National Aeronautics and Space Administration

Asteroid Redirect Mission Virtual Industry Day

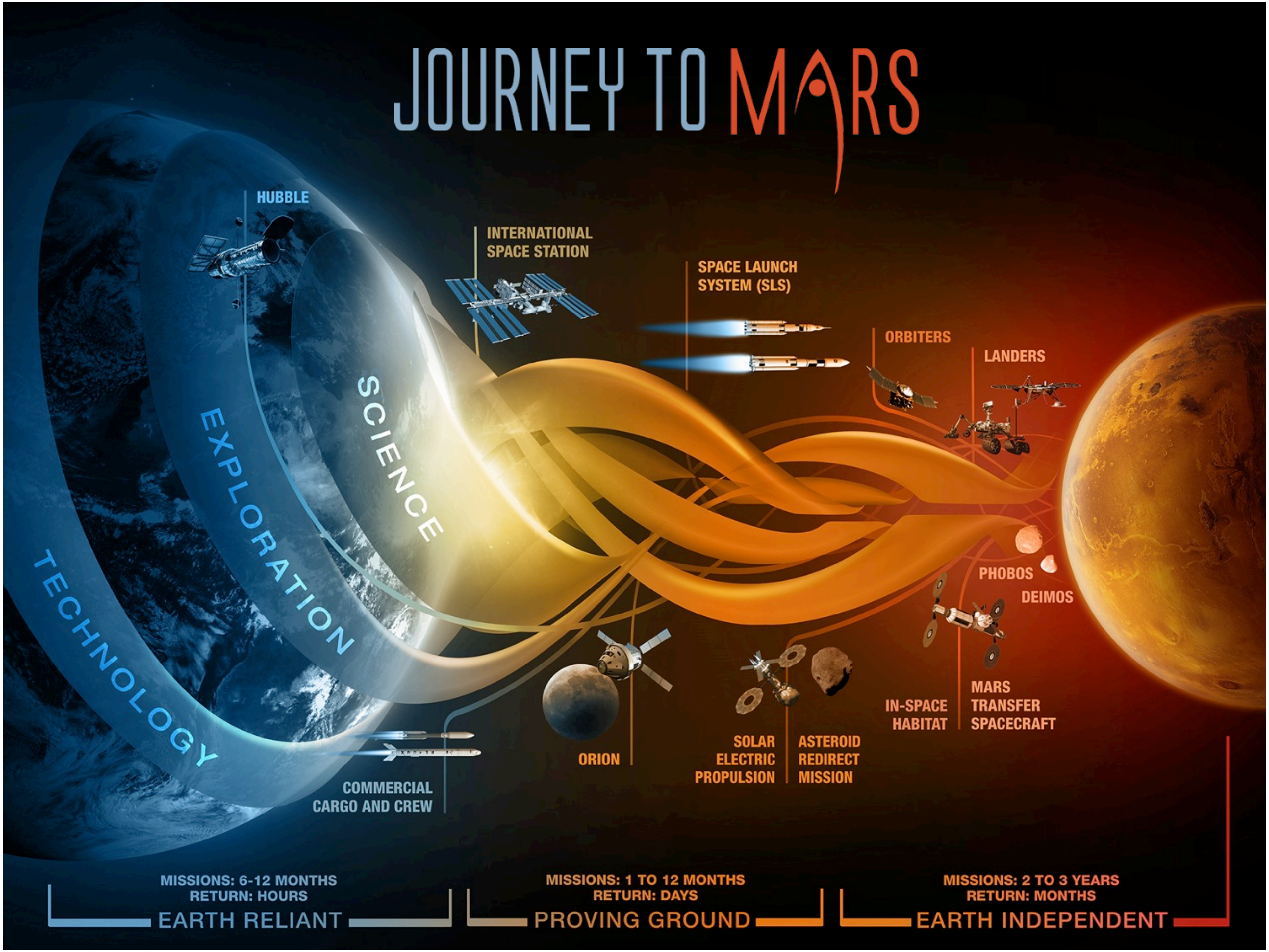
Spacecraft Bus Concepts to Support the Asteroid Redirect Robotic Mission and In-Space Robotic Servicing

INTRODUCTION

May 22, 2015

Outline

- Asteroid Redirect Robotic Mission Overview, Michele Gates
- Request for Information Introduction and Summary, Ron Ticker

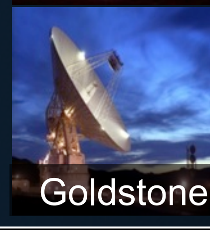


JOURNEY TO MARS
HUBBLE
INTERNATIONAL SPACE STATION
SPACE LAUNCH SYSTEM (SLS)
ORBITERS
LANDERS
SCIENCE
EXPLORATION
TECHNOLOGY
PHOBOS
DEIMOS
MARS TRANSFER SPACECRAFT
IN-SPACE HABITAT
SOLAR ELECTRIC PROPULSION
ASTEROID REDIRECT MISSION
ORION
COMMERCIAL CARGO AND CREW
MISSIONS: 6-12 MONTHS
RETURN: HOURS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

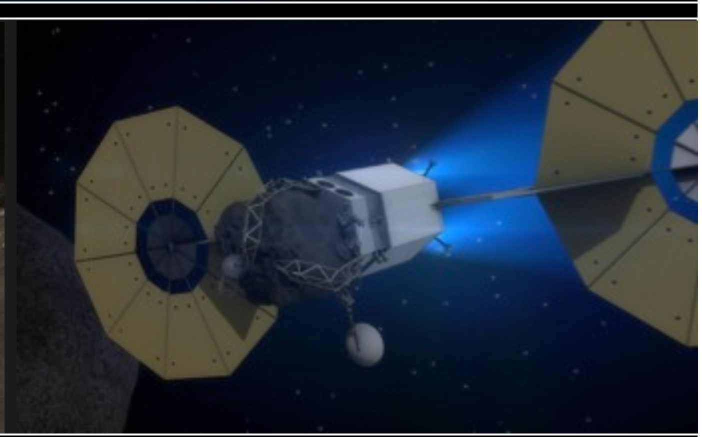
IDENTIFY

Ground and space based assets detect and characterize potential target asteroids



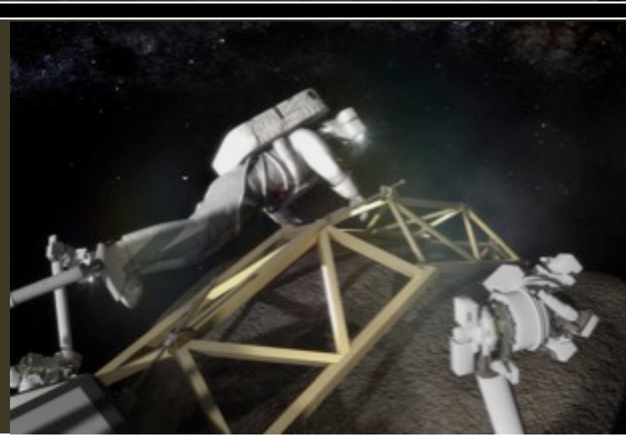
REDIRECT

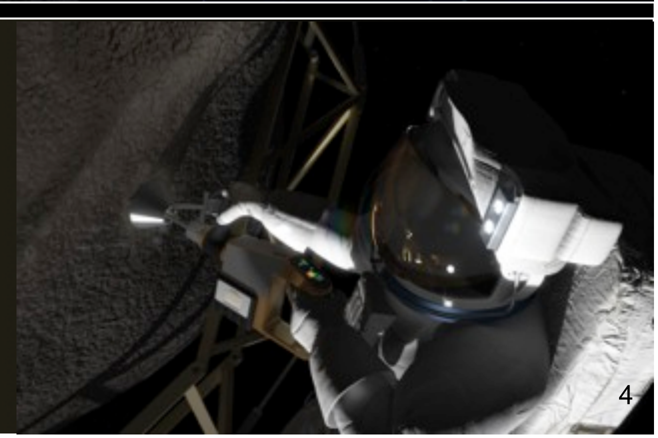
The Asteroid Redirect Robotic Mission (ARRM) uses solar electric propulsion (SEP) based system to redirect asteroid to cis-lunar space.



