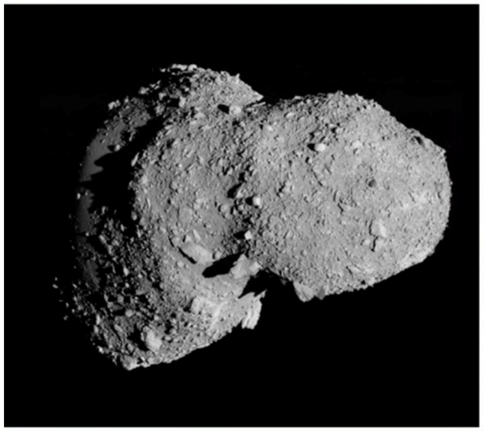
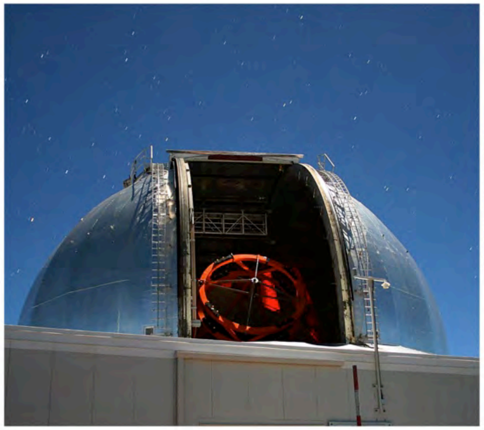
National Aeronautics and Space Administration

Asteroid Redirect Robotic Mission (ARRM) Reference Mission Concept Study Public Information Package V1

August 20, 2013

Contributing NASA Centers:
JPL, GRC, JSC, LaRC, MSFC, KSC, GSFC

Outline

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E. Rendezvous and Proximity Operations
F. Capture Mechanism and Capture Process
G. Asteroid Redirect Robotic Mission Reference Implementation, Schedule, and Cost
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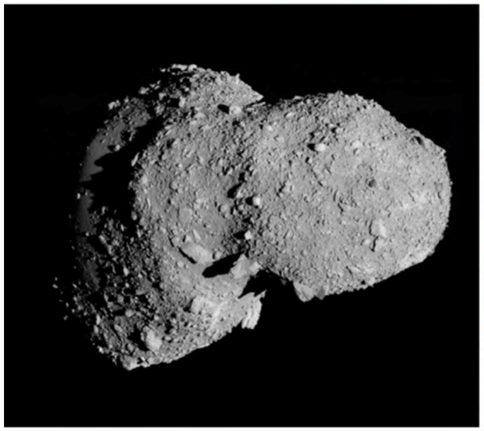
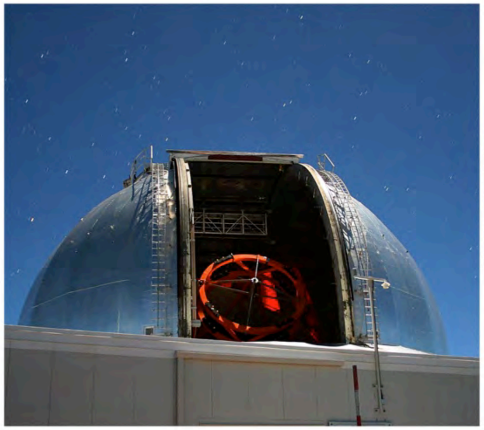
A. Introduction and Objectives

Introduction/Objectives
Executive Summary

- This package contains material briefed to NASA senior leadership on 7/30/2013 on the technical and programmatic feasibility of an Asteroid Redirect Robotic Mission (ARRM) that would launch in 2018 and return an asteroid to a safe lunar orbit for subsequent exploration by a crewed mission. It includes:
  - A technical reference derived from the analysis of numerous options
  - A schedule for a mid-2018 launch with appropriate system-level margin
  - A grass roots current best estimate cost estimate with reserves for direct launch to the asteroid 2009 BD
  - An approach in which risks are balanced across the architecture by not designing to the worst case in every dimension simultaneously, but the solar electric propulsion (SEP) and capture system designs provide flexibility to capture and return a wide range of possible targets
- At this time, based on known information with bounded uncertainties, the candidate target is 2009 BD

Asteroid Redirect Robotic Mission
What Is It?

- Asteroid Redirect Robotic Mission (ARRM) is a robotic mission that leverages advances in SEP to capture a 10-m-class near-Earth asteroid in deep space, with a mass up to 1000 metric tons, and transport it safely to a stable lunar orbit where astronauts can subsequently explore it, extract samples for return to Earth, and determine its overall composition.
- After capturing the asteroid, the SEP-powered spacecraft (S/C) rides along with the asteroid and along the way modifies its orbit sufficiently so that it can be captured into a safe orbit around the Moon.
- The primary enabling technologies are a 40-kW-class SEP system and the capability to capture large uncooperative objects.

Relevance to Human Space Program

- This mission fits well into the overarching objectives of the nation's Human Space Program, which is to enable humans to step ever deeper into space and eventually to Mars. Exploration of the captured asteroid will use assets already under development (SLS and MPCV) as a first step to using these new capabilities even deeper in space. Additionally, the SEP technology will also enable future forays into deep space with larger payloads.
- The result will be human missions farther from Earth than ever before, and the first human missions beyond low-Earth orbit in 50 years.
- It will result in putting humans in contact with only the second celestial object in history.

Relevance to Science

- While the mission is not primarily driven by science, presence of several hundred tons of asteroid material near the Moon will allow scientists to retrieve and examine, in detail, bulk composition of the captured target.
- Furthermore, to find suitable targets for this mission the current asteroid observational campaign will be enhanced. These enhancements will live on beyond the target selection for Asteroid Redirect Mission and extend discovery and characterization of the current observational programs. The result will be a greatly improved knowledge of the near-Earth asteroid population including enhanced discovery of smaller, but still potentially hazardous objects.

Relevance to Planetary Defense & Debris Removal

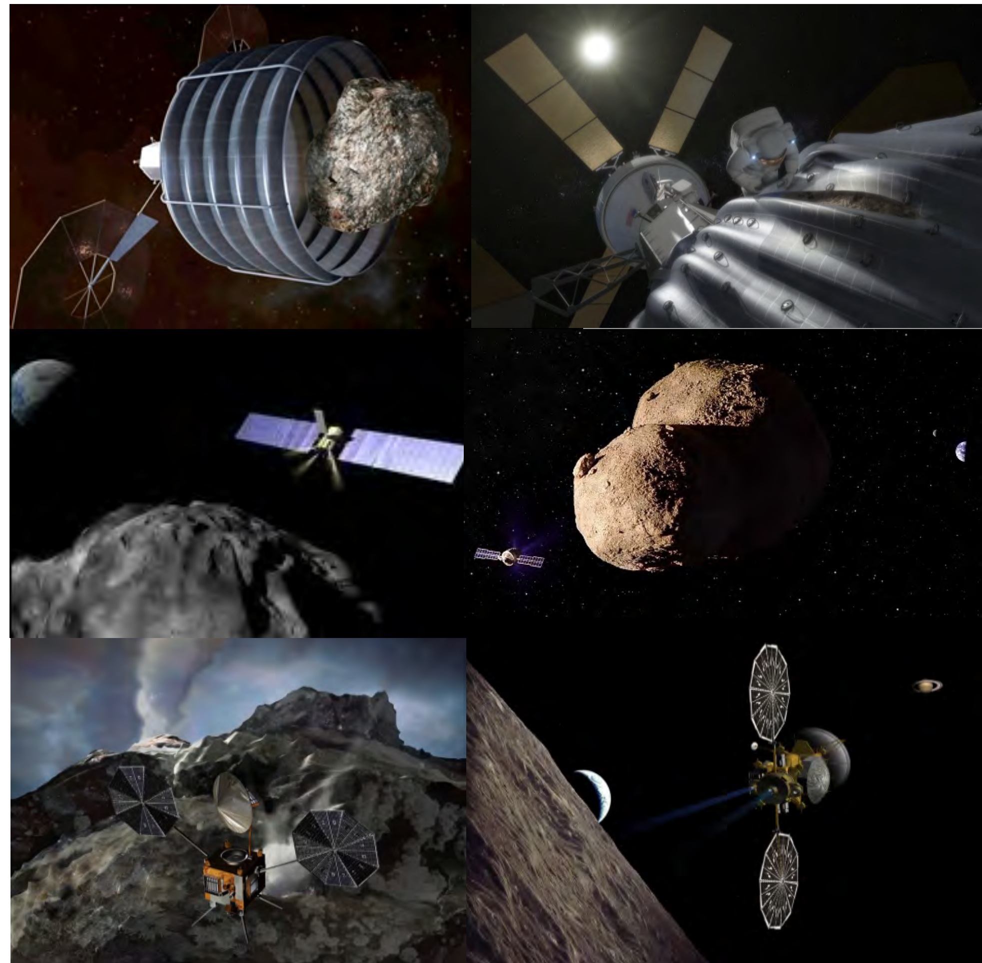
- The capture, return, and close-up inspection of the asteroid will provide insight into the ability to control and deflect a large mass with solar electric propulsion helping to inform future planetary defense measures.
- The methodologies and technologies developed to rendezvous with and capture a tumbling asteroid can be used in Earth orbit to rendezvous and capture large pieces of orbital debris. This would be consistent with the charge given to NASA by the 2010 National Space Policy.

Relevance to Commercial Sector

- The captured asteroid also provides opportunity for the commercial sector which has recently expressed interest in mining asteroids. Sampling techniques and potentially in situ resource utilization (ISRU) will path find future applications. The demonstration of high-power solar arrays and high-power electric propulsion systems will support U.S. competitiveness in the commercial satellite industry.

