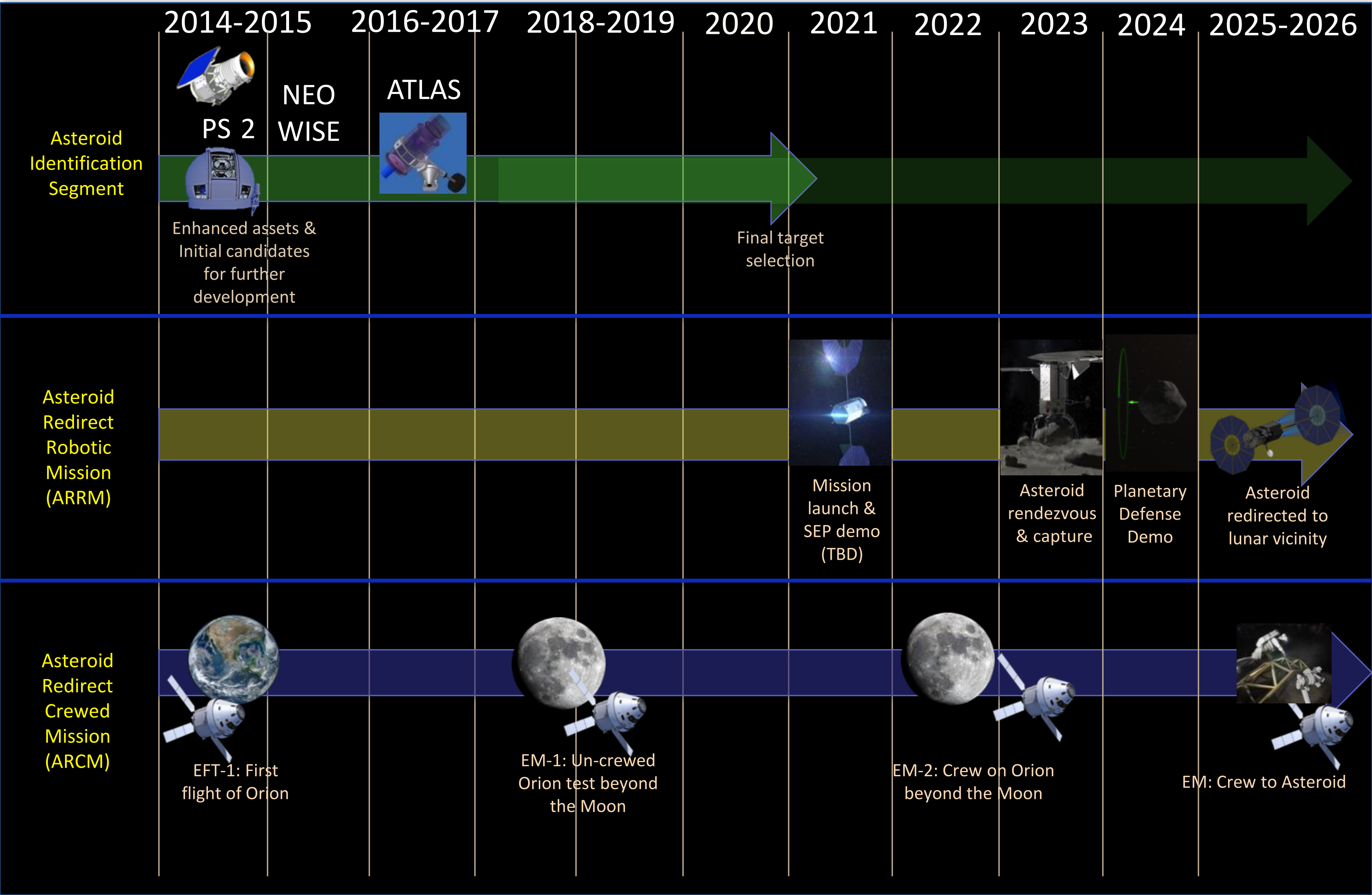
ARRM Formulation Guidance Update Feb 3

Updated Formulation Guidance toward ARRM KDP-B*

- **Revised draft Level 1 requirements Target robotic mission launch date Dec 2021**
- **Robotic mission cost cap $1.25B not including launch vehicle and mission operations (Phase E)**
- **Target crewed mission launch date by Dec 2026**

* Target Dates are expected to continue to be refined as the mission proceeds through formulation.

Asteroid Redirect Mission Alignment Strategy



Collaborative/Participatory Elements

- **Center-to-Center Collaboration and Partnership**
- **Cross-Directorate Collaboration**
- **Evolution of Small Bodies Assessment Group (SBAG) Interaction**
- **Participatory Formulation through the Formulation Assessment and Support Team**
- **Leveraging Commercially Available Spacecraft from US Industry**
- **Potential for "Commercial" (Entrepreneurial) Collaboration**
- **Continued Discussions with Potential International Partners**

Formulation Assessment and Support Team and Investigation Team

- **ARM Formulation Assessment and Support Team (FAST) effort completed.**
  - Two-month effort to support the ARRM Requirements Closure Technical Interchange Meeting on December 15-16, 2015.
  - 18 scientists and engineers selected from 100 applicants from academia and industry along with three NASA leaders.
  - Draft report made available for public comment.
  - Final report, including public comments, released on February 18, 2016.

FAST & ARRM Project Team Members.

- **ARM Investigation Team (IT) and coordination with additional ARRM investigations and associated hardware is in process.**
  - Call for membership planned following KDP-B.
  - IT will include domestic and international participation.
  - IT will support ARM through mission implementation, which includes the operational phases of both the ARRM and the ARCM.