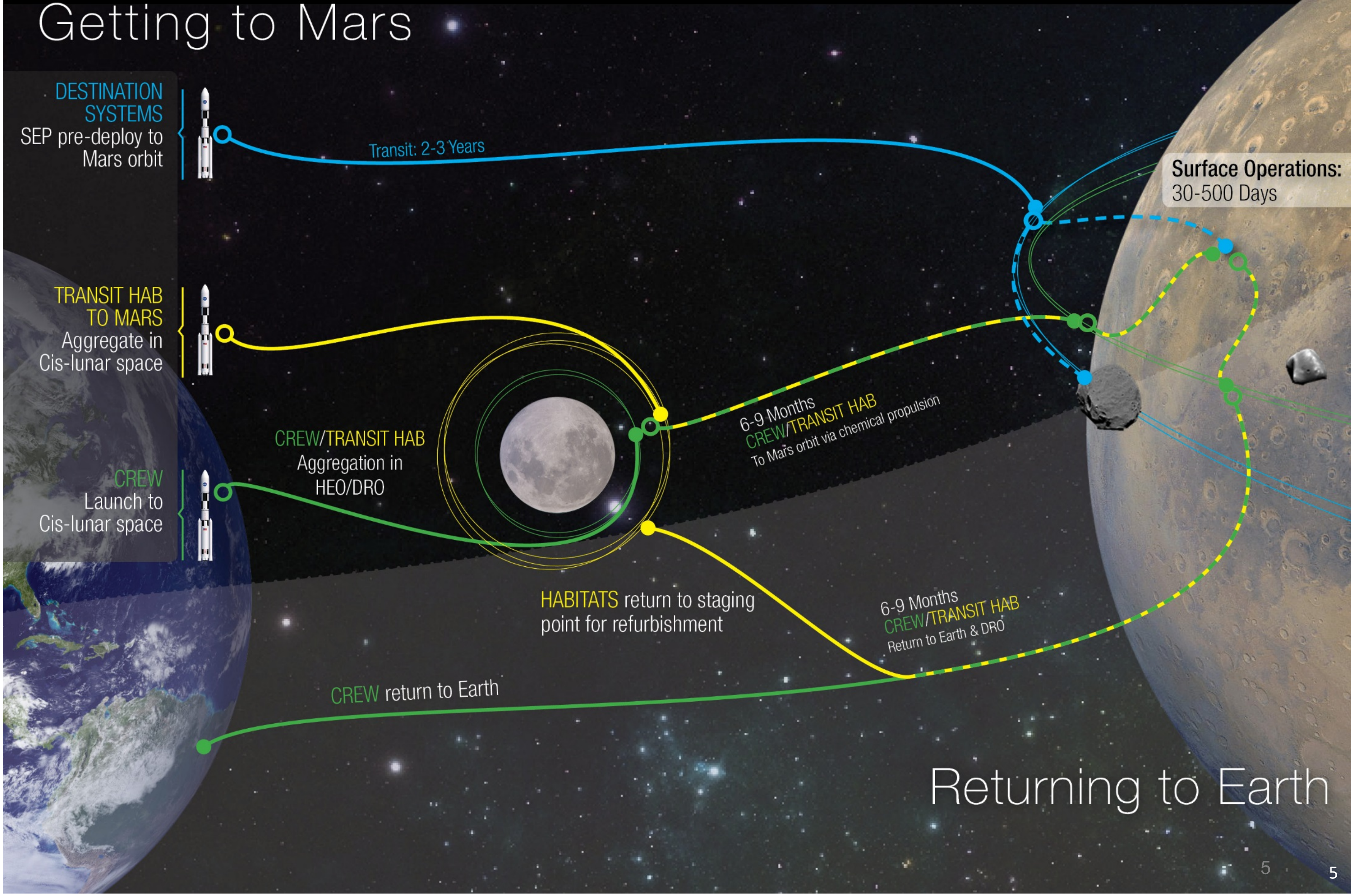
EXPLORE

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

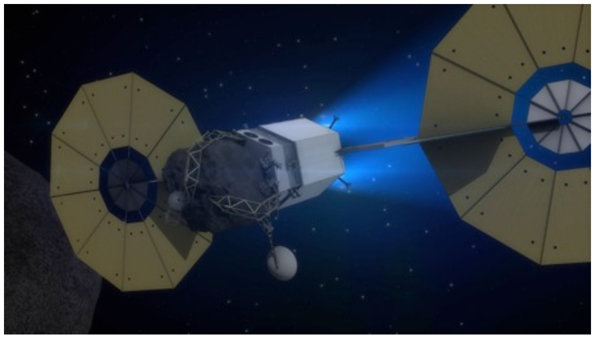




A Sustainable Exploration Approach
Mars Split Mission Concept

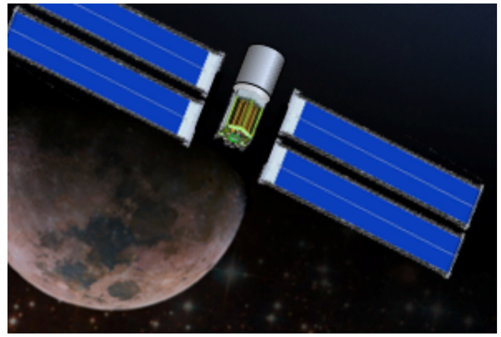


SEP Module Extensibility Concept for Mars



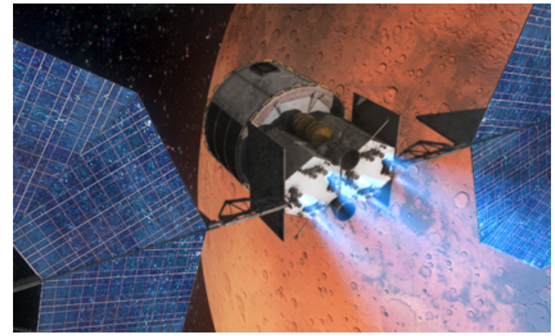
Asteroid Redirect Mission

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



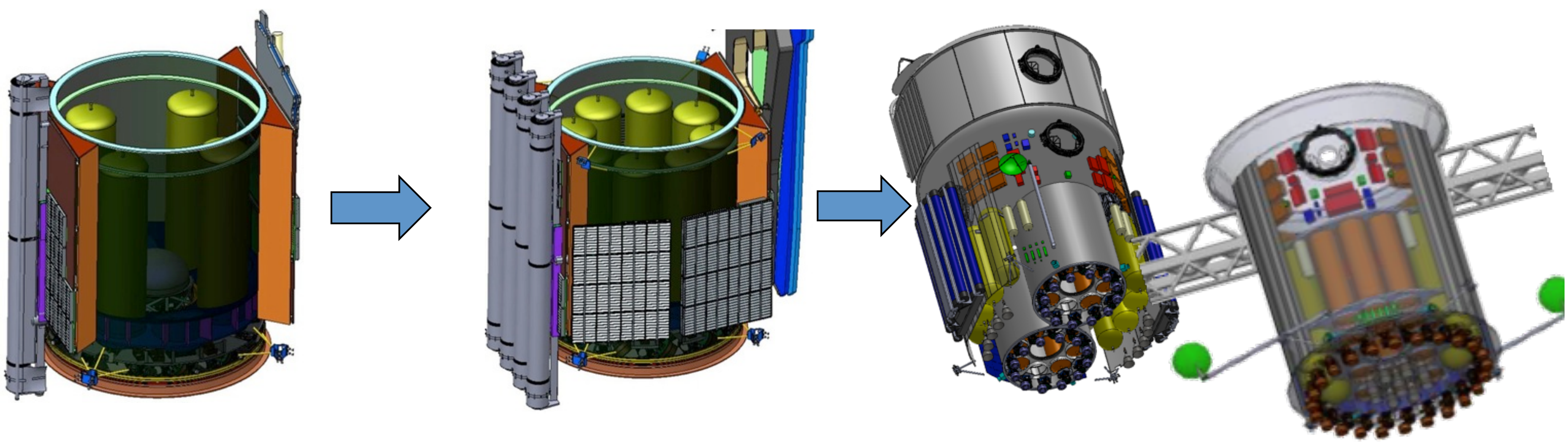
SEP/Chemical

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



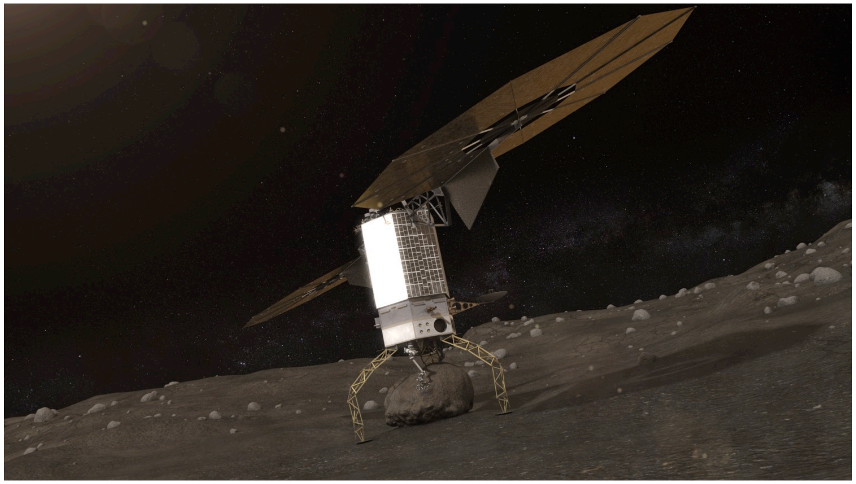
Hybrid

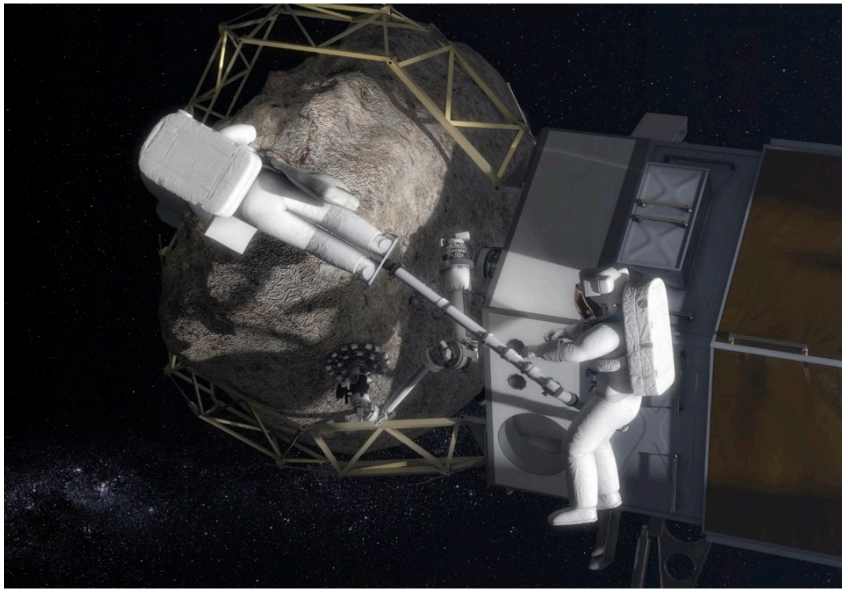
- 250 to 400-kW Solar Array
- 150 to 300-kW EP System
- 24-t Xenon Capacity With Xe Refueling Capability



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





Objectives of Asteroid Redirect Mission

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.

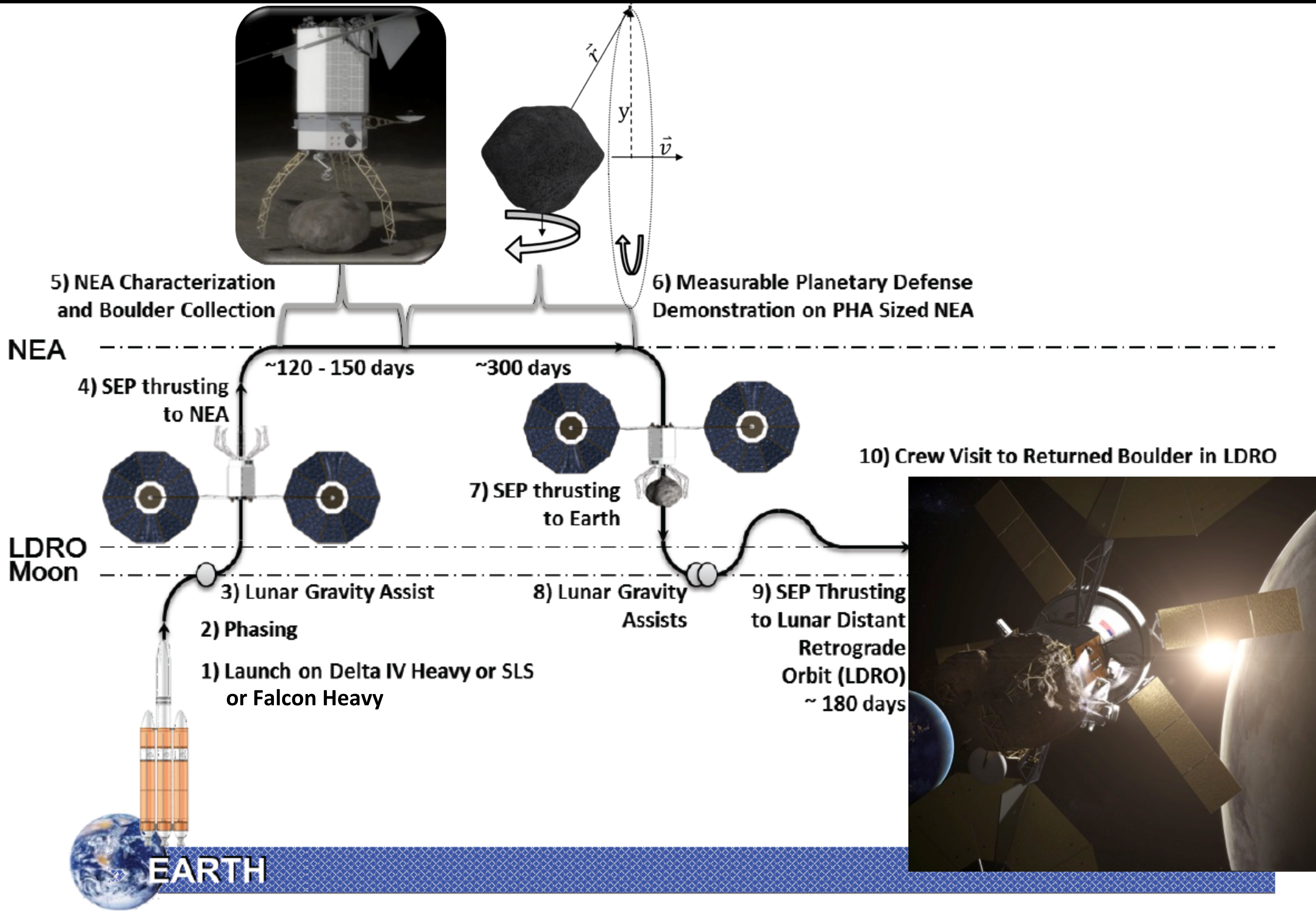
5. Pursue a target of opportunity that benefits scientific and partnership interests, expanding our knowledge of small celestial bodies and enabling the mining of asteroid resources for commercial and exploration needs.