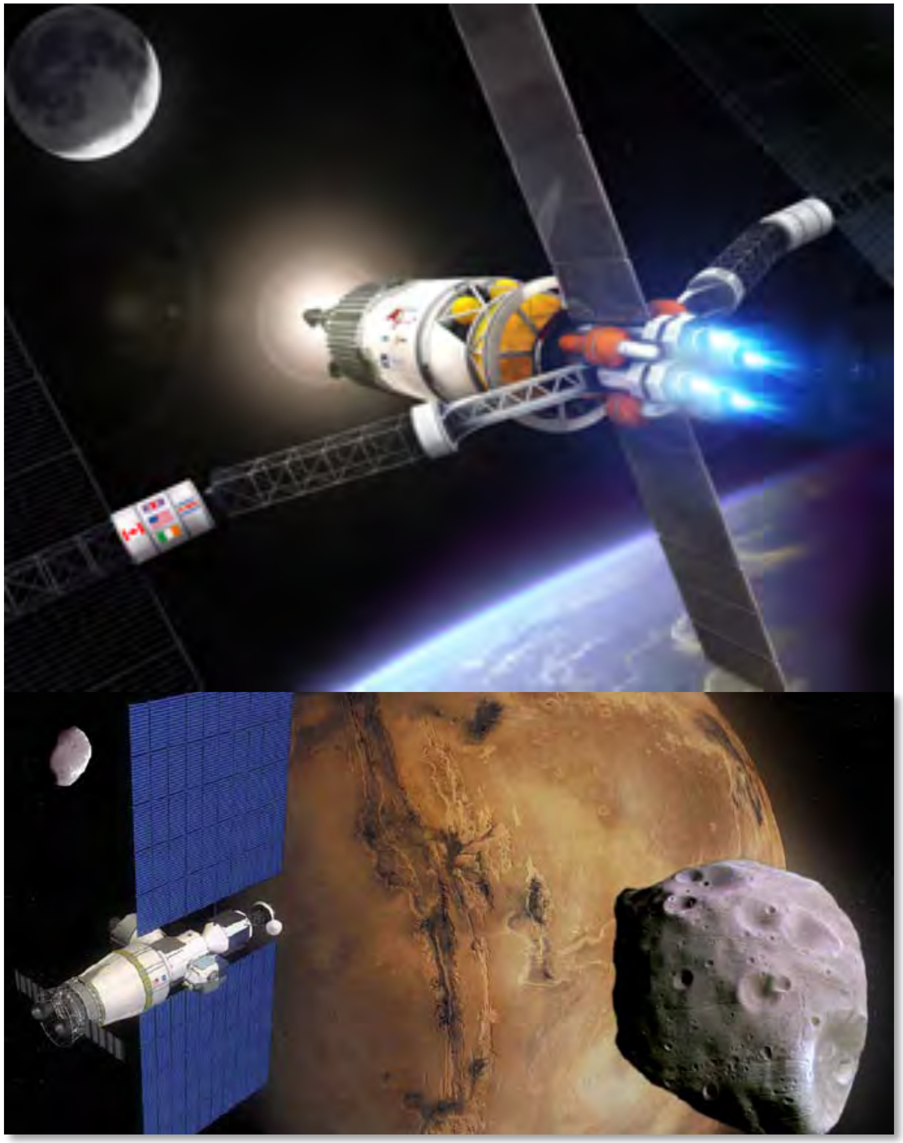
ARRV Versatility

- Study process has identified a suite of capabilities that can be integrated in different ways to enable a broad class of missions within constraints
  - √ Asteroid Redirect Missions
  - √ Planetary Defense demonstrations
  - √ Science Missions
  - √ Exploration Missions



ARRV Extensibility

- The ARRV capabilities, enabled by key SEP technologies—solar arrays and Hall Thrusters—are affordable stepping stones to higher power systems that could support crewed missions to the lunar surface and Mars
  - Lunar Exploration Missions: Cargo delivery in the Earth-Moon system ~100-kW systems
  - Mars Exploration Missions: Cargo delivery to Mars ~hundreds of kilowatts



Introduction

- MFR results built on the Asteroid Redirect Mission Feasibility Study (4/2/13), which was in turn built on previous studies (e.g., Keck Institute for Space Studies, KISS) and are enabled by NASA investments in asteroid observation, low thrust mission tools/design, solar electric propulsion technology and experience from various Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) missions.
- The current ARRM study evaluated a range of observation, mission, system and subsystem technologies and concepts against key figures of merit including cost, schedule, risk and performance including:
  - Mission concepts: range of targets, orbits and mass, retrieval, planetary defense
  - SEP technology: solar array, thrusters, power processor unit (PPU), power level, specific impulse (Isp)
  - Flight system: modular, optimized, launch vehicle independent
  - Capture system: mechanical, inflatable, wide range of targets
  - Observation campaign: discovery and characterization asset enhancements and augmentations for small near-Earth Asteroids (NEAs).

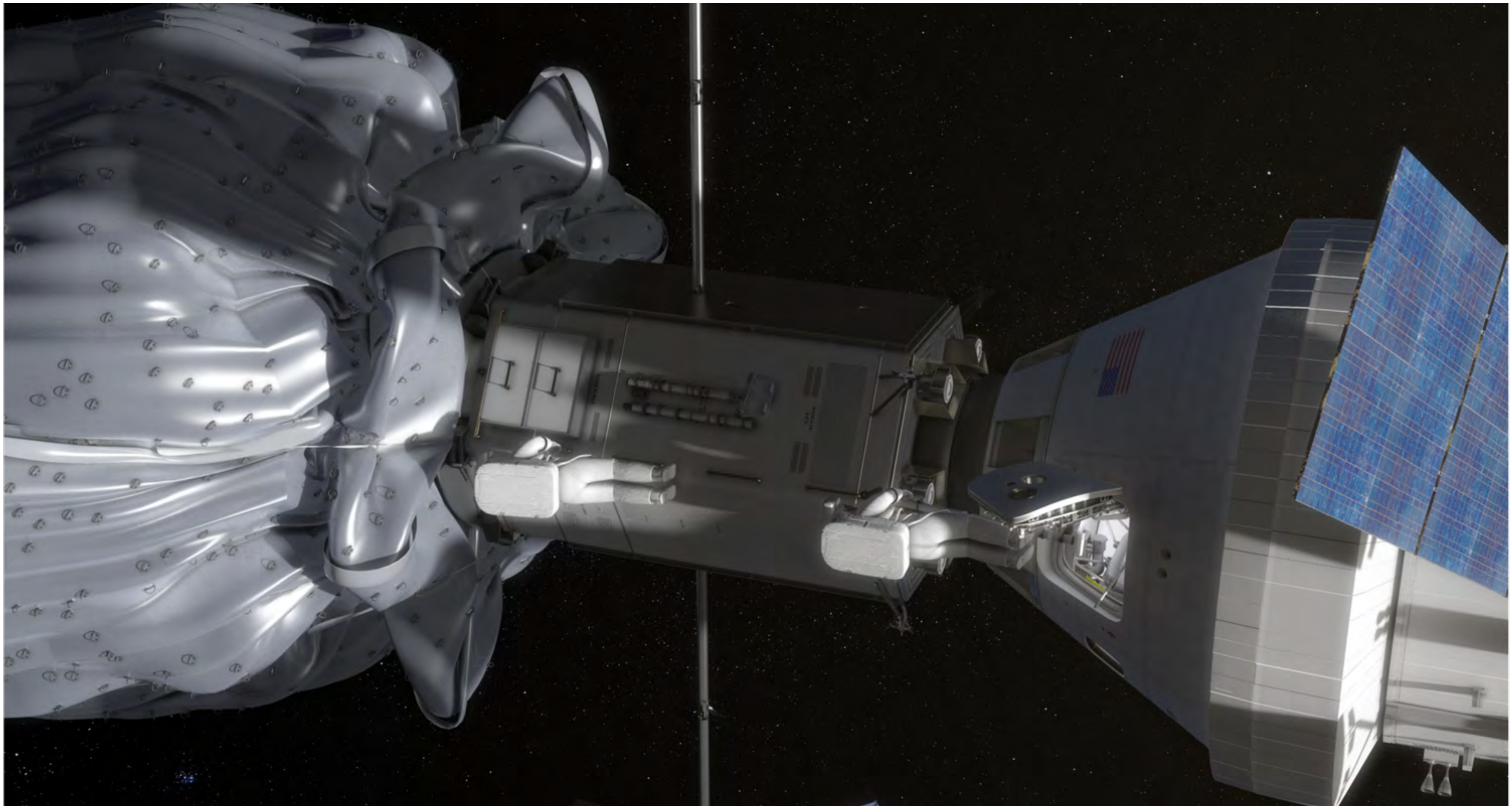
ARRM Reference Mission Features

- The Architecture, mission design and flight system will deliver the following functionality:
  - High performance, high throughput, solar electric propulsion system with power up to 40 kW operating beyond Earth orbit
  - Capability to rendezvous, characterize and operate in close proximity to an Near Earth Asteroid (NEA)
  - Capability to capture and control an asteroid up to the 10-m class with a mass of up to 1000 t
  - Capability to return a NEA, into a stable, crew accessible lunar orbit by the early 2020's, and provide accommodations for a crewed mission to explore the NEA
- The mission is designed to be inherently safe to planet Earth at all times
- The robotic vehicle will be crew safe but not human rated
- The mission includes the ability to perform planetary defense capability demonstration(s) within mission timeline

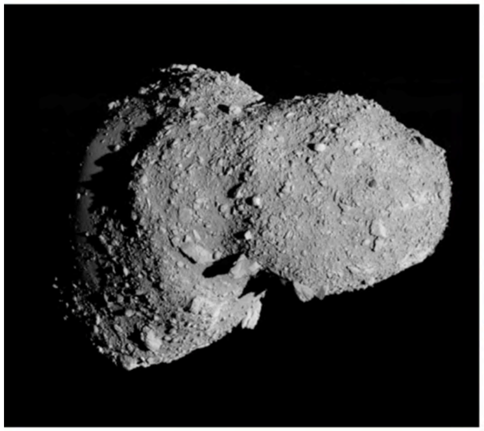
ARRM Reference Mission Objectives and Constraints

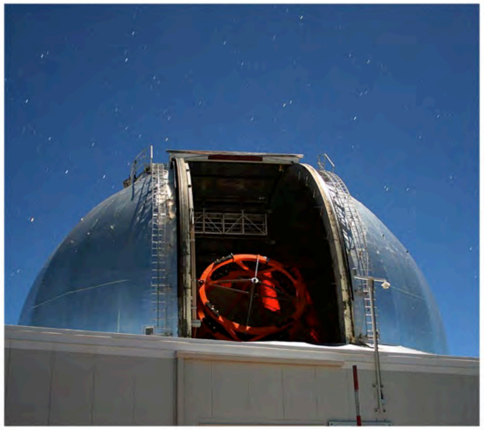
- Demonstrate rapid, lean, agile development under a cost driven paradigm
- For implementation planning assume Authority to Proceed (ATP) in January 2014 with a launch in mid. 2018
- Be compatible with launching on the Space Launch System (SLS), Falcon Heavy, or an Atlas V 551
- Have an operational lifetime at least 6 years

