National Aeronautics and Space Administration

Asteroid Redirect Mission Update

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Today we are…

- **Updating the small bodies community on what we have accomplished since the July SBAG meeting**

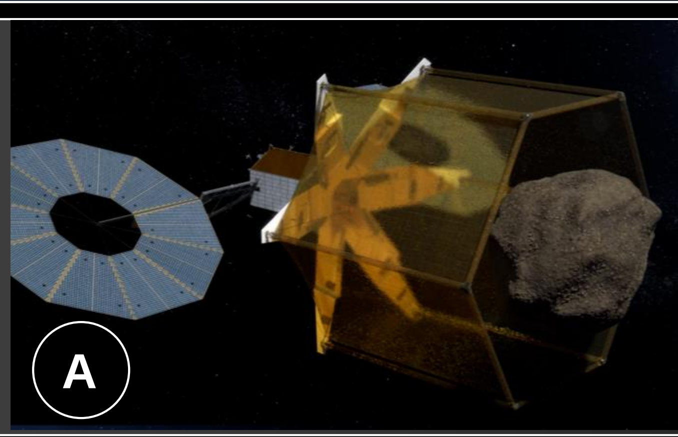
Asteroid Redirect Mission: Three Main Segments

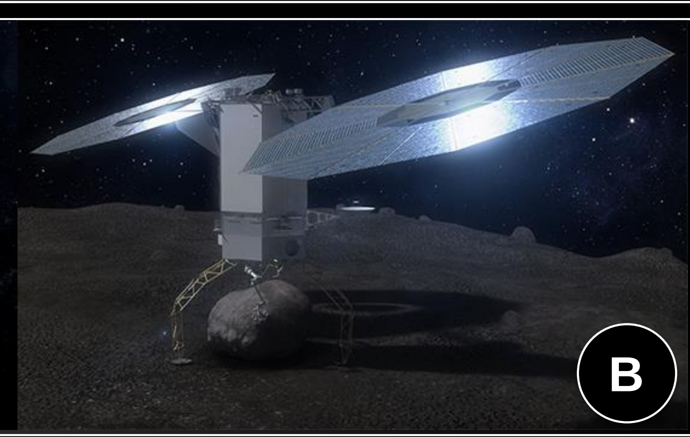
IDENTIFY

Ground and space based assets detect and characterize potential target asteroids

REDIRECT

Solar electric propulsion (SEP) based system redirects asteroid to cis-lunar space (two capture options)



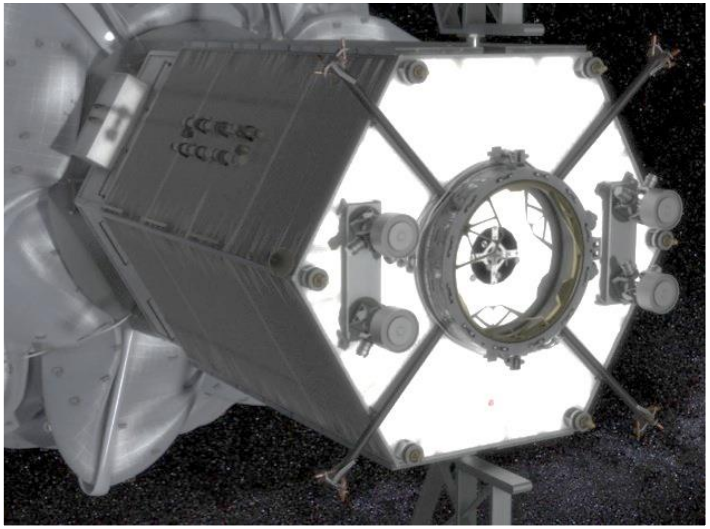


EXPLORE

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

Current Objectives of Asteroid Redirect Mission

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



Accomplishments since July 2014 (1)

- **Enhanced asteroid observations underway with new asteroids identified**
  - Enhanced NEA characterization techniques have been tested, validated and implemented.
    - Rapid Response by IRTF and interplanetary radars (Goldstone and Arecibo)
    - Improved resolution by radar imaging (~8 meters reduced to <4 meters)
    - Use of Spitzer to determine size and rough mass, density, composition of very dim candidates.
    - No new valid candidates identified as of yet
- **Advanced solar electric propulsion technology development and testing completed**
  - Solar arrays, Hall thrusters, power processing units operating at several voltages and power levels
- **Broader engagement through the Curation and Analysis Planning Team for Extra-terrestrial Materials and Expert and Citizen Assessment of Science & Technology**

Accomplishments since July 2014 (2)

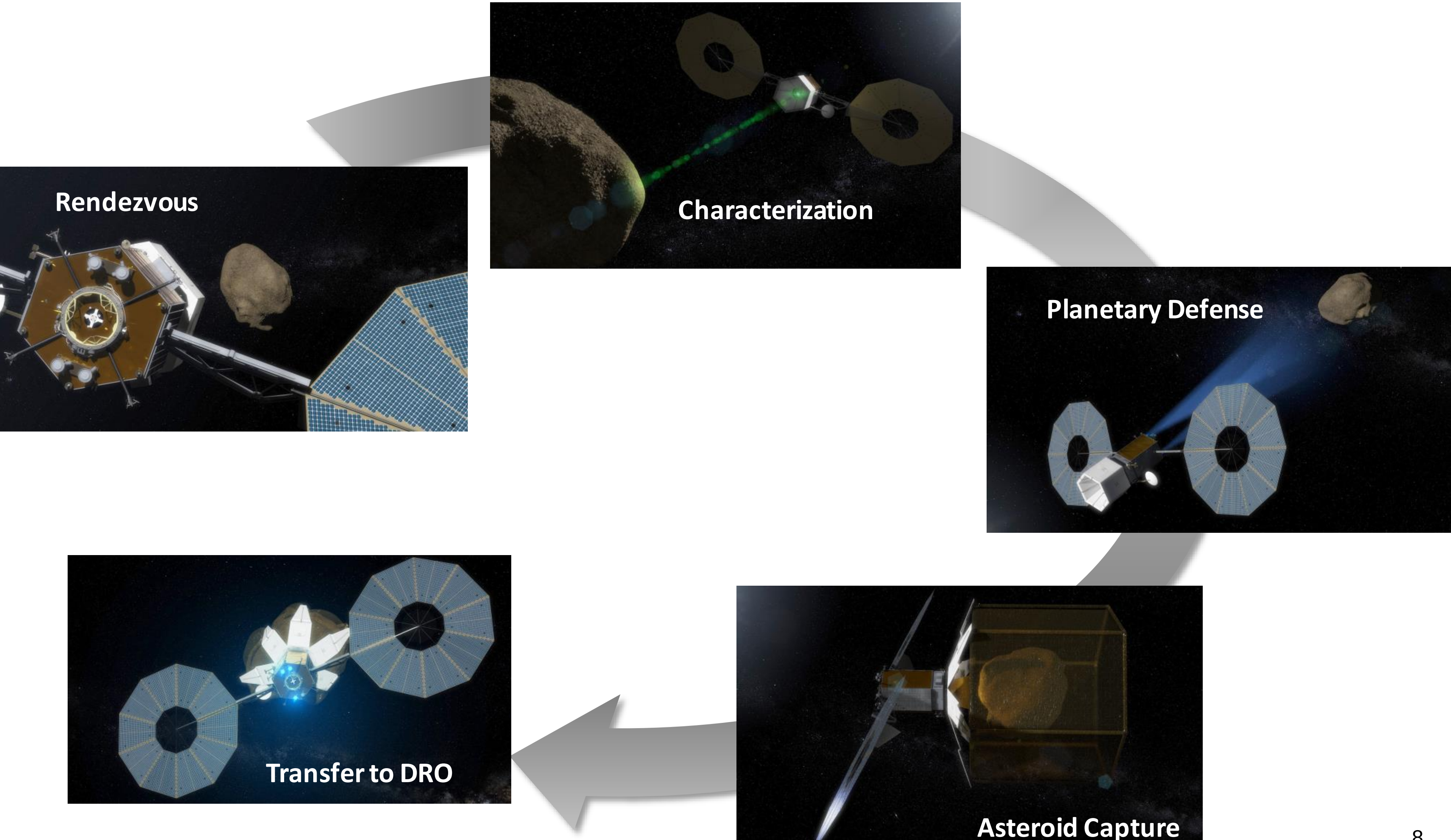
- **Interim reports received for 18 study contracts; selections through Broad Agency Announcement. Final reviews by end of January.**
  – Capture systems
  – Common rendezvous sensor suite
  – Leveraging commercially available spacecraft for robotic mission
  – Partnerships in secondary payloads for robotic mission
  – Partnerships for crewed mission including extensibility
- **Internal design and risk reduction activities to mitigate risk in the capture phase**
  – Option A
    - Higher fidelity 1/5 scale testbed
    - Revised the design
    - Conducted testing of deployment/inflation, “docking” to the asteroid, and bag closure, with force measurements
    - Friction tests using prototype bag material
  – Option B
    - Full scale testbeds
    - Capture arm & tool testing and force measurements; extraction force testing
    - Contact & restraint 2D testing and force measurements
    - Closed loop sims of descent, surface ops and ascent w/ADAMS & structural/thermal analysis
    - Sensor and algorithm testing to validate relative navigation approach
    - Extraction option pull tests

Accomplishments since July 2014 (3)

- **Robotic mission architectures and mission designs**
- **Updated cost and schedule grass roots estimates for reference launch date June 2019; variations**
- **Initiated independent technical and cost assessment for MCR**
  - Relative comparison for capture mission options provided for capture mission downselect
- **Identified applications of ARM technologies, systems, and operations extensibility to future crewed missions**
  - ISS Capability Development Study
  - Evolvable Mars Campaign
- **Continued to evaluate common Automated Rendezvous and Docking sensor approach for robotic spacecraft and crewed mission**
- **Continued prototyping and testing to gain confidence that there is a path to use Orion launch and entry suit derived from the modified advanced crew escape suit (MACES) for these in-space EVAs**
  - Testing in Neutral Buoyancy Lab
- **Conducted robotic capture mission downselect review (Option A/Option B)**

