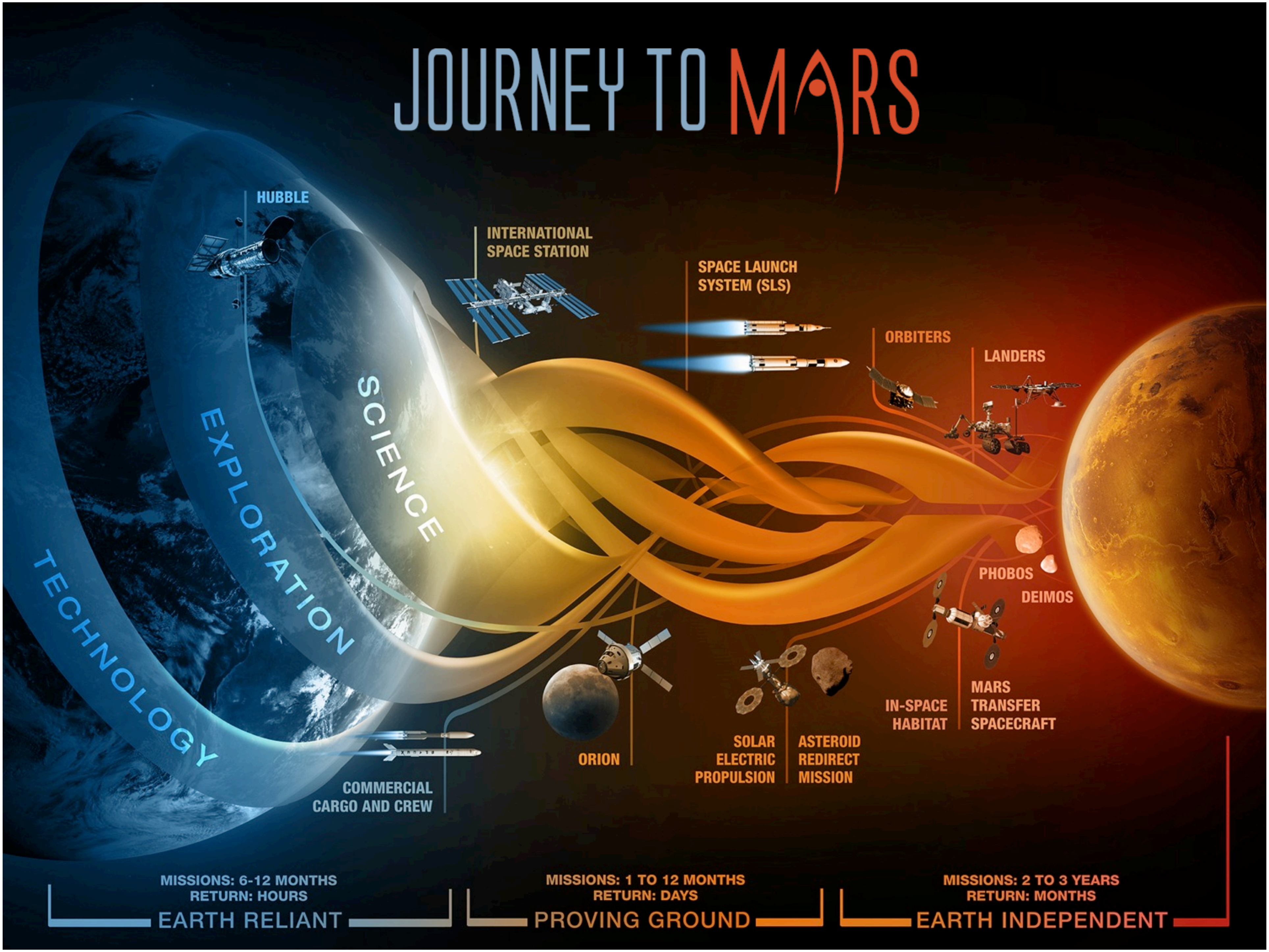
National Aeronautics and Space Administration

Asteroid Redirect Mission Update

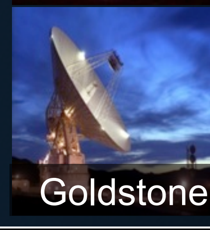
April 2015


JOURNEY TO MARS
HUBBLE
INTERNATIONAL SPACE STATION
SPACE LAUNCH SYSTEM (SLS)
ORBITERS
LANDERS
SCIENCE
EXPLORATION
TECHNOLOGY
PHOBOS
DEIMOS
ORION
SOLAR ELECTRIC PROPULSION
ASTEROID REDIRECT MISSION
IN-SPACE HABITAT
MARS TRANSFER SPACECRAFT
COMMERCIAL CARGO AND CREW
MISSIONS: 6-12 MONTHS
RETURN: HOURS
EARTH RELIANT
MISSIONS: 1 TO 12 MONTHS
RETURN: DAYS
PROVING GROUND
MISSIONS: 2 TO 3 YEARS
RETURN: MONTHS
EARTH INDEPENDENT

Asteroid Redirect Mission: Three Main Segments

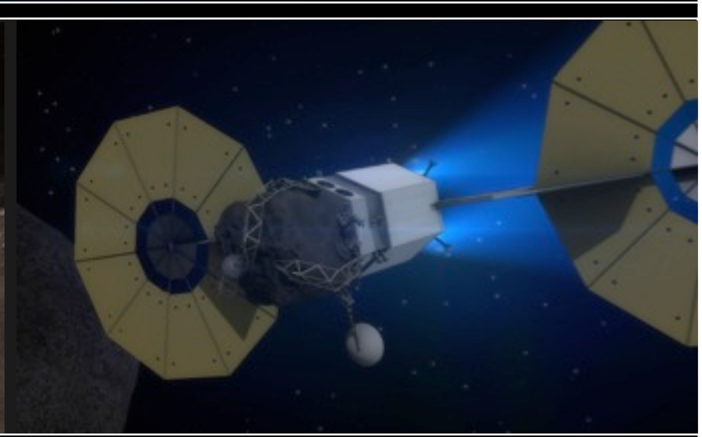
IDENTIFY

Ground and space based assets detect and characterize potential target asteroids



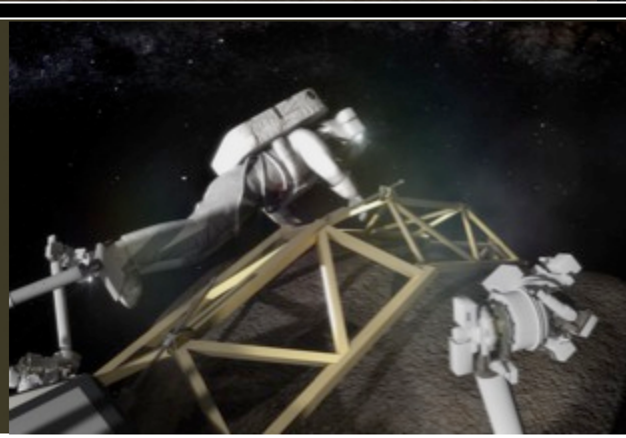
REDIRECT

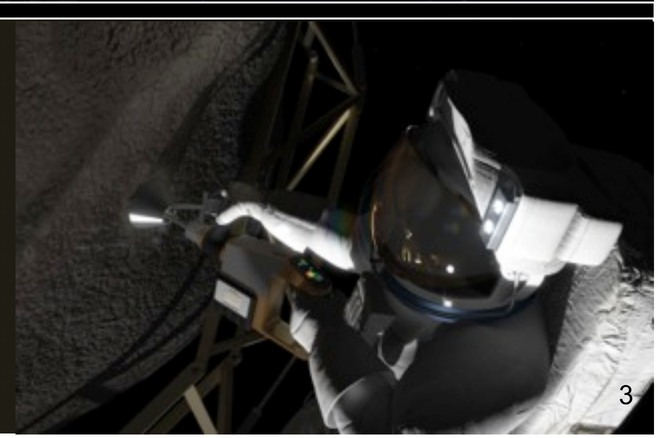
Solar electric propulsion (SEP) based system redirects asteroid to cis-lunar space.



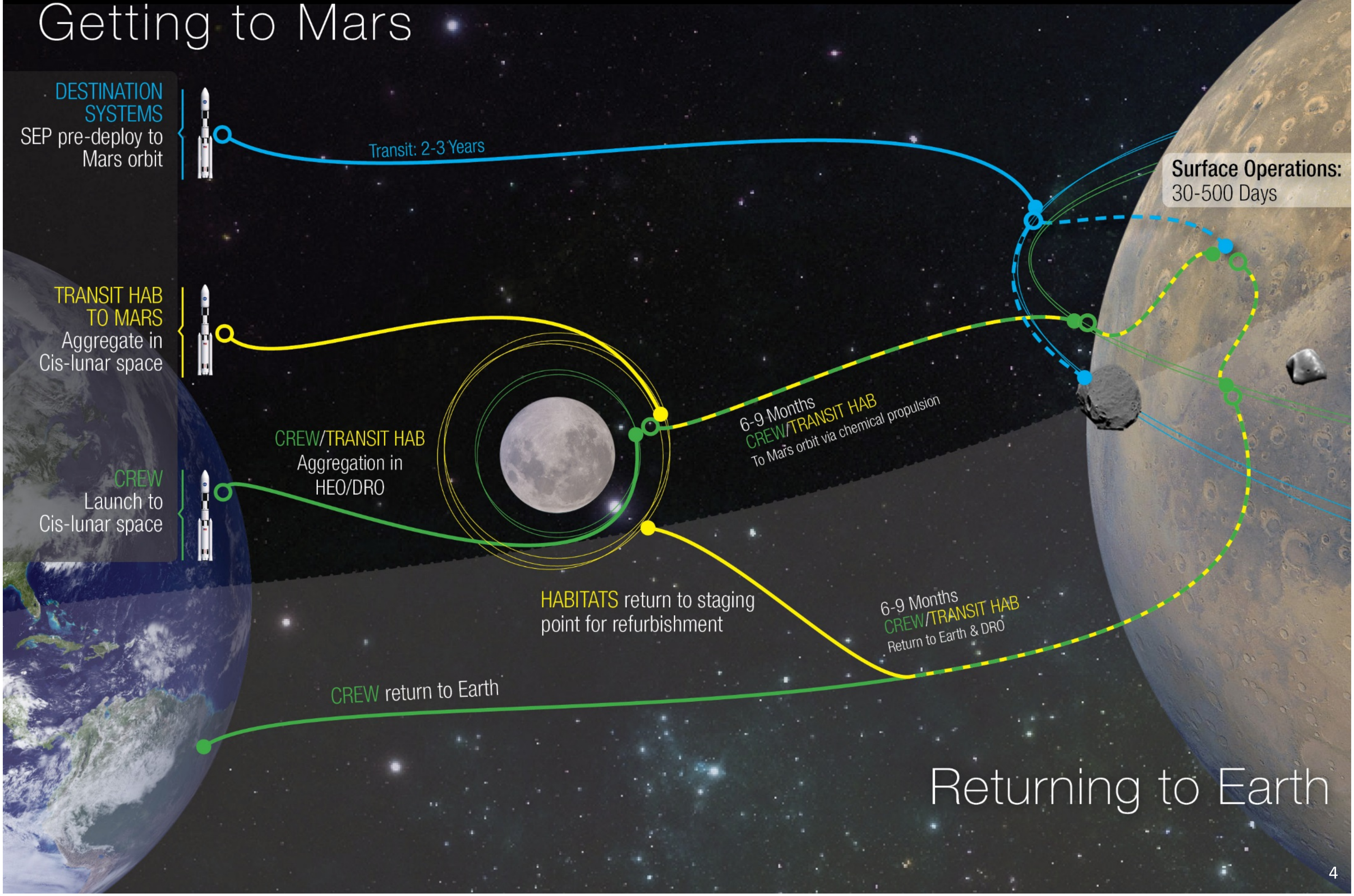
EXPLORE

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





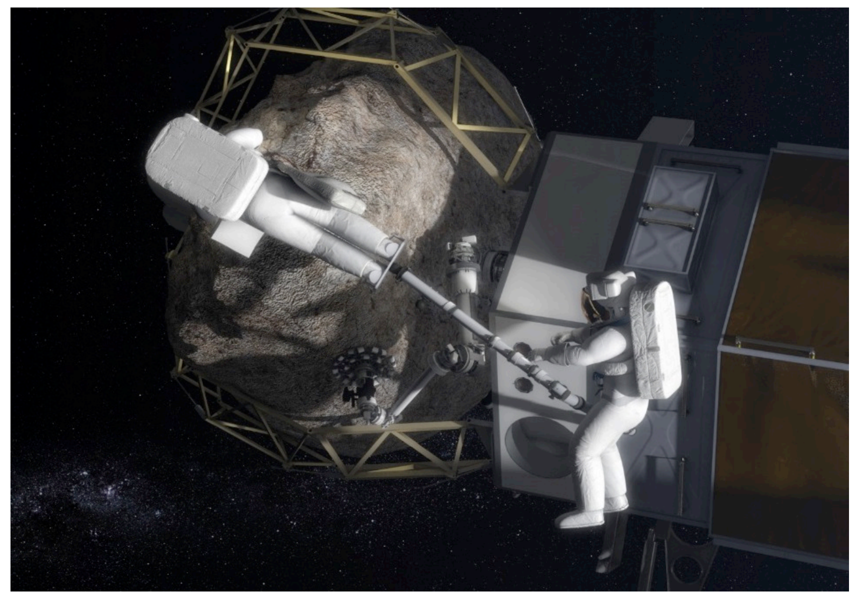
A Sustainable Exploration Approach
Mars Split Mission Concept



Introduction

- A key component of NASA's exploration strategy is to perform early, affordable missions that test and prove key capabilities required for long-duration, deep space exploration while developing the technologies we will need for future exploration and continuing human health and performance research on the International Space Station.

- The Asteroid Redirect Mission (ARM) is a compelling combination of robotic and crewed missions which substantially contributes to advancing technologies, systems, and operational capabilities required for human missions to Mars.



Introduction (cont'd)

- **Through ARM, NASA will develop, test and use a number of key capabilities that will be needed for future exploration purposes, as well as providing other broader benefits**
  - Advanced high-power, long-life, high through-put solar electric propulsion
  - Autonomous rendezvous and proximity operations
  - Capture and control of non-cooperative objects
  - Rendezvous and docking systems
  - Deep space trajectory and navigation methods
  - Advanced crew extra-vehicular activity (EVA) systems and techniques
  - Crewed sample collection and containment
- **ARM will Demonstrate basic asteroid deflection techniques that will inform future planetary defense approaches**
- **Opportunities exist for science and partnership interests, such as for *in-situ* resource utilization and follow-on use of the SEP based spacecraft**
- **ARM provides an opportunity to execute development with lean implementation**
  - Clean interfaces, streamlined processes
  - Common rendezvous sensor procurement

PROVING GROUND OBJECTIVES

Enabling Human Missions to Mars

VALIDATE through analysis and flights

✓Advanced Solar Electric Propulsion (SEP) systems to move large masses in interplanetary space

✓Lunar Distant Retrograde Orbit as a staging point for large cargo masses en route to Mars

✓SLS and Orion in deep space

- Long duration, deep space habitation systems

✓Crew health and performance in a deep space environment

- In-Situ Resource Utilization in micro-g
- Operations with reduced logistics capability
- Structures and mechanisms

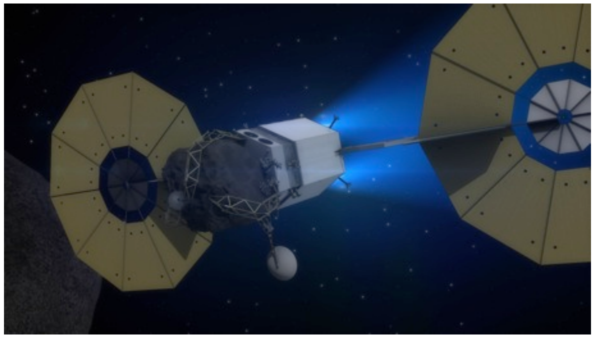
CONDUCT

✓EVAs in deep space with sample handling in micro-g

✓Integrated human and robotic mission operations

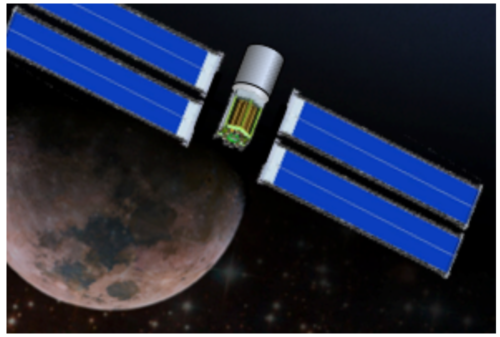
- Capability Pathfinder and Strategic Knowledge Gap missions

SEP Module Extensibility Concept for Mars



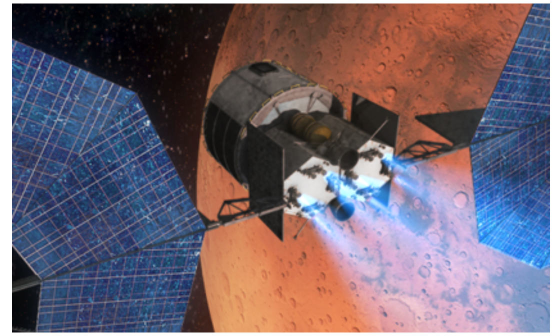
Asteroid Redirect Mission

- 50-kW Solar Array
- 40-kW EP System
- 10-t Xenon Capacity with Refueling Capability