The Vision



B. Mission Design





Mission Design Executive Summary

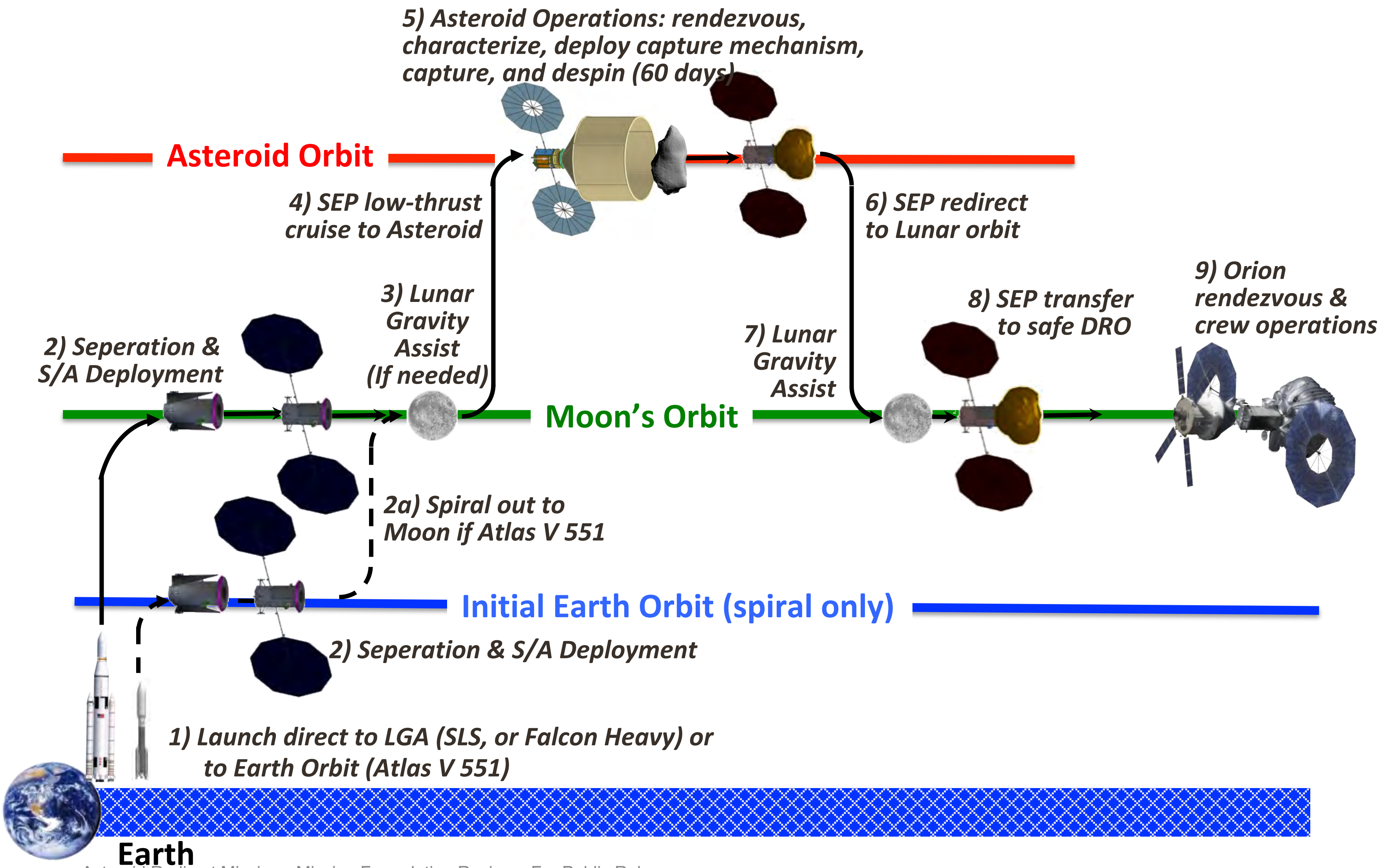
- The ARRV mission design trade space consists of the following areas
  - Target asteroid: mass, trajectory, natural return date and velocity
  - Launch date
  - Propellant mass (Xe)
  - Specific impulse (Isp) of the electric propulsion system
  - Power to the electric propulsion system
  - Launch vehicle
- Selected ARRV technology (propellant, Isp, power, and launch vehicle) exhibits resilience to target selection and schedule. Some examples:
  - Reducing the Isp of the system increases thrust, and can enable later launches to a given asteroid (but at the expense of more propellant)
  - A larger launch vehicle could allow the ARRV to carry more propellant for a later launch or larger asteroid
- An asteroid can be returned without increasing the natural risk of Earth impact and will remain in its storage orbit for hundreds of years
- Trajectories designed to several asteroids to verify asteroid redirection methodology and applicability of analysis tools

Reference Asteroids for Mission Design

- Table below provides status of all candidate targets that have detailed mission design analysis
- 2009 BD and 2013 EC20 are well enough understood to be valid candidate targets (2013 EC20 launch too early and likely too small to be certified)
- 2011 MD and 2008 HU4 need further characterization

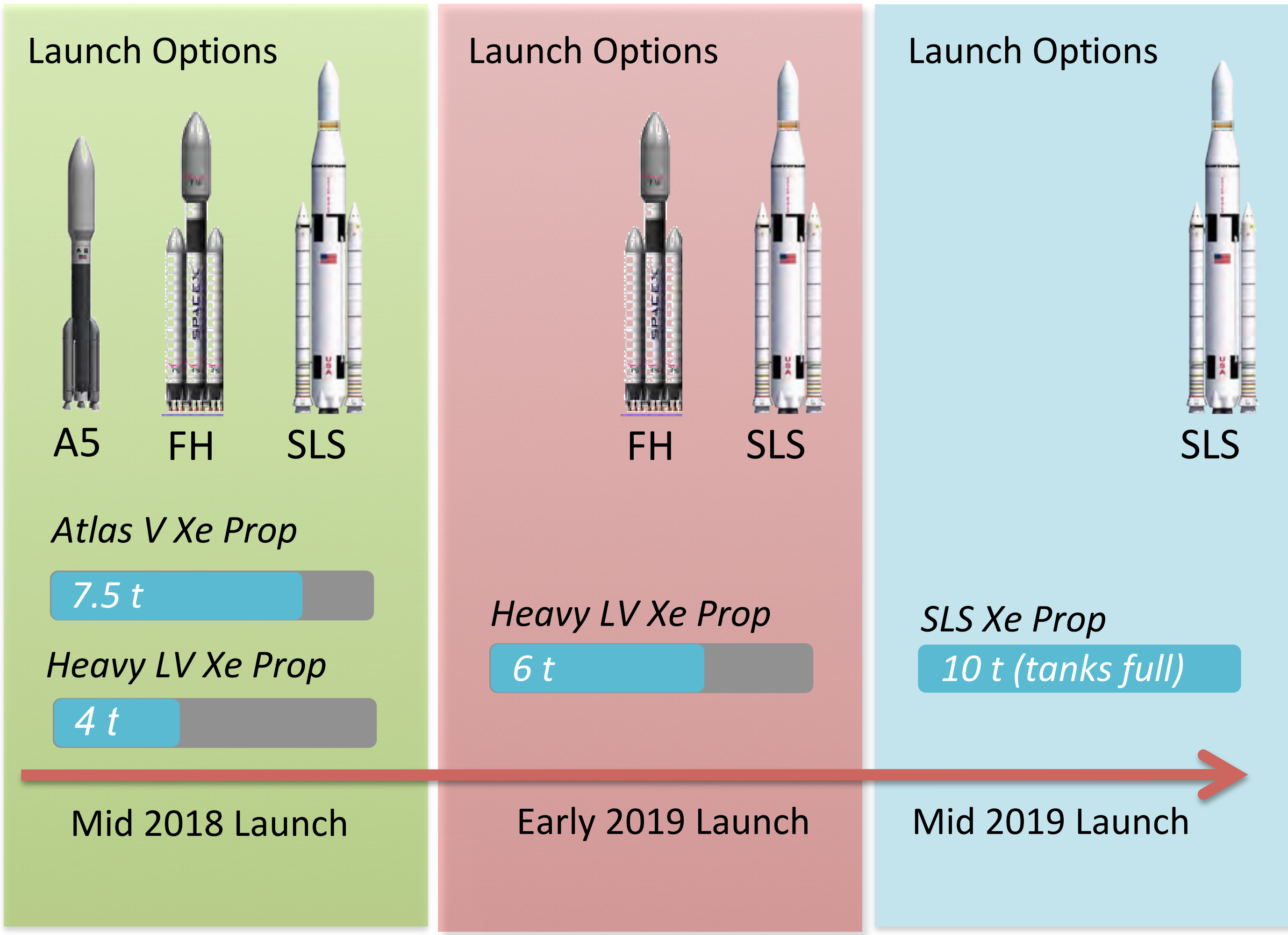
Asteroid	Asteroid Mass Est.	Asteroid V-infinity	Natural Return Date	Crew Accessible Date	Notes	Valid Candidate Target?
2013 EC20	4-50 t max return: 120 t	2.6 km/s	Mar 2020	Mar 2021	Discovered March 2013, can be observed again in Aug. 2013 rotation period ~ 2 min	**Yes, but needs Jan 2018 Launch**
2009 BD	30-325 t max return: 590 t	1.2 km/s	Jun 2023	May 2024	Area/Mass ratio estimated, rotation period > 2hrs, Spitzer opportunity in Oct. 2013	**YES**
2011 MD	7-50,000 t max return: 850 t	1.0 km/s	Jul 2024	Aug 2025	Rotation peroid 0.2 hrs, possible 2009BD-like Area/Mass Spitzer opportunity in Jan. 2014	**Needs Further Characterization**
2008 HU4	5-40,000 t max return: 1600 t	0.5 km/s	Apr 2026	~2027	Close Earth flyby in April 2016	**Needs Further Characterization**

Mission Overview



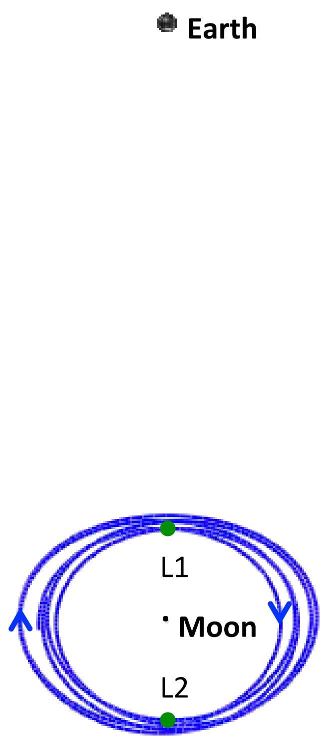
Design Resilience to Launch Date for 2009 BD