Formulation Assessment and Support Team (FAST)

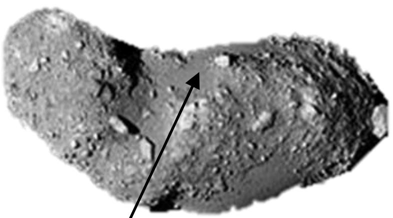
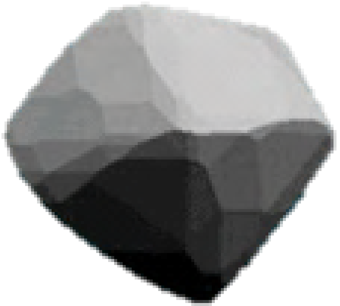
Organization
NASA Langley Research Center (Mission Investigator)
NASA Johnson Space Center (Deputy Investigator)
NASA Langley Research Center (IT Analysis and Integration Lead)
Arizona State University
Penn State University
Arizona State University
Southwest Research Institute
University of Central Florida
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

FAST Leadership

FAST Participants

- **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**

Current Candidate Parent Asteroids

ITOKAWA	BENNU	2008 EV5	1999 JU3
 Muses C – Hayabusa landing	 Radar – OSIRIS-REx target	 Radar – boulders and extremely pronounced bulge at equator suggests movement of loose material	 Expected valid target - Hayabusa 2 target

Asteroids not to scale

Comparison of current candidate parent asteroids

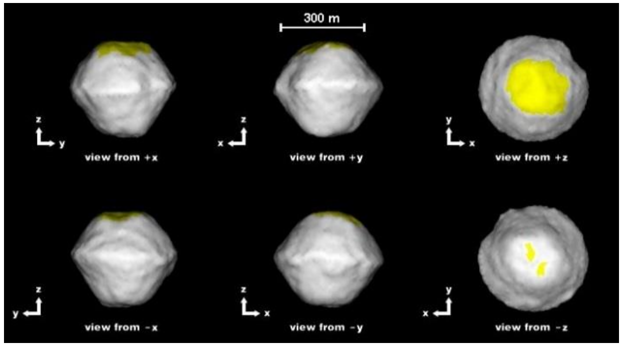
	Itokawa	Bennu	2008 EV_5	1999 JU_3
Size	535 x 294 x 209 m	492 x 508 x 546 m	420 x 410 x 390 m	870 m diameter
V_∞	5.68 km/s	6.36 km/s	4.41 km/s	5.08 km/s
Aphelion	1.70 AU	1.36 AU	1.04 AU	1.42 AU
Spin Period	12.13 hr	4.297 hr	3.725 hr	7.627 hr
Type	S	B (C-grp volatile rich)	C (volatile rich)	C (volatile rich)
Precursor	Hayabusa (2005)	OSIRIS-REx (9/2016 launch, 8/2018 arrival)	None currently planned (boulders implied from 2008 radar imaging)	Hayabusa 2 (launched 12/4/2014, 7/2018 arrival)

NASA continues to look for additional targets in accessible orbits.

Reference ARRM Target

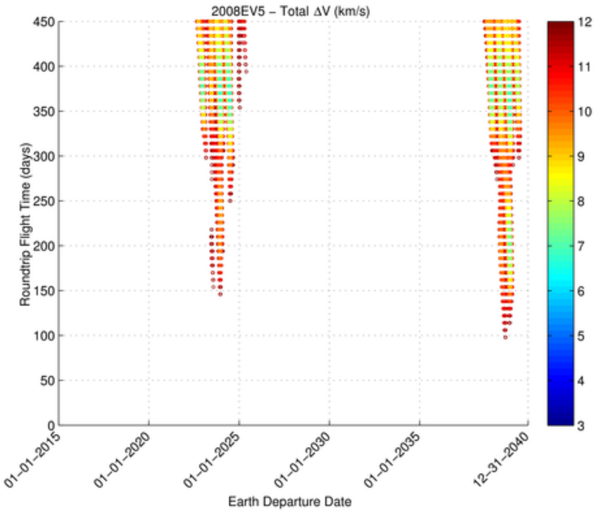
Interest in Reference Target 2008 EV_5

- **Significant interest from the science and small bodies communities with well-documented investigation opportunities.**
  - Primitive, C-type (carbonaceous) believed to be rich in volatiles.
  - Target of ESA's Marco Polo-R candidate sample return mission (not selected).



2008 EV_5 shape model from radar observations.

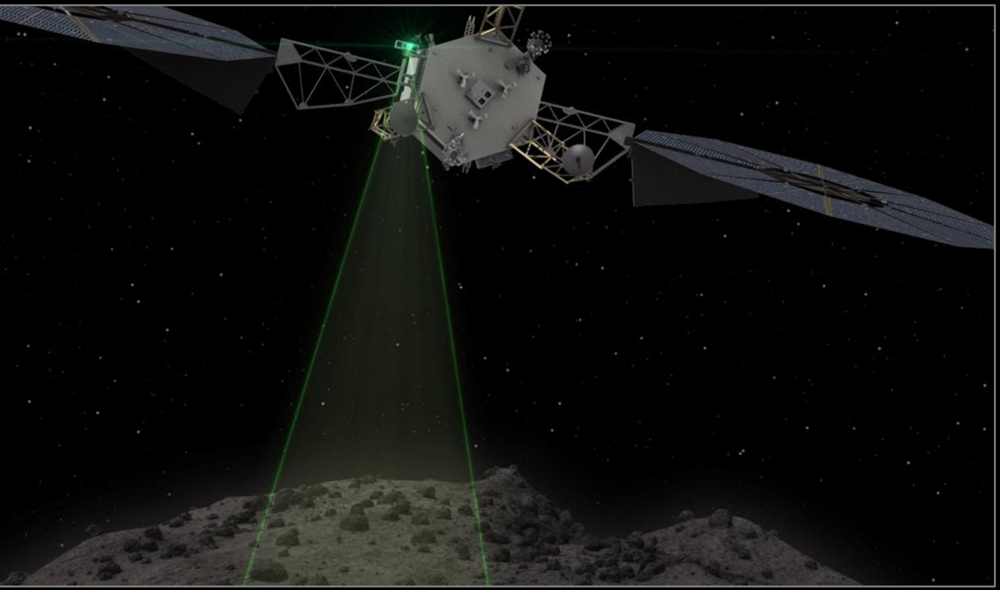
- **Largest asteroid with lowest mission ΔV (6.3 km/s) of the 1619 objects (as of 2/24/16) in the Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) list.**
  - Potential human mission target in late 2030s.
  - Possible target for resource collection.