Asteroid Redirect Robotic Mission (ARRM) Top Level Requirements

In addition to requirements to fulfill the mission objectives:

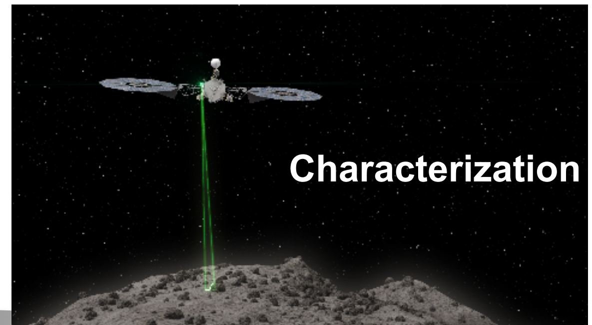
- ARRM shall be interface compatible with EELV-class launch vehicles, Falcon Heavy, and SLS until launch vehicle selection, expected by Project System Design Review.
- ARRM shall implement the project as a capability demonstration mission including defining and applying lean implementation techniques 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).

ARRM Mission Concept Overview

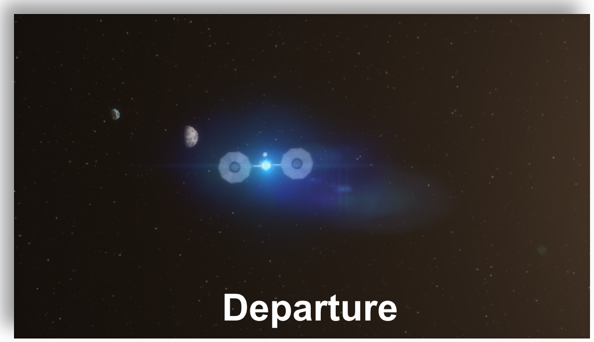


ARRM Capture Phase Overview

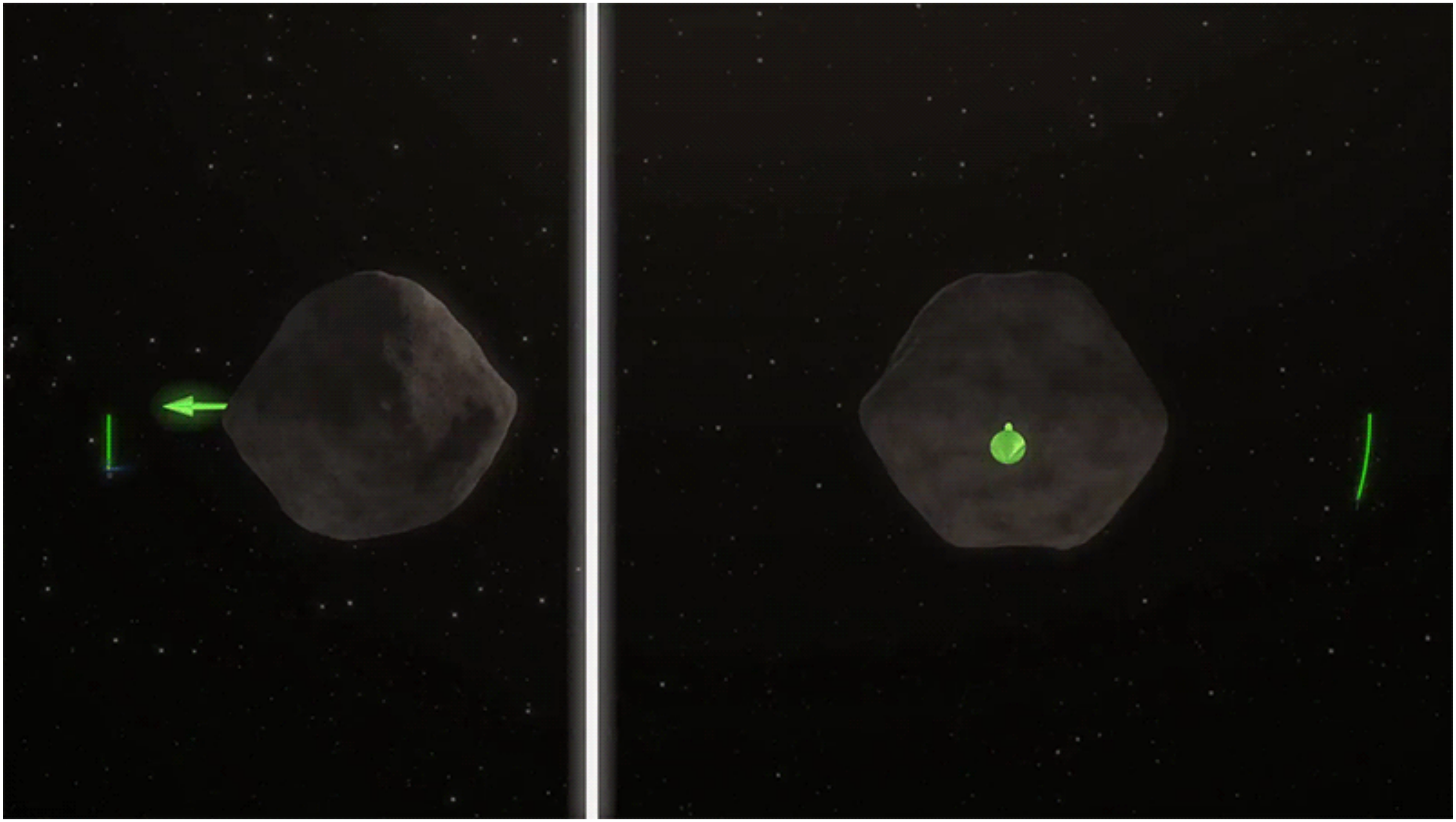
Approach	Characterization	Boulder Collection	Planetary Defense Demo
14 days	72 days	69 days	150 days (30 deflection + 120 hold & verify)



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.

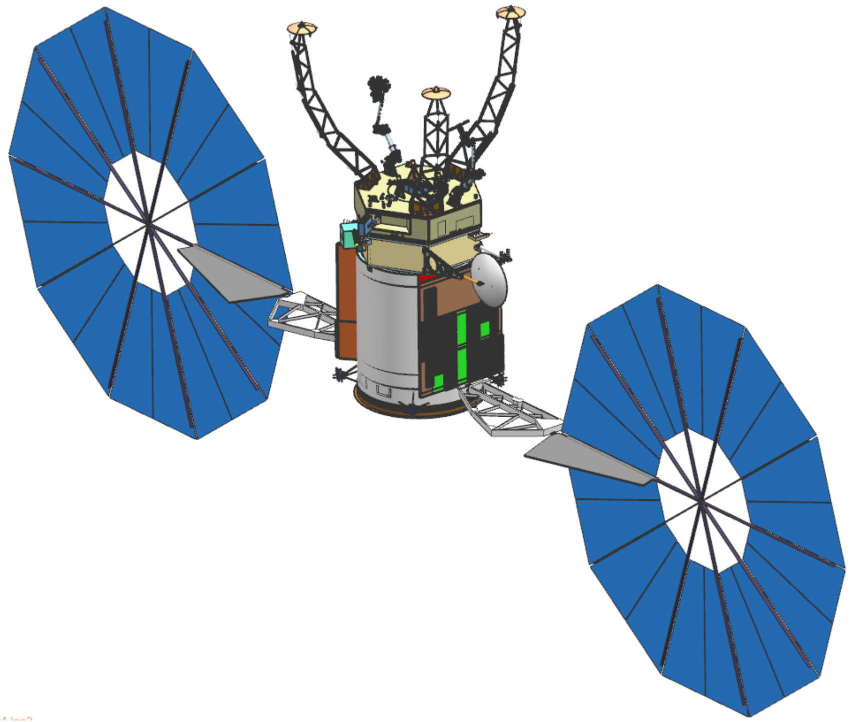


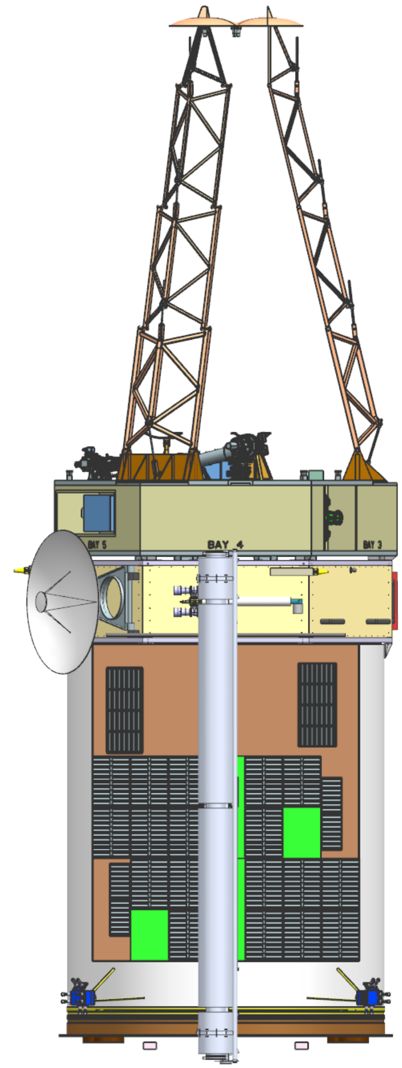
Demonstration of Basic Asteroid Deflection Techniques