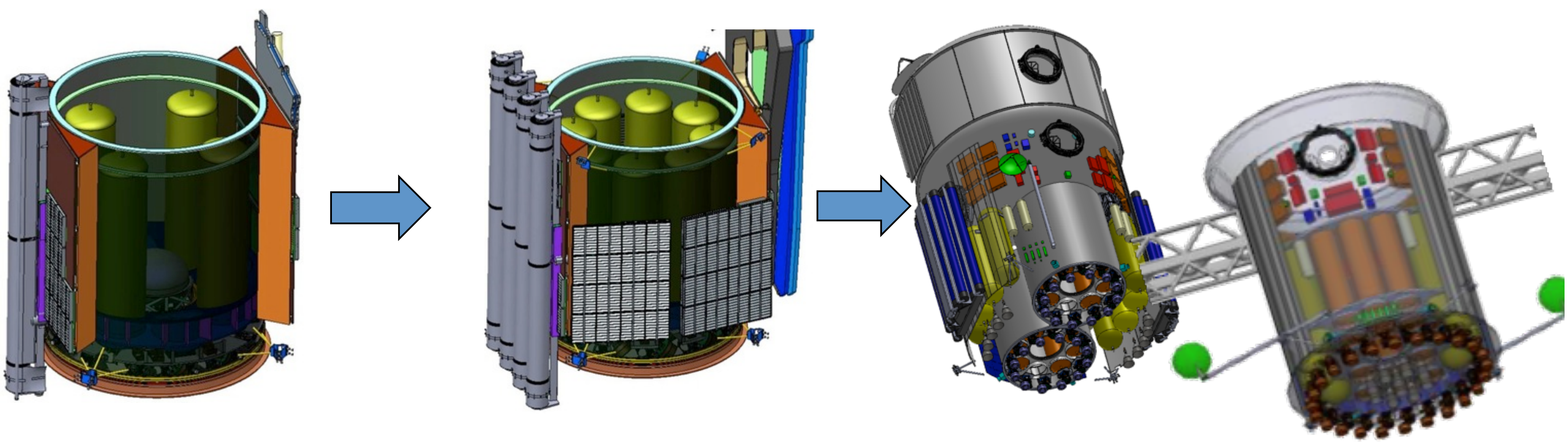
SEP/Chemical

- 190-kW Solar Array
- 150-kW EP System
- 16-t Xenon Capacity



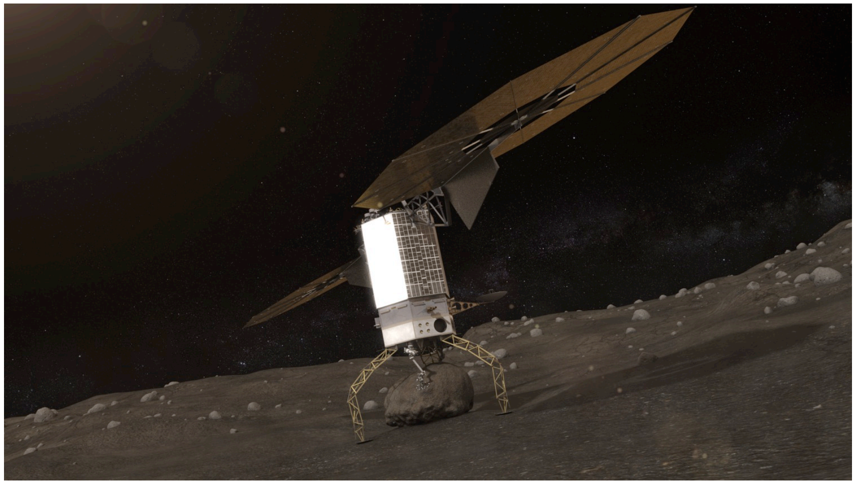
Hybrid

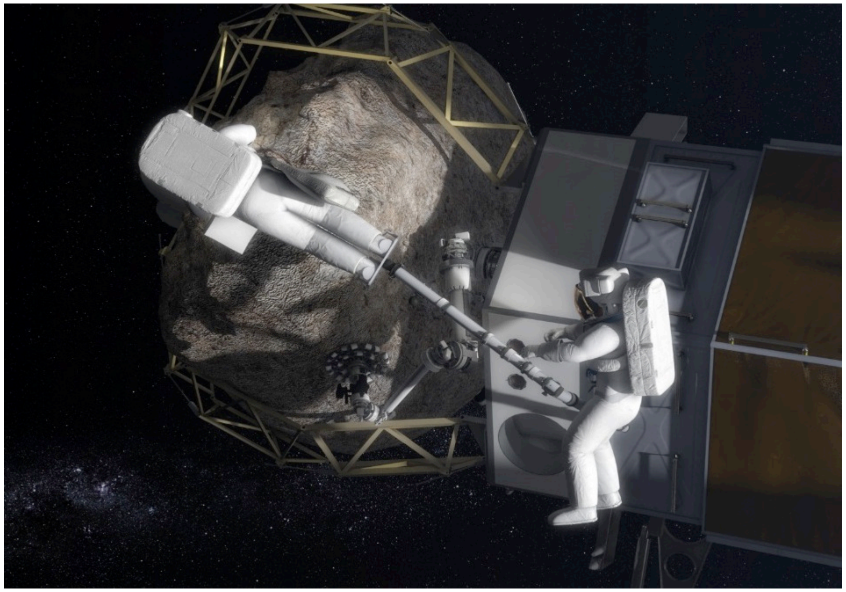
- 250 to 400-kW Solar Array
- 150 to 300-kW EP System
- 24-t Xenon Capacity With Xe Refueling Capability



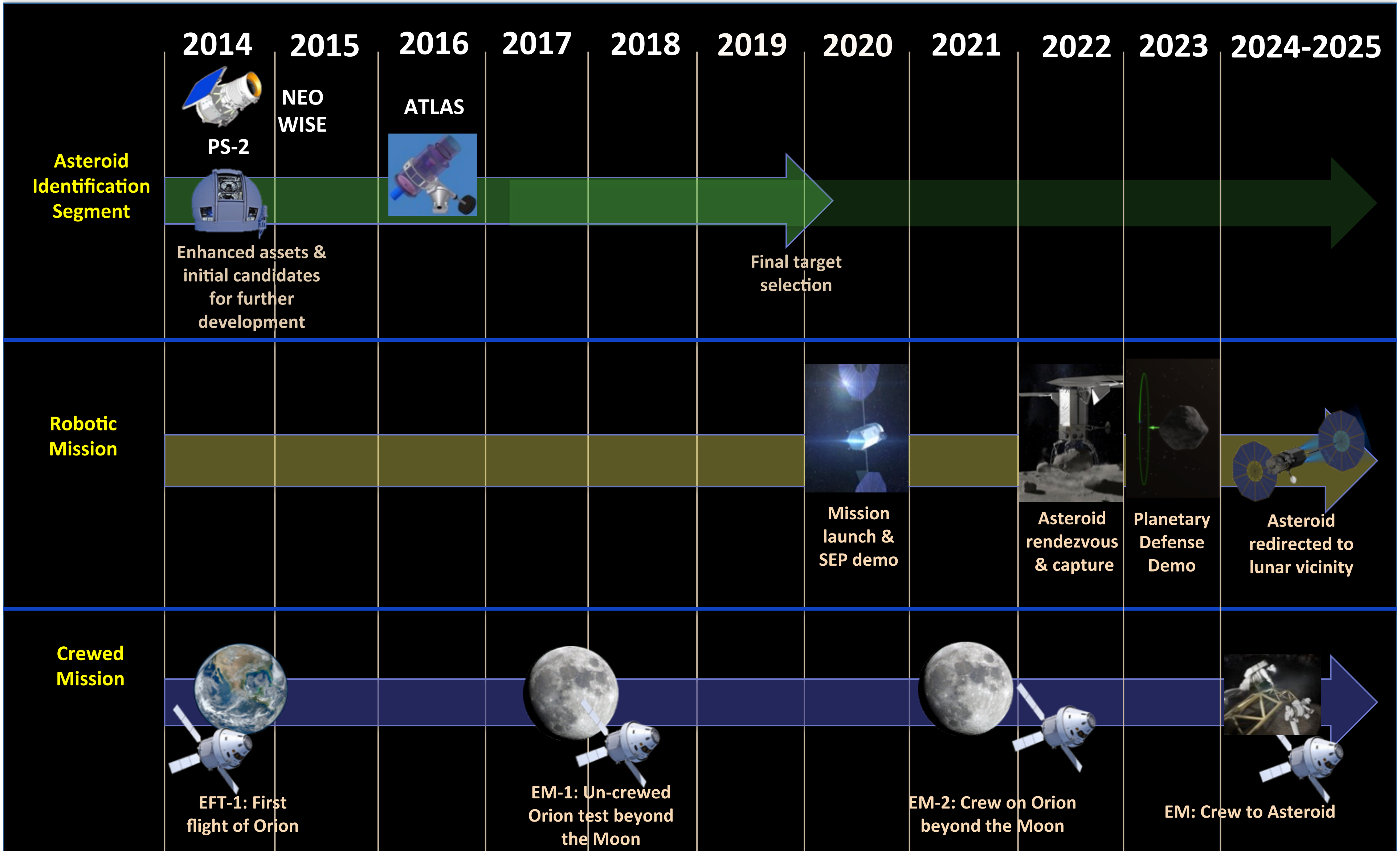
Key Aspects of ARM

- **Moving large objects through interplanetary space using SEP**
- **Integrated crewed/robotic vehicle operations in lunar distant retrograde orbit (LDRO)**
  - Integrated attitude control, e.g. solar alignment
  - Multi hour EVAs
- **Lean implementation**
  - Clean interfaces, streamlined processes
  - Common rendezvous sensor procurement for robotic vehicle and Orion
- **Integrates robotic mission and human space flight (HSF) capabilities**
  - HSF hardware deliveries to and integration and test with robotic spacecraft
  - Joint robotic spacecraft and HSF mission operations





ARM Alignment Strategy



Objectives of Asteroid Redirect Mission
In Order of Priority

1. **Conduct a human spaceflight mission involving in-space interaction with a natural object, providing systems and operational experience required for human exploration of Mars.**

2. **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.**

3. Enhance detection, tracking and characterization of Near Earth Asteroids, enabling an overall strategy to defend our home planet.

4. Demonstrate basic planetary defense techniques that will inform impact threat mitigation strategies to defend our home planet.

5. 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.

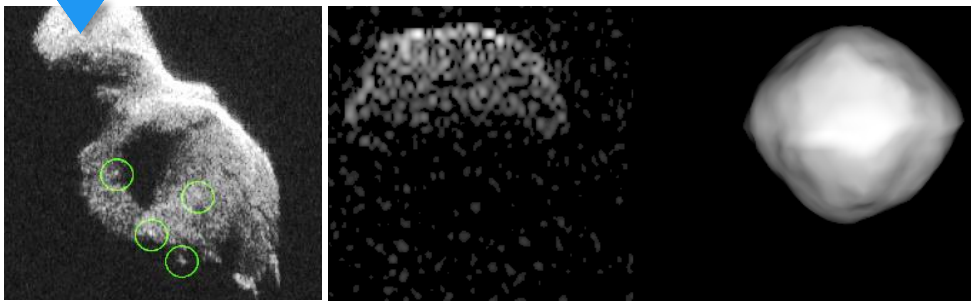
Draft Level 1 Requirements

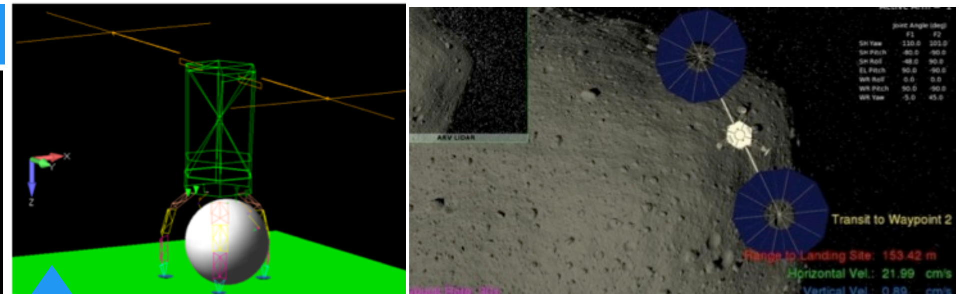
In addition to draft Level 1 requirements to fulfill the mission objectives:

- ARRM shall be interface compatible with EELV-class launch vehicles, Falcon Heavy, and SLS until launch vehicle selection, expected by Project System Design Review.
- ARRM shall implement the project as a capability demonstration mission including defining and applying lean implementation techniques to achieve a launch readiness by the end of 2020 with a cost capped budget of <$1.25B (not including launch vehicle or Operations).
- ARRM shall provide resources including power and communications for future potential visiting vehicles, release of the asteroid and provide the provisions for future refueling (Xe and N_2H_4).

Asteroid Redirect Mission: 2014 Advancements

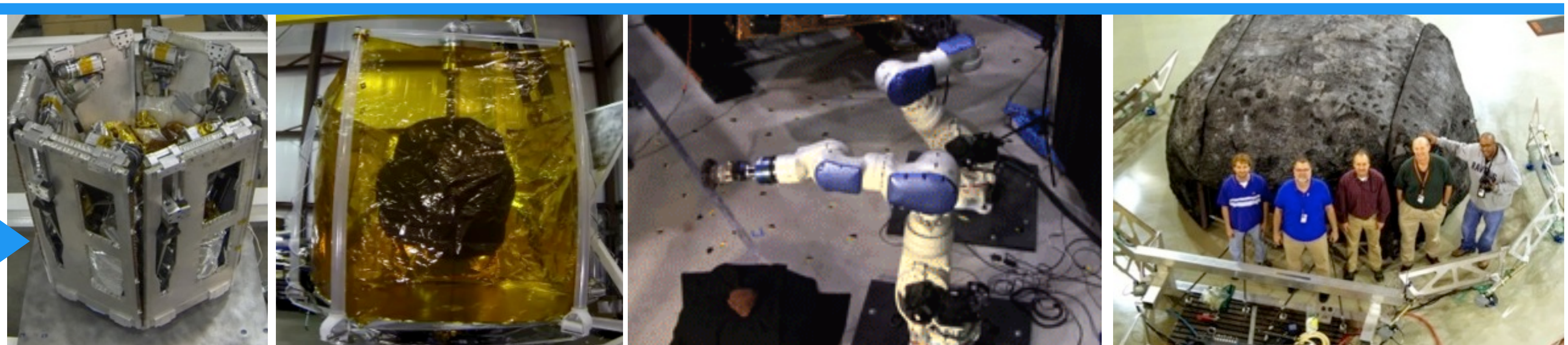
IDENTIFYING CANDIDATE ASTEROIDS





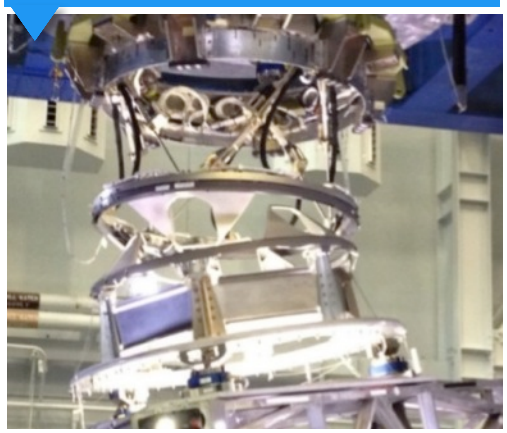
MISSION DESIGN AND SIMULATION OF CRITICAL MISSION OPERATIONS

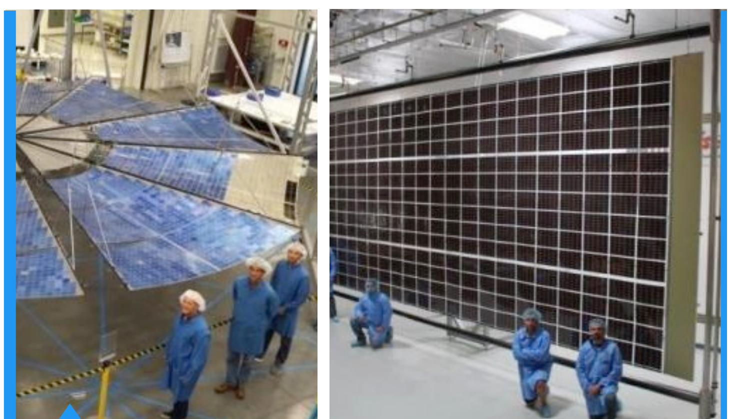
PROTOTYPING AND TESTING CAPTURE OPTIONS



PROTOTYPING AND TESTING MODIFIED LAUNCH AND ENTRY SUIT

INTERNATIONAL DOCKING SYSTEM





SOLAR ELECTRIC PROPULSION

Robotic Mission Concepts and Trades
Summary of Study Contract Results (1)

- **Asteroid Capture Systems (Option A related):**
  - Contractors: Airborne, Jacobs
  - Developed alternate design concepts to capture a small asteroid including all-inflatable and all-mechanical architectures
  - Fabricated and performed demonstrations of approaches
- **Asteroid Capture Systems (Option B related):**
  - Contractors: Altius, SSL MDA
  - Developed alternate robotic system architectures to extract a boulder of the surface of an asteroid
  - Examined augmentation techniques to aid in boulder extraction involving anchoring, excavating, extracting, and dust collection
  - Conducted testing of various design concepts and prototypes
- **Rendezvous and Proximity Operations Sensors**
  - Contractors: Ball Aerospace, Boeing
  - Significant design progress and risk reduction work performed, demonstrating compliance to the common specification supporting Orion, ARM, and satellite servicing
  - Addressed modularity in designs, providing alternate design implementation approaches

Robotic Mission Concepts and Trades
Summary of Study Contract Results (2)

- **Adapting Commercial Spacecraft for the Asteroid Redirect Vehicle**
  - Contractors: Boeing, Exoterra, Lockheed Martin, SSL
  - Provided design concepts, cost and schedule data, and procurement approaches to adapt existing commercial spacecraft to support ARM
  - Demonstrated extensibility options for Mars cargo application
- **Future Partnership Opportunities for Secondary Payloads**
  - Contractors: Planetary Resources, Deep Space Industries, Honeybee Robotics, Johns Hopkins Applied Physics Lab, Planetary Society
  - Provided concepts for secondary spacecraft support to enhance asteroid missions in a public-private partnership approach
  - Provided concepts for secondary payloads which could be manifested on the ARM robotic mission to enhance the missions
- **Future Partnership Opportunities for the Asteroid Redirect Crewed Mission:**
  - Contractors: Planetary Resources, Deep Space Industries, Honeybee Robotics
  - Provided commercial perspectives and addressed economic fundamentals of partnership potential for asteroid resource utilization
  - Developed concepts for drilling tools and sample caching systems that could be used by astronauts during a spacewalk on the asteroid.