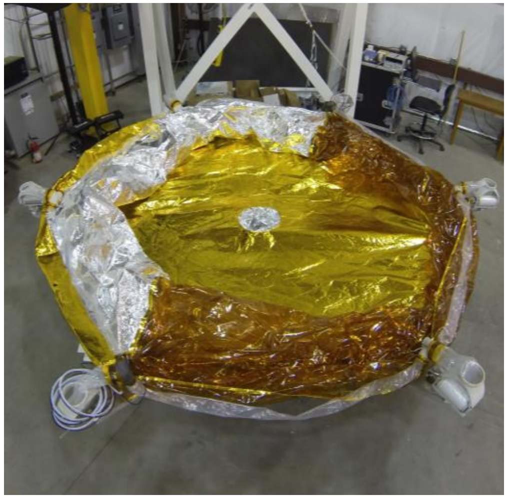
Robotic Capture Mission Option A Overview

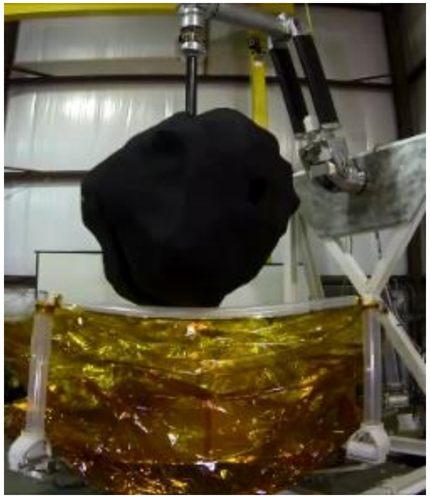
Rendezvous	Characterization	Planetary Defense		Asteroid Capture	Return to Earth-moon System
28 days	14 days	2 days	5 days	(+30 days margin)	~1-3 years

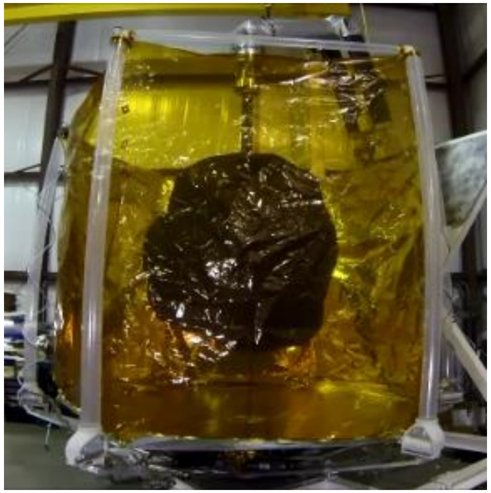


Analysis and Risk Reduction Overview

Asteroid Capture Testbed; ADAMS and DARTS/DSHELL simulations

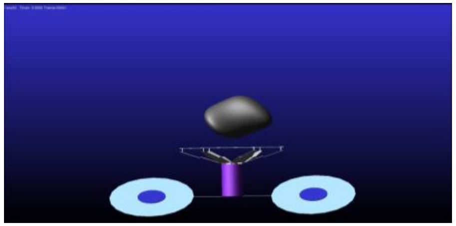




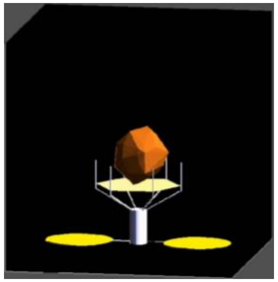


The Asteroid Capture Testbed is a hardware-in-the-loop simulation that measures actual forces between soft goods and asteroid mockup, evolving motion and spin of asteroid per real physics, providing better understanding of soft goods packaging and deployment and defining precisely what force/deflection characteristics are required for the corners of the trampoline to accommodate full range of asteroids while minimizing forces on S/C.

The ADAMS simulation provides high-fidelity finite-element physics giving loads, etc., but slow to compute.

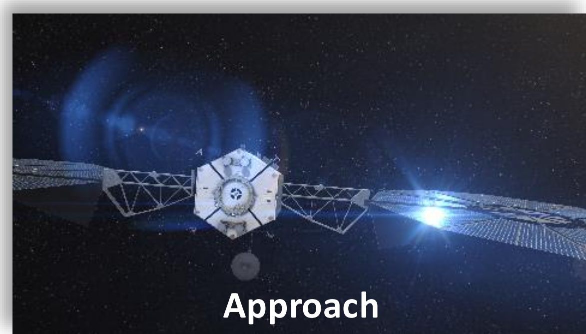


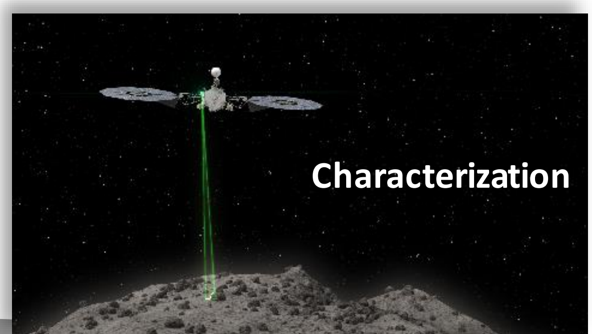
The DARTS/DSHELL simulation is a fast, low-order physics-based model suitable for Monte Carlo and control system modeling.



Robotic Capture Mission Option B Proximity Operations Overview

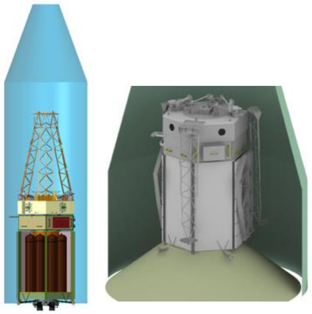
Approach	Characterization	Boulder Collection	Planetary Defense Demo
14 days	72 days	69 days	150 days (30 deflection + 120 hold & verify)



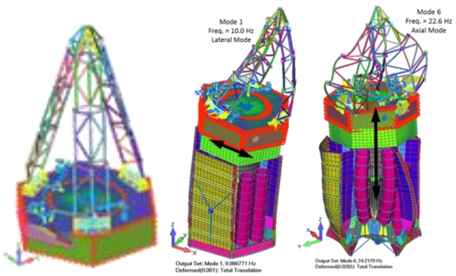


Note: Asteroid operations timeline varies depending on target asteroid. Times shown are for 2008 EV_5: total stay time of 305 days with 95 days of margin.

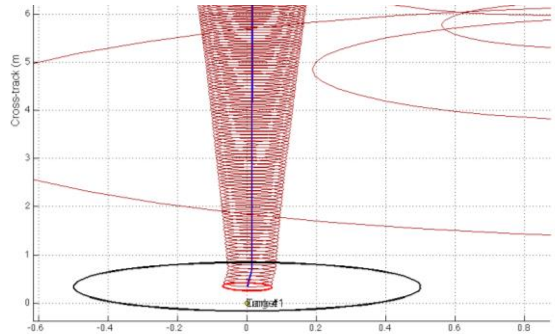
2014 Analysis and Risk Reduction Activities



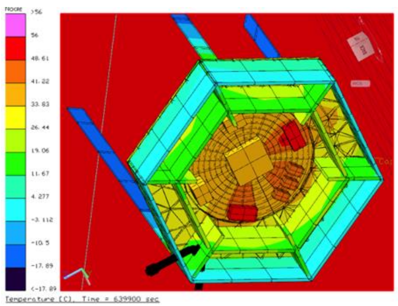
Launch configuration analysis



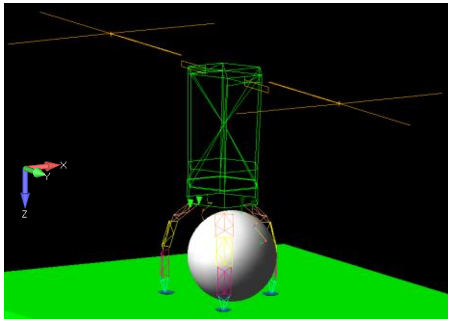
Launch, docking, and EVA modal and loads analyses