2009 BD Mission Options (assuming 325 t asteroid)

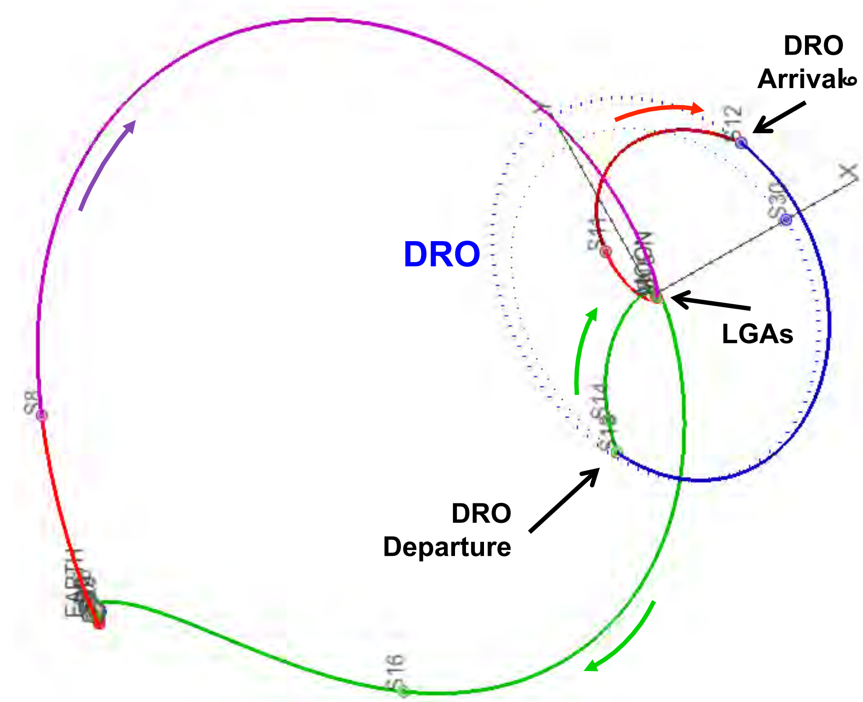


Lunar Asteroid Safe Storage Orbit (LASSO)

- Lunar Distant Retrograde Orbits (DROs) are stable, accessible with Orion MPCV, and require minimal ΔV for the ARRV to enter (~20 m/s)
- Stability of the Lunar DRO has been verified out to 250 years



Lunar DRO in Earth-Moon Rotating Ref. Frame



Orion MPCV DRO Access With Two LGAs

Mission Design Conclusions

- The ARRV SEP configuration can accommodate a wide range of asteroid targets and launch dates
- We currently have two valid candidate targets: 2009 BD and 2013 EC20
- ARRM can return the asteroid safely and store it for hundreds of years

Potential ARRV Planetary Defense Demonstrations

- ARRM could possibly perform one or two asteroid deflection demonstrations of the physics and operations associated with planetary defense before capturing the asteroid:
- Plume impingement on asteroid
  - Requires about 3 hours of thrusting to impart 1 mm/s of ΔV to 500 t asteroid
  - This approach is effective on any size asteroid
- Gravity Tractor
  - ARRV at 20 m could impart 1 mm/s of ΔV in 9 days
  - S/C Doppler ranging coupled with LIDAR could measure to 0.1 mm/s immediately and 0.01 mm/s over 10 days
  - This acceleration depends on the distance from the center of the asteroid and the spacecraft mass, not the asteroid mass

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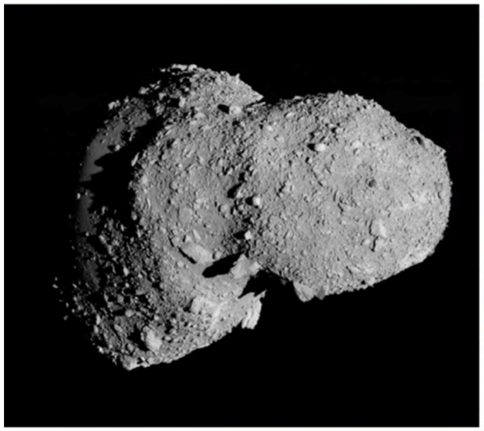
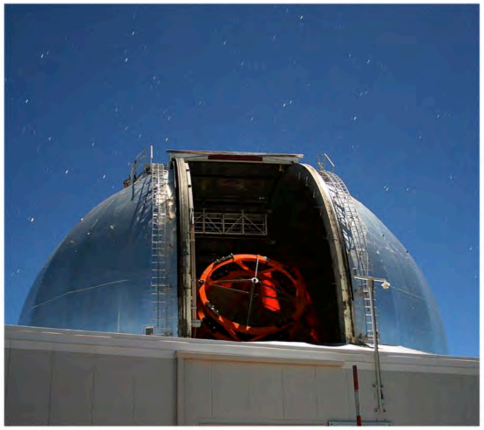
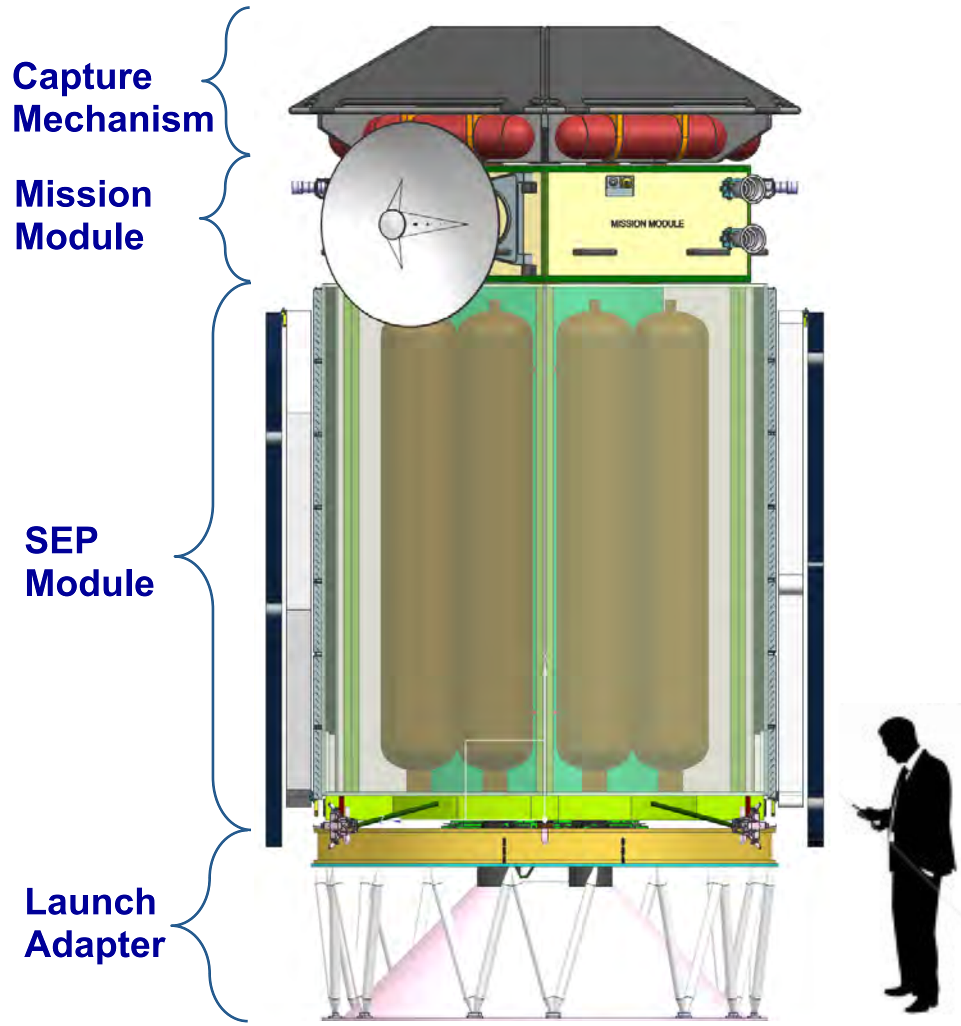
C. Mission and Flight System Baseline





Mission and Flight System Executive Summary

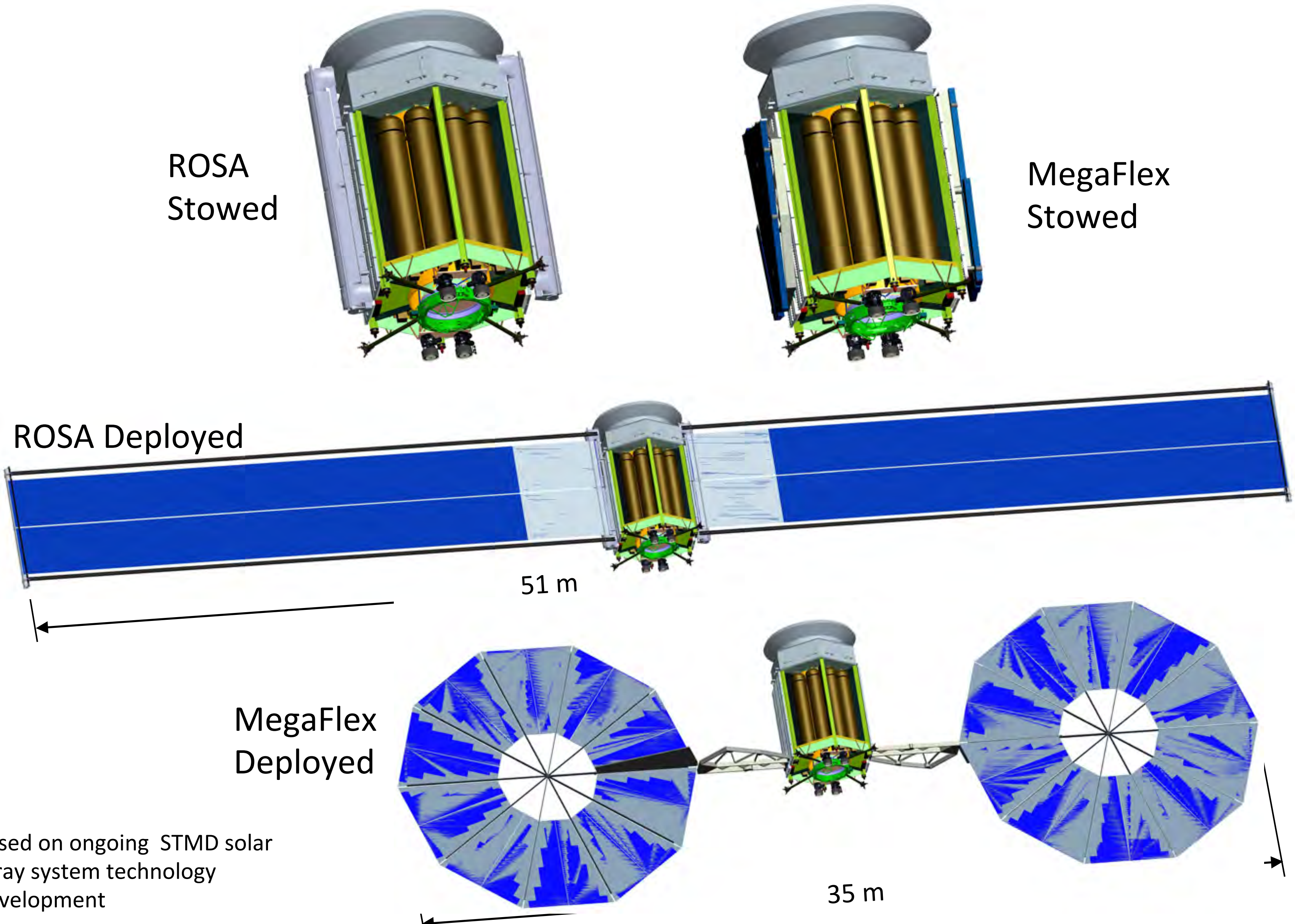
- Key Driving Objective:
  - Minimize the cost and technology development risk for an asteroid redirect mission with extensibility to future missions
- Balanced risk across major elements
  - Asteroid discovery and characterization
  - Transportation technology development
  - Proximity operations time
  - Accessibility of storage orbits
- Developed a baseline flight system and concept of operations (conops) approach
  - Modular Flight System: SEP Module, Mission Module, Capture System
  - Conops validated by model-based systems engineering analysis
- Flight system development is feasible and includes appropriate margins
  - Updated design used in the development of higher-fidelity cost estimate