Asteroid Redirect Robotic Mission (ARRM)
Mission Concept Review and Formulation Authorization

- **Objective: Review and Decisions**
  - **MCR**: Evaluate the feasibility of the proposed mission concept(s) and its fulfillment of the program's needs and objectives. Determine whether the maturity of the concept and associated planning are sufficient to begin Phase A.
  - **For approval to enter Phase A/KDP-A**: Project addresses critical NASA need; Proposed mission concept(s) is feasible; and associated planning is sufficiently mature to begin Phase A, and the mission can likely be achieved as conceived.
- **Held via special Agency Program Management Council on Mar 24**
  - MCR Chair: NASA Associate Administrator Robert Lightfoot
  - Review Team: Mission Directorate Associate Administrators, NASA Chief Engineer, NASA Chief of Safety & Mission Assurance
  - Additional Participants: members of Agency PMC including CFO, Center Directors, Office of Procurement, etc.

MCR Success Criteria

1. Mission objectives and draft level 1 requirements are clearly defined and stated.
2. The mission has evaluated alternative concepts and is shown to be able to meet the draft level 1 requirements and currently defined programmatic constraints.
3. The justification for the mission has been clearly identified including extensibility path to NASA's exploration plans.
4. The cost and schedule estimates are credible and sufficient resources are available for project formulation.
5. Technical and programmatic planning is sufficient to proceed to a project start including an approach for lean implementation
6. Risk and risk mitigation strategies have been identified and are reasonable based on technical risk assessments.
7. System design and functional requirements are sufficiently mature to initiate early procurements (e.g., solar, thrusters, PPU, tanks).

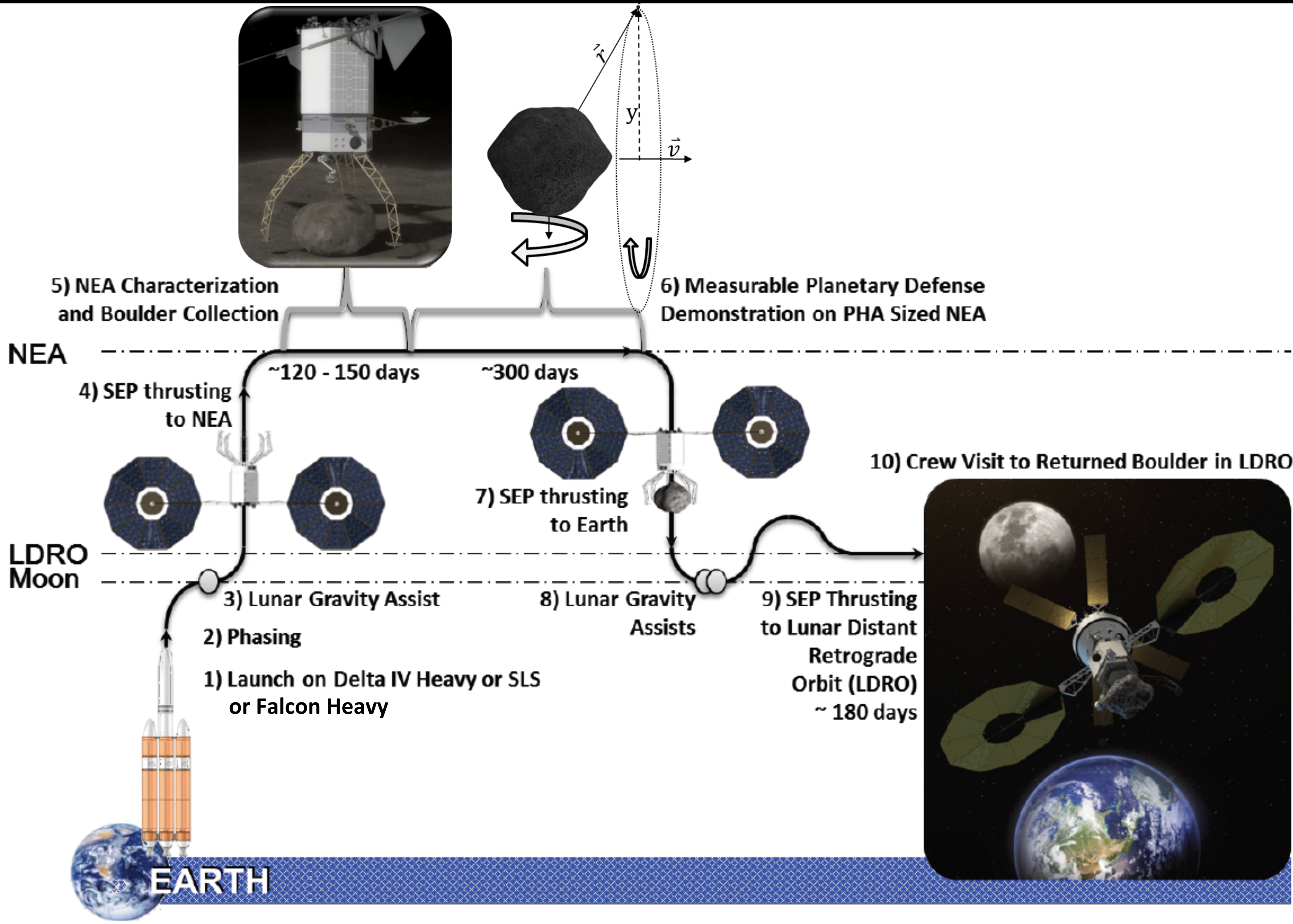
ARRM Formulation Guidance

- Capture option B
- Draft Level 1 requirements
- Target launch date Dec 2020
- Cost cap $1.25B not including launch vehicle and mission operations (Phase E)
- Internal and external dependencies
- Define capability demonstration implementation approach

NASA Approval to Proceed to begin Phase A Formulation for Robotic Mission

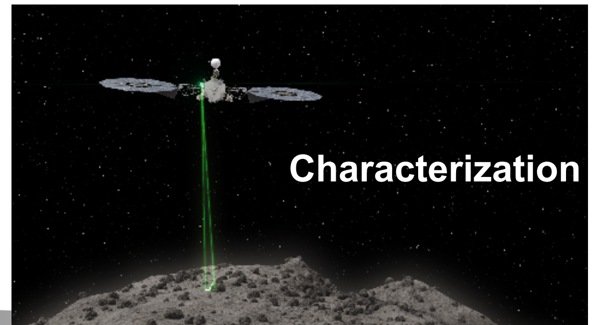
Asteroid Redirect Mission Highlights

ARRM Mission Concept Overview

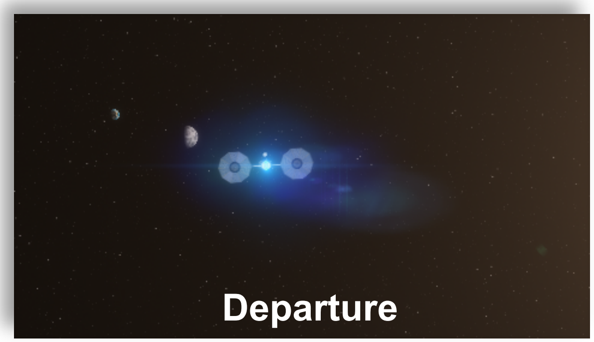


ARRM Capture Phase Overview

Approach	Characterization	Boulder Collection	Planetary Defense Demo
14 days	72 days	69 days	150 days (30 deflection + 120 hold & verify)



Note: Asteroid operations timeline varies depending on target asteroid. Times shown are for 2008 EV_5: total stay time of 305 days with 95 days of margin.



Current Valid ARRM Candidate Asteroid Targets

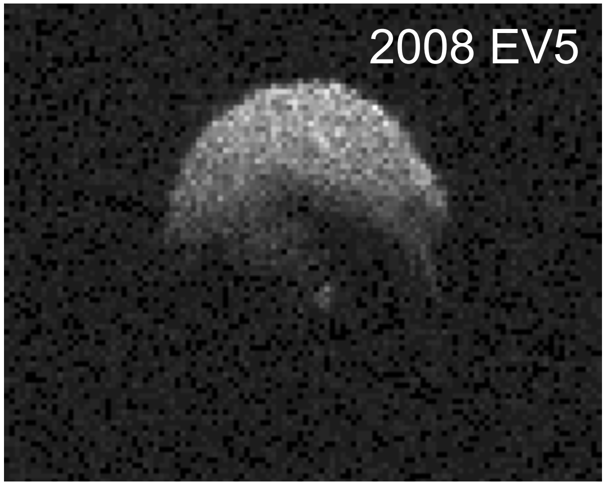
Candidate Option B Targets	Type	Mass, Diameter	Spin Period	V_∞ (km/s)	*Perihelion (AU)*	Absolute Magnitude *H*
2008 EV5	C	7.0×10^7t, 400m	3.73 hrs	4.41	1.04	20.0
Bennu	C	7.8×10^7t, 490m	4.30 hrs	6.36	1.36	20.8
1999 JU3	C	6.9×10^8t, 870m	7.63 hrs	5.08	1.42	19.2
Itokawa	S	3.5×10^7t, 320m	12.1 hrs	5.68	1.70	19.2

Precursors:

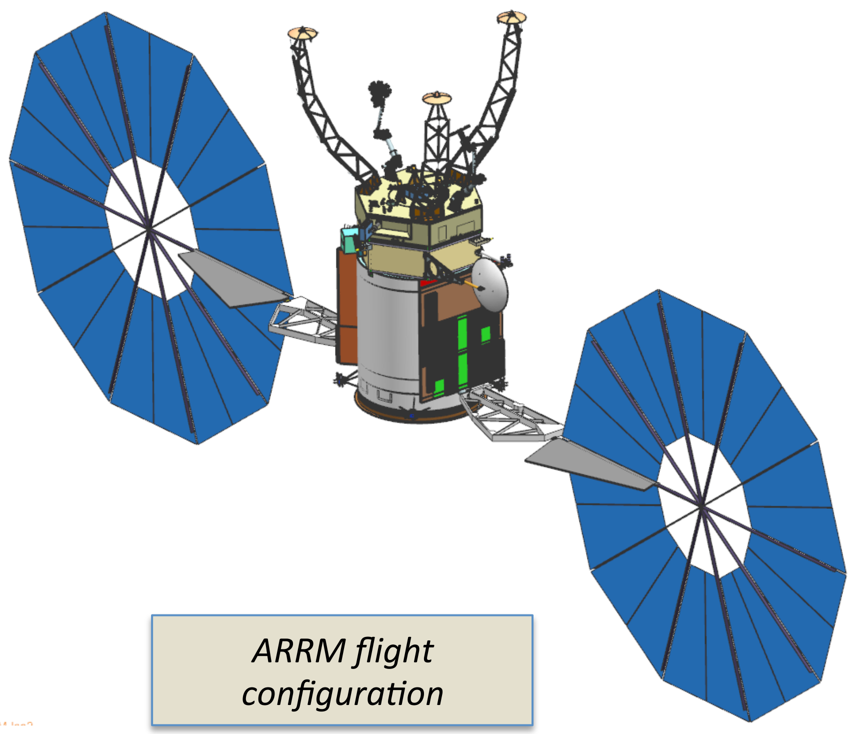
- Itokawa: Hayabusa (visited 2005)
- 1999 JU3: Hayabusa 2 (scheduled 2018)
- Bennu: OSIRIS-REx (scheduled 2018)
- 2008 EV5: No precursor, but radar detected boulders in 2008

NASA continues to look for additional targets in accessible orbits.