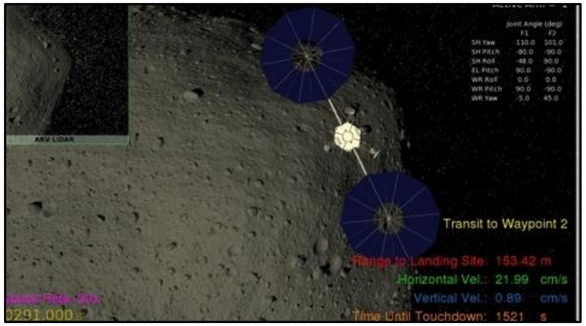
GN&C performance analysis



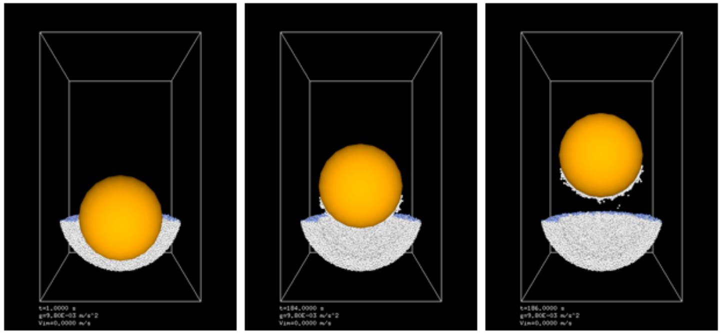
Thermal system modeling



Flexible body dynamics model of touchdown and ascent

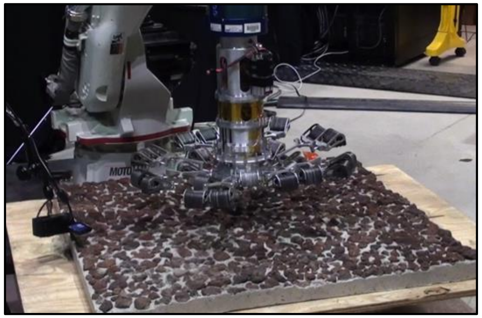


GN&C performance simulation



Boulder extraction simulation

LaRC full-scale CRS flat floor testing

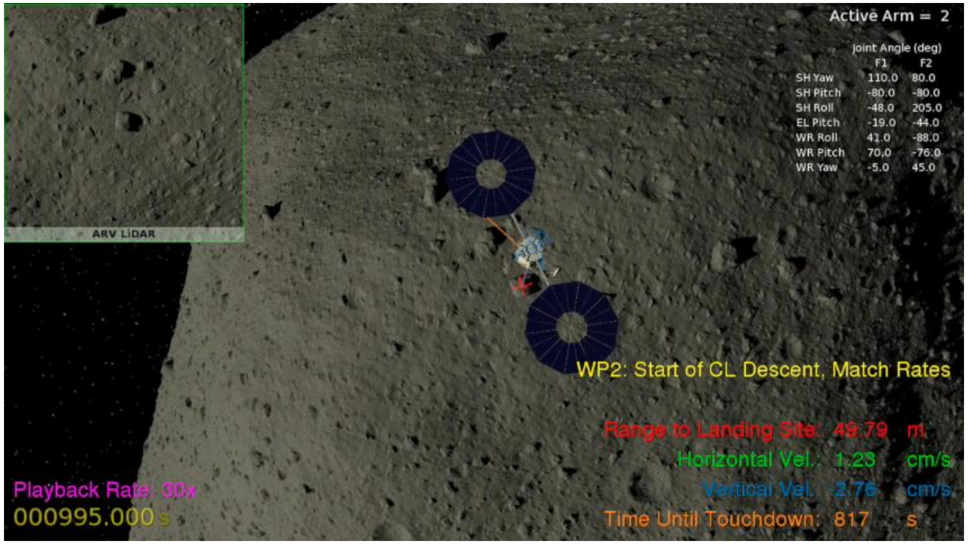


WVRTC/GSFC Microspine testing

KSC Swamp Works full-scale testing of boulder extraction

Descent and Touchdown Performance

ARRM OPTION-B

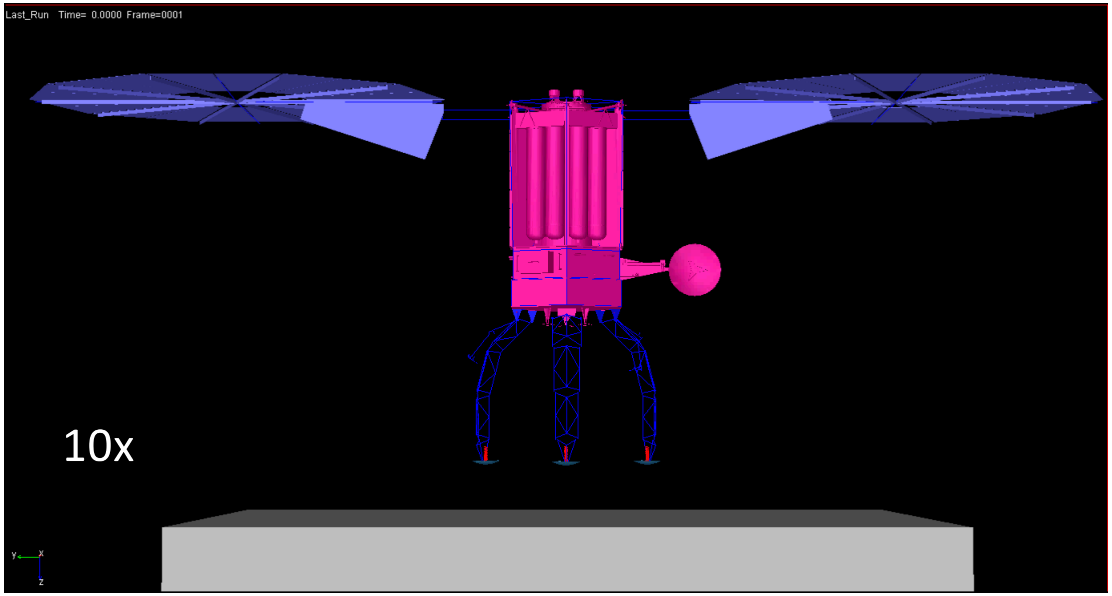


GN&C Performance at Touchdown

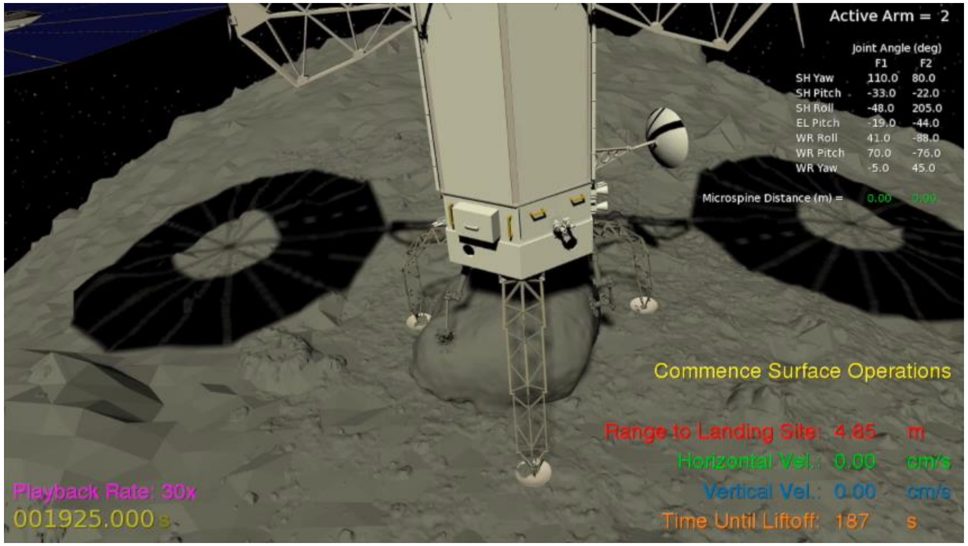
- High fidelity 6-DOF physics-based simulation of descent and landing shows feasibility of nominal control design
- Linear covariance analysis used to validate performance in presence of range of sensor noise/bias characteristics, measurement filter performance, execution error, etc…
- Results show performance of better than 15 cm 3-sigma vs. 50 cm landing requirement

Mechanical Simulation of Touchdown Dynamics

- High fidelity flexible-body ADAMS simulation of touchdown shows safe landing for wide range of asteroid surfaces
- Landing loads within specifications for all components including large flexible arrays
- CRS active damping (simulated) sufficient to absorb touchdown energy and prevent rebound off surface



Boulder Extraction and Ascent Performance

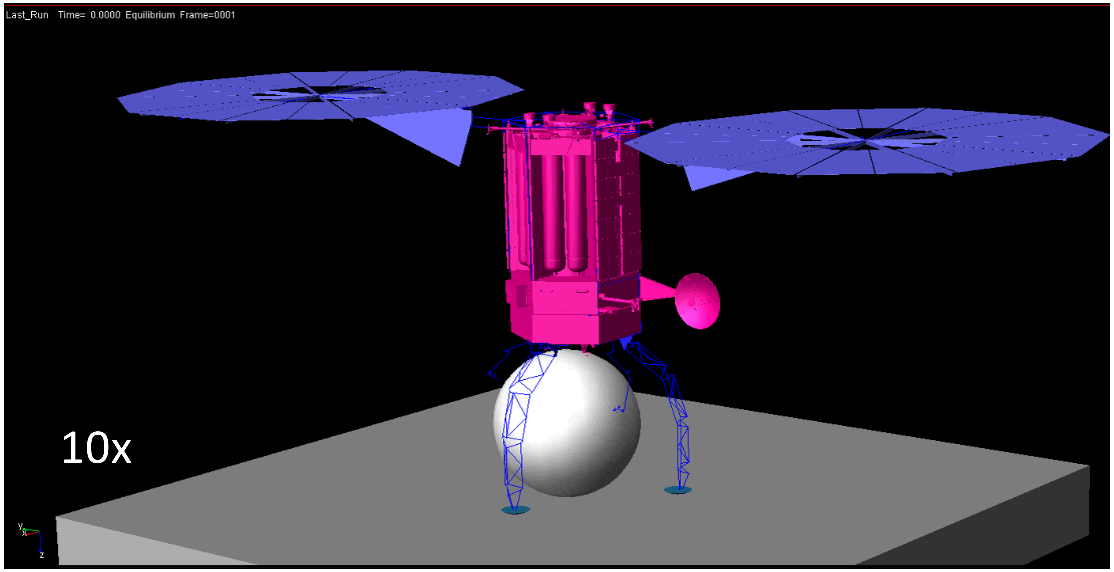


GN&C Performance for Ascent

- Feasible ascent control design successfully demonstrated for hybrid concept
- Stability analysis performed by joint JPL-GSFC GN&C team
    - System stable with unknown boulder mass properties and flexible arrays
    - System performance sufficient to handle wide range of surface push-off transients

Mechanical Simulation of Extraction and Ascent

- Demonstrated boulder sufficiently restrained during push-off to preclude any contact with ARV
- Ascent loads within limits across a wide range of boulder extraction force profiles
- System robust to large boulder CG offset