Key Requirements

Key and Driving Requirements	Derived Key Design Drivers for Costing Baseline
Launch Date: mid 2018	Drives flight system implementation schedule • Drives technology choices (e.g. limit maximum solar array power ~50 kW)
Return Date: 2021 to 2025 Enable capture of asteroids in the 5 to 10-m size with maximum dimension of ≤ 14 m and a mass up to 1,000 metric tons	EP system power: 40 kW; 50-kW BOL solar array EP specific implulse: ~3000 s Accommodate up to 10,000 kg of xenon Proximity operations schedule Capture Mechanism sizing
Launch on an SLS, EELV, or Falcon Heavy	Launch direct to lunar gravity assist or provide the capability for spiral out from low-Earth orbit for EELV launch)
Accommodate asteroid structural integrities ranging from a ruble pile to a single solid rock	Capture the asteroid in a bag as opposed to a net, harpoon, mechanical arms, etc.
Include at least 90% of otherwise acceptable target asteroids based on spin rate	Asteroid spin rates up to 2 RPM Accommodate up to 400 kg of hydrazine
Provide the capability for autonomous capture and despin control	Sensor suite includes cameras and LIDAR Flight software for controls and fault protection
Minimize flight time to the asteroid to maximize return leg thrusting time	Be compatible with operation over solar ranges from 0.8 to 1.3 AU
Asteroid Redirect Crewed Mission and Extensibility	Docking ring, S-Band transponder, EVA tools, Human safe, power interface

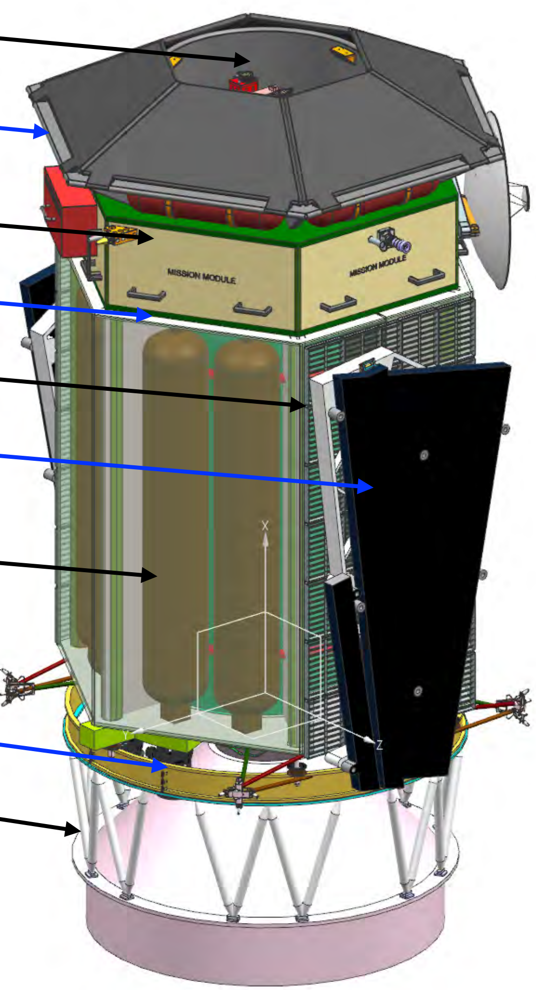
Flight System Configurations*



* Based on ongoing STMD solar array system technology development

Flight System Key Features

- Instrumentation with flight heritage
- Capture bag with force-limiting mechanism
- Deep Space spacecraft avionics with flight heritage
- Simple interface between modules
- Conventional thermal control
- Compatible with either STMD solar array at 50 kW BOL
- Conventional low-cost, light-weight xenon tanks
- Conventional Reaction Control Subsystem
- STMD Hall thruster/PPU technology
- Compatible with Atlas V, SLS, or Falcon H launch vehicles



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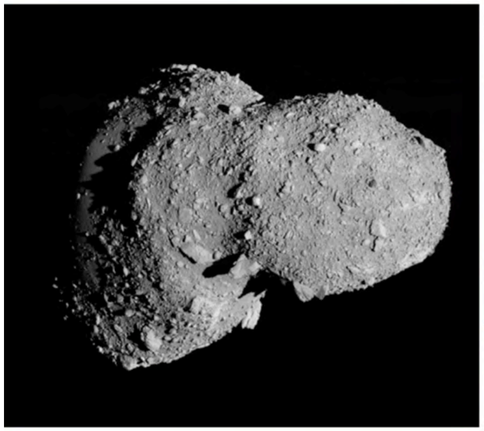
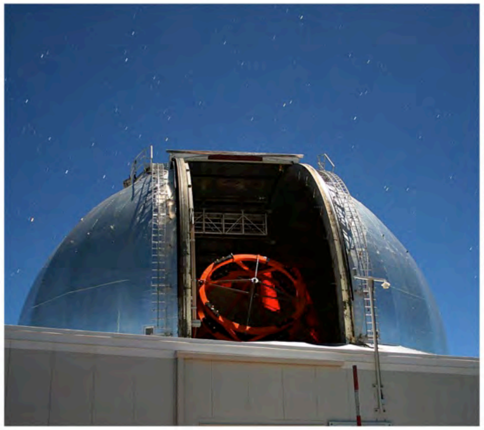
D. Solar Electric Propulsion (SEP) Module

SEP Module Executive Summary

- ARRM is *enabled* by 40-kW-class SEP, powered by a 50-kW solar array, and demonstrates an advanced SEP flight system
  - Leverages electric propulsion technologies currently under development by STMD
  - Demonstrates deployment and operation of lightweight solar arrays at 25 kW/wing
- Study team evaluated SEP technologies against ARRM needs to determine an affordable, extensible approach with reasonable development risk
  - Cost and schedule risk is mitigated by building on existing 50 kW-class development efforts
  - ARRM SEP technology is extensible to exploration, science and commercial missions
- ARRM requires long-life thrusters (achieved with magnetically-shielded Hall thrusters)
  - Reference ARRM Thruster Isp is 3000 s, but other specific impulse levels are useable depending on the target, launch vehicle and launch date
  - Some close using <3000 s Isp
  - ARRM thruster is directly extensible to commercial and other NASA missions

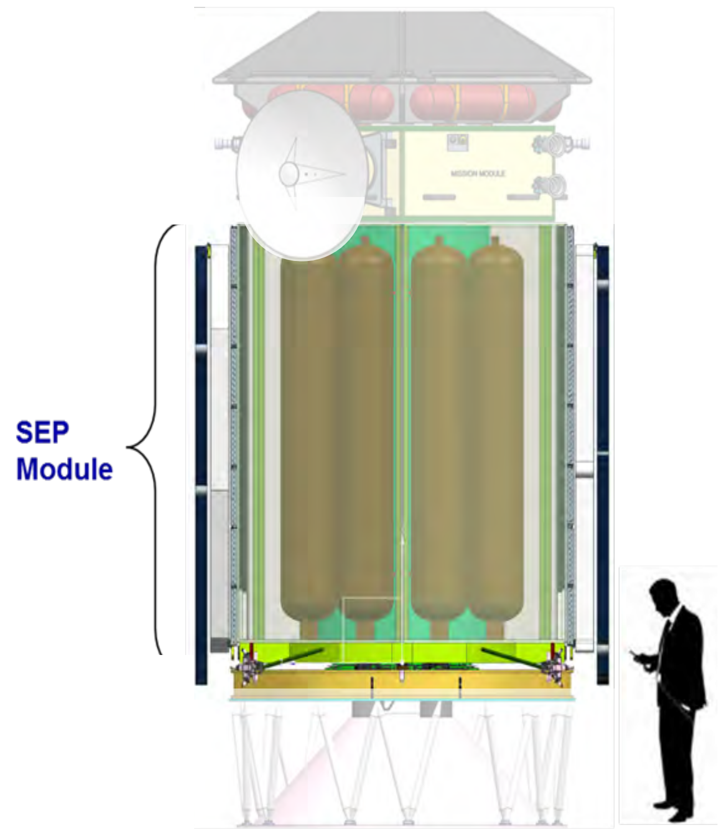
SEP Module Overview

Module-level Design Drivers and Constraints

- Propellant load, 5-meter fairing, power level, throughput, cost and schedule

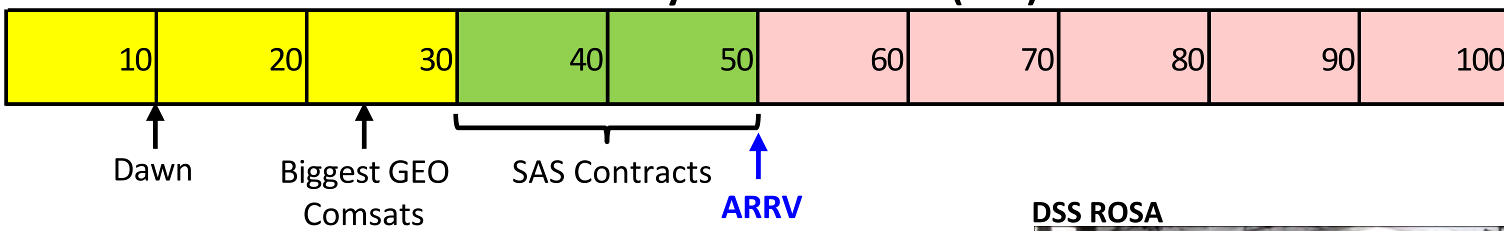
Module Subsystems

- Ion Propulsion: 4 Hall thruster/gimbal/PPU strings, 10,000 kg of Xe in 8 seamless tanks
- Power: Solar Arrays, Solar Array Drive Assemblies, Power Management and Distribution
- Mechanical & Structure: Conventional construction
- Thermal Control: Conventional cold plates with heat-pipe radiators
- Reaction Control: Conventional hydrazine monopropellant system