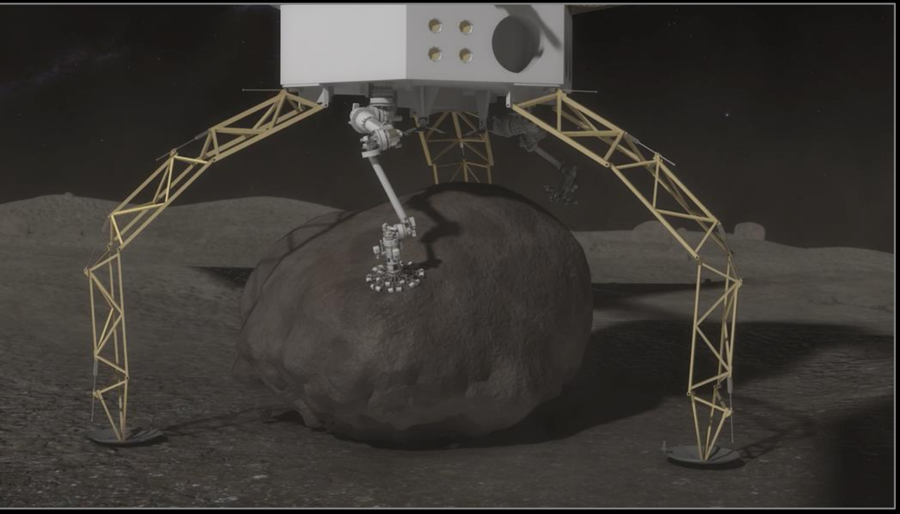


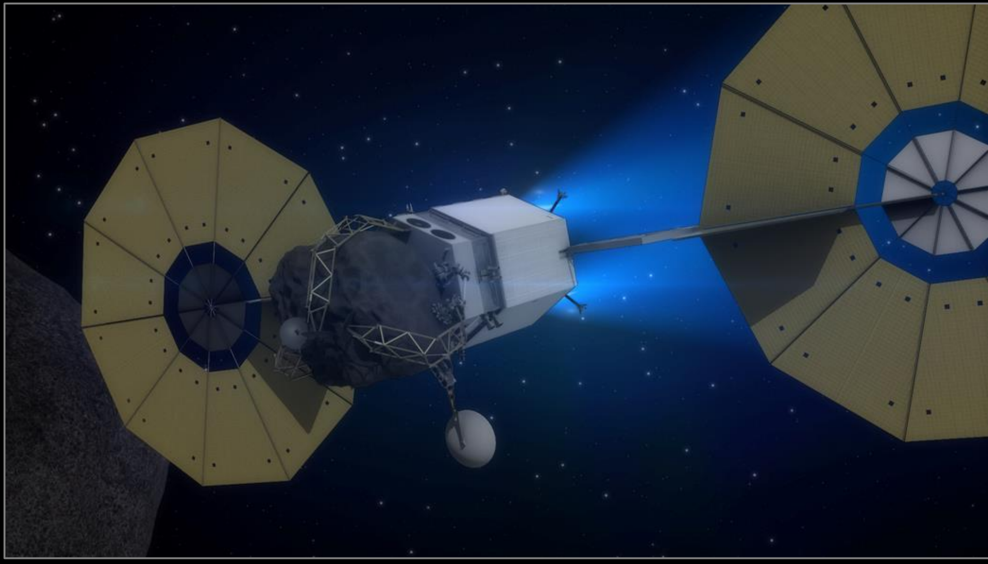
2008 EV_5 Minimum Mission ΔV for 2015-2040.

- **Large, hazardous-size asteroid provides representative target for planetary defense demonstration.**

ARM Robotic Mission (ARRM)







Leveraging Commercially Available Spacecraft Bus Capabilities

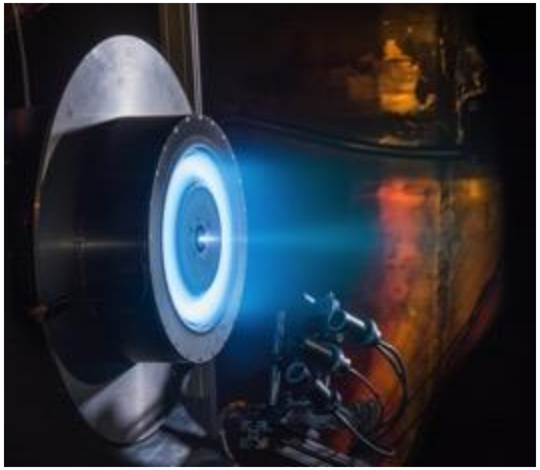
- **The acquisition strategy for the ARRM spacecraft leverages existing commercially available U.S. industry capabilities for a high power solar-electric-propulsion (SEP) based spacecraft for the agency's Asteroid Redirect Robotic Mission**
  - Align with U.S. commercial spacecraft industry plans for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

Electric Propulsion String
Electric Thruster & Power Processing Unit (PPU)

Demonstrated full performance compatibility between thruster and PPUs



Hall Effect Rocket with Magnetic Shielding Technology Development thruster with radiator