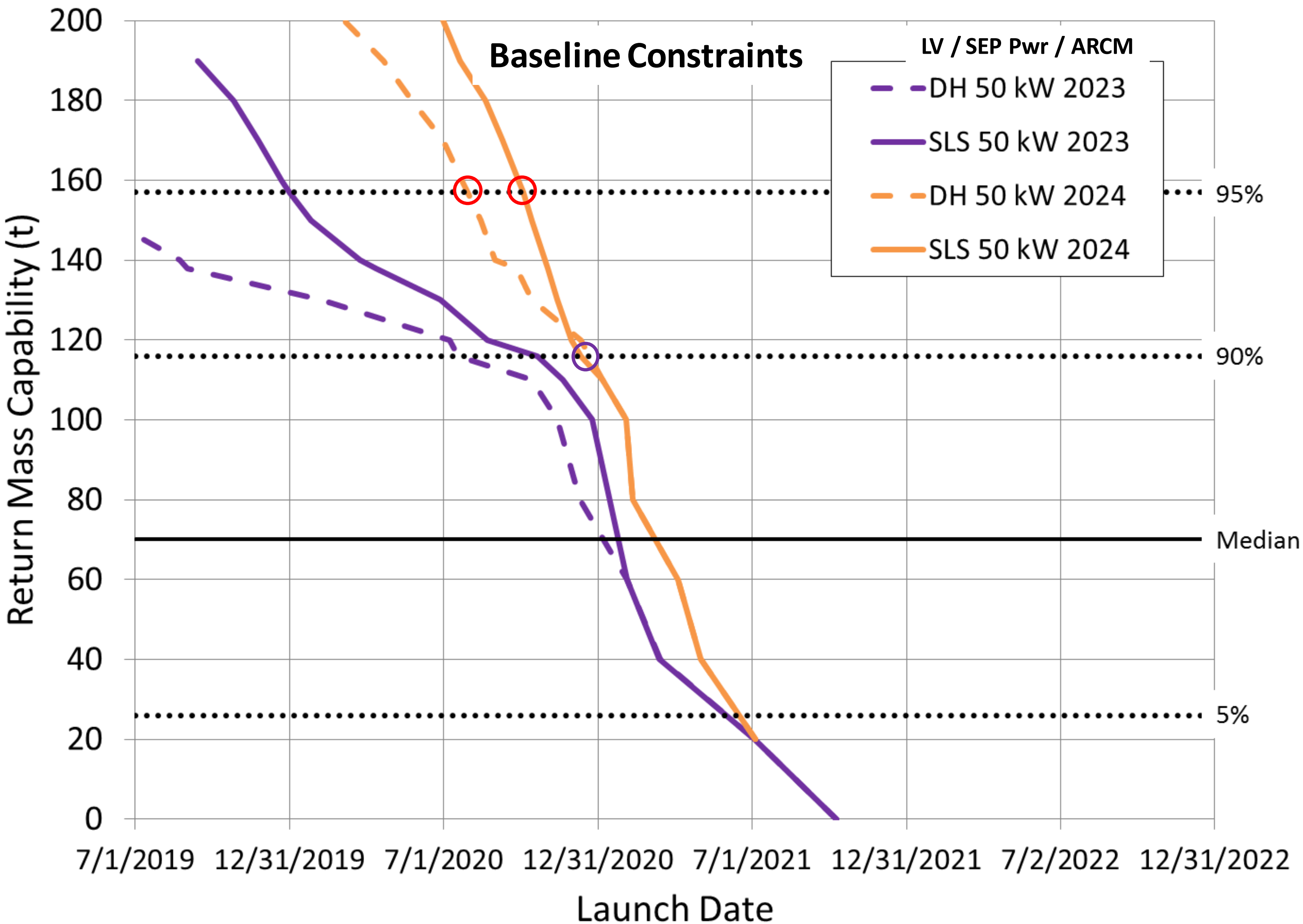


Launch Date Flexibility Assessment: Mission Design

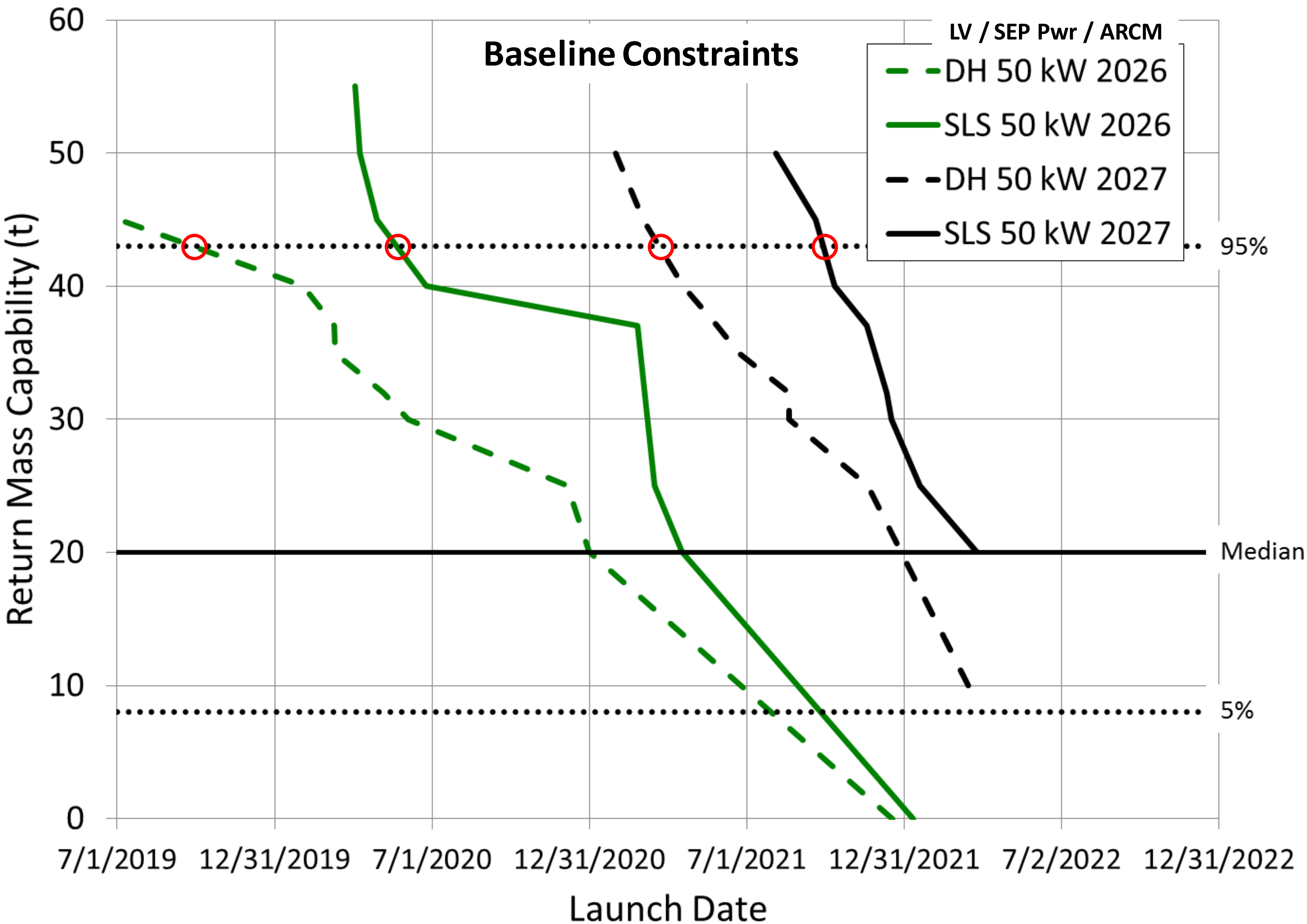
	Option A	Option B
Trajectory Analyses	Create and implement common set of assumptions across both options	
Launch Date Sensitivity	• 95% mass upper bound • Sensitivity to 90% mass	• 95% mass for 2-m boulder • Sensitivity to 1-m boulder
Launch Vehicles	Delta IV Heavy, SLS	
SEP Solar Array Power	50-kW Sensitivity to higher power (82-kW)	
Stay time at Asteroid	60 days	400 days Sensitivity to 215 days
Launch Dates	Mid. 2019 through 2021	
Earliest Crew Accessible Dates	2023 through 2027	

~ 44,000 low-thrust trajectories calculated to explore the trade space

Launch Date Flexibility Example 1 (Baseline Constraints)
Option A: 2023-2024 ARCM with 2009 BD