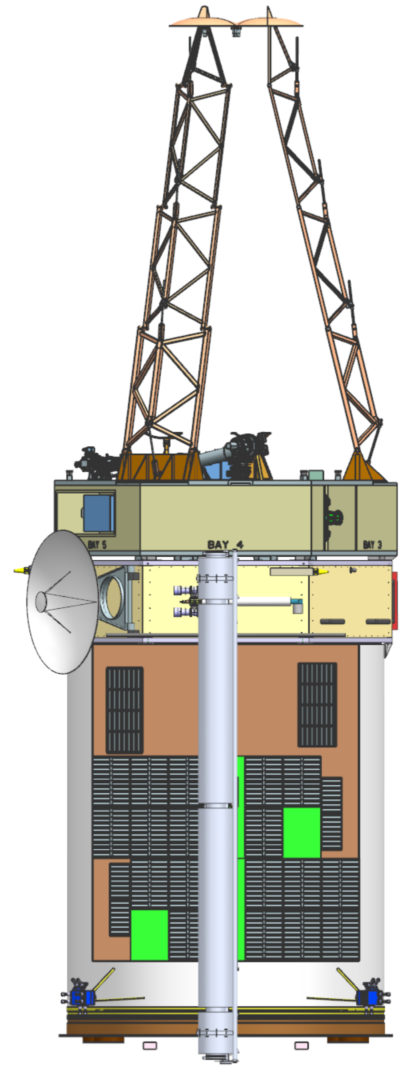
Reference ARRM Target



ARRM Baseline Concept Flight System Configurations

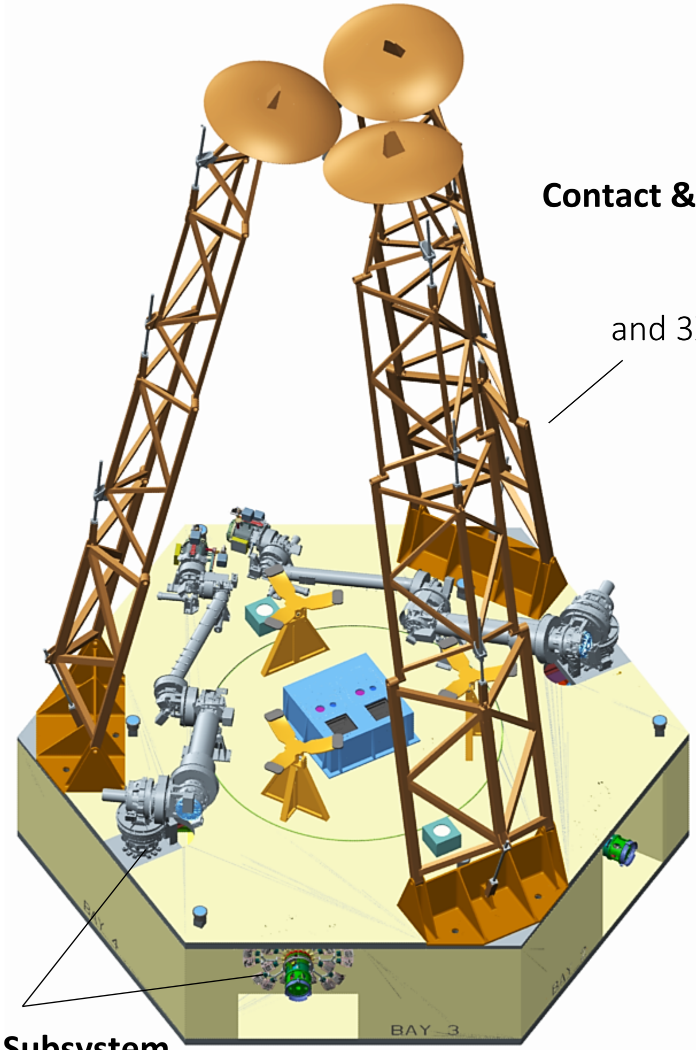


ARRM flight configuration

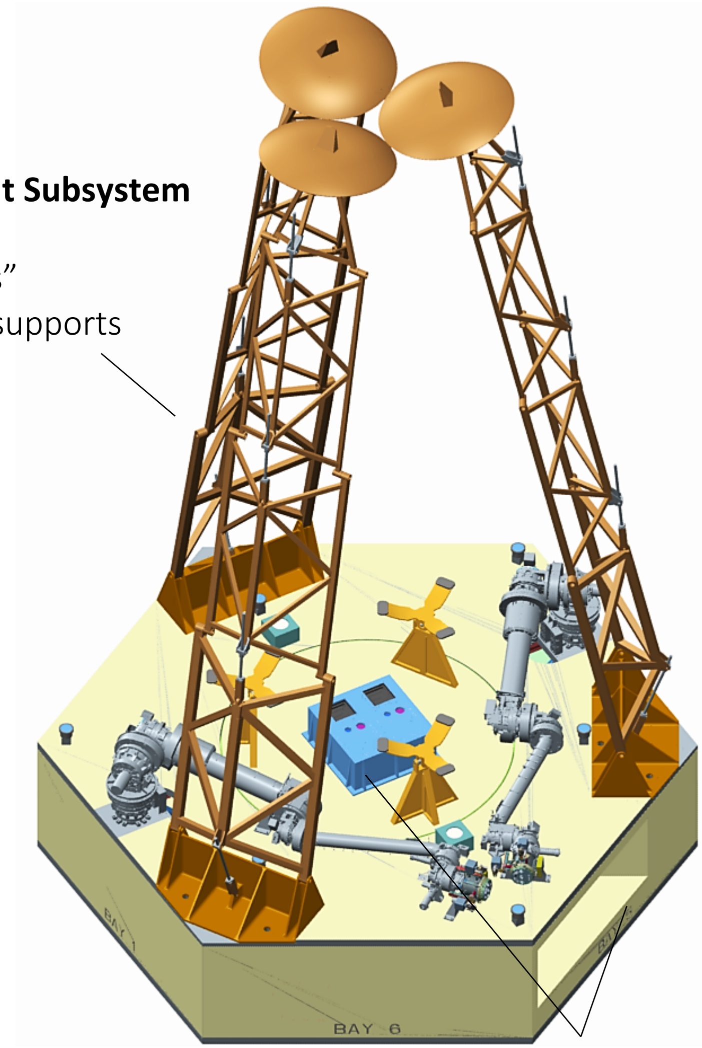


ARRM launch configuration

ARRM Baseline Concept Capture Module



Contact & Restraint Subsystem (CRS)
3X "legs"
and 3X cradle supports

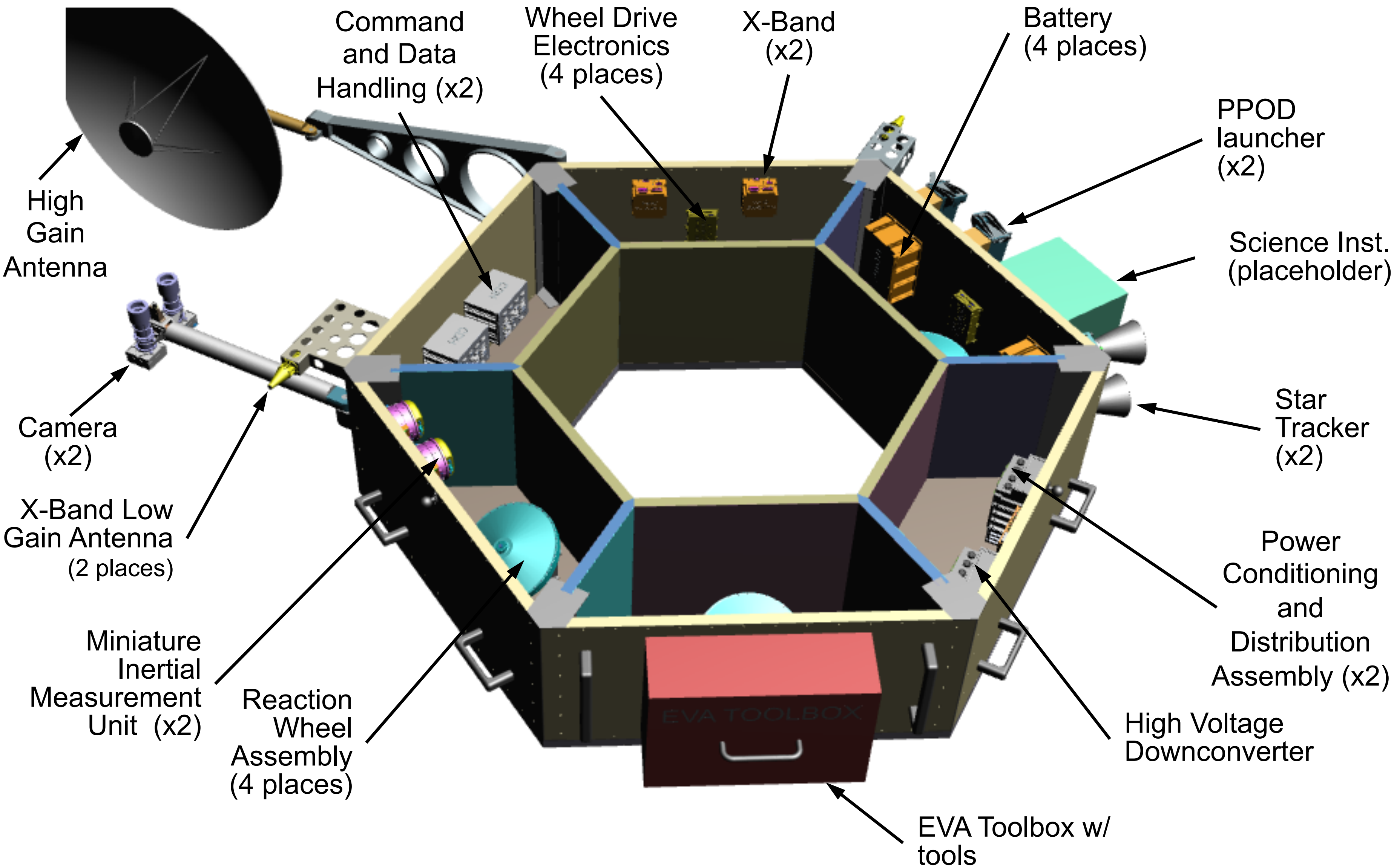


Robot Subsystem
Capture arms (2X)
and tool stowage (2X)

3 SpaceCube computers, Video Distribution and Storage Unit w/ 128 Gigabytes storage

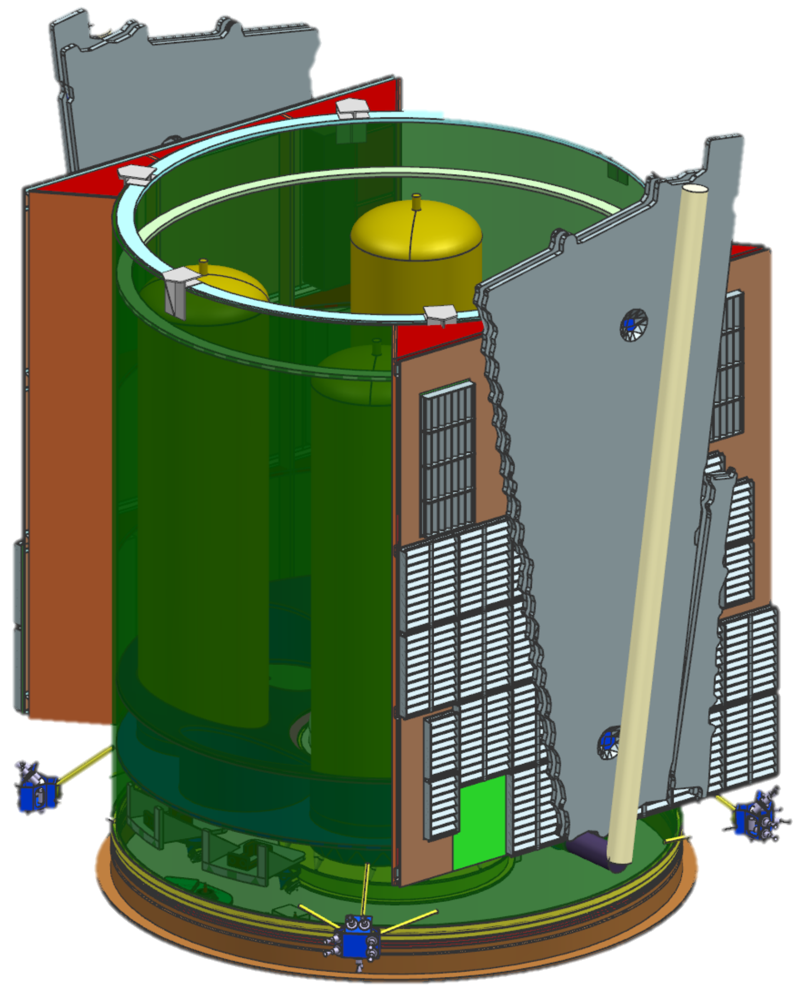
Relative Navigation Subsystem (RNS)
Deck sensor assembly and
gimbal sensor suite (shown stowed)

ARRM Baseline Concept Mission Module

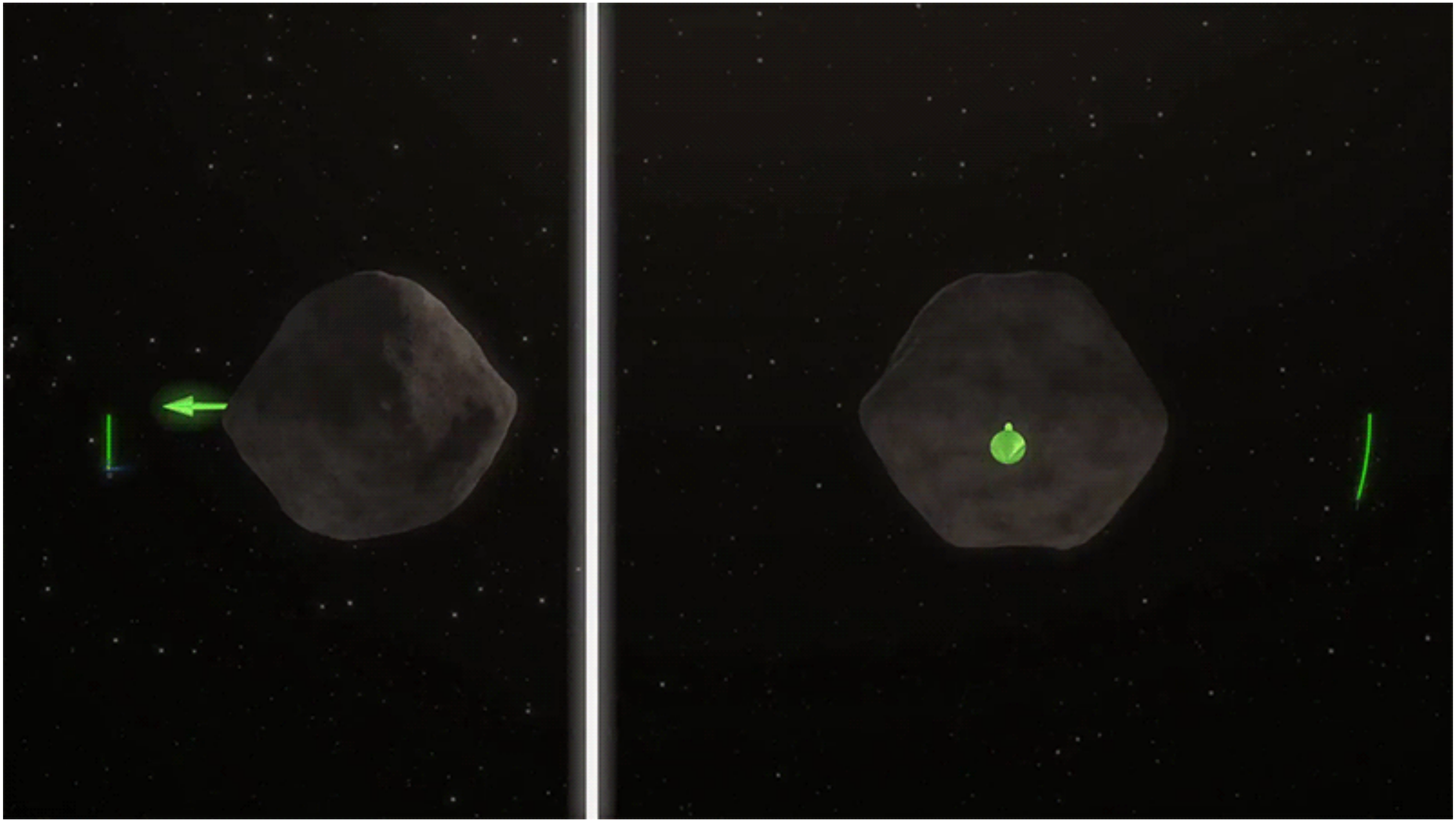


ARRM Baseline Concept Solar Electric Propulsion Module

- 50kW of Solar Array (SA) power Beginning-of-Life
- 40kW of Electric Propulsion (EP) power at 1 AU End-of-Life
- EP with Isp of at least 3000 s and 6 year life
- Up to 24kW power transfer capability
- Operates from 0.8 to 1.9 AU
- Fits within 5 meter fairing
- Accommodates docking interface
- Compatible with crewed operations
- Extensible to 16 t of xenon
- Extensible to 190 kW of SA power
- Extensible to 150 kW of EP power at 1 AU



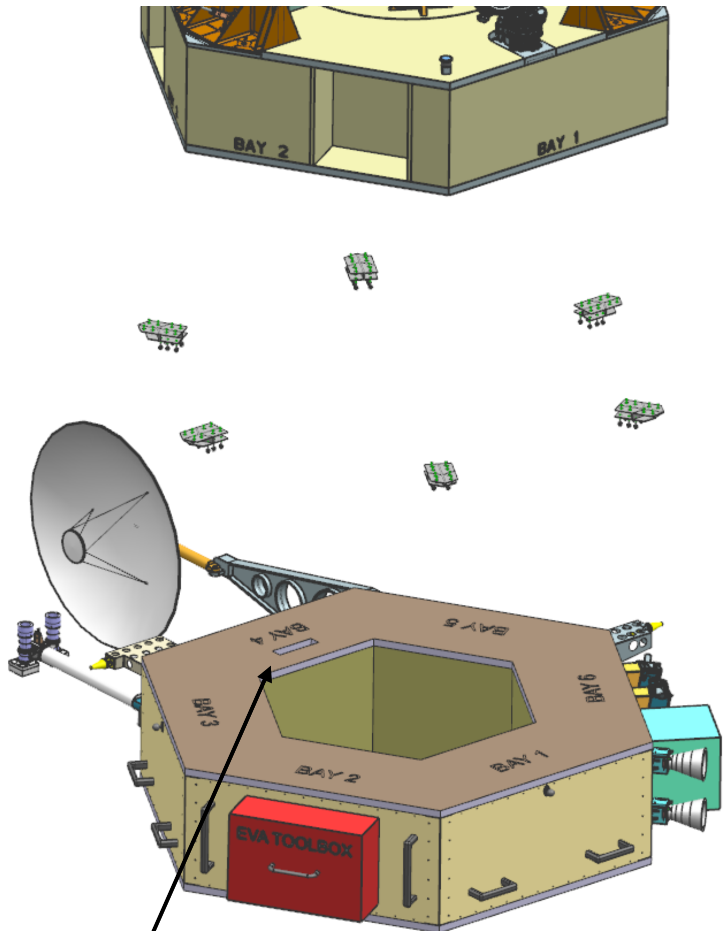
Demonstration of Basic Asteroid Deflection Technique



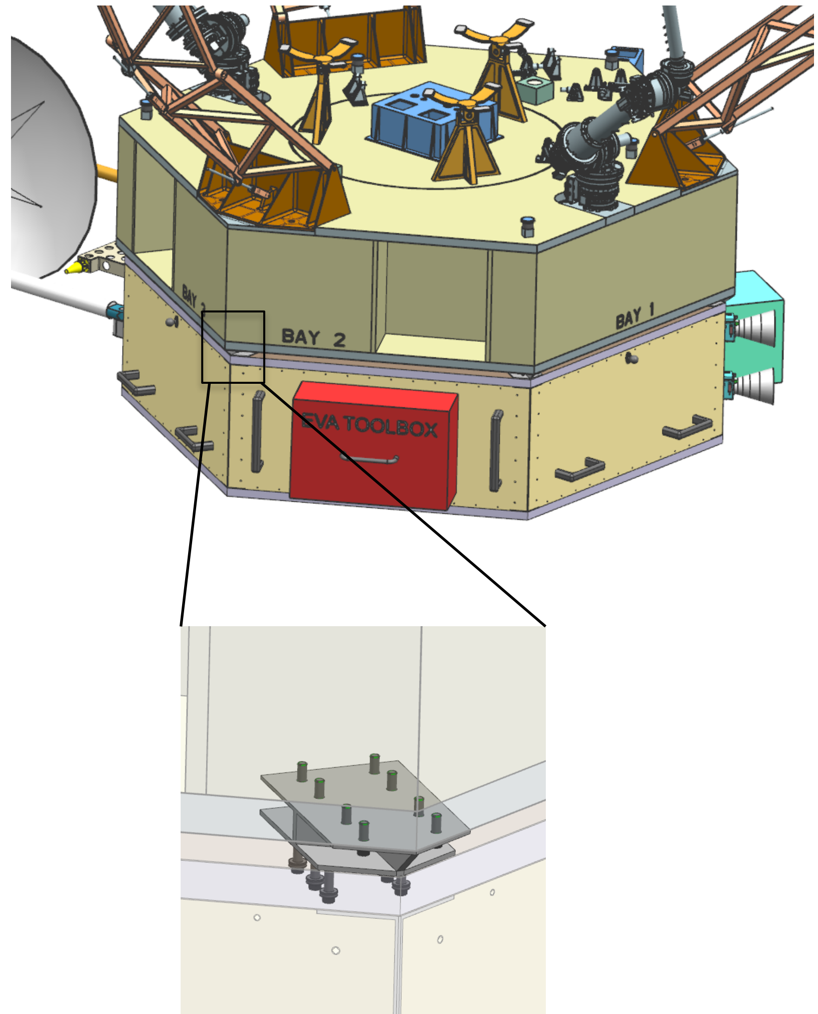
Animated version also available here: http://www.nasa.gov/content/asteroid-redirect-mission-images?id=350296

Capture Module/Mission Module Interface

The Mission Module (MM) to Capture Module (CM) mechanical interface is through 6 flanged brackets at the perimeter of the MM/CM interface.