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

ARRM Reference Concept Flight System Overview

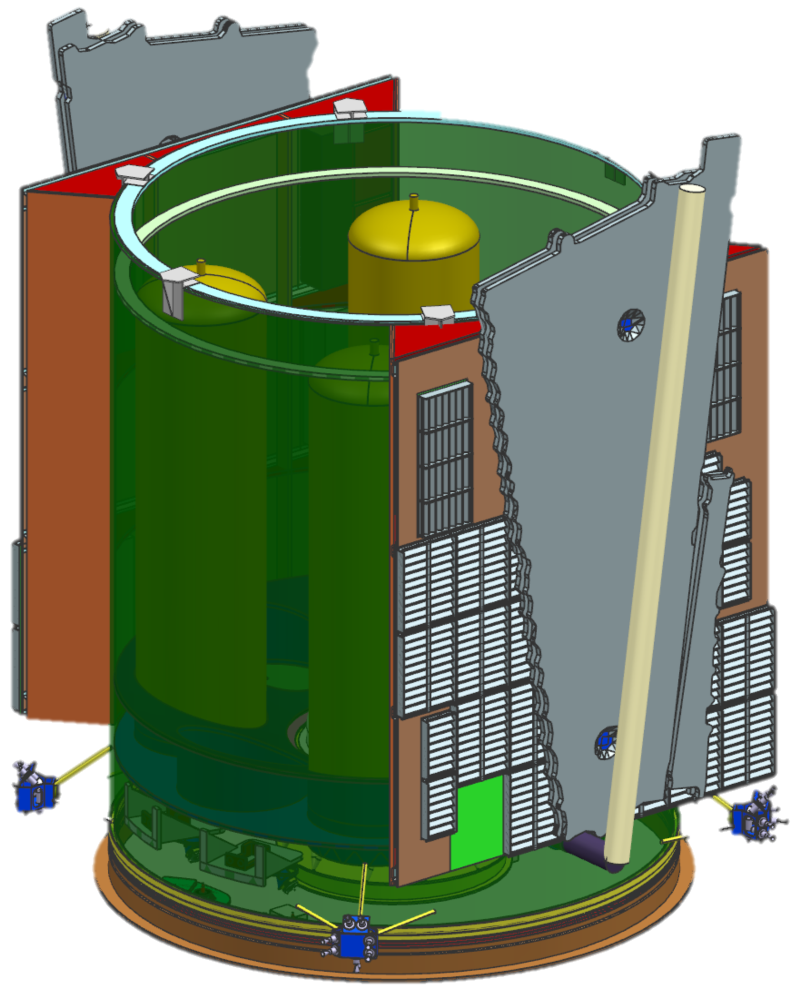




ARRM launch configuration

ARRM Reference 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



Current Valid ARRM Candidate Asteroid Targets

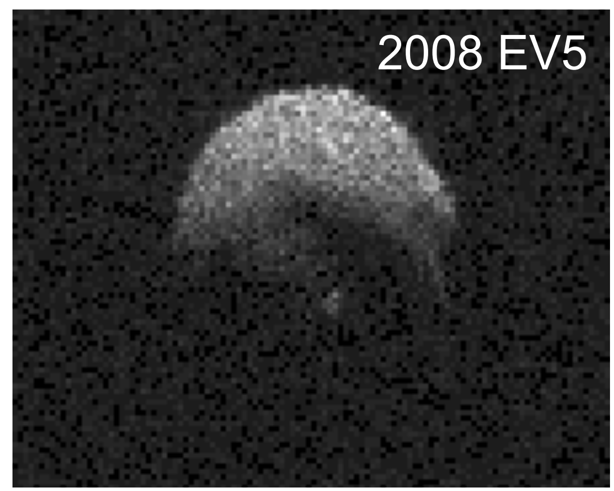
Candidate Option B Targets	Type	Mass, Diameter	Spin Period	V_∞ (km/s)	*Perihelion (AU)*	Absolute Magnitude *H*
2008 EV5	C	7.0×10^7t, 400m	3.73 hrs	4.41	1.04	20.0
Bennu	C	7.8×10^7t, 490m	4.30 hrs	6.36	1.36	20.8
1999 JU3	C	6.9×10^8t, 870m	7.63 hrs	5.08	1.42	19.2
Itokawa	S	3.5×10^7t, 320m	12.1 hrs	5.68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

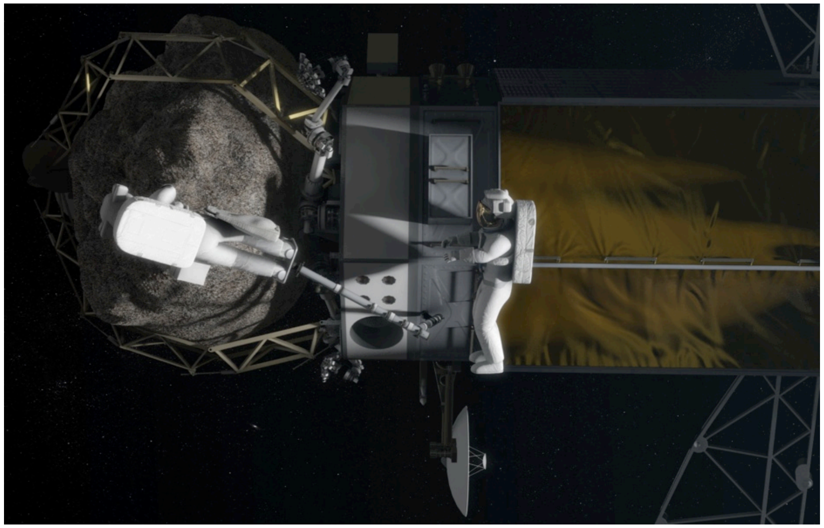
NASA continues to look for additional targets in accessible orbits.

Reference ARRM Target



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 Formulation Guidance

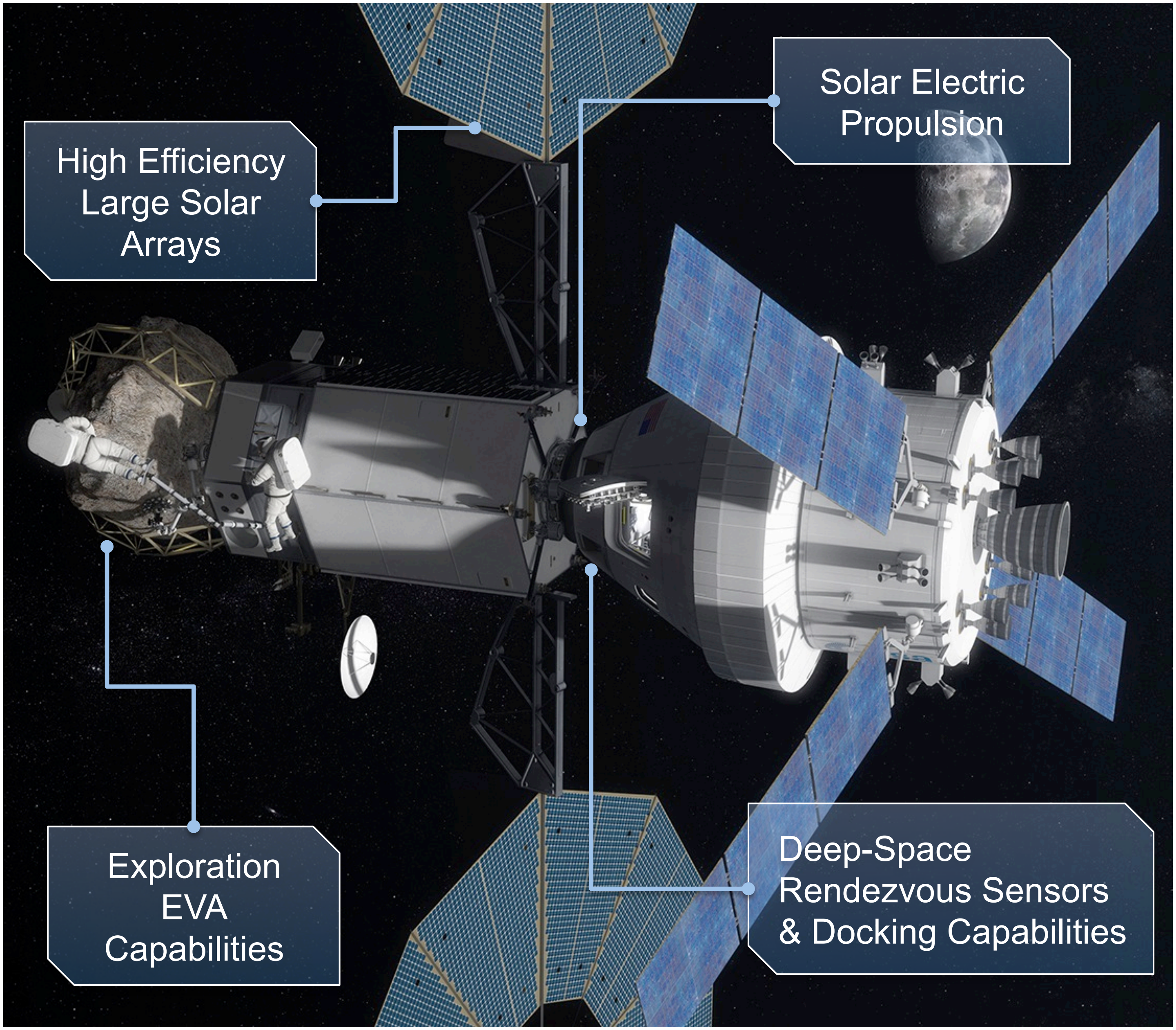
- Capture option B
- Draft Level 1 requirements
- Target launch date Dec 2020
- Cost cap $1.25B not including launch vehicle and mission operations (Phase E)
- Internal and external dependencies
- Define capability demonstration implementation approach

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

Additional RFI Summary Request

- **This RFI provides more information on:**
  1. The reduced capacity Xe load idea for ARRM
  2. The idea of commonality of a reduced capacity Xe load bus for ARRM and notional LEO satellite servicing demo mission (Restore-L)
  3. The idea of a separable bus for ARRM with a chemical bus which does the ‘landing’ and capture, and is common with Restore-L bus, and a bigger SEP tug.

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 DRO 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

National Aeronautics and Space Administration

Asteroid Redirect Mission Virtual Industry Day

Spacecraft Bus Concepts to Support the Asteroid Redirect Robotic Mission and In-Space Robotic Servicing

DESCRIPTION OF REQUEST FOR INFORMATION

May 22, 2015

RFI Introduction

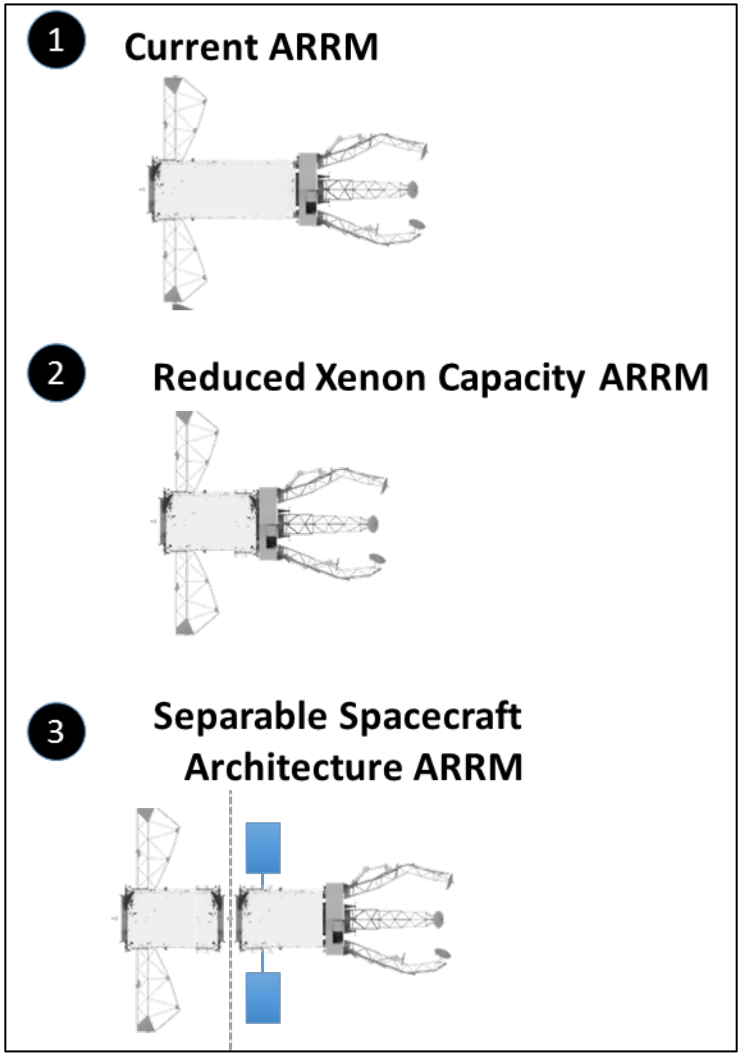
- NASA is formulating the Asteroid Redirect Mission (ARM) to advance technologies and gain operational experience critical for future human spaceflight beyond low Earth orbit.
- In 2014, NASA released a Broad Agency Announcement (BAA) to study concepts from industry in support of ARM pre-formulation activities. Eighteen study contracts were awarded in five areas: Asteroid Capture Systems, Rendezvous Sensors, Adapting Commercial Spacecraft, Partnerships Opportunities for Secondary Payloads, and Partnerships Opportunities for the Asteroid Redirect Crewed Mission.
- The robotic segment of ARM has successfully passed its Mission Concept Review (MCR) and baselined the robotic boulder capture options.
- NASA is seeking additional information from industry on a range of spacecraft implementation approaches and procurement options that may achieve further cost savings