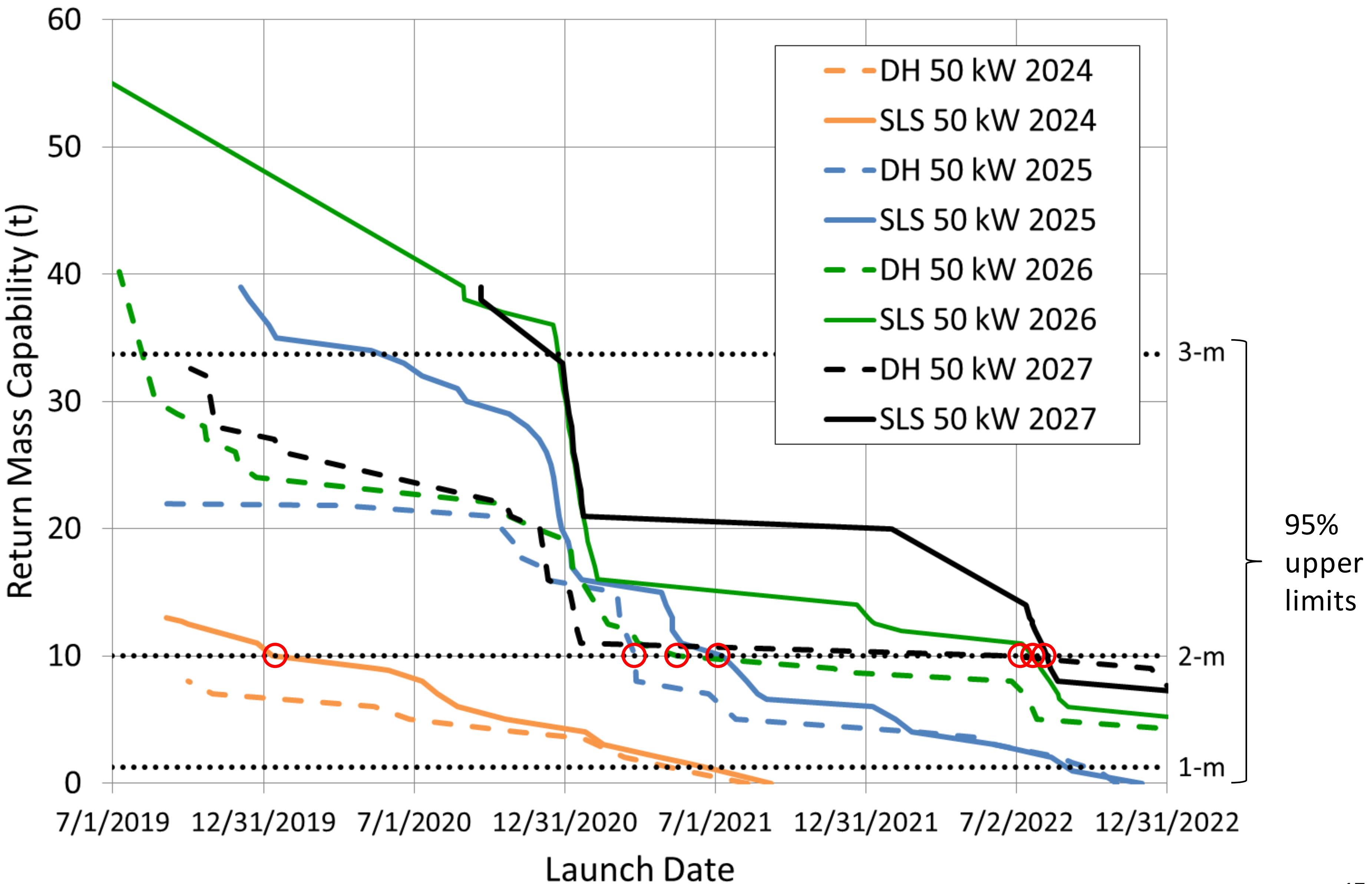


Launch Date Flexibility Example 3 (Baseline Constraints)
Option A: 2026-2027 ARCM with 2013 EC20



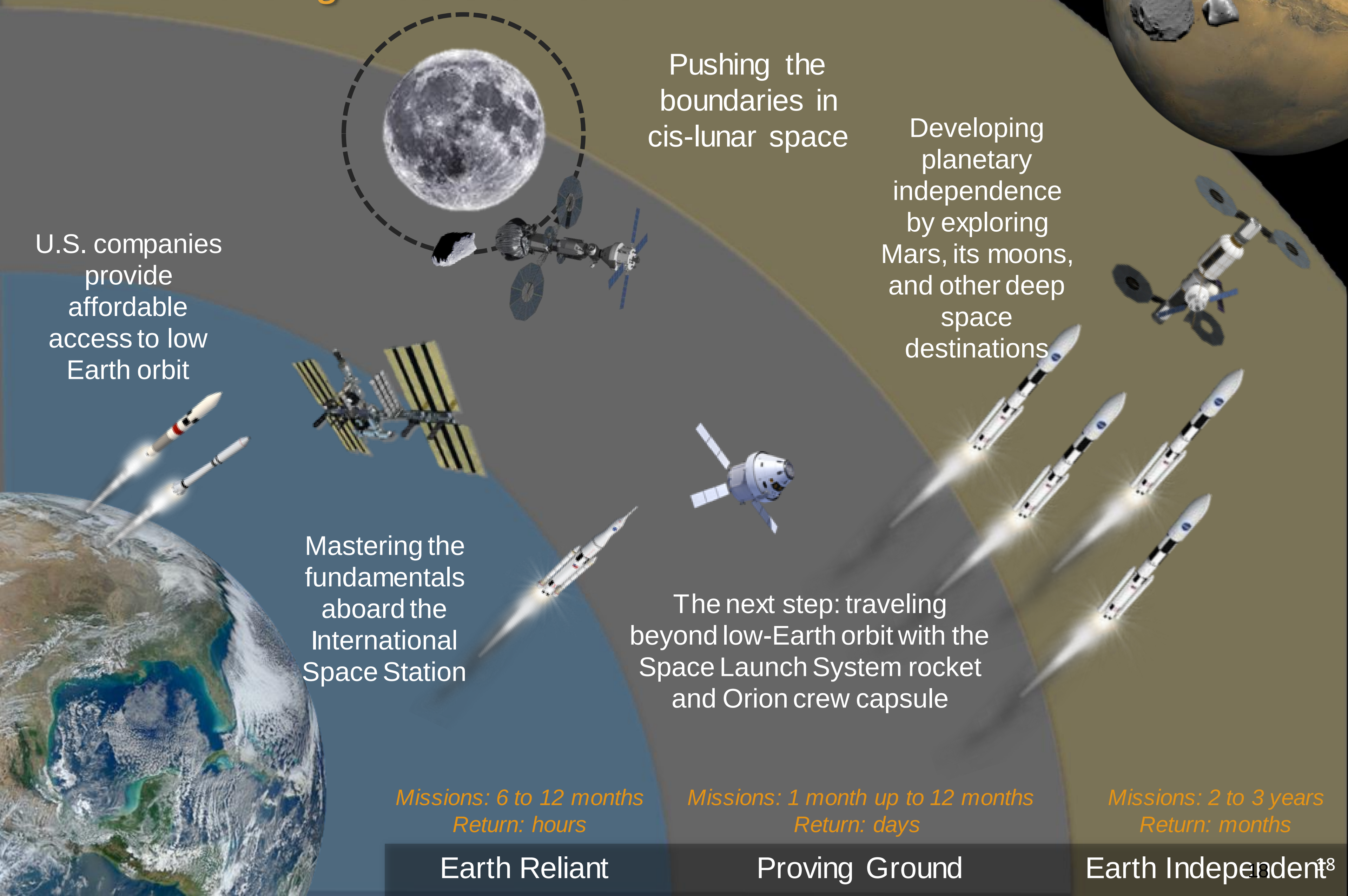
Launch Date Flexibility Example 4 (Baseline Constraints)

Option B: ARCM in 2024-2027 for 2008 EV5



The Future of Human Space Exploration

NASA's Building Blocks to Mars




ACCESS PANEL

Key ARM Contributions in the HSF Proving Ground

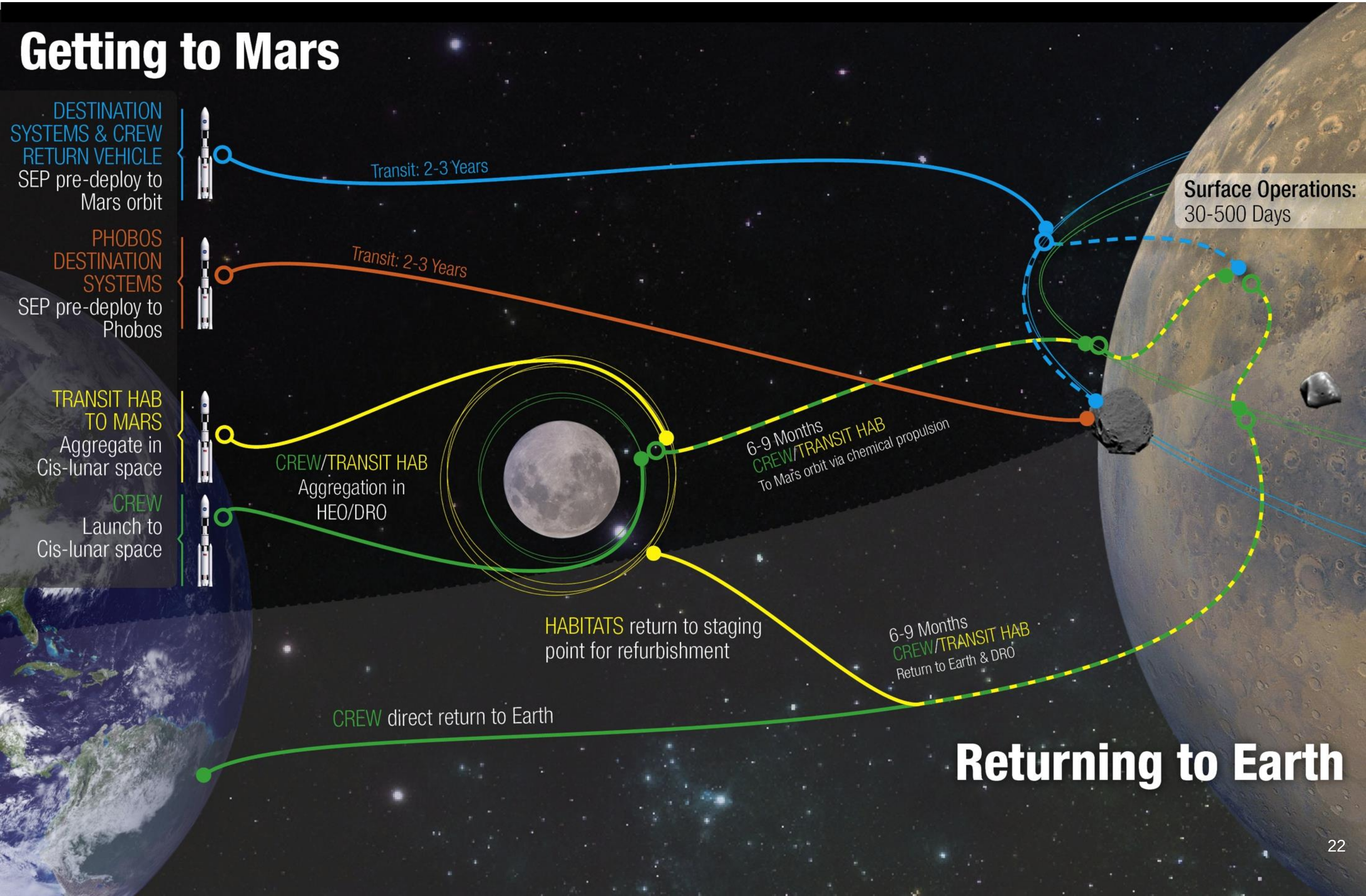
- **Moving large objects through interplanetary space high-powered, long-life SEP**
- **Placing a large object into lunar orbit provides direct design and operations experience in moving large masses, such as Mars cargo.**
- **Use of the lunar distant retrograde orbit for staging point**
- **Integrated crewed/robotic vehicle stack operations beyond low Earth orbit**
  - Integrated attitude control, e.g. solar alignment
  - Multi-hour EVAs
  - SEP vehicle can provide power for future missions
- **In-space EVAs; sample selection handling and containment**
- **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