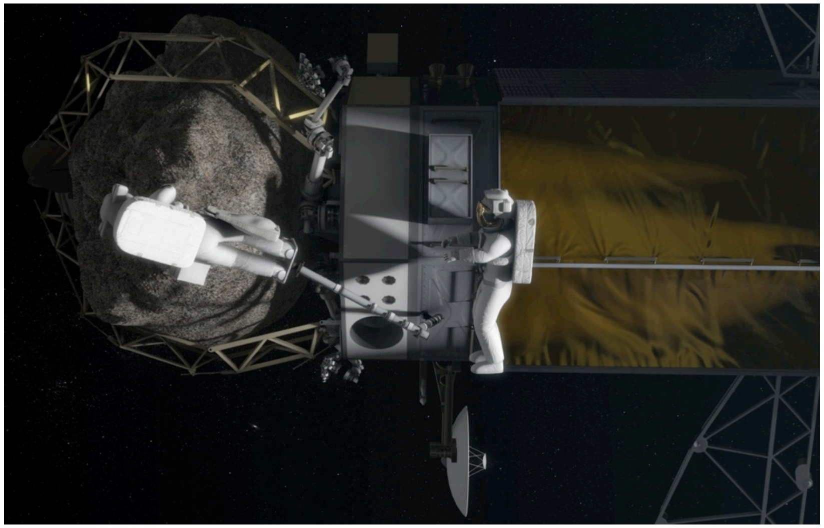


Electrical harness mates are via a pass-through

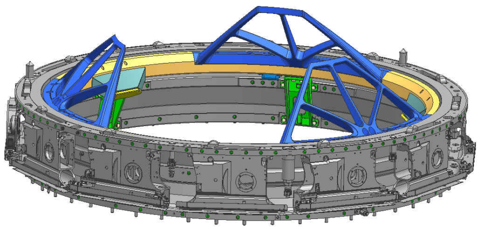


Compatibility for Visits by Crewed Missions

- **The ARRM Flight System will support visits by crewed missions by:**
  1. Carrying GFE hardware to make docking and EVA possible
     - IDSS IDD-Compliant Docking Mechanism (passive) with:
       - FRAM-type connectors for data and power transfer
       - Retro-reflectors
     - Docking target
     - LED Status Lights
     - Rendezvous aid (S-band transponder)
     - 24” EVA Handrails mounted to the spacecraft exterior
     - WIF Socket for Orion-to-ARRM Telescopic Boom
     - WIF Sockets for EVA Boom Installation
     - EVA Telescoping Booms
     - EVA Tool Box with tools
  2. Providing resources to a crewed spacecraft (e.g., Orion)
     - 300 V unregulated power
     - Data transfer to Earth via X-band or Optical Communications demonstration
  3. Having a system that is crew safe

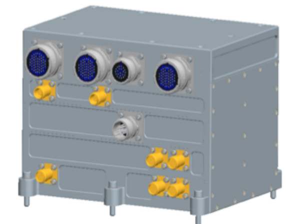


ARRM Crewed Mission Accommodations (Docking)



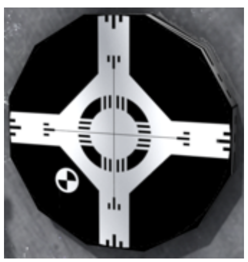
IDSS IDD-Compliant Docking Mechanism

Passive docking mechanism on ARRM
(active mechanism on crewed vehicle)



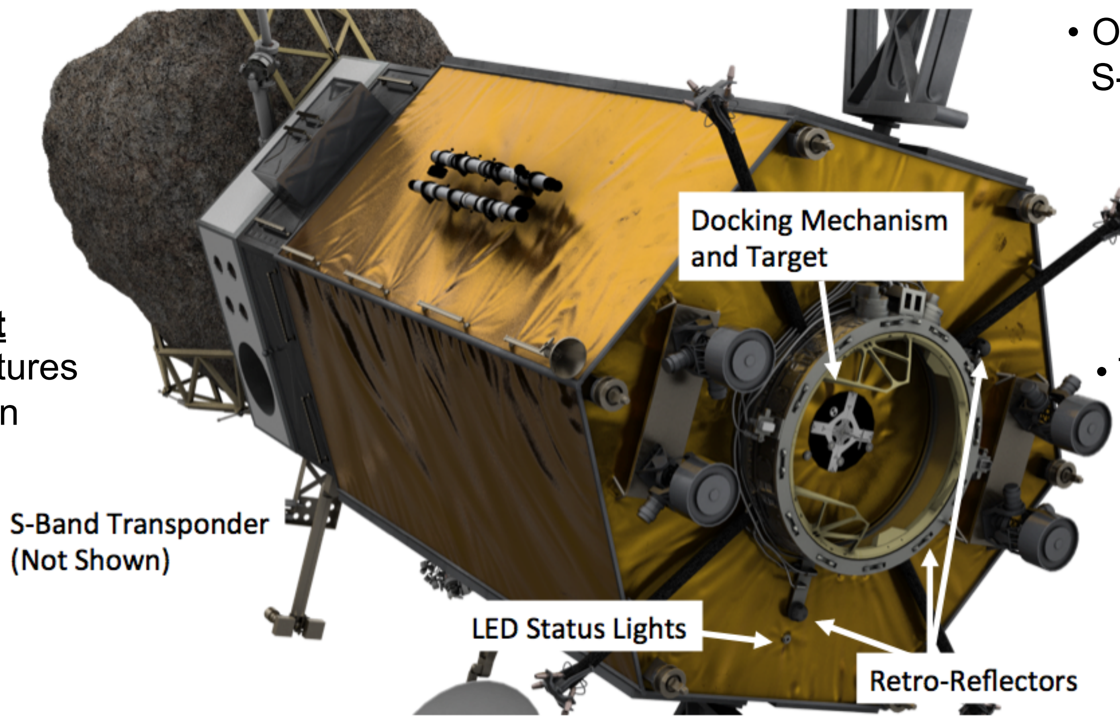
Rendezvous Aid

- Orion-compatible low-rate S-band transponder



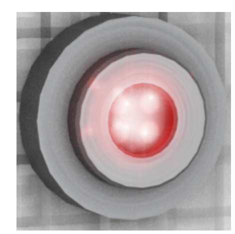
Docking Target

- Augmented with features for relative navigation sensors
- Visual cues for crew monitoring



Retro-Reflectors

- Tracked by the LIDAR during rendezvous and docking



LED Status Lights

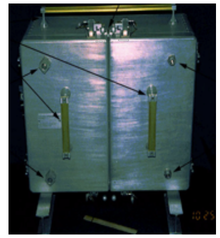
- Indicate the state of the ARRM systems, inhibits and control mode

Power and Data Transfer

- Power and data connectors integrated into the docking mechanism.
- Data transfer used during ARCM
- ARRM power transfer is available for future missions.

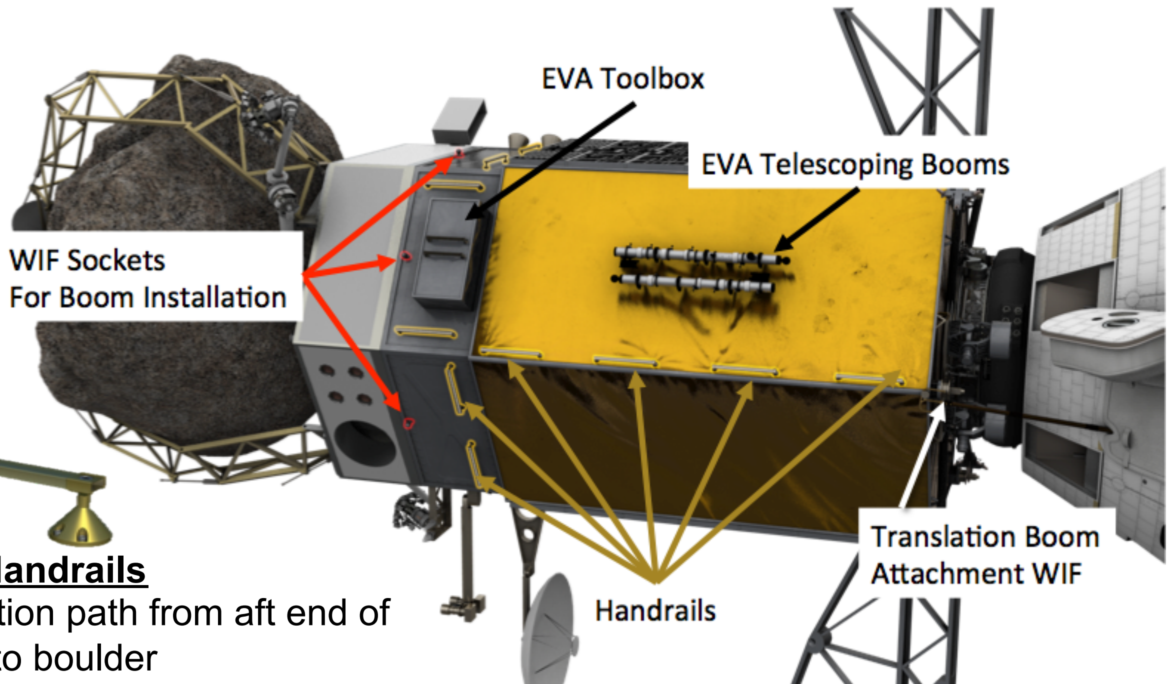
ARRM Crewed Mission Accommodations (EVA)

EVA Telescoping Booms
- Telescoping Booms for positioning the EVA astronaut on the boulder



EVA Tool Box with tools
- Tool box to offset Orion mass (85kg tools)

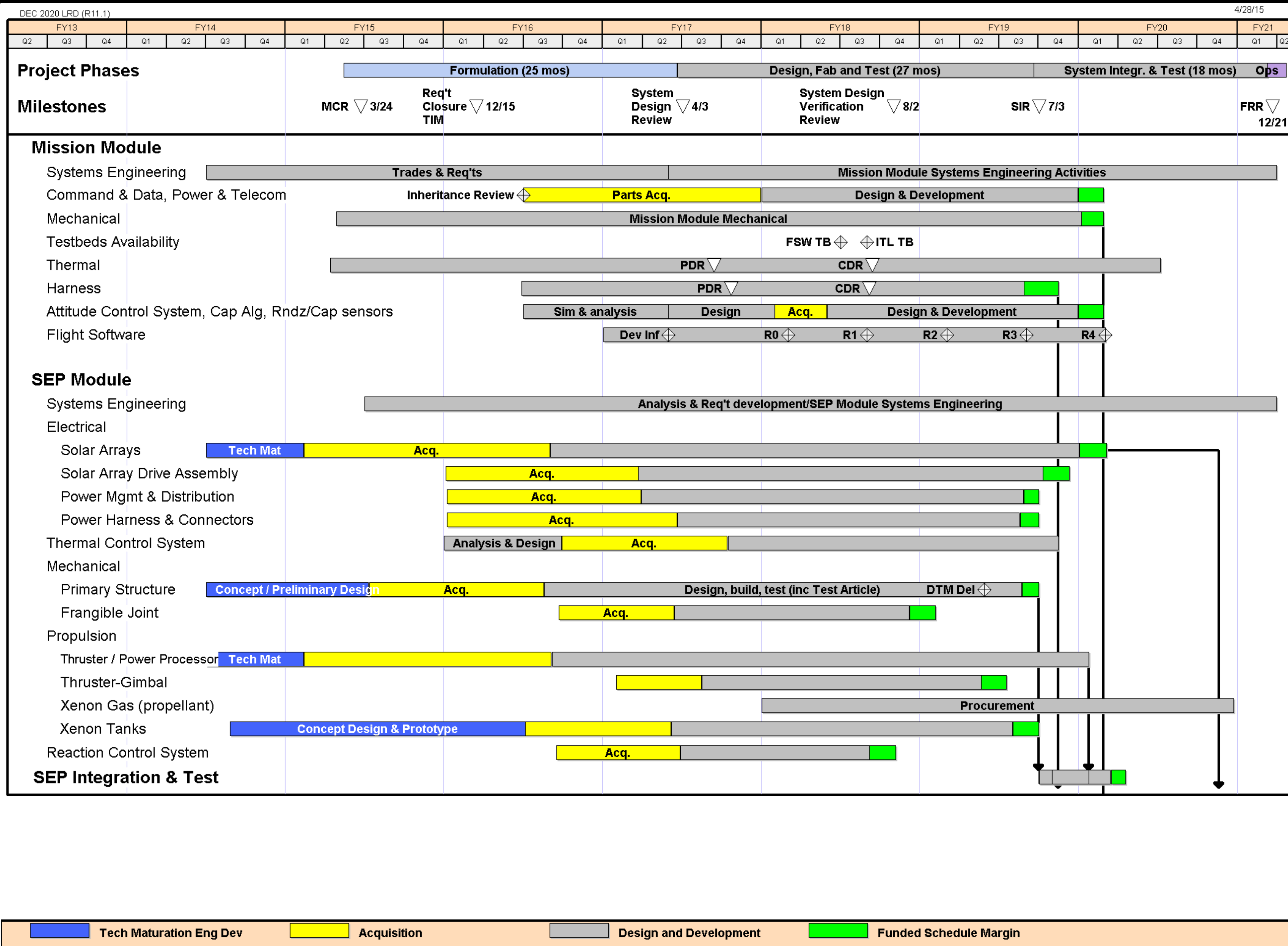
Worksite Interface Fixture Sockets
- Provide boom attach points to ARRM.



Crew Safe Certification
- Spacecraft designed for Crew Safety including EVA kick loads, sharp edge, safety inhibits and Caution and Warning annunciation.
- ARRM Systems are Human Rated for Crew Interfaces instead of entire spacecraft

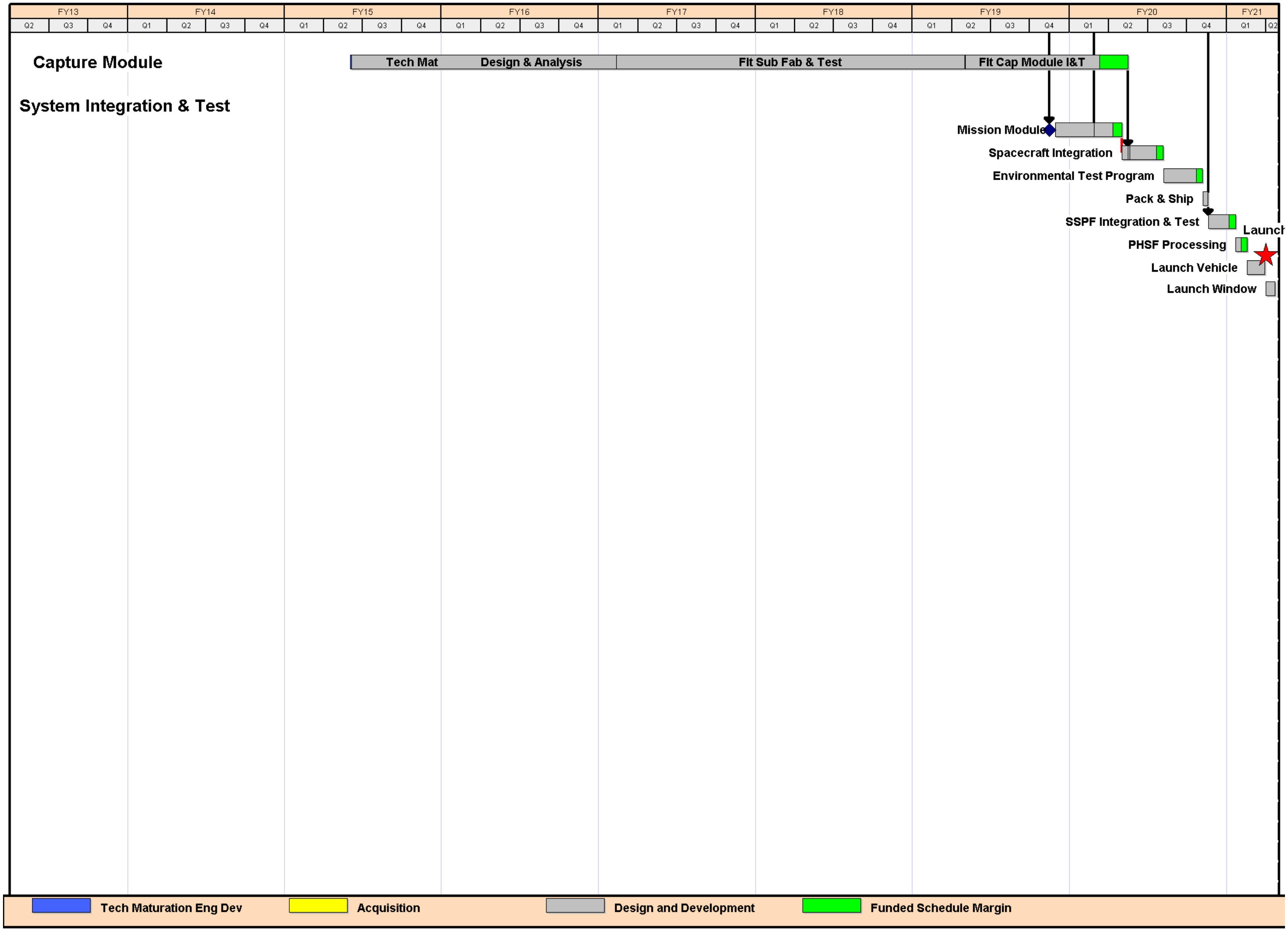
24” EVA Handrails
- Translation path from aft end of ARRM to boulder
- Ring of handrails around the Mission Module near the boulder