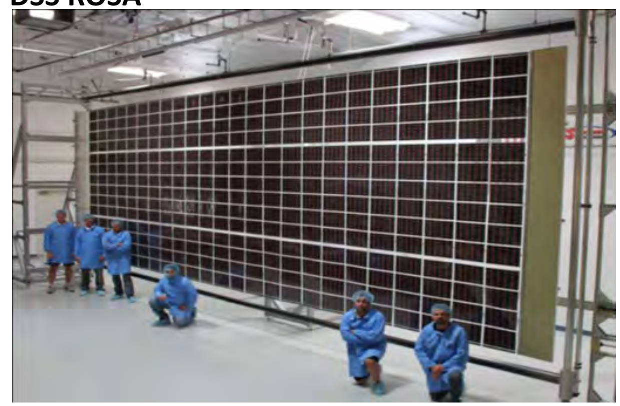
Power Subsystem

Solar Array Power Levels (kW)



- Technology assessment
  - Solar Array System (SAS) contracts underway for both ROSA and MegaFlex technologies
  - Extensibility to ≥ 250 kW required in SAS contracts
- Key driving goals/requirements
  - 50-kW solar array
  - 40 kW input to PPU
  - 300-V main bus voltage
- Basic implementation characteristics
  - Solar array; 2 Wings at ~ 25 kW each
  - 0.1 g deployed strength; >0.1 Hz stiffness
  - Sequential Shunt Units (SSU) with high-voltage switch
  - Power transfer to docking mechanism

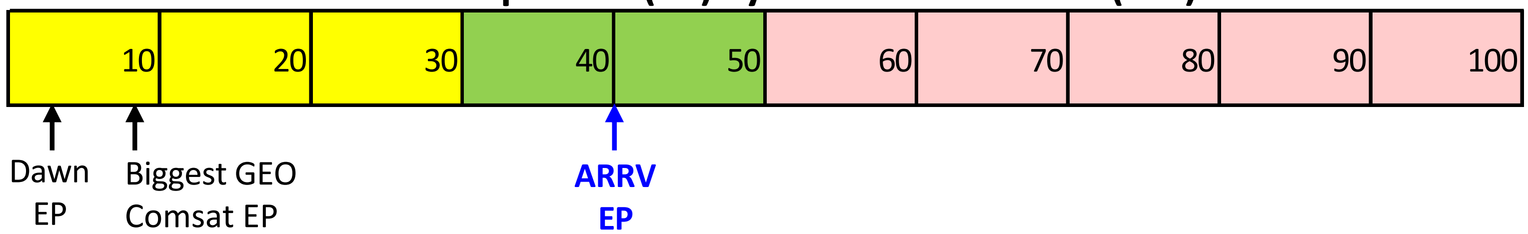
DSS ROSA



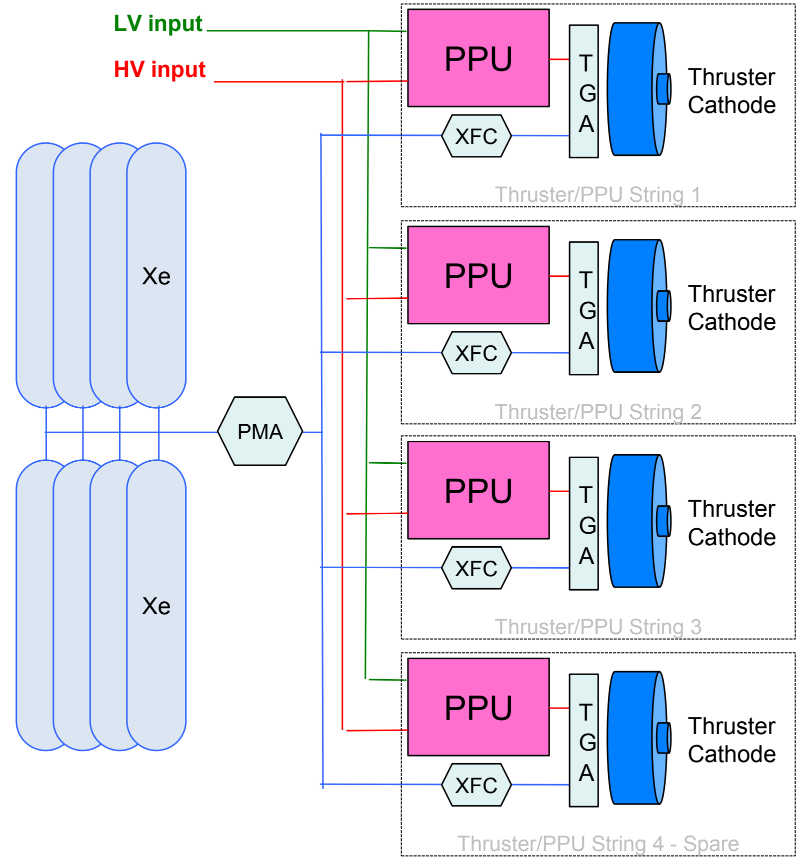
ATK MegaFlex "Gorelet"

Ion Propulsion Subsystem: Overview

Electric Propulsion (EP) System Power Levels (kW)



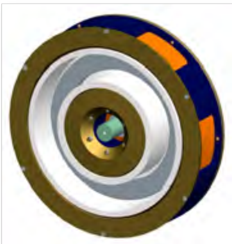
- Key driving goals/requirements
  - 40-kW input power; 60% efficiency
  - 3000 s Isp; up to 10,000 kg xenon throughput
  - Extensibility to future exploration applications
- Basic design characteristics
  - Three 13.3 kW thruster/PPU strings + 1 spare
  - Leverages high-Isp, long-life Hall investments



Ion Propulsion Subsystem: Uses STMD Developments

STMD enabled Asteroid Redirect Mission by addressing PPU & Hall thruster technology risks

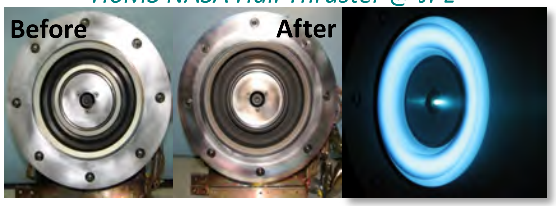
Hall Thruster & PPU development currently underway



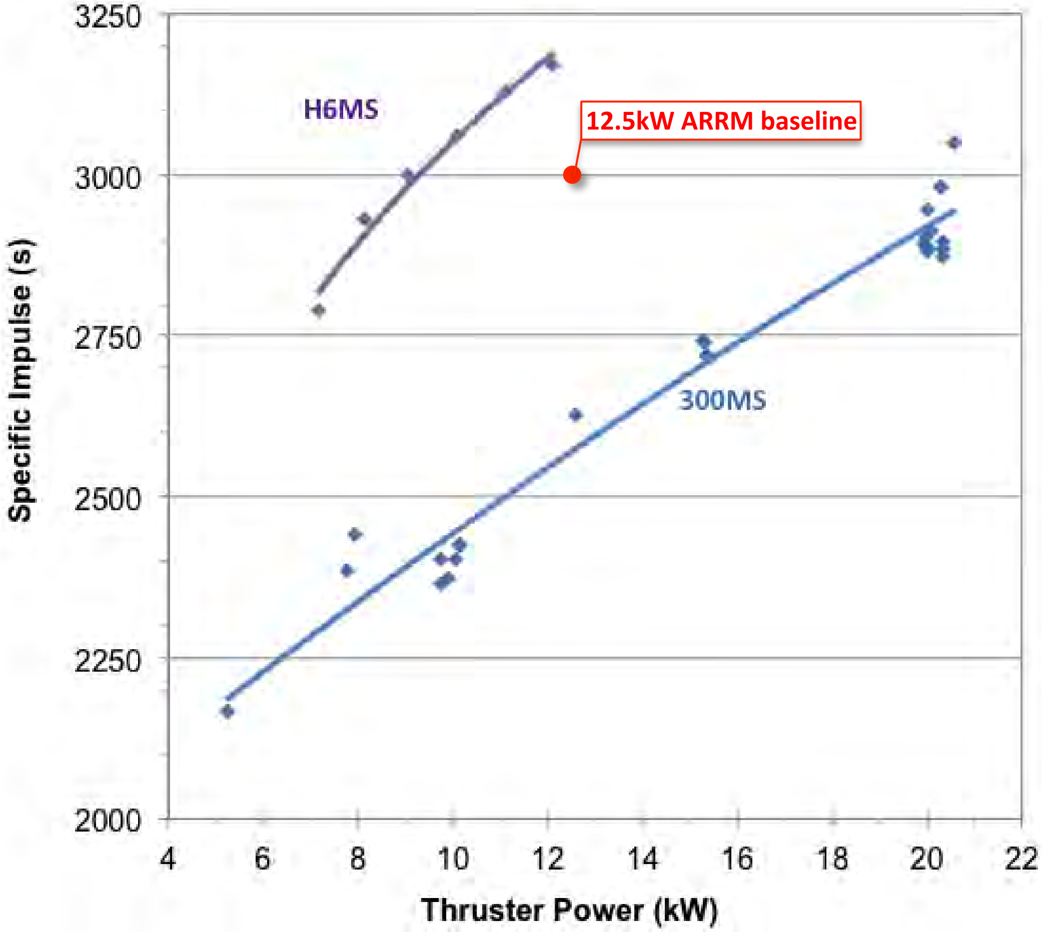
Erosion testing addressed propellant throughput risk

300MS NASA Hall Thruster @ GRC

H6MS NASA Hall Thruster @ JPL



12.5kW Hall maintains performance flexibility with extensibility to science & commercial applications