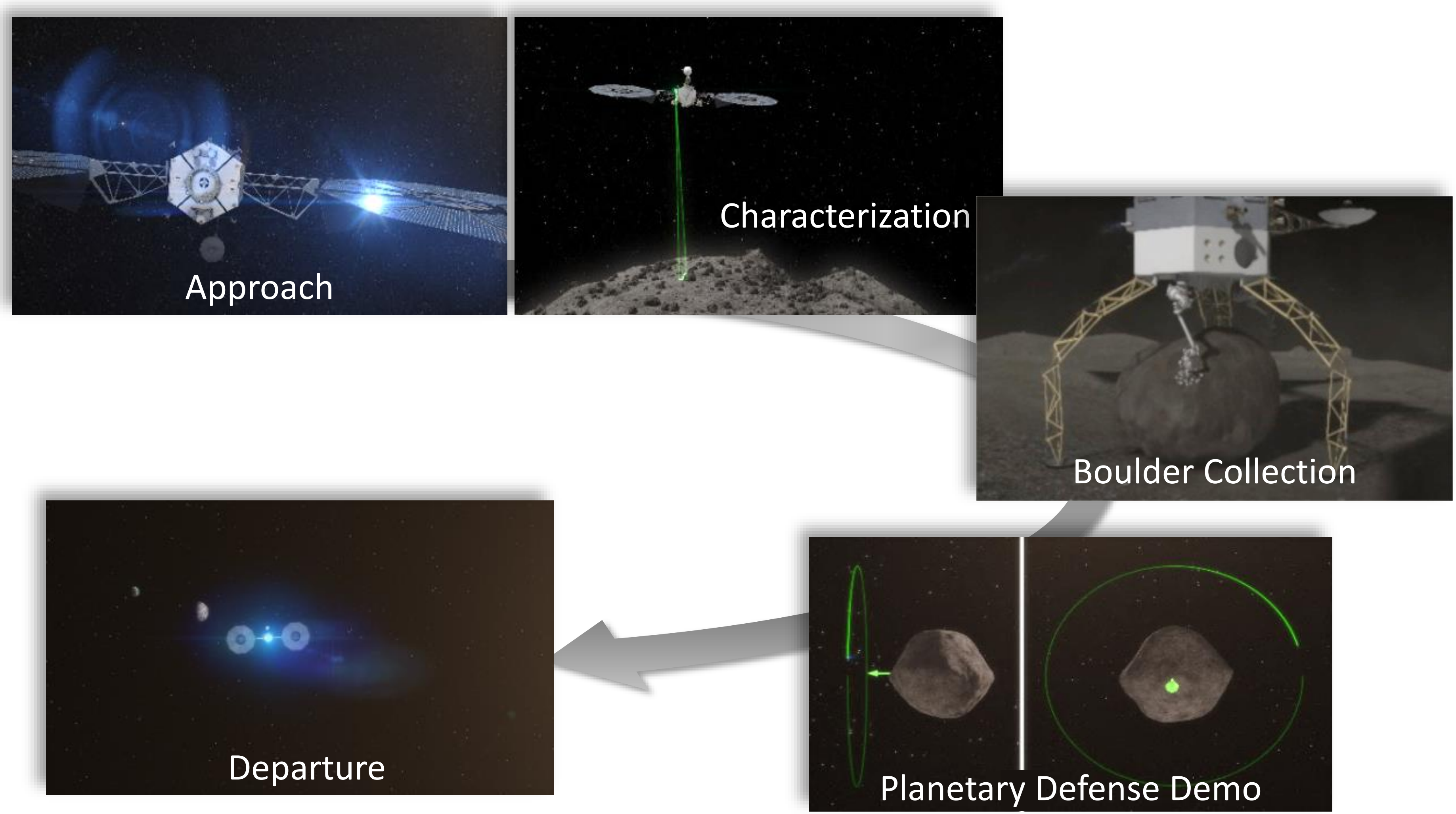
12.5 kW, 3,000 s hot-fire thruster test in GRC Vacuum Facility-5

Electric Propulsion System Procurement
Thruster & Power Processing Unit Development for an Advanced EP System

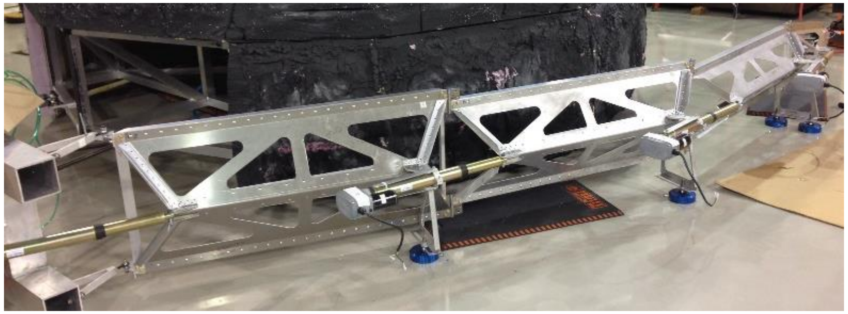
- RFP released in July 2015, final proposals received and under evaluation
- Anticipated award in late Spring 2016

Capture Phase Overview
Asteroid Redirect Robotic Mission

Approach 14 days | Characterization 85 days | Boulder Collection 60 days + 30 day margin