Performance of ARM SEP spacecraft after ARM mission

- **ARM robotic vehicle reference design can provide the following capabilities for docked vehicles:**
  - **~40 kW of power at TBD voltage (currently 300 V unregulated)**
  - **A two way data interface through the FRAM* connector for a docked element**
  - **S-Band transponder, useful for approach/docking**
  - **X-Band comm link allowing downlink or uplink of docked element data**
  - **A passive docking mechanism compliant with the International Docking Standard**
  - **Coarse attitude control to maintain power and thermal constraints of the ARV vehicle when Orion is not docked**
  - **Four 13 kW Hall thrusters, three of which will be operated in parallel to provide approximately 40 kW of SEP at 1 AU, limited by how much xenon propellant remaining in the tanks**
  - **Various tools for EVA**

* Flight Releasable Attachment Mechanism

Mars Split Mission Concept



ARM Crewed Mission Assessment of Option A/B

- **As part of the assessment, the JSC team evaluated each mission phase and determined EVA is the only phase with significant differences between the capture options.**

Mission Phase	Option A and Option B Comparison
Orion Launch to Rendezvous	Not a discriminator between Option A and B
Orion Rendezvous, Proximity Operations, and Docking with ARV	Design Considerations for Integrated Stack mass properties: • Option A asteroid can be heavier than Option B Boulder • Docking loads impart different attitude excursion, however, Orion can arrest rates and return stack to nominal attitude in either option.
Joint Operations	
- Integrated Attitude Control	Orion can maneuver integrated stack for either option. Mass is higher for Option A for complete range of asteroid sizes.
- EVA	Either Option is Acceptable (Small diameter asteroid/boulder require special considerations-discussed in later slides). Cutting through Option A bag has been demonstrated in NBL.
Orion Return to Earth	Not a discriminator between Option A and Option B

Curation and Planning Team for Extraterrestrial Materials

Curation and Planning Team for Extraterrestrial Materials (CAPTEM) recommendations provided for:

- Activities conducted during EVAs that are relevant for characterization, selection, collection, stowage, and transport of multiple samples to Earth.
- Tool/instrument protocols relevant for sample collection and characterization.
- High level objectives required to maximize the scientific usefulness of the EVAs and ensure the scientific integrity of the returned samples.

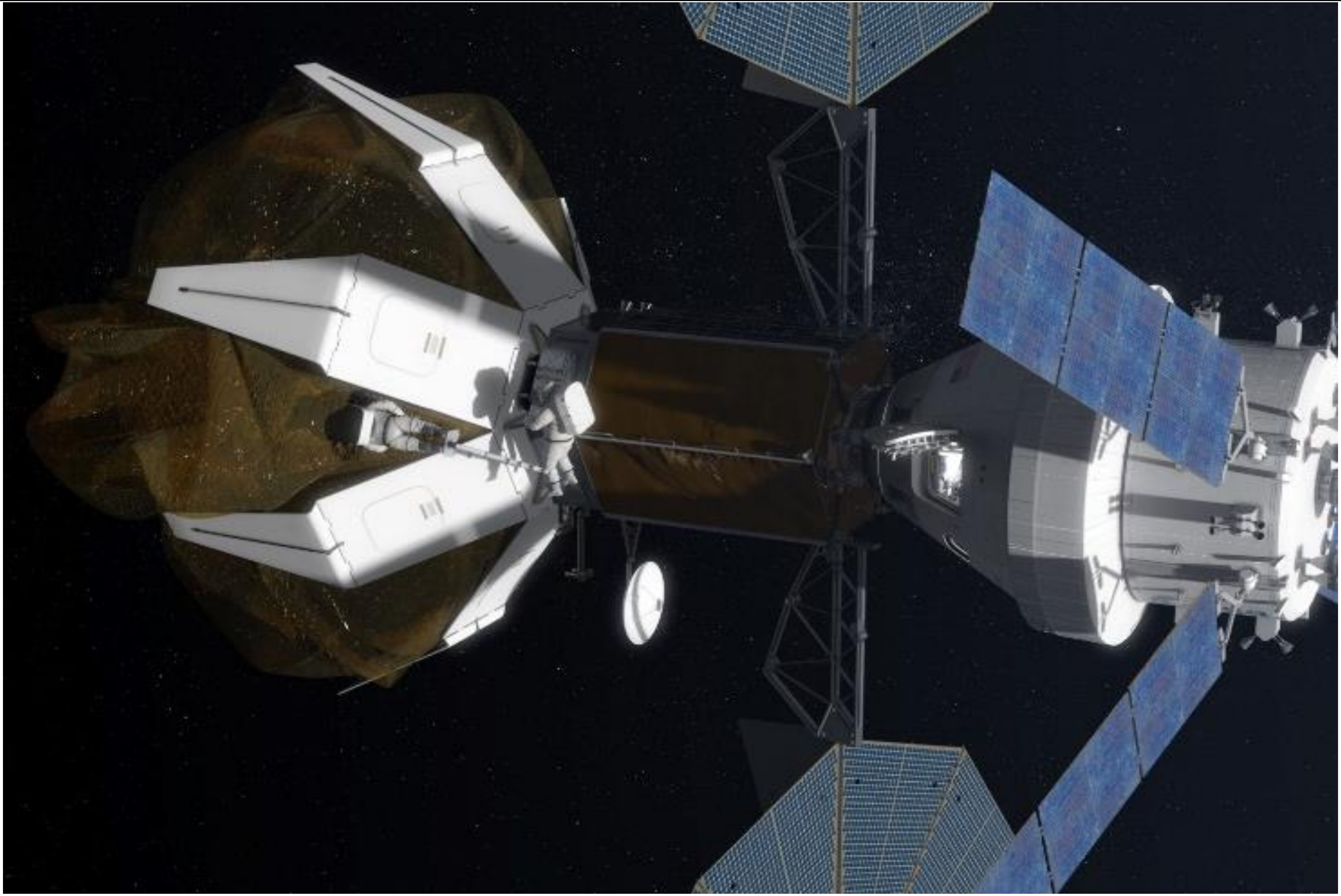
Key Findings:

1. Sampling site contamination control is vitally important.
2. Contamination control is important across all stages of mission.
3. Scientific return is likely maximized by picking option that presents least risk of contamination.
4. Assessment of textural and mineralogical heterogeneity of body is critically important.
5. Active participation of ground-based Science Team is critically important.
6. Hand-held high-resolution cameras and analytical instruments is valuable during EVA.
7. Collection of at least 1000g from two diverse sites is recommended.
8. If practical, collection from at least one 5-cm diameter core sample.
9. Preservation of volatiles is desirable (<20°C)
10. Surveying tools on the surface could assess deformation of body.
11. Optical albedo measurements and measurements of the Yarkovsky effect are not of high priority.

Comparison of Option A and B:

Commonality exists in various areas of both options. In aggregate Option A provides limited situational awareness due to obstructed view from petals and bags while Option B provides superior situational awareness and access for crew due to open spaceframe CRS legs. (see backup CAPTEM Finding Tables).