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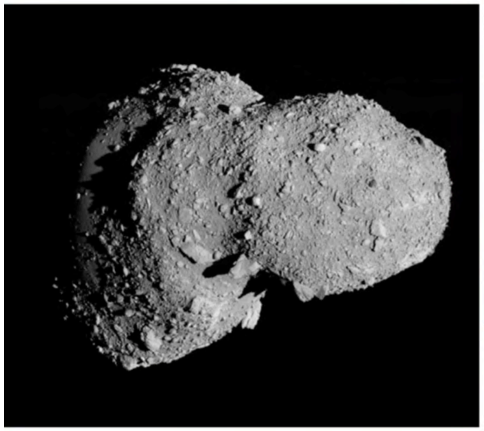
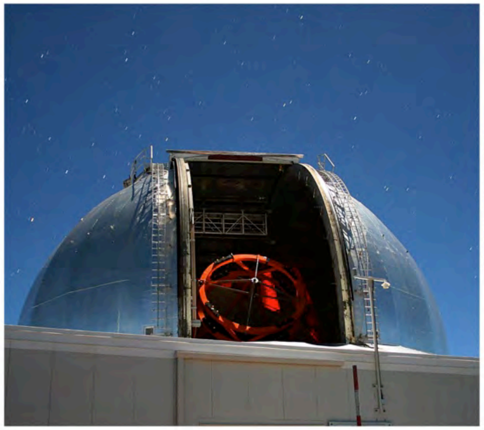
E. Rendezvous and Proximity Operations





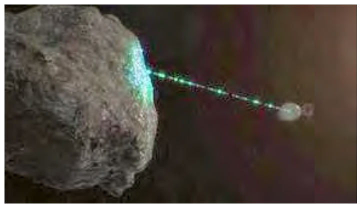
Rendezvous and Proximity Operations Executive Summary

- Rendezvous and proximity operations phase covers the approach, rendezvous, characterization and capture approach to the point that the capture mechanism process is activated, and then picks it up after the capture is complete
- Includes: High level conops, sensors, controls approach
- An architecture for ProxOps and Capture has been selected that uses a simple GN&C system and relies on the mechanical Capture Bag mechanism to handle asteroid rotation dynamics and limit to forces on the spacecraft to an acceptable level
- Sensor suite that accommodates all phases of the process has been defined
- Proposed approach can handle a large range of asteroids sizes and rotation states

Rendezvous and Proximity Operations Phases

Orbit Refinement and Rendezvous
(Radio and Optical)

Characterization



Pre-Capture
Capture System Deploy

Final Approach

Attitude Control Disabled

Capture
Mechanical Capture

Capture Bag Retraction

Attitude Control Enabled

Characterize, Spin down, and Detumble

Asteroid Orbit Refinement and Rendezvous Phase

- Optical Navigation starts at ~50K km
  - Narrow Angle Camera (NAC) acquires and identifies the asteroid
- Ground Optical Navigation and SEP burn arcs deliver ARRV to within ~1km
- Optical Navigation demonstrated on the Dawn and Deep Impact missions

Characterization Phase

- During the Characterization phase the ARRV position and attitude is autonomously controlled in an asteroid-centered reference frame
  - The asteroid is observed from a series of different lighting geometries to determine shape and rotation dynamics
  - Parabolic hops with no RCS firings enable gravity-derived estimation of asteroid mass
- Asteroid-relative navigation is based on measurements from a 3D LIDAR sensor
- Trajectory control is done using Formation Flying RCS continuous control techniques about an uncooperative target
  - Developed at JPL by NASA and DARPA technology programs
  - Also leverages experience and capabilities in sensors, algorithms, simulation and physical test/demonstration.

Pre-Capture Phase

- Simple Guidance Navigation and Control (GN&C) design places the capture bag around asteroid
  - 3D LIDAR sensor used to maintain clearance between capture bag
  - The relative translational velocity between the ARRV and the asteroid is minimized prior to mechanical capture
  - The relative rotational motion between the ARRV and the asteroid is minimized by spinning the spacecraft about capture bag axis of symmetry to match asteroid rotation about that axis
- The capture mechanism deals with the loads and transients resulting from residual rotational motions, keeping the ARRV accelerations within acceptable limits
  - ARRV Solar Arrays are the limiting factor (< 0.1g)
  - ACS disabled during mechanical capture and resulting transients

Pre-Capture and Capture Phases

- Pre-Capture Process Sequence
  - Approach to pre-capture stand-off distance (~50 m) and STOP
  - Establish final position for initiation of capture sequence using scanning LIDAR
  - Deploy capture mechanism and validate readiness to proceed
  - Ground Go/No-Go decision
  - Synchronize rotation rate (if needed)
  - Start approach trajectory. Approach direction optimized to minimize relative rotation and spin-down fuel
    - Use LIDAR to measure asteroid limbs and maintain clearance between bag and asteroid
- Capture Phase
  - When asteroid inside bag: STOP, disable ACS, start mechanical capture
  - Wait for capture transients to subside and ARRV in lock with asteroid
    - Use inertial sensors to declare capture phase complete

Characterize, Spindown and Detumble Phase

- Once the asteroid is in the bag and system determines that it is safe, re-enable the Attitude Control Subsystem (ACS)
  - Ground Go/NoGo
- ACS performs rate damping and spin-down to power and communications safe attitude
- Characterize and update system inertia properties
- Establish attitude for initiation of Hall thruster operation

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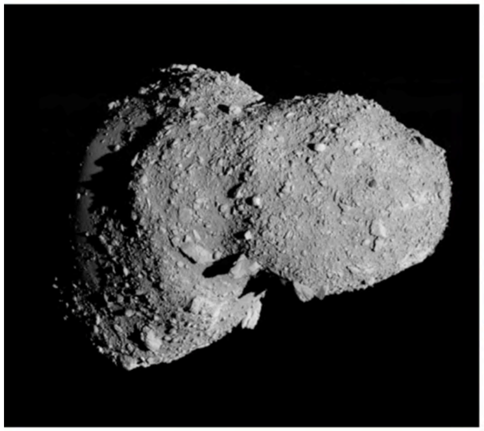
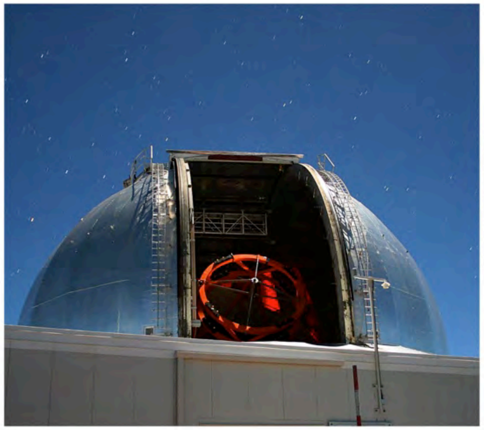
F. Capture Mechanism and Capture Process





Capture Mechanism Executive Summary

- Capture implementation is dominated by spin state of target. At low spin-rates (< 0.2 rpm) about all axes the problem is straight forward
  - Forces are small and accelerations reflected back into the spacecraft are < 0.1 g
- ARRM is working to solve the case (at the limit of known objects) of up to ~2 RPM to show robustness
  - Passive and active capture strategies have been studied
  - Two approaches have been identified that appear to meet force limits
  - Strategy is to match spin; quickly inflate air bags to "lock" asteroid to the spacecraft at low contact pressure; force-controlled winches gather and deflate fabric and position center-of-mass; detumble and despin using RCS thrusters
- Uses non-rigidized inflatable capture bag
  - Deals effectively with range of target uncertainties in composition, strength and spin state
  - Can be verified and validated in Earth gravity
- Received industry inputs on concepts and costs that are consistent with concept presented here

Key Characteristics of Asteroid for Capture

Composition/ Strength

- Rock (>>1 PSI)
- Dirt Clod (~1PSI)
- Rubble Pile(<<1PSI)

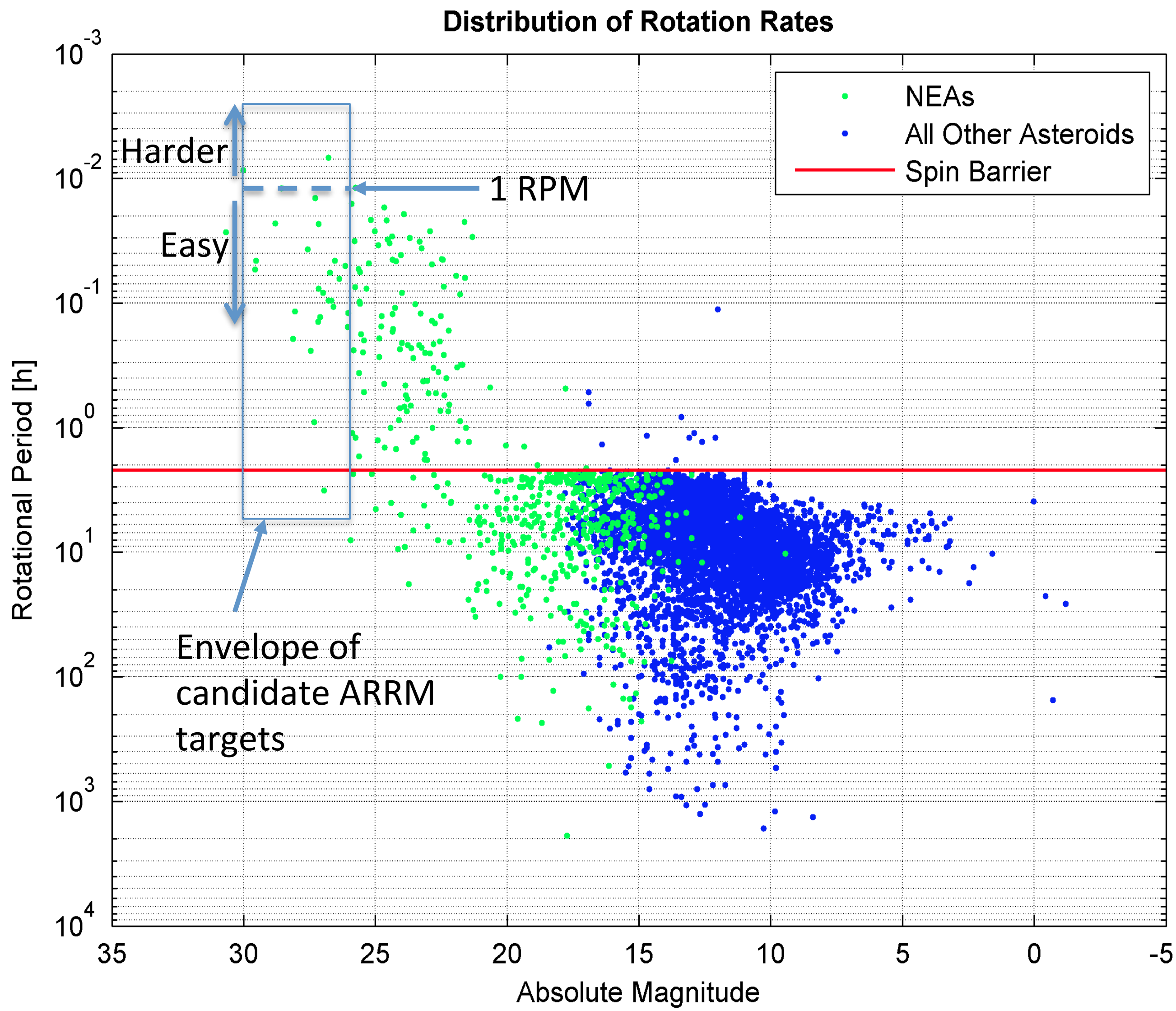
Spin State

- Slow (<<1 RPM), Simple Spin
- Slow (<<1RPM), Tumbling
- Fast (~>1RPM), Simple Spin
- Fast (~>1RPM), Tumbling