ARRM Concept Development Summary Schedule
LRD December 31, 2020 (1/2)

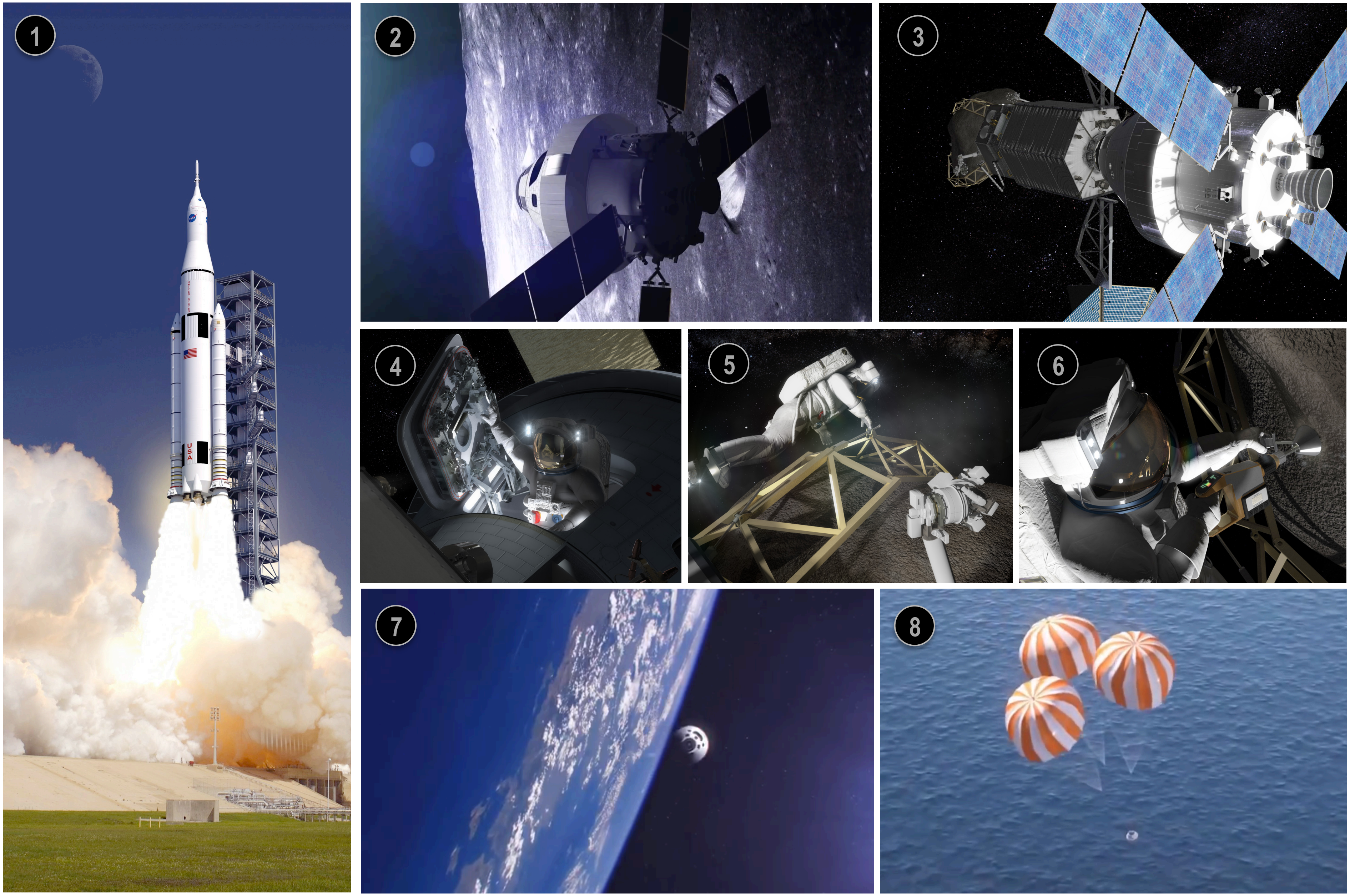


ARRM Concept Development Summary Schedule LRD December 31, 2020 (2/2)

4/28/15

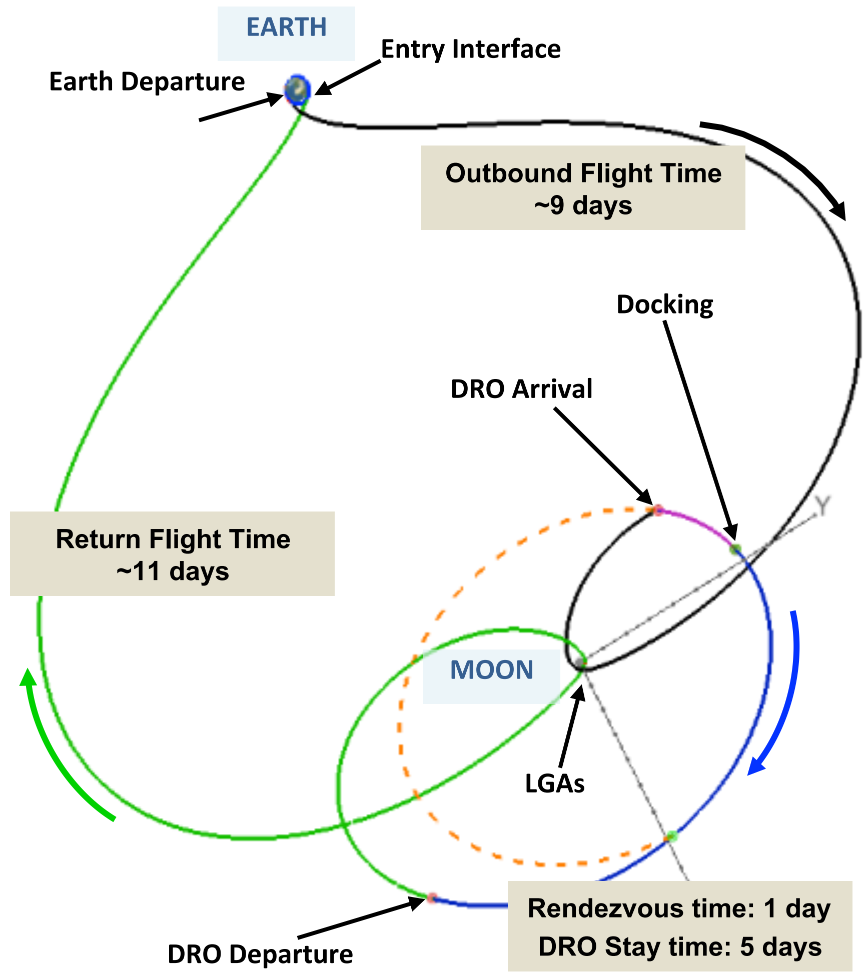


Asteroid Redirect Crewed Mission Overview



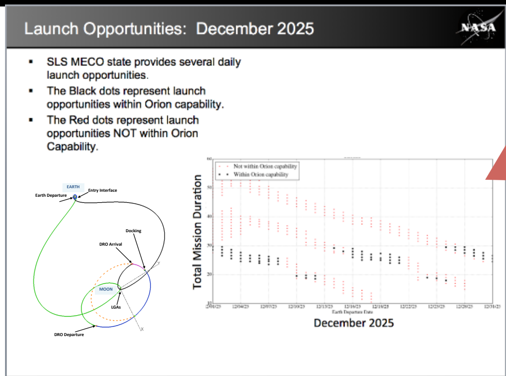
December 2025 Reference Crewed Mission Overview

- Orion launch via Block 1 SLS/ICPS
- Use Lunar Gravity Assist (LGA) trajectories for outbound and Earth return.*
- Total mission duration 26 Days with 5 days docked with Asteroid Return Vehicle (ARV).⁺
- Two person crew launched aboard Orion.
- Rendezvous/dock with ARV in ~71,000 km LDRO above lunar surface.
- Conduct 2 four-hour EVAs using adapted Modified Advanced Crew Escape Suits (MACES) to observe, document and collect asteroid samples.
- DRO ops for 5 days: one day for rendezvous, one day for each EVA, one day in between EVAs and one day for undock/ contingency
- Orion returns to Earth on an LGA trajectory, with a skip targeted return near San Diego, CA



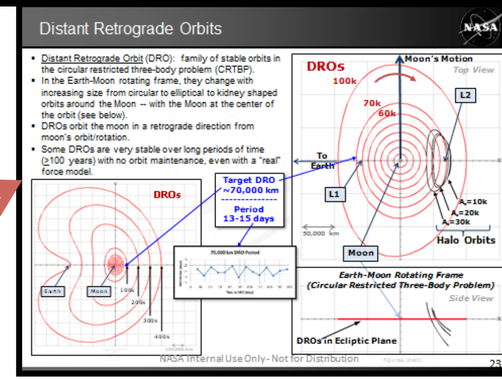
*LGA Flight days shown represent one possible trajectory. Other trajectories may require additional flight days.
⁺Orion Consumables allow for a 30 day total mission duration.

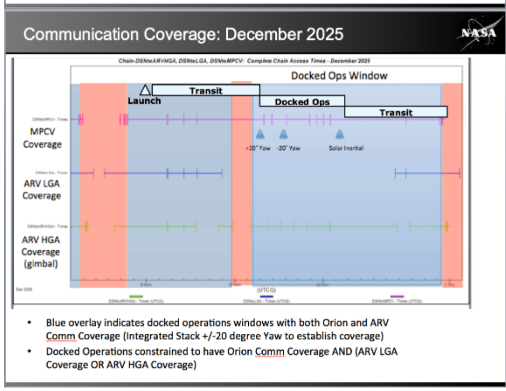
Mission Design: Launch Opportunities



Launch Availability:
2 Launch Opportunities (Dec 7 and Dec 8) in December 2025

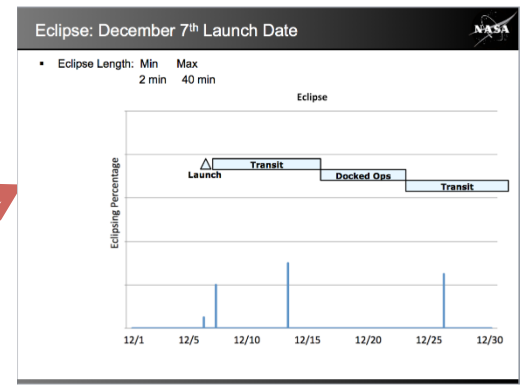
Selection of 71433km LDRO improves Launch Availability by syncing with Lunar period

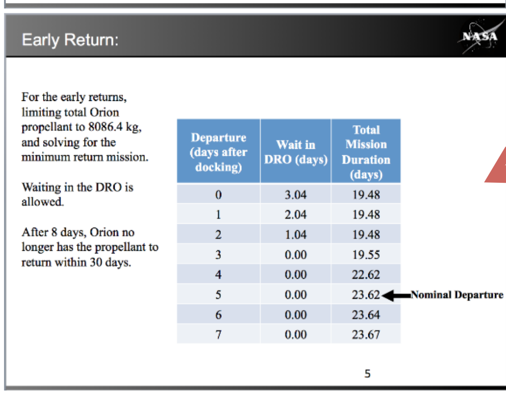




Yawing the integrated stack provides acceptable Orion and ARV coverage periods

Avoid flying when Orion would experience long Solar Eclipse

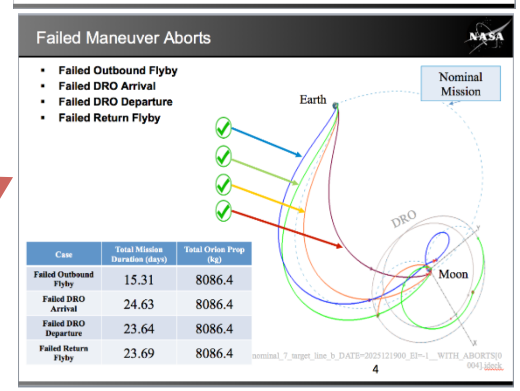




Departure (days after docking)	Wait in DRO (days)	Total Mission Duration (days)
0	3.04	19.48
1	2.04	19.48
2	1.04	19.48
3	0.00	19.55
4	0.00	22.62
5	0.00	23.62
6	0.00	23.64
7	0.00	23.67

Allow for adequate ΔV for Early Return Constraints

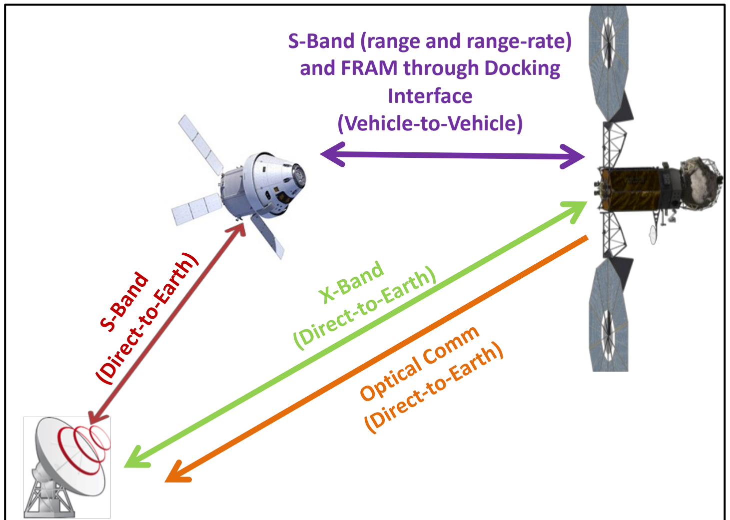
Allow for Auxiliary Thruster Contingency Return Cases



Case	Total Mission Duration (days)	Total Orion Prop (kg)
Failed Outbound Flyby	15.31	8086.4
Failed DRO Arrival	24.63	8086.4
Failed DRO Departure	23.64	8086.4
Failed Return Flyby	23.69	8086.4

- **All constraints currently satisfied for December 2025 MCR Reference Mission**

Joint Mission Communications Strategy



Vehicle Comm

Undocked Ops

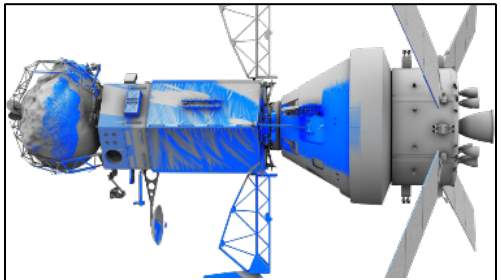
- Each spacecraft uses native space to ground communications system
  - Orion uses the baseline S-Band to communicate with MCC
  - ARV uses a X-Band and Optical comm systems to communicate with ARV control center
- Caution and warning and vehicle status provided between spacecraft via ground relay

Proximity Ops

- Orion S-Band provides relative Range and Range-Rate with ARV during approach
- A copy of the Orion S-band transponder installed on ARV to relay ranging signal to Orion

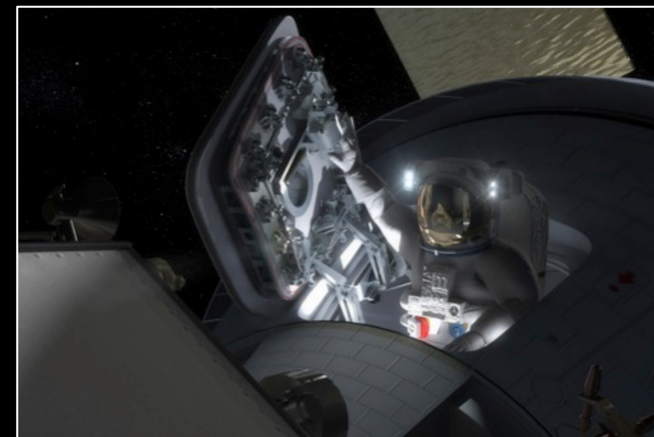
Docked Ops

- Vehicle-to-vehicle hardline communication via FRAM-type connector through docking interface
  - ARV Caution and Warning provide to Orion
  - Orion EVA video sent to ARV for near real time downlink
- EVA Comm Kit is a repackaged PLSS radio configured to integrate with Orion power and serial Ethernet data ports
  - Orion EVA Comm antenna located on or near hatch provides adequate coverage to EVA crew


EVA Comm Coverage

Mission communications strategy feasible based on current designs

Crew Operations For EVA



Space Suit Feasibility Prototype Testing
Modified Advanced Crew Escape Suit (MACES)

Initial NBL testing has shown feasibility of doing many asteroid retrieval sampling tasks using a MACES. Continued testing with a variety of crew member sizes, along with incremental suit and tool enhancements is critical in order to validate the concept.