Capture System Prototyping/Testing
Asteroid Redirect Robotic Mission

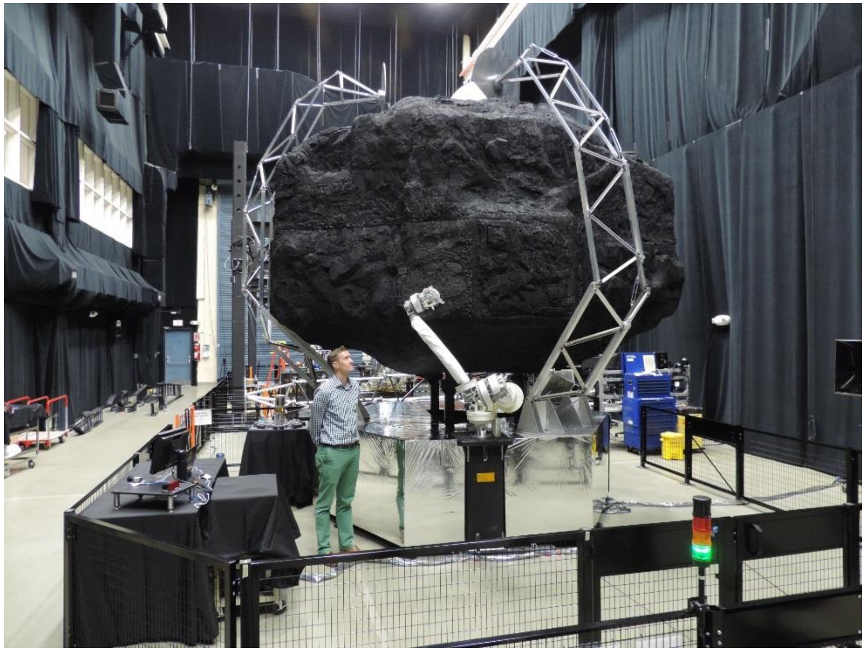


Prototype contact and restraint system development at LaRC

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

Microspine gripper development at JPL

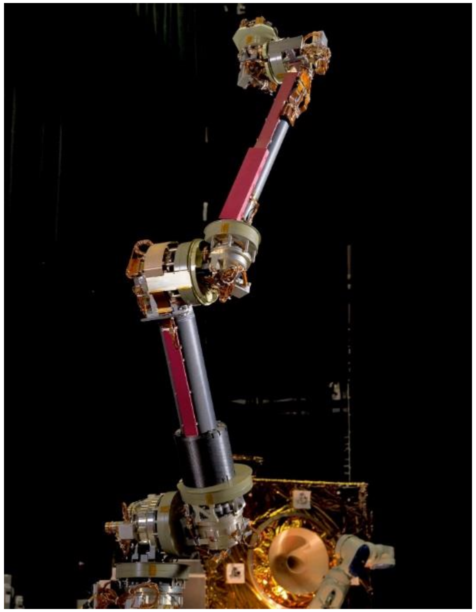
- Updated design of gripper, drill, drivetrain, and anchor
- Prototypes completed and tested with surrogate asteroid material



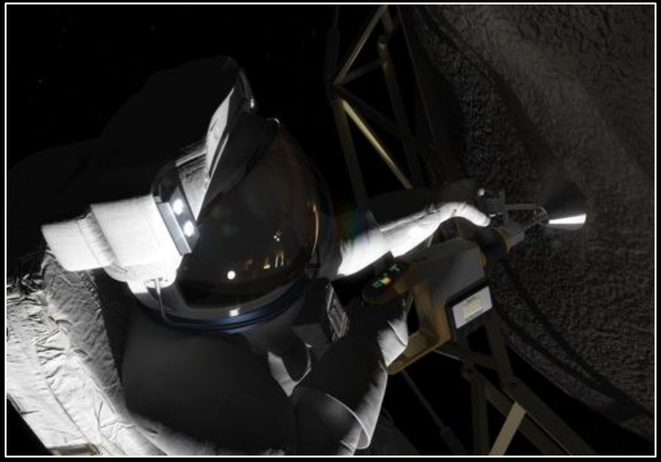
Capture System Prototyping/Testing at GSFC

7-DOF Robot "Capture" Arm at GSFC

Leveraging satellite servicing technology common development robot arm and controller



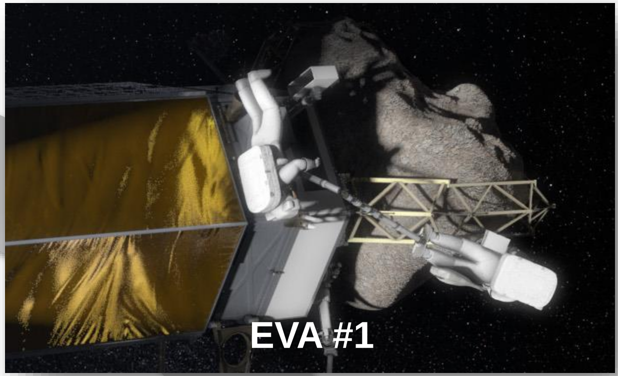
ARM Crew Mission (ARCM)



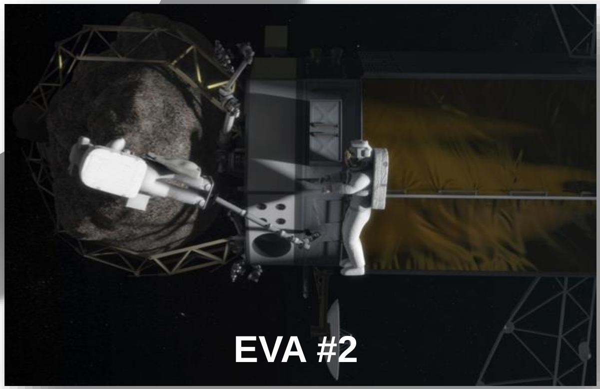
Asteroid Redirect Crewed Mission Summary

Launch	Outbound Transit with LGA	DRO Operations	Inbound Transit with LGA
1 day	11 days	5 days	8 days

LGA — EVA #1 — EVA #2 — LGA — Landing

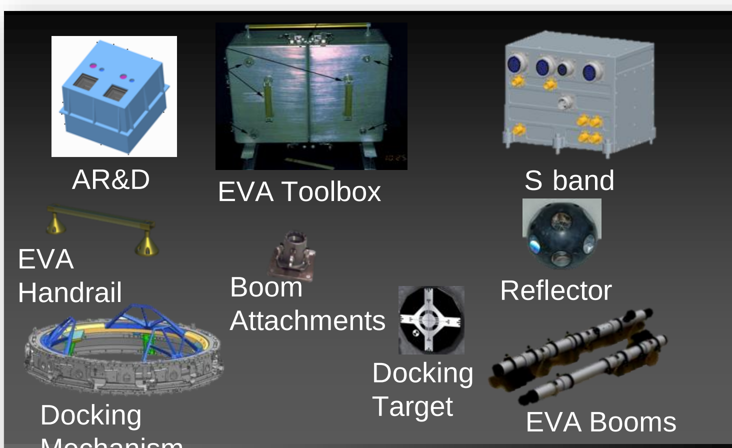


- Total mission duration 24.3 Days
- A 2-person crew is launched aboard an Orion augmented with the ARCM mission kits.
- Rendezvous and dock with the robotic spacecraft in a ~ 71,000 km lunar DRO.
- Conduct 2 four-hour EVAs to observe, document and collect asteroid samples.
    - Orion performs 20˚ yaw prior to EVAs to ensure proper EVA worksite thermal conditions and adequate space-to-ground communication coverage.
- Crew safely returns to Earth with samples.