RFI Released Monday May 18, 2015 -- Responses due June 29, 2015

ARRM Reduced Xenon Capacity Concept

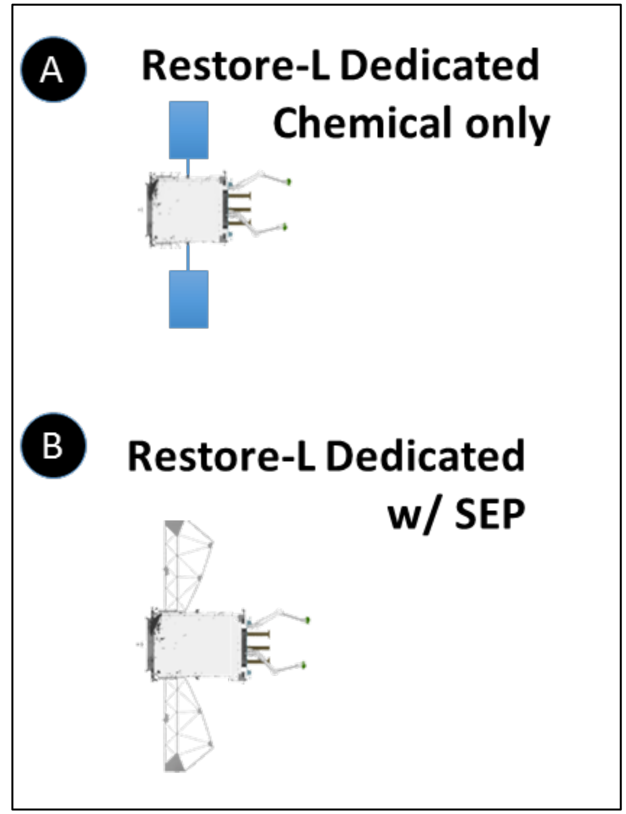
- **The reduced xenon capacity ARRM concept (depicted as drawing 2) emerged from the recent ARM BAA work, and while it involves less propellant mass for the ARRM spacecraft, it retains substantial extensibility at a potentially lower cost.**

- **The reduced xenon capacity ARRM concept includes the same power, power processing and other capabilities as the reference concept, but with a reduced xenon propellant storage capacity (5,000 kg). As compared to the reference ARV design, the reduced xenon capacity alternative would still have a 58 kW solar array and a 40 kW EP system; the same type and number of solar arrays, thrusters, and power processing units; and the same reaction control subsystem.**



Background on Notional LEO Satellite Servicing Demo Mission (Restore-L)

- **Restore-L Restore Servicing Vehicle (RSV) consists of the government provided Servicing Payload (SP) and a commercial spacecraft bus and would service a LEO polar-orbiting government owned satellite.**
- **The Restore-L SP and ARRM Capture Module exhibit a significant amount of commonality. (two 7-DOF robot arms, RPO, avionics)**
  - The SP also includes refueling tools and a Propellant Transfer Subsystem
  - The ARRM Capture Module also contains the Contact and Restraint Subsystem "legs".
- **The current Restore-L dedicated spacecraft concept (A) has a chemical propulsion system only with no SEP. Addition of a reduced-performance version of the ARRM SEP system (B) could enhance the Restore-L mission, and introduce increased synergy between the two mission concepts.**



Separable Spacecraft Architecture ARRM Concept

- **NASA may also consider a separable spacecraft architecture ARRM concept (depicted as drawing 3) if it can be cost effectively implemented for ARRM and Restore-L.**
- **As distinguished from the monolithic ARRM spacecraft concepts described above, the separable spacecraft architecture ARRM concept would consist of a two-spacecraft configuration, partitioning the spacecraft into a dedicated SEP vehicle or "tug" and a smaller Asteroid Capture Vehicle (ACV).**
- **This concept is envisioned to utilize the same EP elements (thrusters, power processing, and solar arrays) as the reference ARV and reduced xenon capacity concepts while providing flexibility in systems architecture and acquisition.**

RFI Response Requests

- **Reduced Xenon Capacity ARRM concept:**
  - Describe your suggested approach to achieving the reduced xenon capacity alternative spacecraft bus concept, including the potential extensibility to NASA's goals. Include a rough order-of-magnitude (ROM) cost estimate, milestone schedule and list of benefits and technical challenges consistent with a December 2020 ARRM launch readiness date.
  - Describe your suggested approach to evolving the reduced xenon capacity ARRM concept to the current ARRM concept and future exploration architecture concepts including ROM cost estimates.
  - Discuss potential markets and alternative uses of this reduced xenon capacity ARRM concept beyond ARRM including commercial adaptation.
  - Discuss procurement approach options, including potential for commercial partnership and cost sharing.
  - Discuss, if applicable, any relevant, cost-effective system or subsystem-level technology demonstrations that should potentially be conducted in advance of the ARRM capability demonstration that might reduce technical risk for that mission or accelerate development of capabilities for future exploration architectures or commercial applications.
- **Reduced Xenon Capacity ARRM spacecraft common with Restore-L dedicated spacecraft:**
  - Describe your approach toward utilizing a common SEP spacecraft for ARRM and Restore-L considering the reduced xenon capacity ARRM concept. Include OM cost estimates, milestone schedules and list of benefits and technical challenges consistent with a December 2020 ARRM launch readiness date.
  - Discuss the potential for a joint ARRM and Restore-L spacecraft procurement.
- **Separable Spacecraft Architecture ARRM concept:**
  - Describe your suggested approach to achieving a separable spacecraft architecture ARRM concept, including your suggested SEP tug and ACV approach. Include a ROM cost estimate, milestone schedule and list of benefits and technical challenges consistent with a December 2020 ARRM launch readiness date.
  - Describe your suggested approach to evolving your SEP vehicle concept design to achieve the goals of the current ARRM concept and future exploration architecture concepts including ROM cost estimates.
  - Discuss potential markets and alternative uses of the separable spacecraft architecture ARRM concept or any of its elements including commercial adaptation.
  - Discuss the potential for partnership and cost sharing in development of the separable spacecraft architecture ARRM concept or any of its elements.
  - Describe your approach for utilizing a common ACV and Restore-L dedicated spacecraft and the potential for a joint ACV and Restore-L spacecraft procurement.

RFI Response Request Logistics

- All responses shall be submitted via e-mail to HQ-ARM-ISRS@mail.nasa.gov by 5:00 PM EDT on June 29.
- Files may be submitted in MS Word, PDF, or RTF format. Paper submissions will not be accepted. All responses shall be no more than seventy (70) pages including graphs, charts tables, illustrations, and other figures. A page is defined as one (1) sheet 8 ½ x 11 inches using a minimum of 12-point font size for text.
- **NO CLASSIFIED INFORMATION SHOULD BE INCLUDED IN THIS RFI RESPONSE.**
- Additional Information
  http://www.nasa.gov/feature/arm-spacecraft-bus-request-for-information
- Point of Contact
  Name: Ron Ticker
  Phone: (202) 358-2429
  Email: HQ-ARM-ISRS@mail.nasa.gov

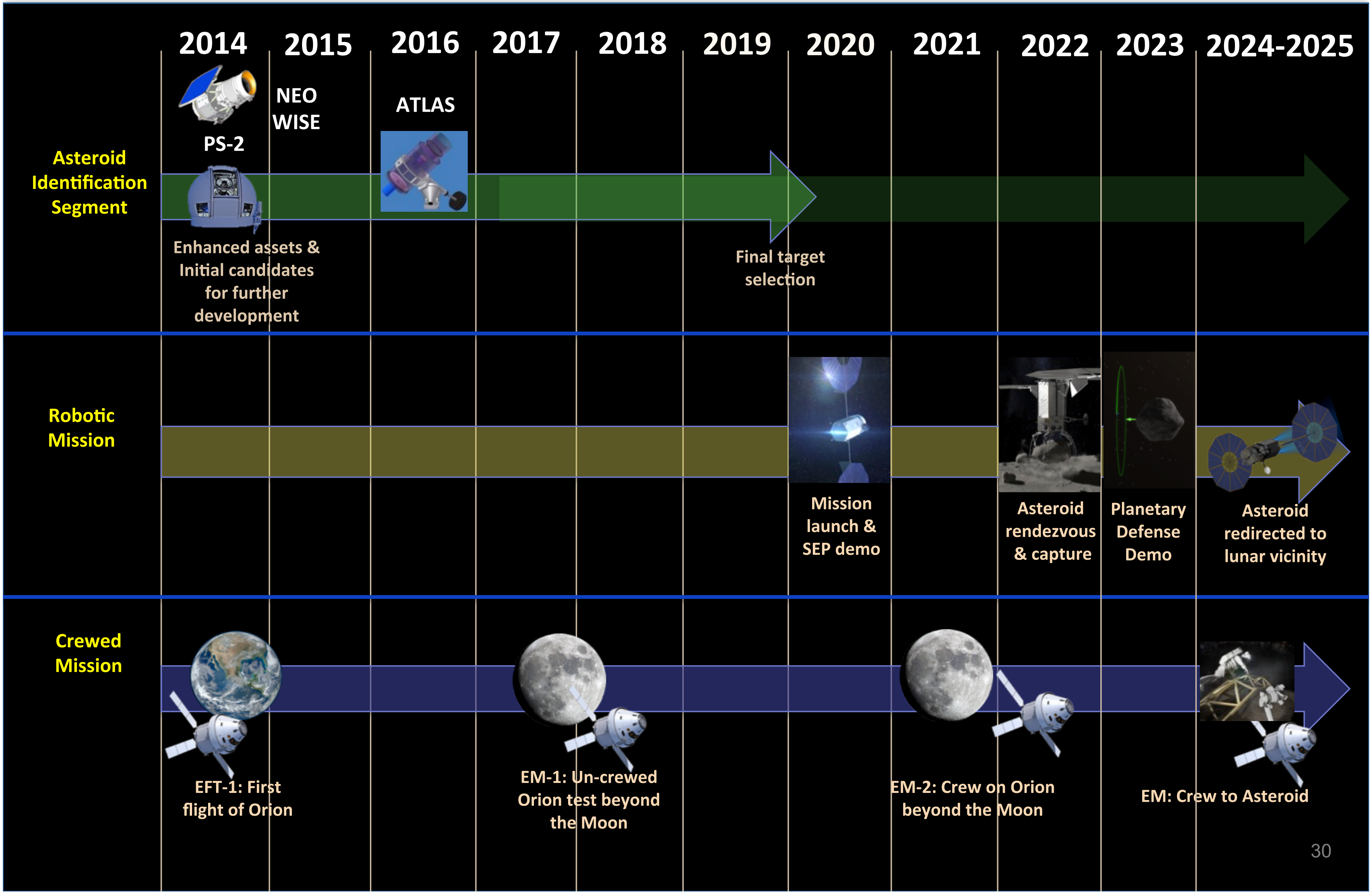
NASA

Back Up

ARM Contributions to Future Deep Space Missions

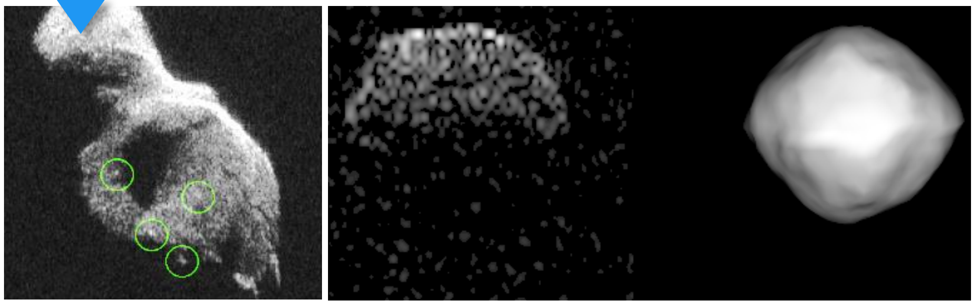
- **Through ARM, NASA will develop, test and use a number of key capabilities that will be needed for future exploration purposes, as well as providing other broader benefits**
  - Advanced high-power, long-life, high through-put solar electric propulsion
  - Autonomous rendezvous and proximity operations
  - 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