Lab, Zero G, ARGOS tests

MACES EVAs are demonstrated as feasible and neutrally buoyant testing is warranted

Neutral Buoyancy Lab Series #2 – 5 tests (2, 3 and 4 hours long)

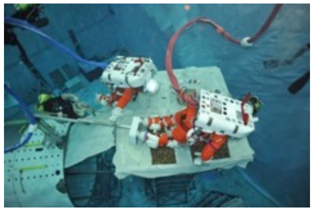
Task complexity increases while improvements are made to the suit including Extravehicular Mobility Unit gloves, drink bag, etc. Need for improved stability and work envelope

May | June | July | August | Sept | Oct – Jan | February | March | April | May

NBL Series #1 – 3 tests (2 hours long)

Established NBL Interface, ability to weigh-out the suit, and the subject's ability to use the suit underwater.

NBL Series #3 – 5 tests (4 hours long)



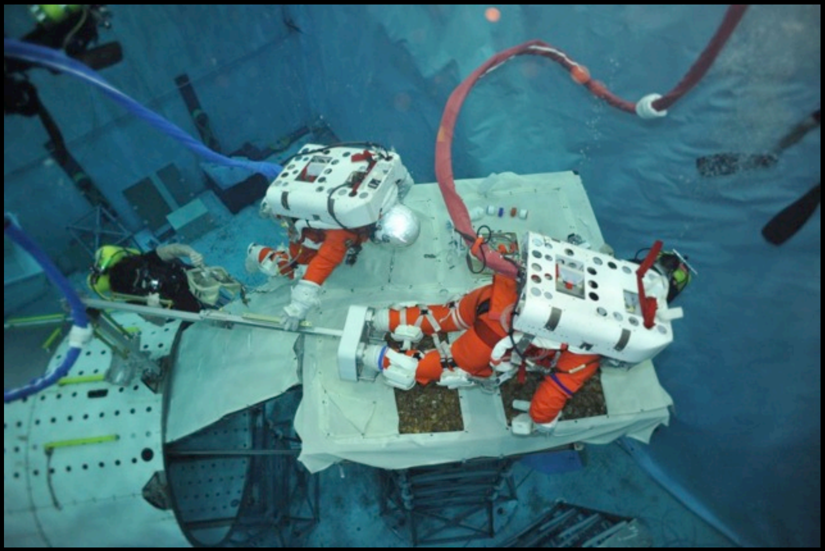
Evaluation of mobility enhancements, improved worksite stability, and testing on higher fidelity capsule mockups with tools culminating in a full ARCM EVA timeline.

Hardware and Procedure Improvements

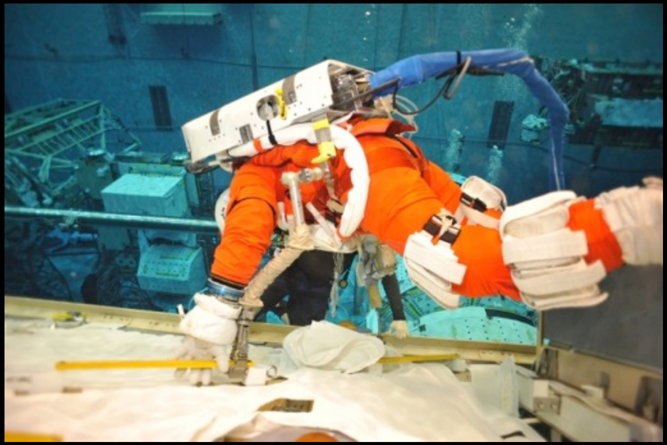
- Improved weights
- EMU Gloves
- Added tool harness
- Drink bag included
- New liquid cooling garment
- Mobility Enhancements
- Dual Suit Ops
- EMU Boots
- Portable Life Support System Mockup
- Body Restraint Tether

EVA Feasibility Testing
Worksite Stabilization in Neutral Buoyancy Laboratory

Adjustable Portable Foot Restraint operations were tested and execution is very similar to the ISS Extravehicular Mobility Unit

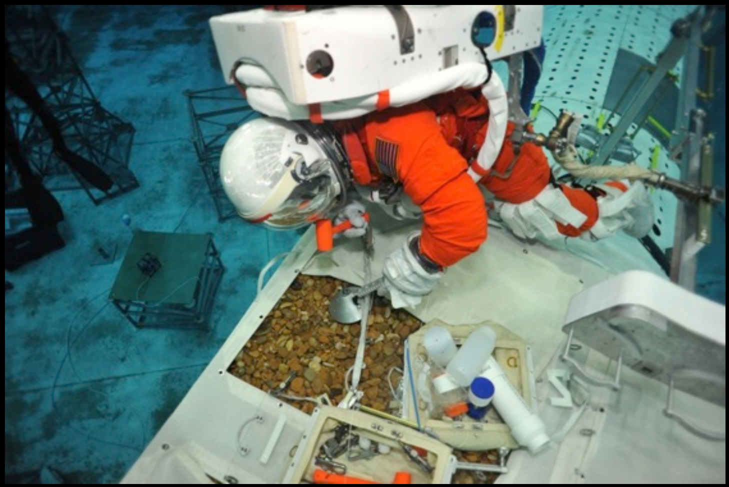


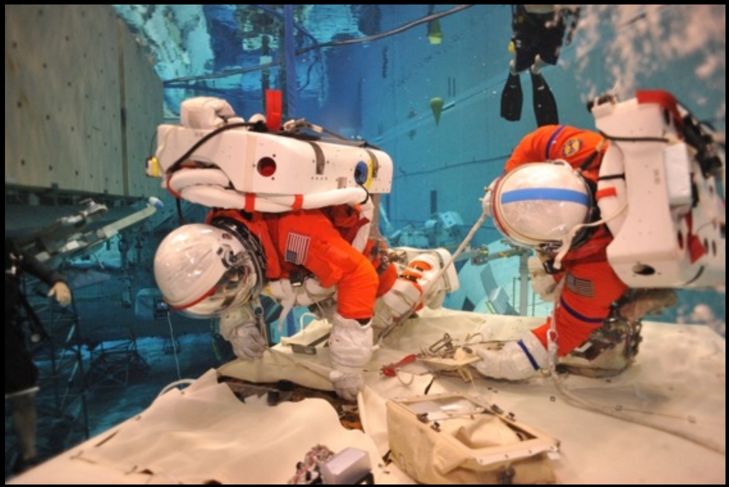
Body Restraint Tether allowed the crew to perform two handed task



EVA Feasibility Testing
Sampling Tasks in Neutral Buoyancy Laboratory

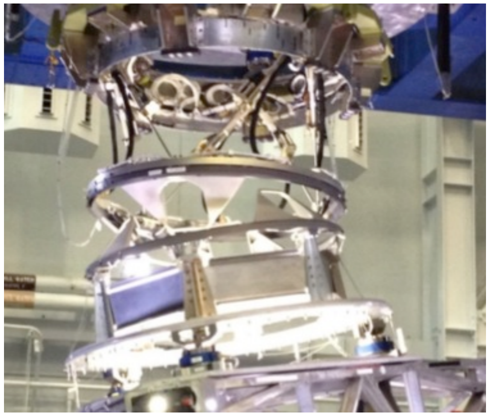
Crew was able to perform several sampling tasks including worksite imaging, float sample collection, hammer chiseling and pneumatic chiseling.

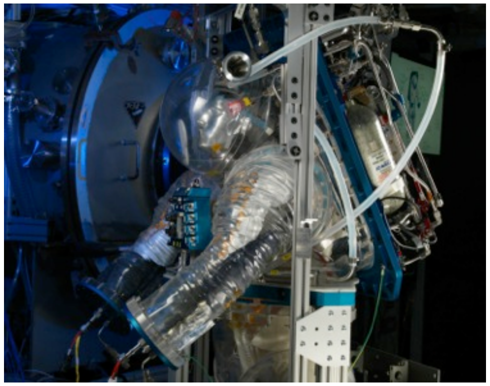


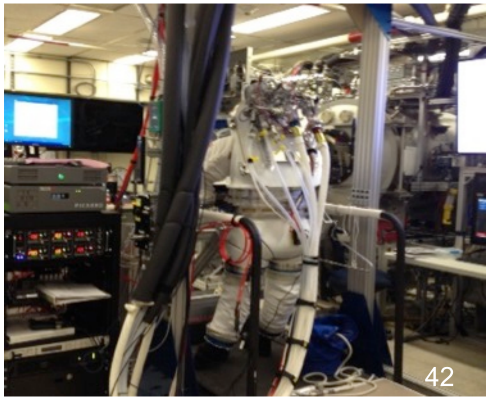


Asteroid Redirect Crewed Mission: Progress

- **Completed feasibility testing series in Neutral Buoyancy Laboratory to evaluate EVA techniques and modifications in launch and entry suit (MACES) mobility**
- **Matured analyses of extensibility of ARM components, systems, vehicle for reuse and upgrade for future missions**
- **Determined existing and matured AR&D sensors can meet specification for common sensor suite**
    - Concept study contracts completed by Ball Aerospace and Boeing
- **Significant Progress on NASA Docking System Block I**
    - 90+% drawings have been released in CDR Phase
    - Component development testing
    - Successful 6 Degree of Freedom testing at JSC for a wide variety of contact conditions and vehicle masses
- **Completed Portable Life Support System (PLSS) 2.0 integrated testing primary objectives**
    - Full integrated test system with human metabolic simulator
    - Integrated system performed as designed
- **PLSS/Mark-III Prototype Suit Human-in-the-Loop Testing**
- **PLSS/MACES Human-in-the-Loop Testing planned for FY15**

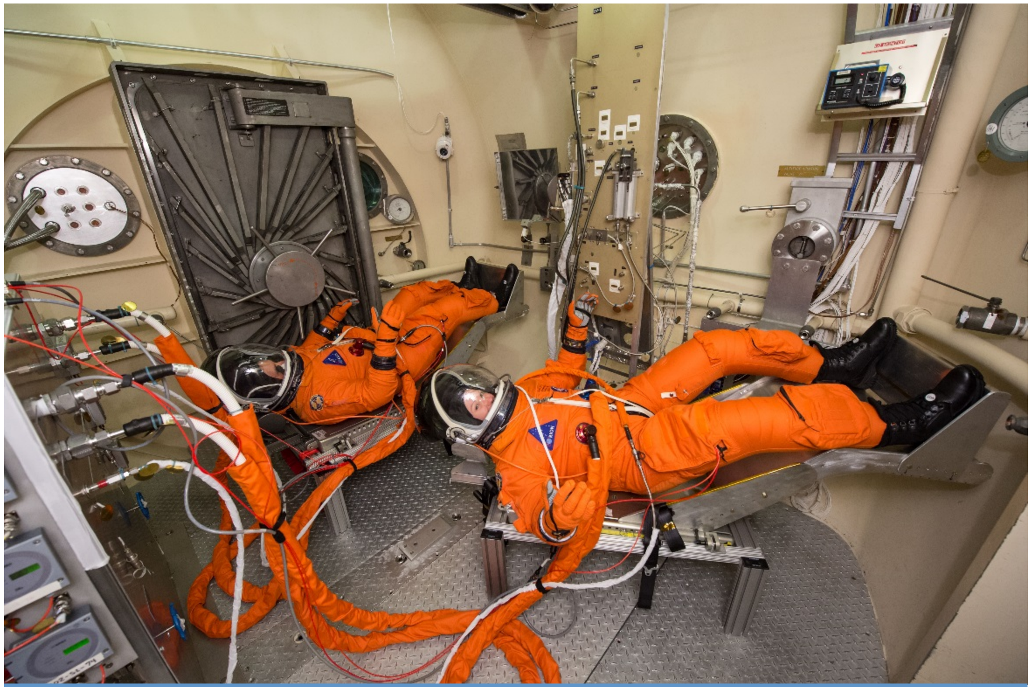






Orion MACES Testing

- Orion completed four MACES suited evaluation in the March Vacuum Pressure Integrated Suit Test (VPIST).
- Modified ACES is an evolutionary step from shuttle crew survival suit for closed-loop crew protection for launch, entry, aborts.
- Testing evaluated integrated performance of Orion’s vehicle ECLSS hardware in a vacuum chamber.
    - 100% oxygen
    - MACES
    - Orion Suit Loop with Amine Swingbed CO2 Scrubbing
- Testing verified ability of MACES and Orion ECLSS systems to operate as designed.



VPIST Testing is first time since Apollo that developmental pressure suits have been combined with a vehicle-level closed loop ECLSS system to provide life support while test subjects are at full vacuum.

Asteroid Redirect Crewed Mission (ARCM) Mission Feasibility Summary

- **The Asteroid Redirect Crewed Mission Concept is feasible**
- **Trajectory, consumables, and operations within Orion and SLS capabilities**
- **Mission Kits augment Orion while minimizing mass and integration impacts for EM-1 and EM-2**
- **Mission provides opportunity for incremental expansion of Orion capabilities for more ambitious exploration missions**
  - Rendezvous and Docking Sensors use common AR&D approach to minimize development expenditure (commonality with ARV and Satellite Servicing)
  - Docking system leverages Commercial Crew Block I System under development by the ISS Program
  - Docking with ARRV enables integrated vehicle attitude control and extensibility
  - Addition of EVA Capability is the largest development challenge
- **Initial NBL Testing shows use of MACES to perform required sampling tasks is feasible. Continued testing with variety of crew member sizes, along with incremental suit and tool enhancements is critical in order to validate concept**

Independent Review Team (IRT) Charter

- Independent NASA Review team comprised of technical and programmatic experts from across the Agency to:
  - Report assessment at mission capture concept down-select decision (Option A vs. Option B) and the subsequent ARM Mission Concept Review (MCR).
  - Conduct an independent cost and risk assessment of the robotic portion of the overall Asteroid Redirect Mission (ARM)
  - Incorporate the results of the ARM Broad Agency Announcement (BAA) contractor studies into the assessments.
- The task was completed in two phases:
  - Phase 1 focused on the unique cost and risk aspects of the capture concepts to support the down-select decision in December 2014.
  - Phase 2 provided the ARM MCR with an independent cost and risk assessment of the full robotic mission.

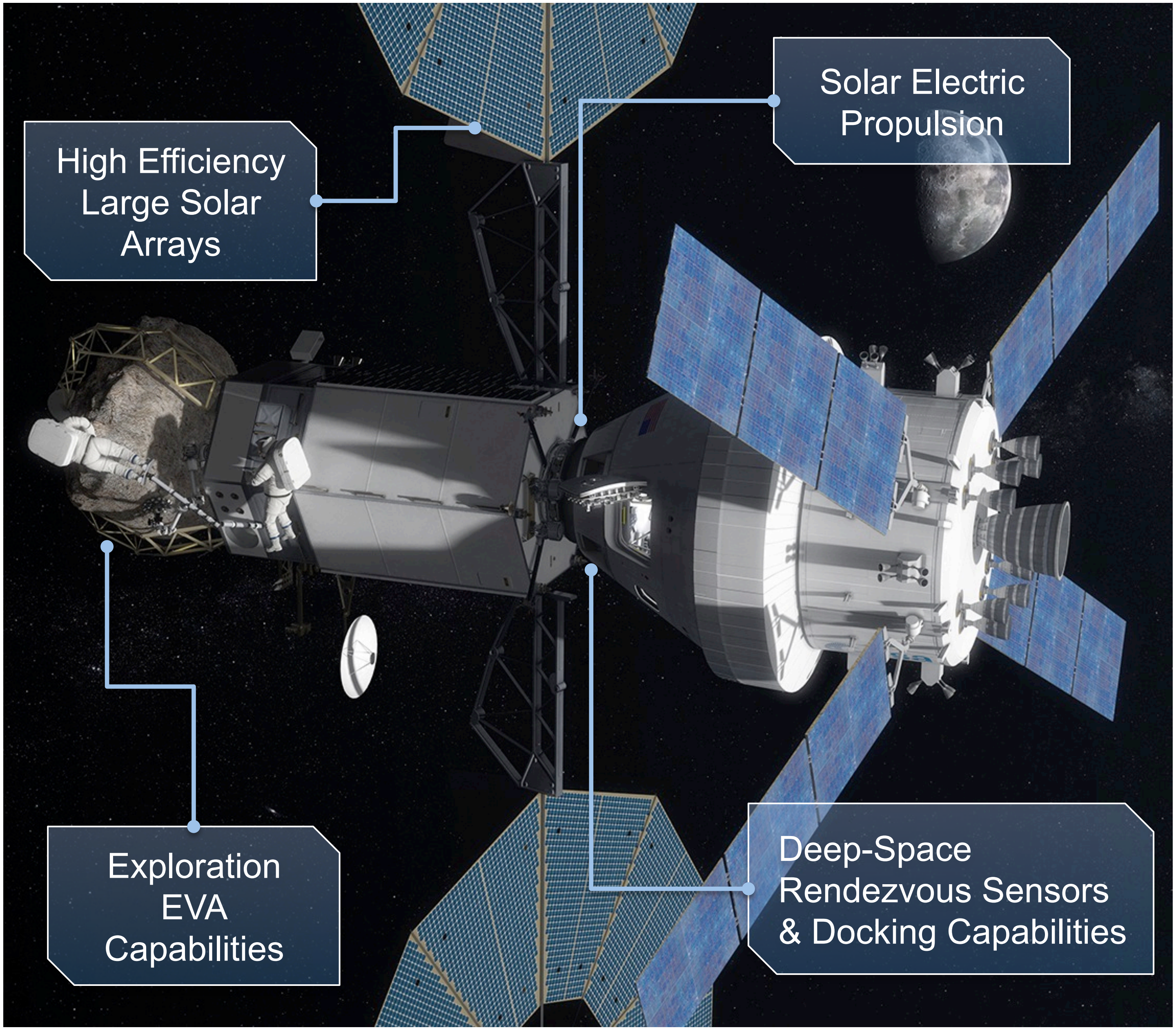
IRT Approach and Conclusions

- **Evaluated MCR review material and BAA contractor inputs via multiple face to face and telecons including presentations by ARRM, ARCM, Human Spaceflight Architecture Team, Extensibility**
- **Utilized additional subject matter experts to perform three focused independent technical assessments**
  - Electrical Power System (particularly voltage trades)
  - Electric Propulsion Thruster Development
  - Xenon Tank Development
- **Reviewed ARM risk assessments related to ARRM for completeness and risk categorization**
  - Iterated with ARRM on significant risks and mitigations
- **Developed two independent cost assessments (GSFC and JPL) for ARRM development, including both Option A and B capture systems**
  - Reconciled to assure consistency in major assumptions
- **IRT Conclusions for MCR:**
  - Assessment of the options A & B capture systems unchanged
  - MCR Success Criteria satisfied

Next Steps

- Continue asteroid observations and enhancements.
- Continue high power, long life solar electric propulsion system technology development toward demonstration.
- Entering Phase A to design integrated technology demonstration through ARRM.
- Continue toward industry and international partnerships
- ARRM Acquisition Strategy Meeting late July 2015
- ARRM Integrated Requirements review December 2015
- ARRM KDP-B January 2016
- Continue human spaceflight system development and technology maturation as part of a sustainable exploration strategy.
- Continue concept development toward Asteroid Redirect Crewed Mission. Prepare for hardware deliveries (common sensors, docking, and EVA accommodations) to ARRM team.