Option A EVA Concept

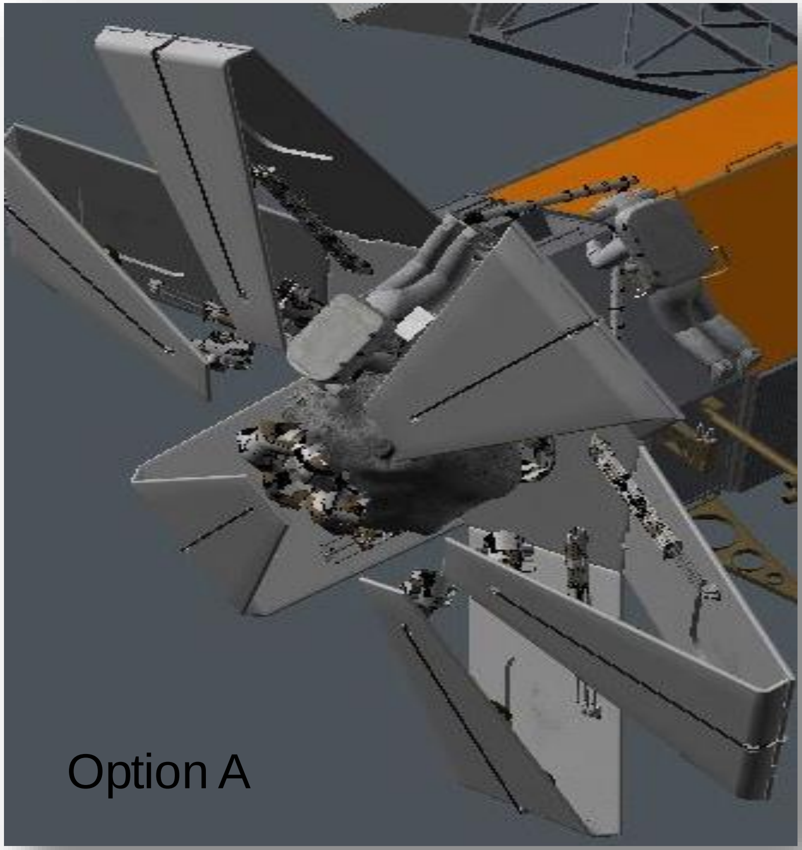


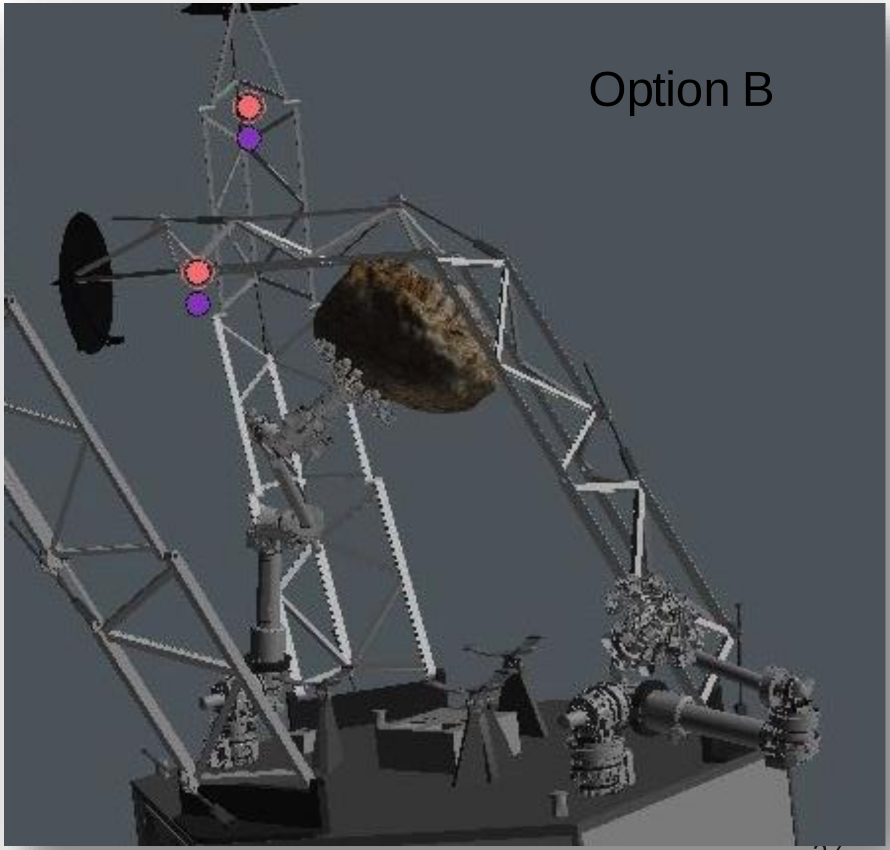
Option B EVA Concept

Small Asteroid/Boulder Repositioning

- Identified options for repositioning asteroid/boulder for EVA by placing asteroid in line with ARV edge to will provide adequate thermal conditioning and EVA access
- Both Options require additional analysis after MCR

- Option A: One or more petals are unfolded and asteroid is shifted toward ARV edge
- Option B: Boulder is secured using microspines on 7 DOF arm in joint of one CRS limb.