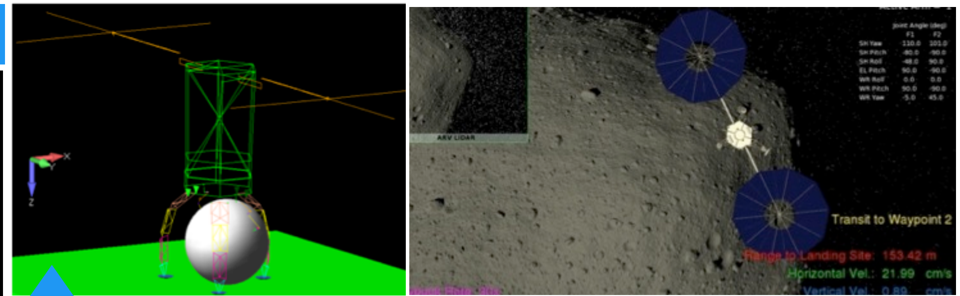
ARM Alignment Strategy



Asteroid Redirect Mission: 2014 Advancements

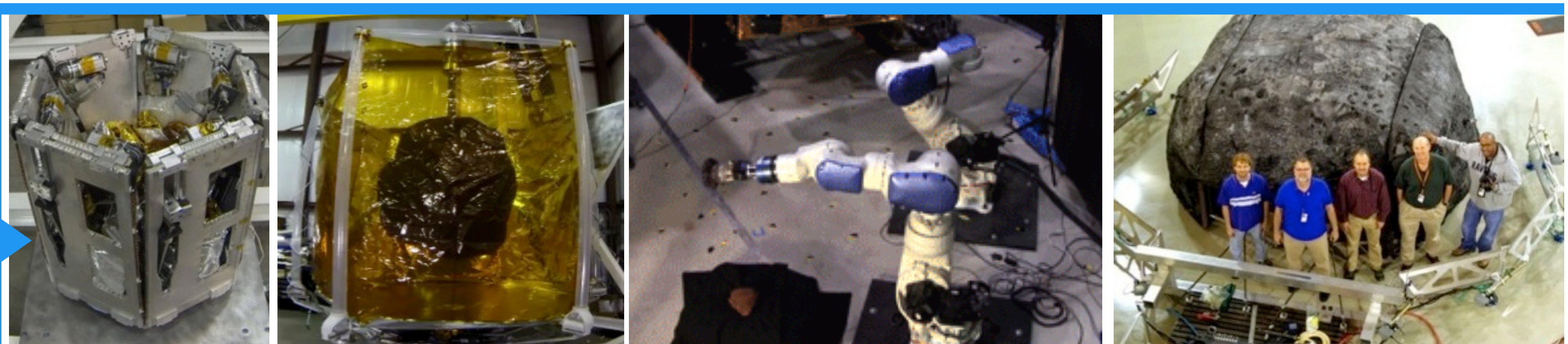
IDENTIFYING CANDIDATE ASTEROIDS





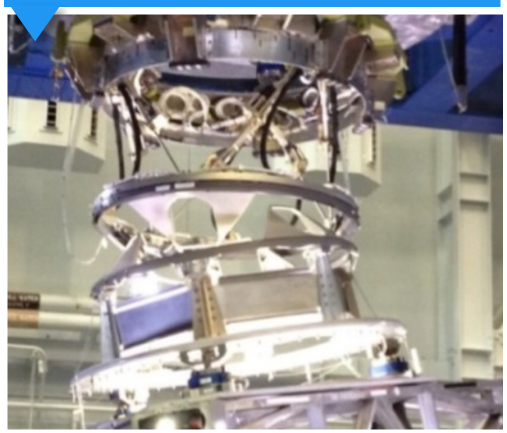
MISSION DESIGN AND SIMULATION OF CRITICAL MISSION OPERATIONS

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 Mission Highlights

ARRM Reference 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
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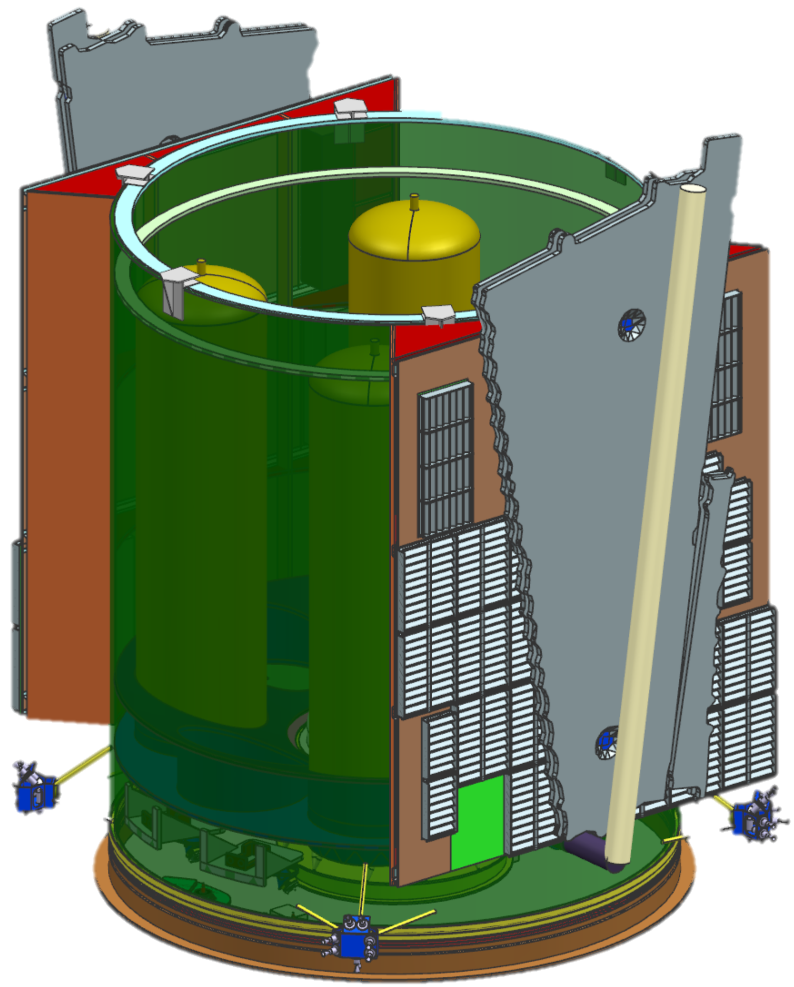
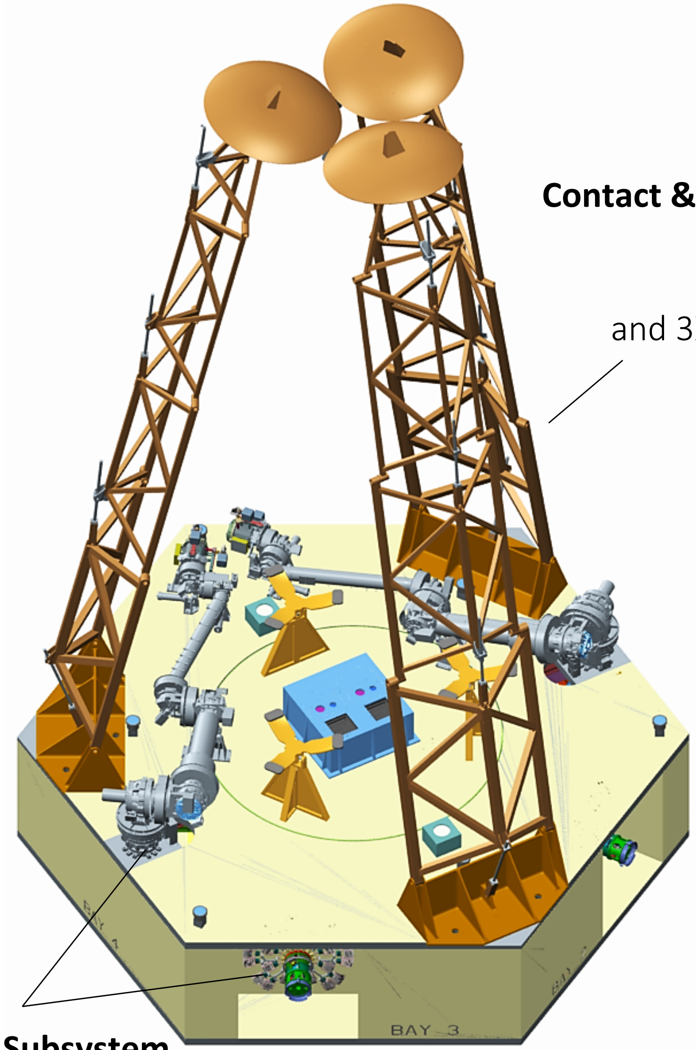
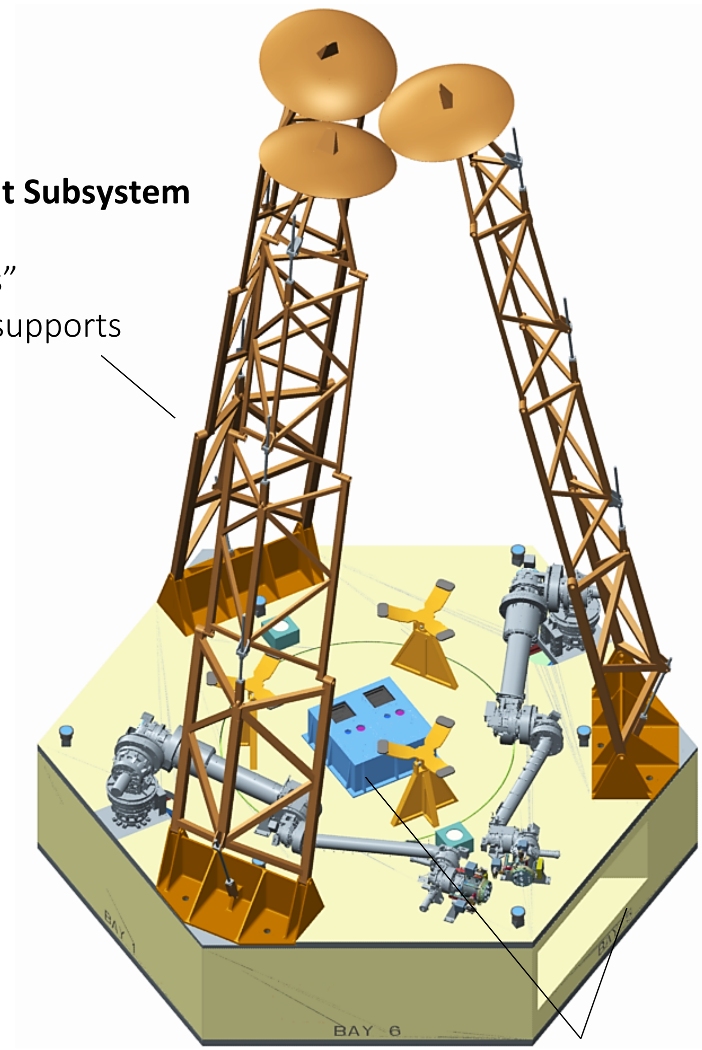