ARM: A Capability Demonstration Mission



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:
- Primary Life Support System design accommodates Mars
- Sample collection and containment techniques
- Follow-on missions in LDRO can provide more capable exploration suit and tools

TRANSPORTATION & OPERATIONS:
- Capture and control of non-cooperative objects
- Rendezvous sensors and docking systems for deep space
- Cis-lunar operations are proving ground for deep space operations, trajectory, and navigation

NASA

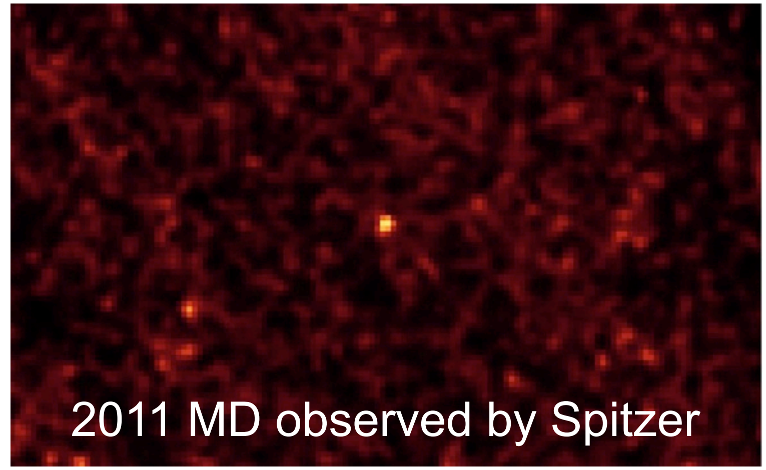
Back Up

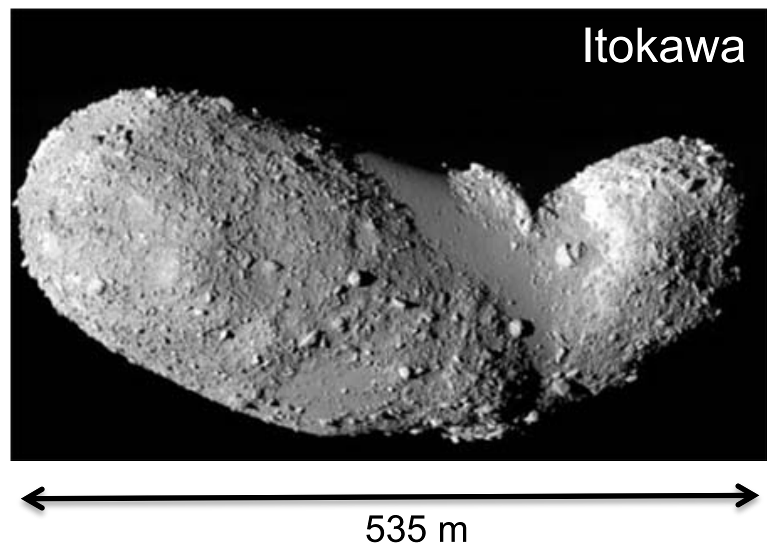
Asteroid Target Identification and Characterization

- ARM target identification leverages off of NASA's Near-Earth Object Observation Program, which supports and coordinates a world-wide network of discovery and tracking teams
- Vast majority of asteroids are discovered and tracked by NASA-funded ground-based optical telescopes
- Candidates for ARM require detailed physical characterization (size, shape, spin state, presence of boulders):
  - Ground-based radar (Goldstone)
  - Ground-based IR (IRTF) and optical
  - Space-based IR measurements (Spitzer Space Telescope, NEOWISE)

ARM Candidate Asteroid Targets

- The surfaces of candidate asteroids must be characterized well enough to see boulders
- Three candidates will have been characterized by precursor missions: Itokawa (Hayabusa 1), Bennu (OSIRIS-REx in 2018), 1999 JU3 (Hayabusa 2 in 2018)
- A fourth candidate, 2008 EV5, was characterized by ground-based radar well enough to infer boulders.
- All candidates except for Itokawa are carbonaceous (C-type) asteroids





NASA Solar Array Technology Development

Designed, Built and Tested Solar Arrays to TRL 5+

- ATK MegaFlex
- DSS Mega-ROSA

Environmental Testing Completed

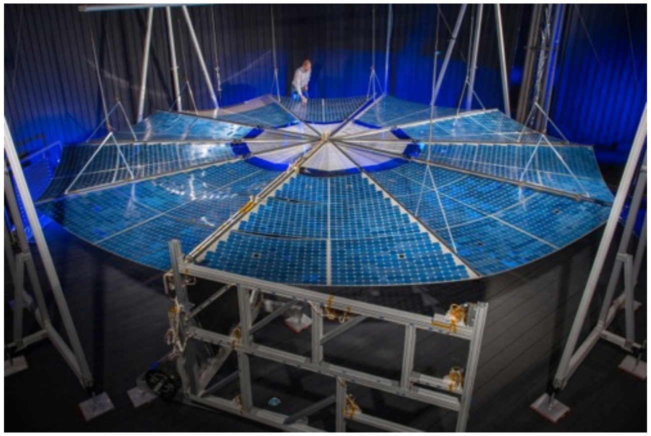
- Thermal vacuum full scale deployment, Vacuum structural dynamics, Stowed wing strength and stiffness, Deployment dynamics, Photovoltaic plasma and thermal balance testing, Single event radiation testing on high voltage electronic parts

Analyses and Models Completed

- Demonstrated extensibility to 250kW system
- Finite element, CAD models, Structural dynamics, Deployed thermal model

Technology Infusion

- ROSA being incorporated into a commercial product line
- Joint ISS/AFRL ROSA flight demo under development (~3 kW)
- Strong interest in one or both arrays by at least five commercial vendors (ARRM-scale); DARPA and USAF SMC (15-25 kW); and Discovery-class mission proposers (deep space applications)
- At least one commercial vendor has invested substantial IR&D funds to develop a similar capability in response to this demonstrated interest for 25 kW-scale arrays and smaller versions for GEO



Innovative flexible-blanket arrays are sized for nominally 20kW, with highly compact stowage.

Definitions for Programmatic ‘Leveraging’

- **Synergy** – work or product deliverable development primarily for other project objectives or other technology efforts that is also deliverable to ARM. Funded in the originating project, not bookkept as ARM LCC, but carried by ARM as a lien/ dependency should content or the other relevant technology tasks be cancelled or delayed.
  - e.g., SEP technology development, common rendezvous sensor development and qualification, robotic capture option B arm engineering development unit
- **Leverage** – work specifically for or product deliverable to ARM, generally consistent with the “on-going program/project” objectives and capability development. Funded in the referenced project and scheduled through ARM. Budget and costs are accountable in ARM Life Cycle Cost (LCC).
  - e.g., ARRM solar electric propulsion system flight demonstration deliverables, capture option B contact and restraint flight system risk reduction
- **ARM funded** – work specifically for ARM, funded and managed by ARM and accountable in ARM LCC.
- **Extensible**—work or product deliverable which potentially supports future human spaceflight objectives beyond ARM. Funded in the on-going program/project but neither attributable to ARM LCC nor a lien on ARM.
  - e.g., reuse of ARM elements (Xenon propellant refueling experiment); technology relevant to Mars architecture, future space operations or infrastructure development (advanced EVA PLSS, cryogenic methane transfer experiment)

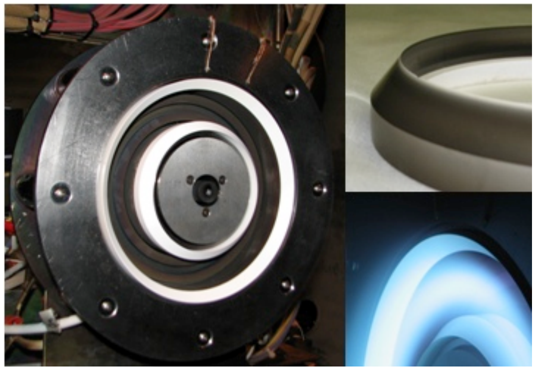
NASA Electric Propulsion Development

NASA Goal

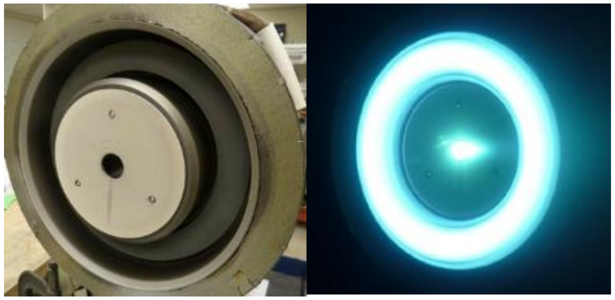
- Develop high power Hall thruster 12.5 kW-class (2X current State-of-the-Art)
- Develop magnetically-shielded design to provide long life commensurate with ARM and future missions
- Pursue high-voltage (i.e. 300V input) PPU system compatible with high power thrusters

Accomplishments

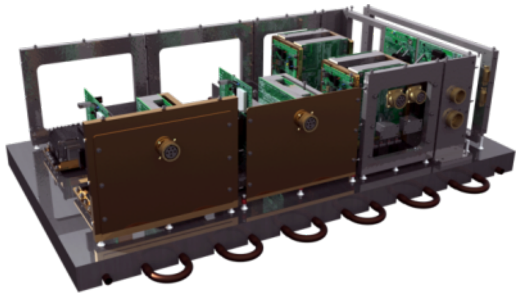
- Designed and built 12.5 kW EDU at GRC; in vacuum testing
- Demonstrated magnetic-shielded design up to 3000-sec specific impulse and 20 kW power with JPL H6 and NASA 300M thrusters.
- Designed and built moderate and high-voltage Power Processing Unit (PPU) Test Development Units (TDU) (120 V input with 800 V output to thruster, 300 V input with 400 V output to thruster; both are throttleable)
- Designed and built high-voltage Direct Drive Unit TDU
- Integrated thruster EDU and PPU for testing



JPL H6 with magnetic shielding

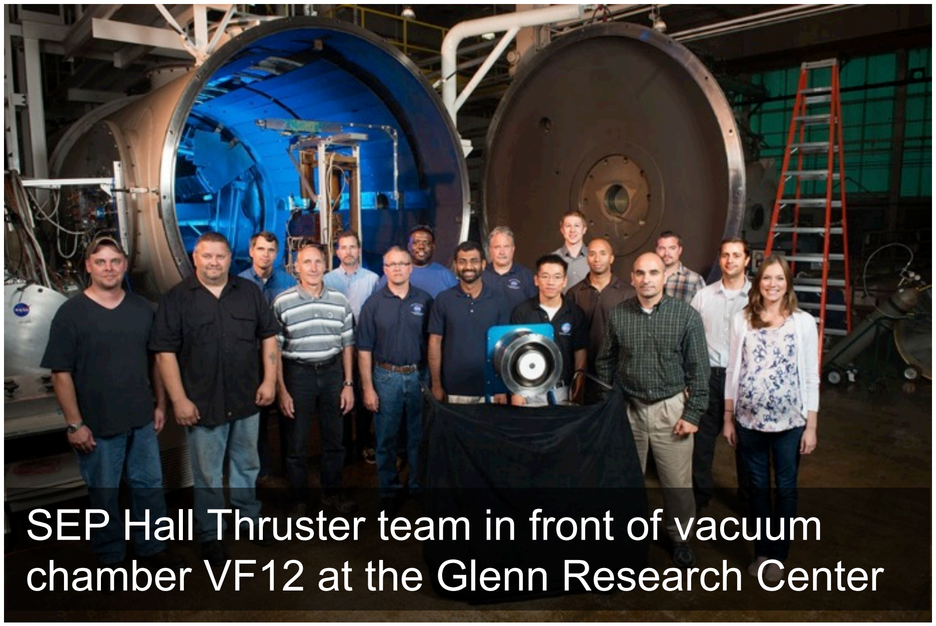


GRC 300M with magnetic shielding

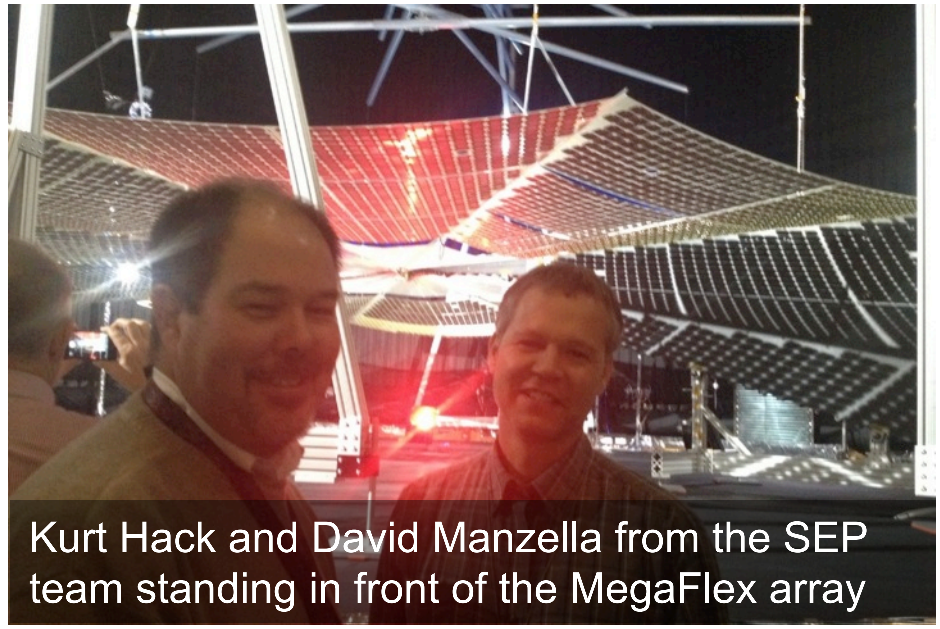


Cut away of NASA 300V PPU

STMD Advanced SEP Technology Testing



SEP Hall Thruster team in front of vacuum chamber VF12 at the Glenn Research Center



Kurt Hack and David Manzella from the SEP team standing in front of the MegaFlex array

Reference Concept Flight System Overview

System	• **Capability driven, single fault tolerant design using high heritage components** • **Crew safe but not human-rated**
Power	• 51 kW, deployable solar arrays (2 arrays with single-axis gimbals) • Four 75 Ah Batteries for launch and eclipses
Propulsion	• 4 magnetically shielded Hall thrusters (only 3 are required) • 8 t Xenon in 4 tanks (ARRM could fly up to 16 t with 8 tanks) • Hydrazine monoprop. reaction control subsystem (400 kg in 1 tank) • Cooperative in-space refueling interface for xenon and hydrazine
Avionics	• RAD750 flight computer and 128 Gbytes data storage
Telecom	• X-band: uplink & 100W TWTA downlink via 1.5-m 2-axis gimbaled HGA and 2 LGAs • Optical communication system (non-critical enhancing capability)
Attitude Control	• 3-axis: reaction wheels (4), RCS thrusters for control and desaturations; star trackers, IMUs, sun sensors
Thermal	• Heat pipe PPU radiators, MLI, heaters, louvers
Structure and Mechanical	• 4.5 m tall x 3.3 m diam. cylindrical SEP Module structure • Hexagonal Mission Module and Capture Module structures
Crew Access	• Passive docking ring with data and power transfer connectors (FRAM) • S-Band rendezvous transponder, toolbox, handholds, transition poles