Crewed Mission Kits

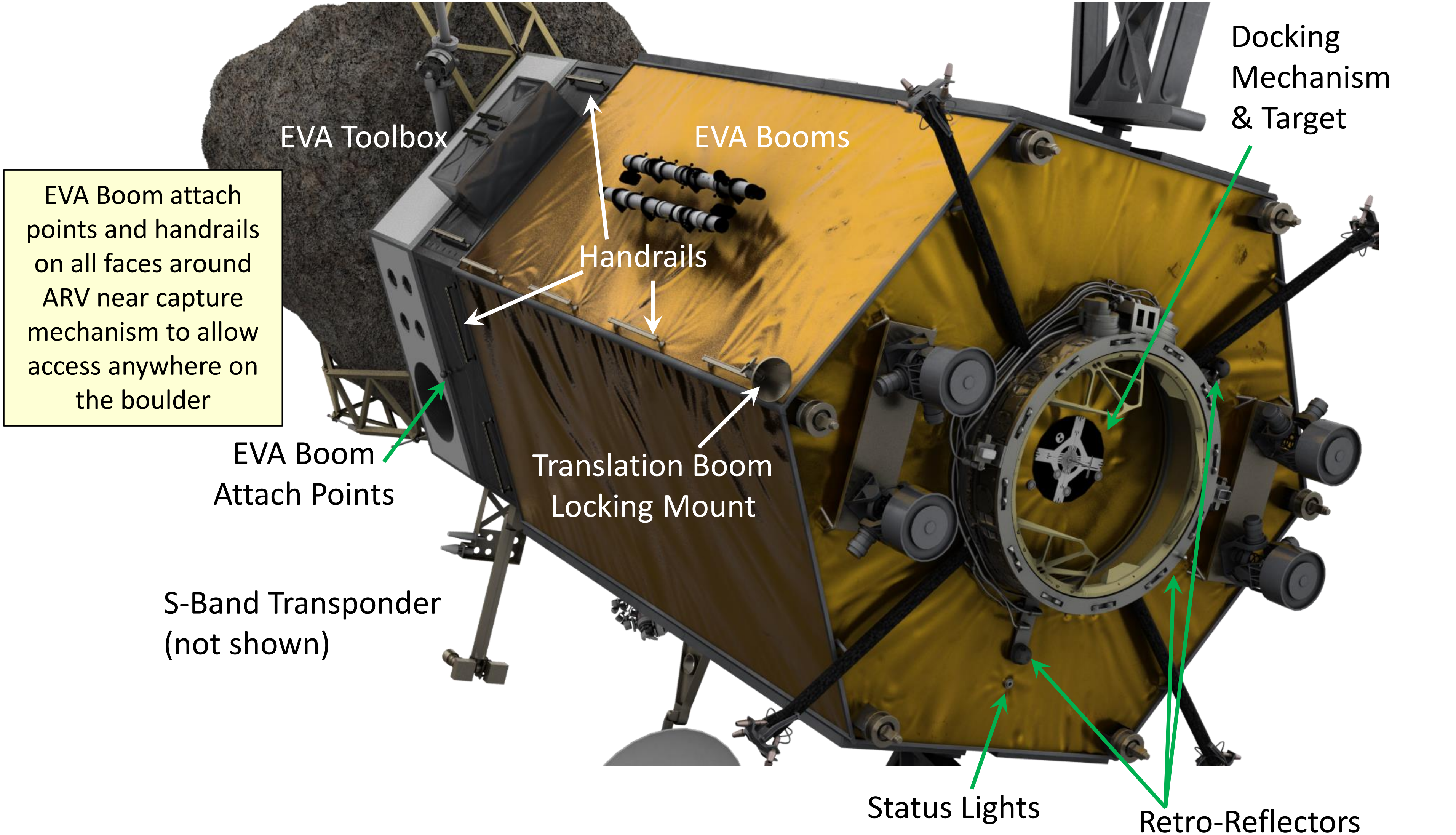
- **ARM robotic spacecraft and Orion are augmented with mission kits to enable crewed exploration of the returned asteroid material**
  - **Robotic vehicle**
    - **Passive International Docking Standard System compliant docking mechanism**
    - **EVA handrails and boom attachment points**
    - **Common AR&D Sensors**
    - **S-Band Comm**
    - **EVA tool box with tools**
  - **Orion Kits**
    - **Common AR&D Sensors**
    - **EVA Tools and Translation Aids**
    - **EVA Communications**
    - **Cabin Repress**
    - **Active IDSS Docking Mechanism**
    - **EVA Capable Suit**
    - **Exploration Portable Life Support System**
    - **Suit Servicing and Recharge**