Reference Concept Flight System Overview

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

ARRM Reference Concept Capture Module





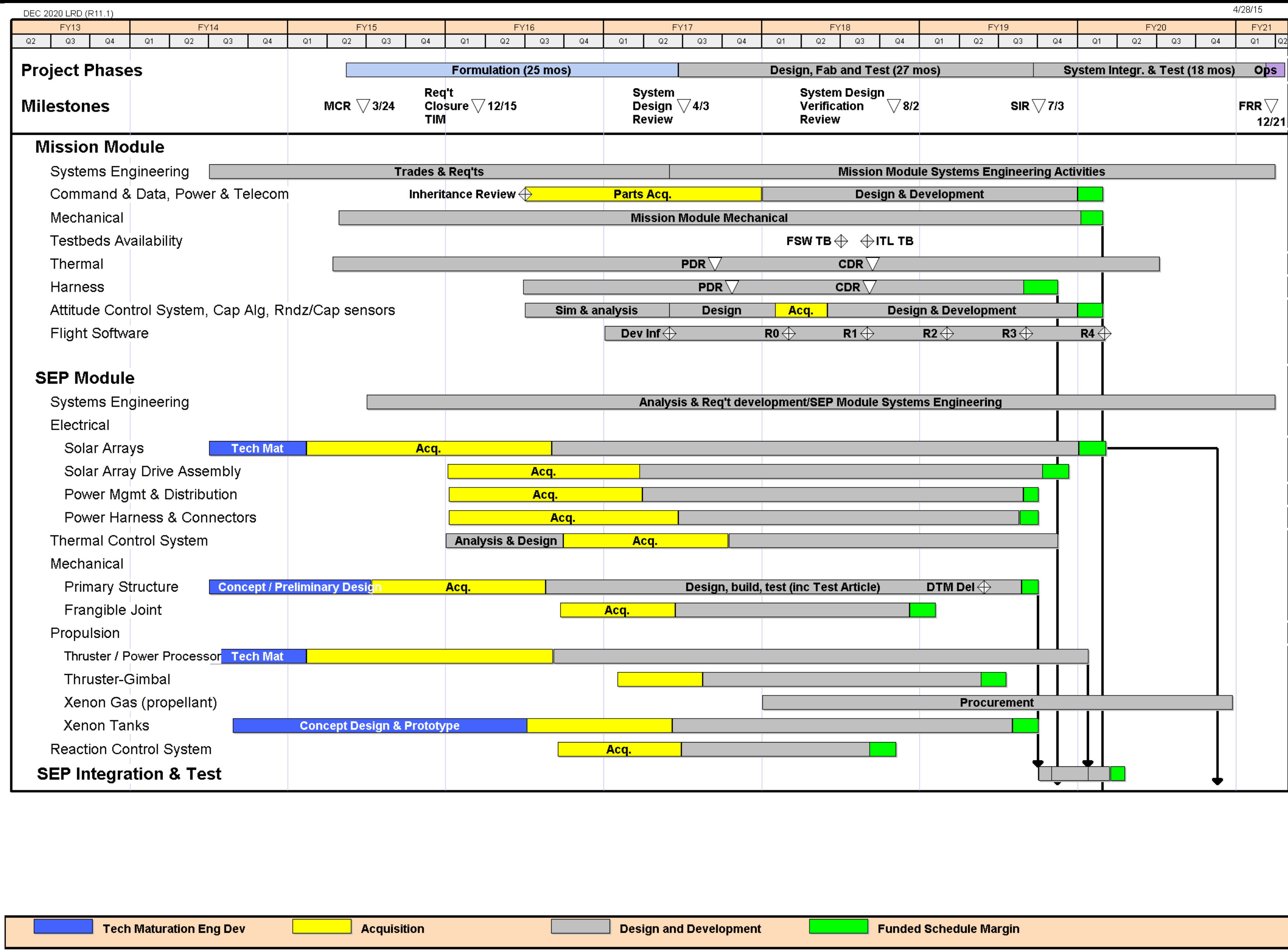
Contact & Restraint Subsystem (CRS)
3X "legs"
and 3X cradle supports

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

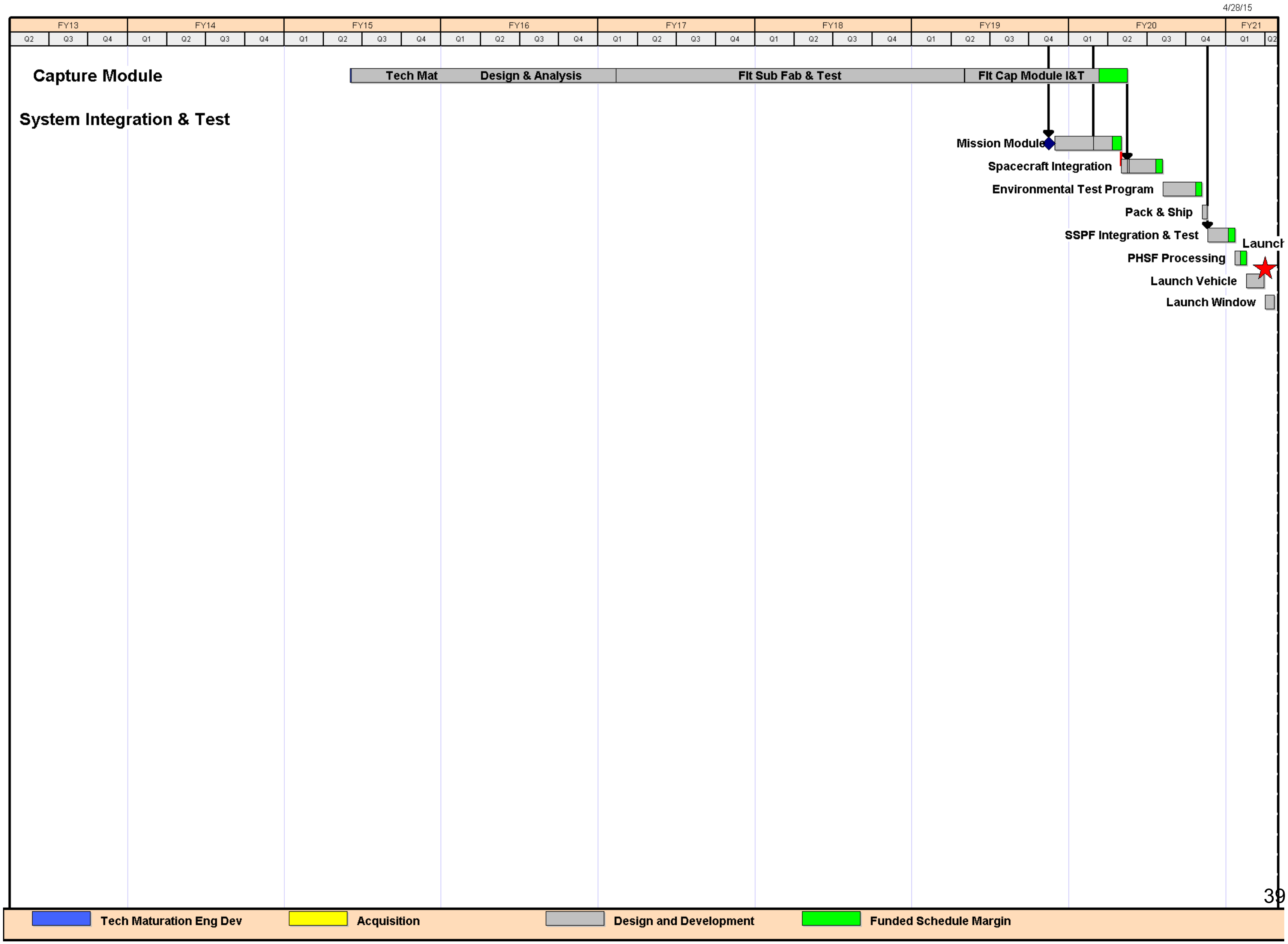
3 SpaceCube computers, Video Distribution and Storage Unit w/ 128 Gigabytes storage

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

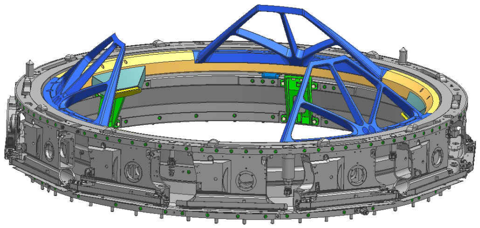
ARRM Concept Development Summary Schedule LRD December 31, 2020 (1/2)



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

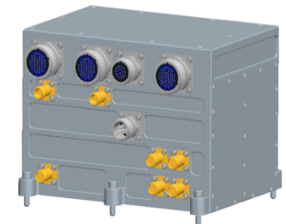


ARRM Crewed Mission Accommodations (Docking)