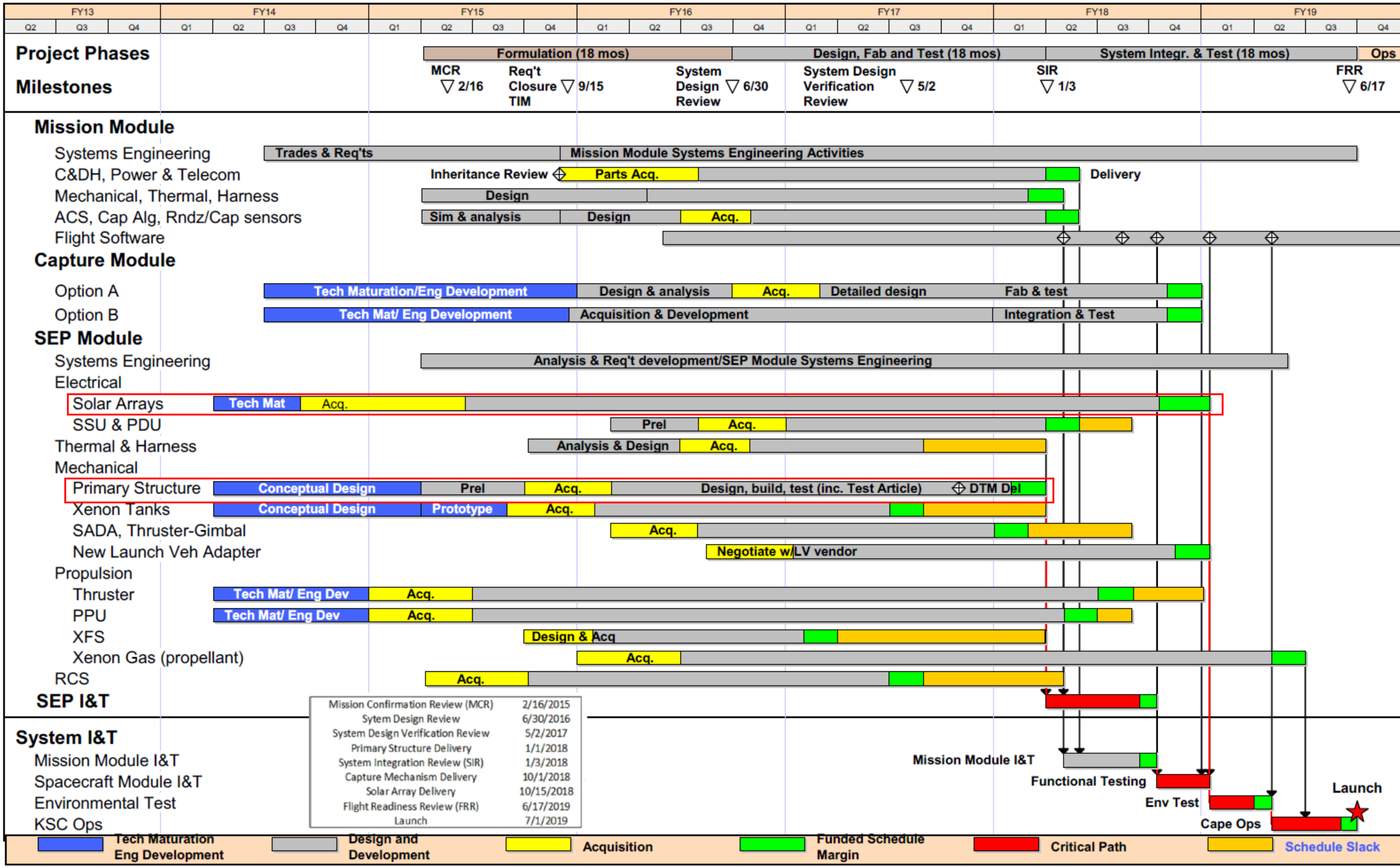




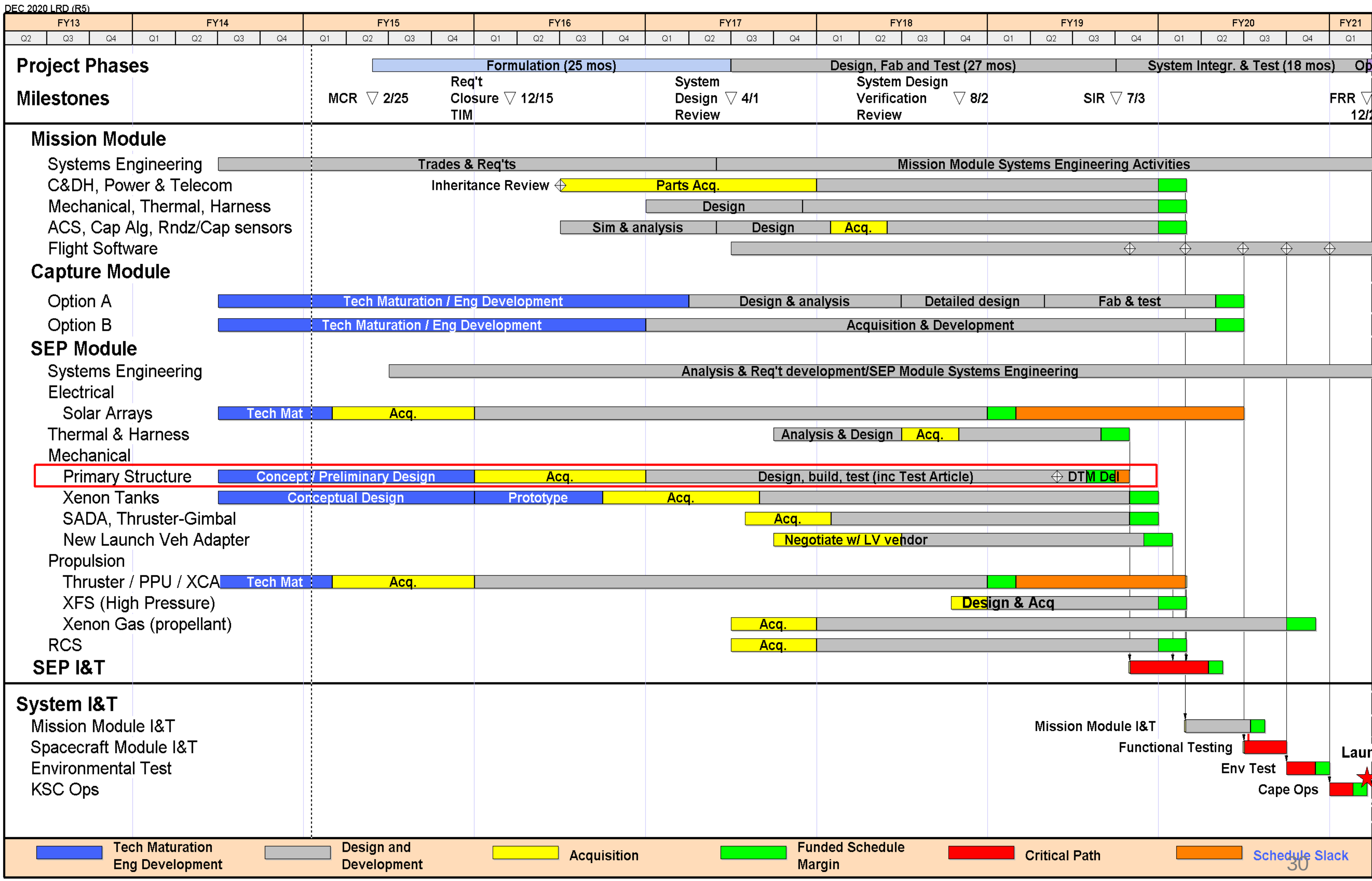
Schedules

- **Reference schedule for June 2019 LRD remains unchanged**
- **Scenario for a late 2020 LRD**
  - Assumed launch in Dec. 2020
  - Additional 1.5 years of schedule time was split 50/50 between formulation and implementation
  - Some activities were kept on early schedules (e.g. EP components and solar arrays) to reduce risk and be consistent with STMD funding

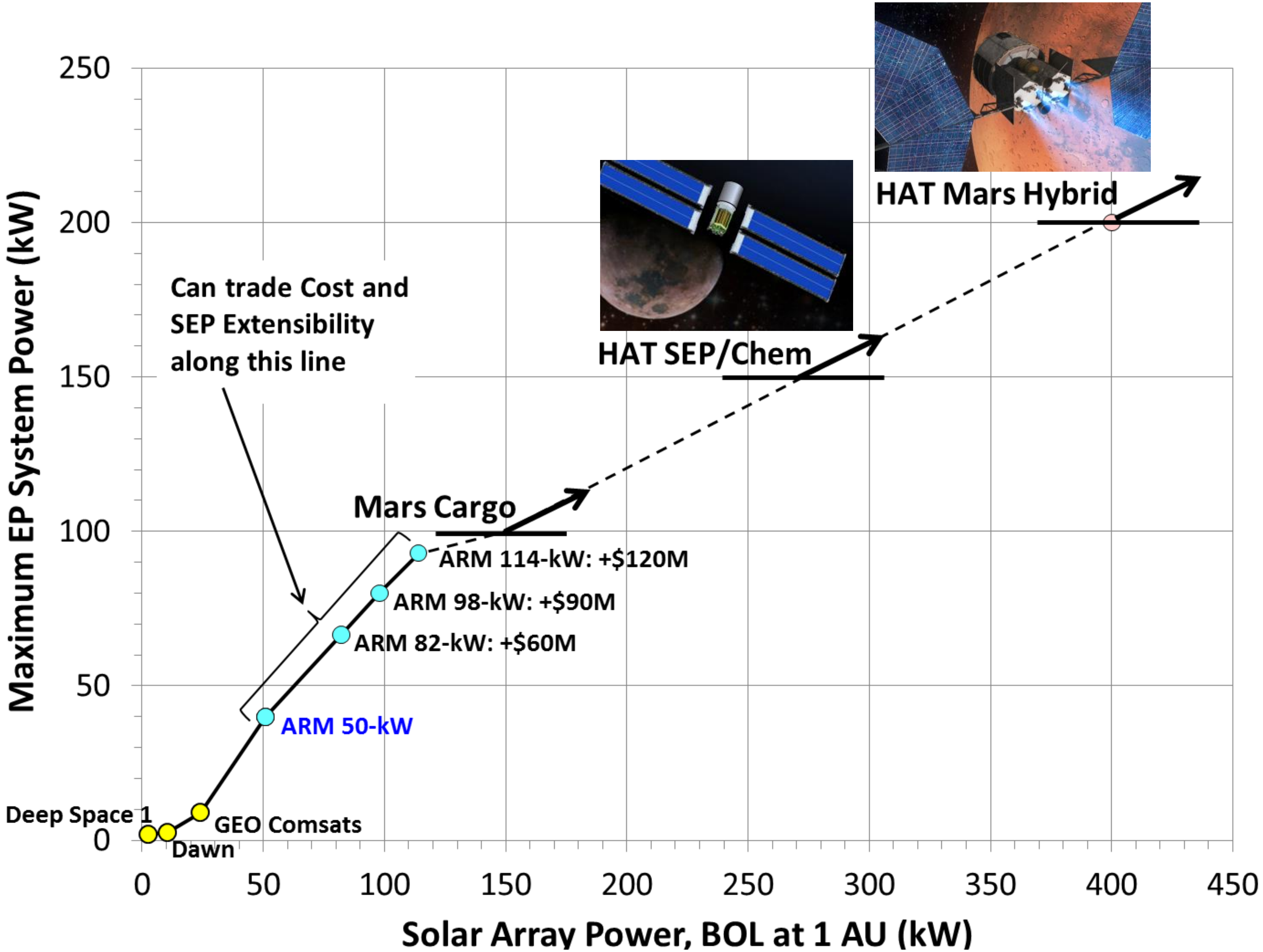
ARRM Conceptual Development Summary Schedule LRD June 2019



ARRM Conceptual Development Summary Schedule LRD December 2020



Extensibility of the SEP System to HEOMD

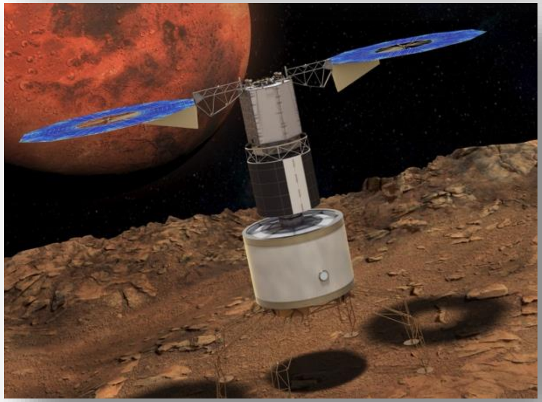


Human Exploration Mission Extensibility

Common Attributes	
• SEP Module is designed to meet ARRM needs as well as grow to higher power and greater propellant storage in support of human cislunar and Mars missions (Solar Arrays, Thrusters, PPU, PMAD, Xenon storage) – moving large masses through interplanetary space • Long duration human-scale systems operating in deep space • Interaction with non-cooperative, low gravity targets and use of terrain relative navigation • Demonstration of sensor suites and proximity operations required for aggregating Mars mission vehicle stacks, deep space rendezvous and Orion docking • Demonstration of sample handling and dust mitigation • Gain experience in EVA operations around near zero-g bodies • Supports cislunar proving ground habitat; addition of cislunar habitat & logistics with ARV enables follow-on 4-crew extended duration missions and accomplishment of all CAPTEM objectives	
Option A	**Option B**
• Large Inflatable structures and encapsulation (habitats, space debris)	• Capture mechanism and enhanced large-body proximity operation experience that could be applied to human missions to NEAs or Martian Moons

Extensibility: Phobos/Deimos

- **Potential applications of ARRM to moons of Mars missions would come in terms of usage of ARRM technology, SEP, and possible reuse of the ARRM vehicle**
- **Applications of Option B to future human exploration**
  - Proximity and surface operations (including TRN), including helping to understand key design and operations parameters needed to accommodate the larger size, higher gravity, and surface features/composition
  - Robotic surface exploration and EVA operations using CRS, 7-DOF robotic arms, and microspines
  - Possible extensibility of CRS for delivery of future surface elements
- **Applications of Option B to future science missions**
  - Returns multi-ton boulder/surface regolith and potential for returning Mars surface sample cached in Mars orbit
  - EVA techniques for sample acquisition including contamination control
- **Possible reuse of ARRM vehicle:**
  - Requires refueling and likely refurbishment/servicing of elements of the system for longer life, addition of new science instrumentation
  - The ability to refuel ARV significantly improves Mars cargo delivery (currently being explored by HAT to enable lander delivery)
- **Applications of Option A include possible uses of inflatables and encapsulation**



Science Potential

- **SBAG SAT Report**
  - The type of asteroid sampled is of major scientific importance. The Planetary Decadal Survey states that primitive asteroids associated with prebiotic materials (water, carbon, organics) are prioritized for science.
  - Characterizing and returning a sample from an asteroid not already, or planned to be, sampled is of greater science value than characterizing and returning a sample from one that has been.
  - Involvement of a science team is critically important to maximize the science, including during the concept development portion of the mission.
  - Ground-based characterization of the target asteroid is scientifically important.
  - Remote characterization prior to, during, and following sampling provides scientific context.
  - An asteroid sample return mission offers a range of possible science investigations, both with remote characterization and through study of the returned sample.

Next Steps

- Complete assessing the budget and complexity differences versus the extensibility advantage in option A/B decision
- Continue asteroid observations and enhancements
- Continue high power, long life solar electric propulsion system technology demonstration activities
- Continue human spaceflight system development and technology maturation
- For selected robotic mission capture concept, refine independent technical risk, schedule and cost assessment.
- Hold Mission Concept Review – scheduled for February 26, 2015