Robotic Vehicle Enhancements

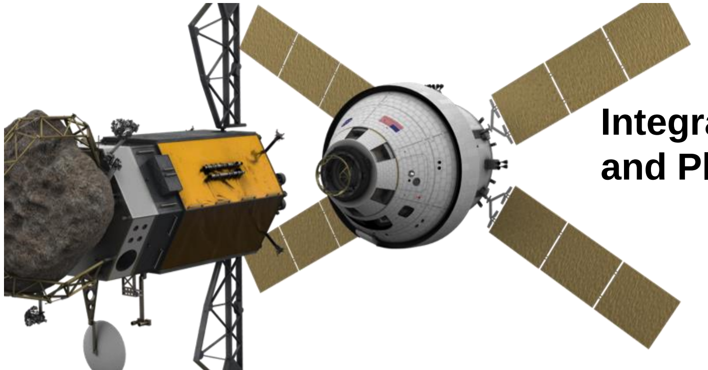
Orion Kits

ARRM Support for Crewed Mission

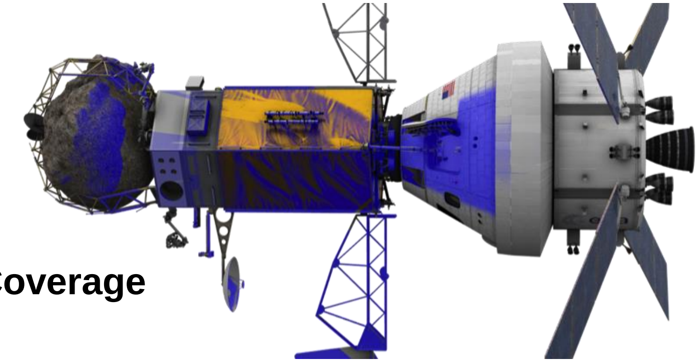


Crewed Mission Integrated Analysis

- **Orion/Robotic Vehicle Integrated Analysis**
  - Deliverables synced with robotic mission milestones including requirements TIM in Dec 2015, SDR and SDVF
- **Integrated Loads**
  - Integrated loads analysis - including docking, plume loads, attitude control, intravehicular and extravehicular activity (EVA) - for Orion/robotic vehicle mission phases
  - Early loads analysis informs robotic vehicle requirements development
- **Integrated Thermal Analysis**
  - Orion and robotic vehicle thermal control capability during docked attitudes.
- **Integrated Communications Coverage**
  - Error budgets and link margins for joint mission communications
  - Robotic vehicle and Orion space-to-ground comm coverage during critical mission phases. Early analysis will inform robotic vehicle antenna placement to minimize interference with EVA operations.
  - Vehicle-to-crew member communications coverage and multipath analysis for EVA operations
- **Crewed Mission Trajectory**
  - Design reference mission including Orion nominal, abort and early return analysis
  - Integrated trajectory analysis with ARRM project to examine robotic mission DRO phasing.



Integrated Docking and Plume Loads



EVA Comm Coverage

Small Bodies Assessment Group Engagement

- **Summary briefing of the FAST effort provided at the 14th Meeting of the NASA Small Bodies Assessment Group (SBAG) on January 28, 2016.**

- **ARM draft finding was released by SBAG on February 4, 2016:**

“SBAG continues to appreciate NASA’s efforts to engage and communicate with the planetary defense and small bodies science communities regarding the Asteroid Redirect Mission (ARM). **The 100 applications for the Formulation Assessment and Support Team (FAST) show the high level of interest of the community in participating in the formulation of ARM.** SBAG thanks the ARM team for creating the FAST and the community members that volunteered and were selected for the FAST, for the substantial work completed in a short timeframe. **SBAG encourages the continued engagement between the ARM team and the small bodies community as the mission moves forward and supports the plan for a competed opportunity this year to establish the Investigation Team membership.** Consistent with previous findings, for science-driven missions, SBAG continues to support the priorities identified in the Decadal Survey to guide use of Planetary Science Division (PSD) resources and funds.”

SMPAG Statement on Asteroid Orbit Deflection Demos

- **Statement on Asteroid Orbit Deflection Demonstrations – agreed at the 6th Space Mission Planning Advisory Group meeting, February of 2016:**

“Given the degree of international interest in asteroid research and awareness of the impact hazard, advantage should be taken of opportunities to investigate asteroid deflection physics, techniques and effects as a part of science and technology demonstration missions. While general science and technology efforts are vital, the Space Mission Planning Advisory Group (SMPAG) has identified the need to gain sufficient confidence in the viability of any proposed technique to deflect an asteroid from an impact trajectory. **Therefore the performance of the deflection technique to be utilized must have been actively demonstrated in a realistic planetary defence scenario to increase the current level of confidence.**

The SMPAG encourages actual demonstration of the kinetic impactor technique with a space mission, as it appears at this point in time to be the most technologically mature method of asteroid deflection. **SMPAG also supports the investigation of the gravity tractor technique for demonstration as a part of any space mission using ion or other low-thrust propulsion technology planned to visit an asteroid.** SMPAG also encourages the investigation and technology maturation of other potential deflection and impact mitigation techniques to determine their viability, particularly in combination with other missions.”

ARM Upcoming Events

- **Electric Propulsion Thruster and PPU contract award** **May 2016**
- **ARRM Key Decision Point – B** **Summer 2016**
- **Investigation Team Call Release** **Summer 2016**
- **Completion of study contracts and initiation of Phase 2 for spacecraft bus** **Summer 2016**
- **Actuated prototype of contact and restraint system complete** **Sep 2016**

NASA

Back Up

External Engagement (1)

- **June 2013: NASA issued a Request for Information (RFI) to seek new ideas on how to implement the ARM and Agency Grand Challenge, alternative ARM concepts, and innovative approaches to broaden participation from partners and the public.**
  - Received 402 responses, invited 96 response ideas for further exploration, acted on many of them
- **Ideas Synthesis**
- **March 2014: NASA issued the Asteroid Redirect Mission Broad Agency Announcement (BAA), soliciting proposals for concept studies in areas including asteroid capture systems, rendezvous sensors, adapting commercial spacecraft for the Asteroid Redirect Mission and feasibility studies of potential future partnership opportunities for secondary payloads and the crewed mission.**
  - In June 2014, NASA announced it selected 18 of the 108 BAA proposals for six-month studies, totaling $4.9 million in awards.

External Engagement (2)

- **Interactions and assessments, information during pre-formulation**
  - Briefings and interactions with feedback
  - SBAG Special Action Team – August 2014
  - Curation and Planning Team for Extra-Terrestrial Materials input – December 2014
- **Expert and Citizen Assessment of Science and Technology**
  - Phoenix, AZ and Boston, MA: fall and winter 2014
- **May 2015: NASA issued another RFI for Spacecraft Bus Concepts to Support the Asteroid Redirect Robotic Mission and In-Space Robotic Servicing**
  - Additional information for acquisition strategy
- **June 2015 Notice of formation of FAST**
  - Toward Investigation Team for mission

Small Bodies Assessment Group (SBAG) Semi-Annual Meeting June 2015

SBAG appreciates NASA's efforts to engage and communicate with the planetary defense and small bodies science communities about the Asteroid Redirect Mission (ARM) and the extent to which modifications in mission design have been responsive to concerns from those groups.

In particular, the reference target asteroid 2008 EV_5 offers well-documented opportunities, having been previously the sample return target for ESA's MacroPolo-R candidate mission. SBAG encourages continued engagement between mission planners and the small bodies community as the mission moves forward and supports the plans for the competed Formulation Assessment and Support Team (FAST) and the succeeding Investigation Team (IT). However, it is important to note that for science-driven missions, SBAG continues to support the priorities identified in the Decadal Survey to guide use of Planetary Science Division (PSD) resources and funds.