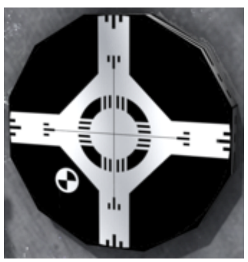
IDSS IDD-Compliant Docking Mechanism

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



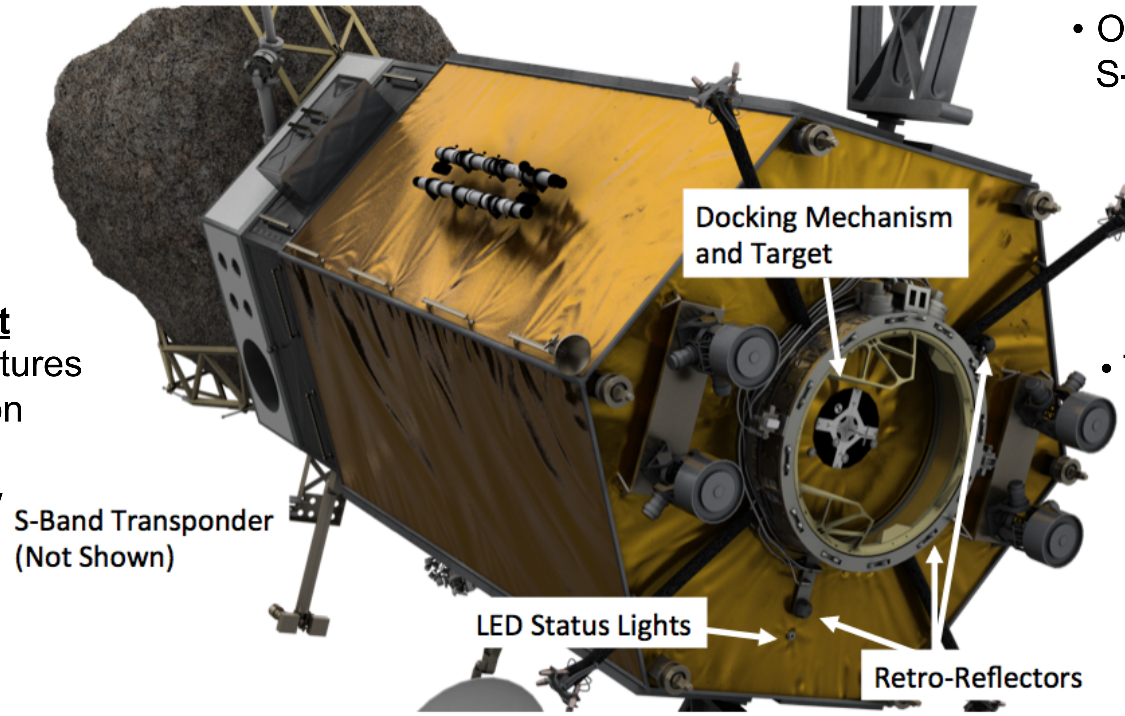
Rendezvous Aid

- Orion-compatible low-rate S-band transponder



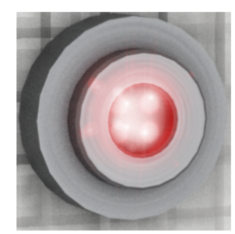
Docking Target

- 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

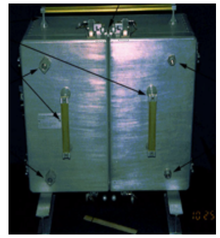
- Indicate the state of the ARRM systems, inhibits and control mode

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.

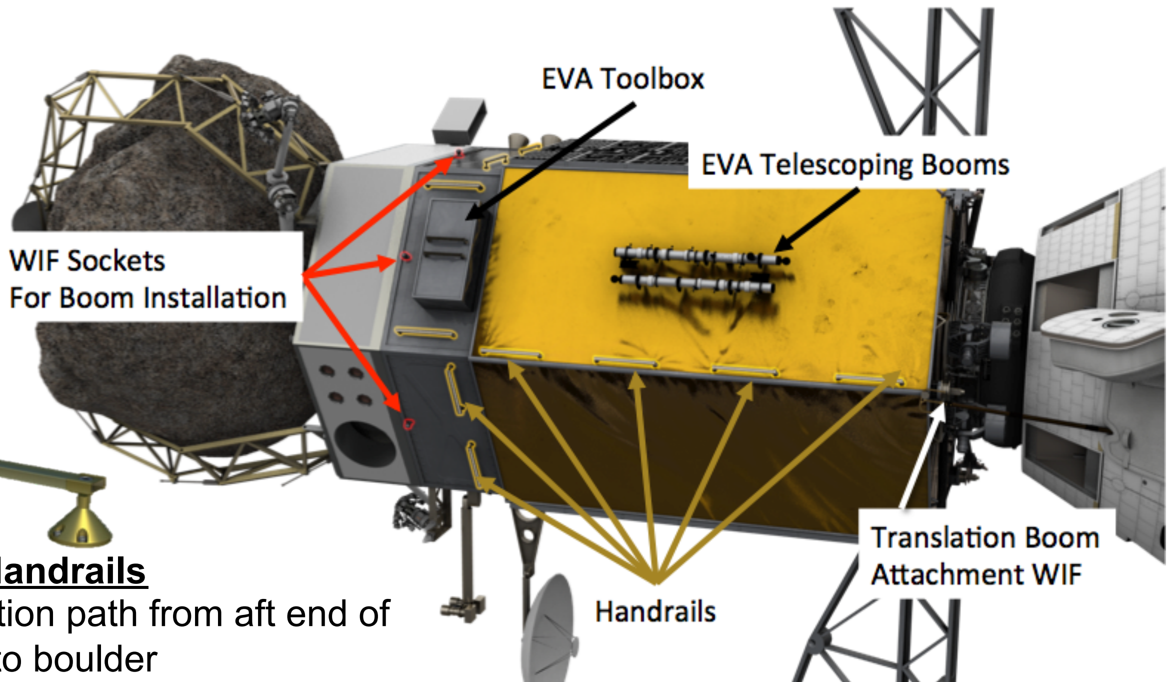
ARRM Crewed Mission Accommodations (EVA)

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)

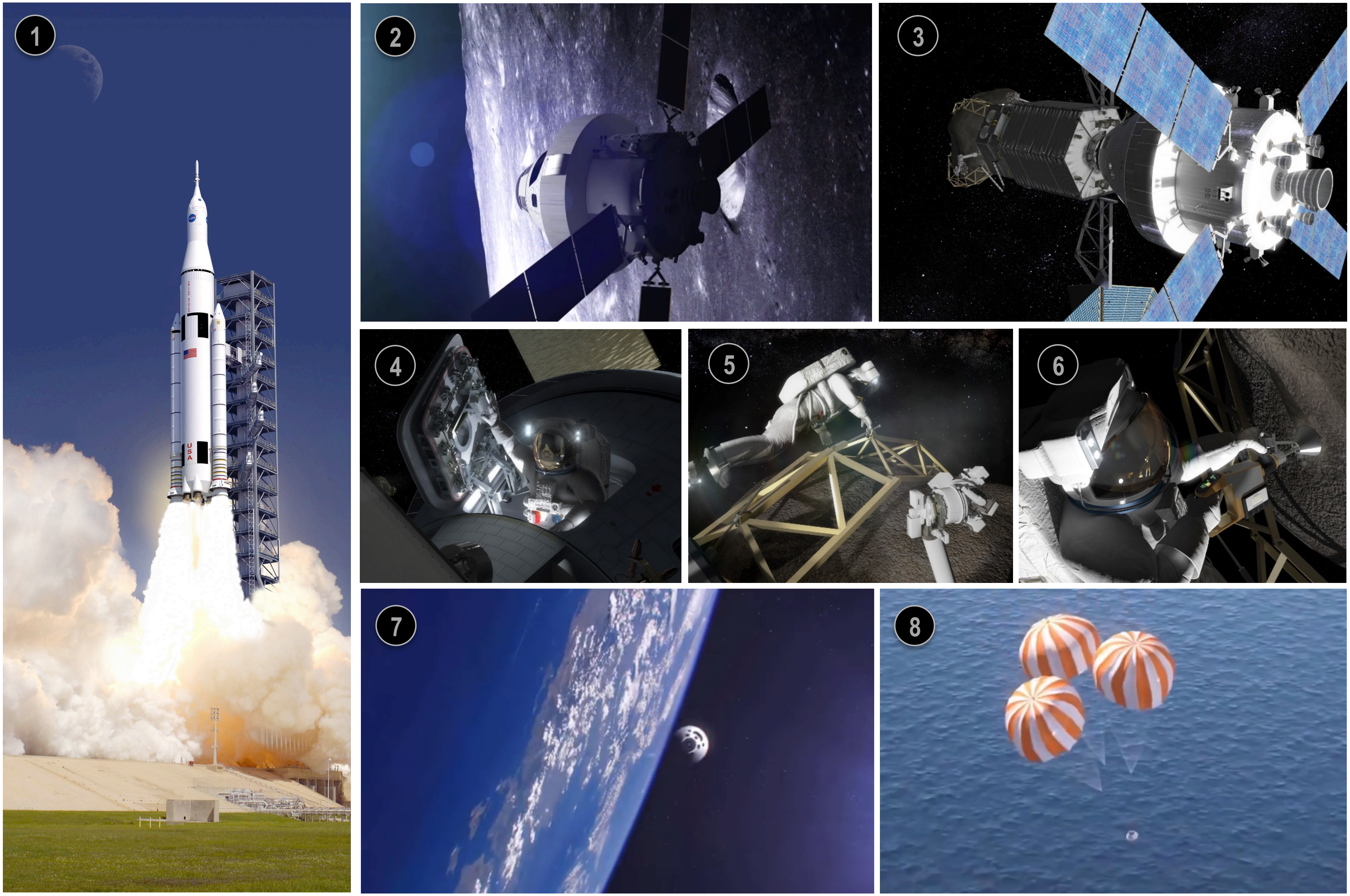
Worksite Interface Fixture Sockets
- Provide boom attach points to ARRM.



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

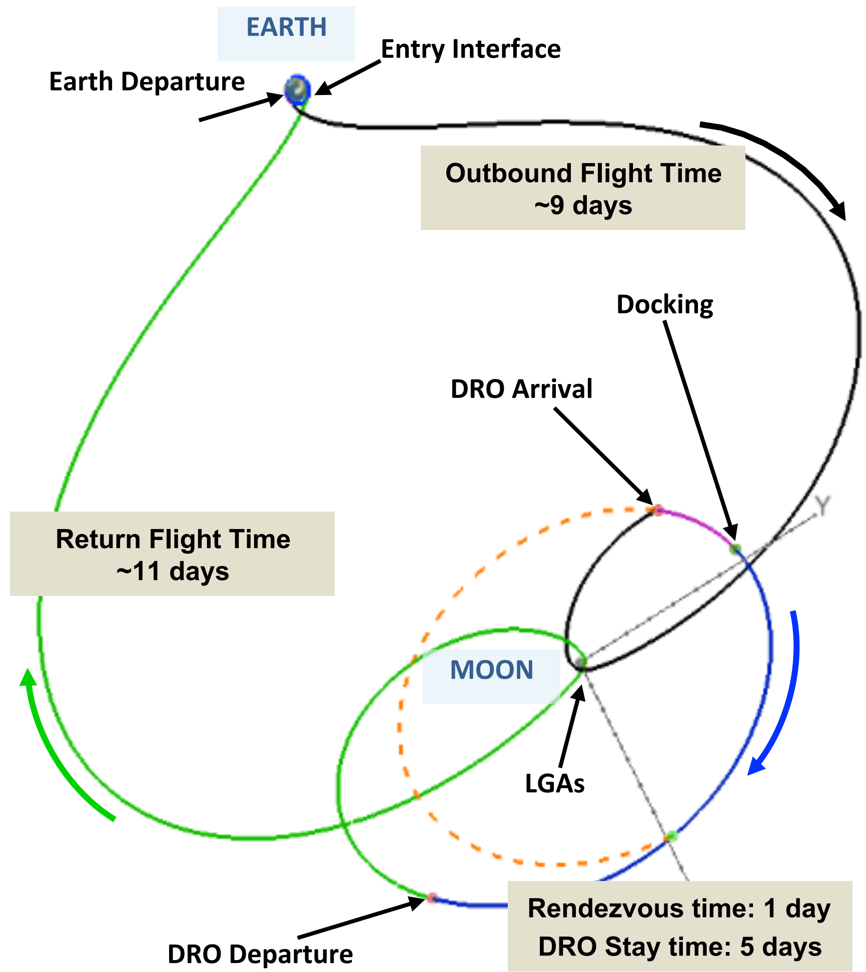
Crew Safe Certification
- Spacecraft designed for Crew Safety including EVA kick loads, sharp edge, safety inhibits and Caution and Warning annunciation.
- ARRM Systems are Human Rated for Crew Interfaces instead of entire spacecraft

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 DRO 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.***