Draft Finding Released July 22, 2015

http://www.lpi.usra.edu/sbag/findings/SBAG13_07102015.pdf

2015 IAA Planetary Defense Conference

Regarding planetary defense deflection demonstrations such as ARM and AIDA:

The joint NASA-ESA Asteroid Impact and Deflection Assessment (AIDA) mission, which will measure the effect of a kinetic impactor on a moon of a binary asteroid, and NASA's test of the enhanced gravity tractor concept as part of its **proposed Asteroid Redirect Mission (ARM),** which would utilize a boulder from the target asteroid to increase the mass of the gravity tractor, **would both help lower uncertainties of these two deflection techniques and give confidence about capabilities to move an asteroid in a controlled way.**

Both of these missions have significant science benefits and are representative of how we can build confidence in deflection technologies by merging the two interests.

Final Report Posted July 22, 2015

http://iaaweb.org/iaa/Scientific%20Activity/pdcreportfinal.pdf

ARRM Alternate Target List

Asteroid	H (mag)	Estimated Diameter (m)	Semi Major Axis (au)	Orbit Period (yr)	Eccentricity ( )	Next Optical Opportunity	Next Arecibo Radar Opportunity	Next Goldstone Radar Opportunity	Asteroid returned mass (t)*
2008 EV5 (reference)	20	~ 400m	0.958	0.94	0.084	2021-12 [21.8]	2023-12 [9600]	2023-12 [320]	20
1999 JU3	19.2	251-1124	1.189	1.3	0.19	2016-01 [21.7]	2020-12 [1200]	2020-12 [76]	5.9
Bennu	20.9	~ 500m	1.126	1.2	0.203	2017-02 [20.1]	2037-01 [34]	none	1.2
2014 YD	24.3	24-107	1.07	1.11	0.087	2024-10 [22.0]	none	none	83.4
2000 SG344	24.7	20-89	0.978	0.97	0.067	2028-04 [19.1]	2028-05 [3.e3]	2028-05 [59]	34.7
2013 BS45	25.9	11-51	0.993	0.99	0.084	none	none	none	35.8
2001 QJ142	23.7	33-142	1.06	1.09	0.086	2023-11 [19.6]	2024-04 [74]	none	35.7
2012 UV136	25.5	14-62	1.01	1.01	0.138	2016-07 [22.3]	2020-05 [570]	2020-05 [22]	34.6
2001 CQ36	22.5	55-246	0.938	0.91	0.178	2021-01 [20.5]	2021-02 [18]	2031-02 [150]	9.5
2006 FH36	22.9	46-205	0.955	0.93	0.198	2019-03 [23.7]	2021-08 [17]	none	11.3
2007 UY1	22.9	46-205	0.951	0.93	0.175	2019-09 [23.4]	2020-10 [32]	2022-02 [18]	6.8

** Trajectory assumes Dec 2020 launch, 2025 return, medium thrust curve, 4820 kg SEP dry mass, 50% duty cycle on asteroid approach*

ARRM Level 1 Requirements (Updated 11/18/15)

Level 1 Requirements (11/18/15) Draft	
1	ARRM shall develop and demonstrate a high-power, high-total impulse solar electric propulsion (SEP) system with an input power level of at least 40kW and a useable capacity of 5 t of propellant that is extensible to future human and robotic missions to Mars at a power level of at least 150 kW.
2	The ARRM shall demonstrate solar array technology with the power-to-mass ratio, stowed volume efficiency, deployed strength and radiation tolerance applicable for future robotic and human missions to Mars.
3	ARRM shall be capable of acquiring a boulder with a maximum extent of 6 m from a near-Earth asteroid.
4	ARRM shall be capable of placing the ARRM Flight System and at least 20 t of acquired asteroid material in a crew-accessible orbit in cis-lunar space by 2025 and shall then be compatible with crew-safe joint operations with Orion.
5	ARRM shall be capable of redirecting the acquired asteroid boulder to a final, stable lunar distant retrograde orbit (LDRO), and releasing the boulder there up to 6 years after launch.
6	ARRM shall have the capability to perform a demonstration of a “slow push” planetary defense asteroid deflection technique.
7	ARRM shall provide volume, mass, power, and data for contributed hardware.
8	ARRM shall be interface and performance compatible with Delta IV Heavy, Falcon Heavy and Space Launch System (SLS) until launch vehicle (L/V) selection by Project System Design Review.
9	ARRM shall implement the project as a capability demonstration mission (including defining and applying unique implementation techniques) for launch readiness by the end of 2020 (TBR) with a cost capped budget of <$1.25B (TBR) (not including L/V or Operations).
10	ARRM shall provide: power and communications interfaces for future potential visiting vehicles and provisions for being refueled (Xe and hydrazine).

ARRM SRB Charter: Success Criteria for Review for KDP-B

1. The proposed mission/system architecture is credible and responsive to program requirements and constraints, including technical and programmatic resources.
2. The mission can likely be achieved within available resources with acceptable risk.
3. The project's mission/system definition and associated plans are sufficiently mature to begin phase B.
4. The architecture tradeoffs are completed, and those planned for Phase B adequately address the issues and option space.
5. A sound process for the allocation and control of requirements at all levels has been defined, and maturity of the requirements definition, achievability, verification and associated plans are sufficient to begin Phase B.
6. Interfaces with external entities and between major internal elements, especially the crewed mission, have been identified and plans for adequate definition during Phase B are defined
7. Significant development, mission, and health and safety risks are identified and technically assessed, and a process and resources exist to manage the risks.
8. Adequate planning exists for the development of any enabling new technology.
9. The operations concept is consistent with proposed design concept(s) and is in alignment with the mission requirements.
10. The project has demonstrated appropriate compliance with applicable NASA and implementing Center requirements, standards, processes, and procedures.
11. TBD, TBC (to be confirmed) and TBR items are clearly identified with acceptable plans and schedule for their disposition.

Reference: Derived from NASA NPR 7123.1b success criteria for SRR and MDR