- For capture, the primary concerns are composition/strength and spin state
- Have been evaluating passive and active control options that limit forces on the spacecraft/solar arrays to <0.1 g peak for the fast/tumbling state

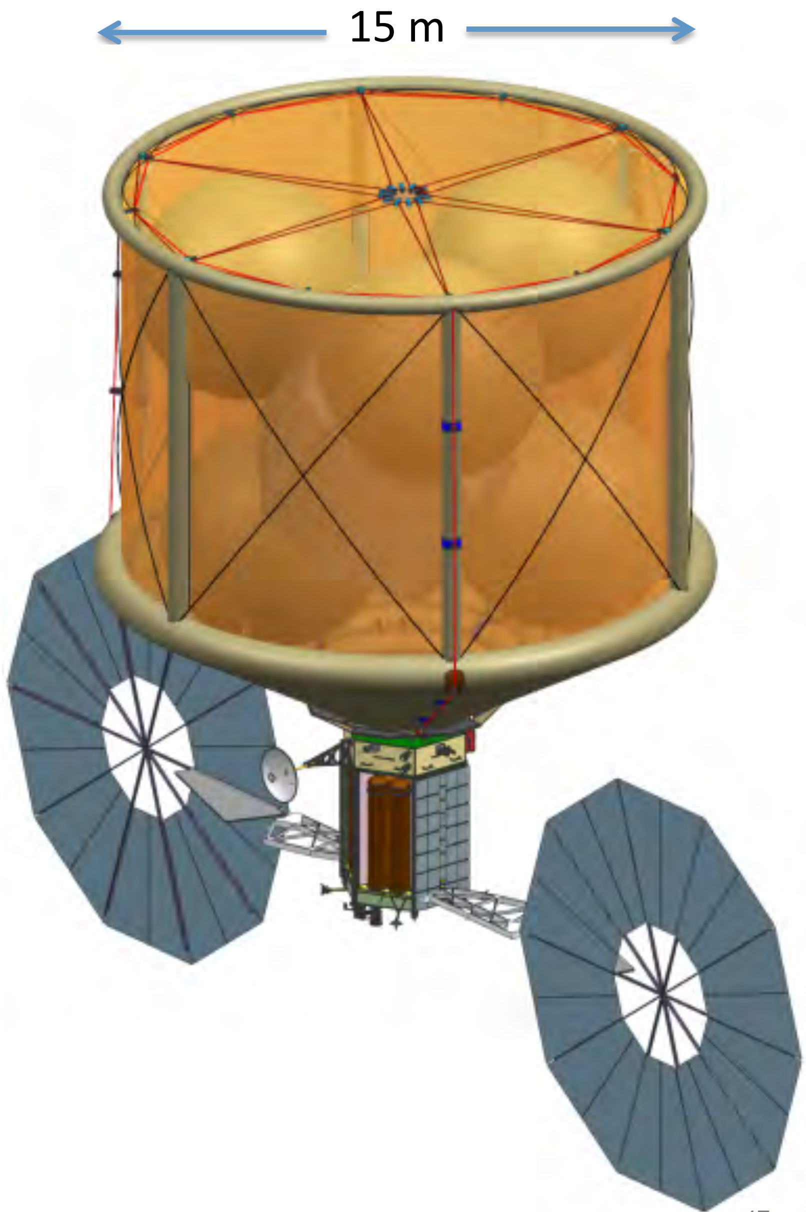
Spin Periods of Near-Earth Asteroids

- Many small NEAs spin faster than the rubble pile spin barrier, but may be "dirt clods"
- Worst case assumed to be 5-13 m diameter NEA with a spin rate of 2 RPM and tumbling

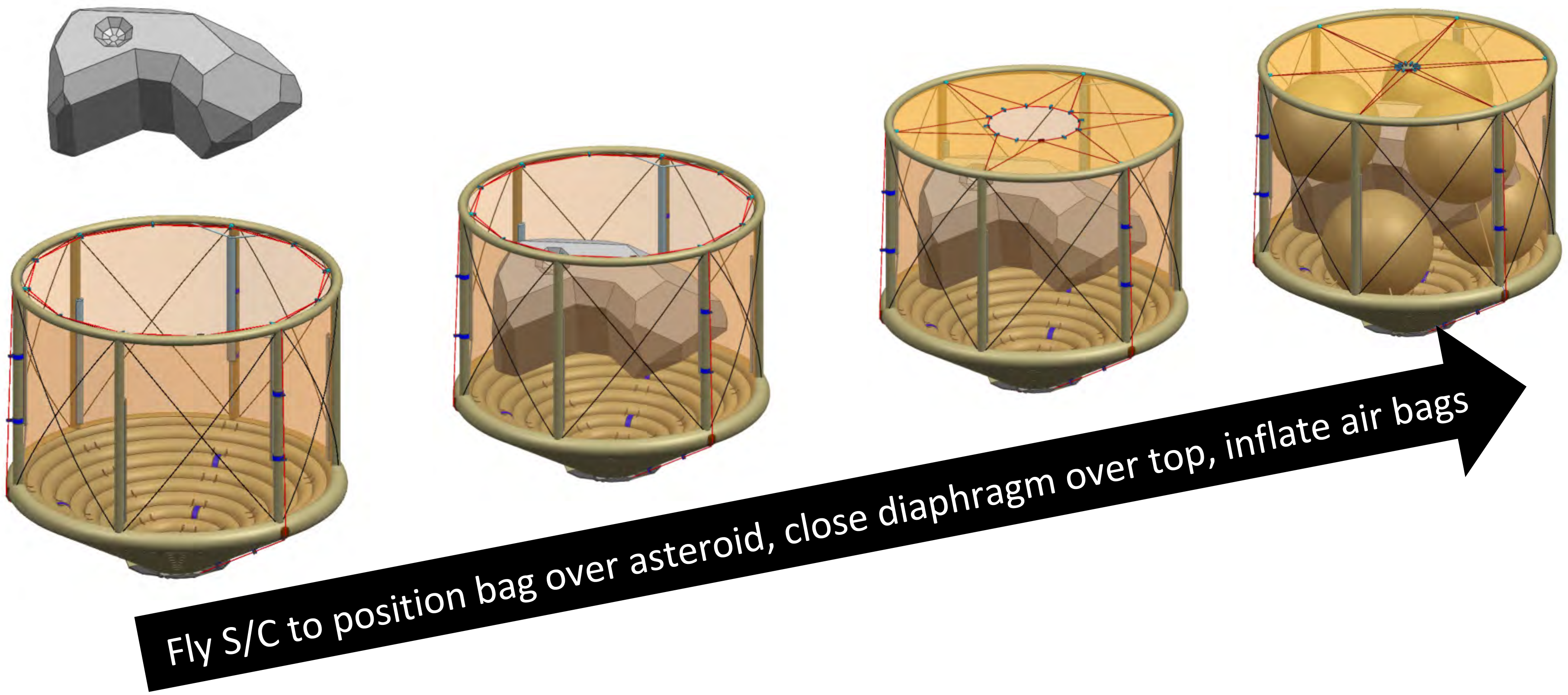


Capture Mechanism Concept

- Capture bag formed of cylindrical barrel section and conical section attached to S/C
- Inflatable exoskeleton to deploy bag after arrival at asteroid
- Inflatable "stack of torroids" at base of cone to form passive cushion between asteroid and S/C
- Circumferential cinch winches close diaphragm at top of cylindrical section; confine asteroid after deflation
- Air bags quickly immobilize bag in asteroid frame at very low contact pressure (<<1 PSI)
- Axial cinch winches control motion, retrack bag, and position asteroid center-of-mass.



Capture Sequence



- Spacecraft approaches and matches spin along projected asteroid spin vector a short time in the future.
- When asteroid is centered in the bag, close top diaphragm, and at the moment spin is matched, inflate air bags w/pressure <<1 PSI to limit loads on surface of asteroid, achieving controlled capture quickly; cinch asteroid tight to S/C while venting.
- Mechanism provides elasticity to control loads to solar arrays .

Capture Testbed

- Questions that will be answered by scale model and full scale testing (not likely answerable by physics-based simulation) include:
  - Cinch cords behavior and control of bag fabric, demonstrating full closure of the bag?
  - Characterizing snagging of the bag by the asteroid, forces on the bag, and general control of the bag
  - Determining the best cinching and GN&C algorithms to manage the asteroid motion in the bag

- Initial 1/8 scale capture testbed has inflatable exoskeleton with winches suspended from gantry over asteroid on end of 8-DOF robot arm that can spin and tumble the asteroid in the S/C (lab) reference frame.

Summary and Conclusions

- Continuing to explore options to capture asteroid under a wide range of initial conditions while limiting forces on the spacecraft
  - Inflatable exoskeleton deploys fabric capture bag; air bags inflate at the moment of capture to "lock on" when the spacecraft spin matches that of asteroid.
- Have evaluated two classes of capture using separate strategies and models: passive and active
- Two passive approaches appear to meet constraints
  - Match primary spin rate and let flexibility of bag mechanism accommodate capture forces of other axes, works up to 1 rpm transverse rate
  - Match instantaneous spin vector and initiate capture at moment instantaneous relative spin rates are ~ zero, works for up to 2 rpm
- Monte Carlo simulations starting to be applied for wide range of asteroid inertial, spin and tumble states and indication are that asteroids can be safely captured at ~2 rpm

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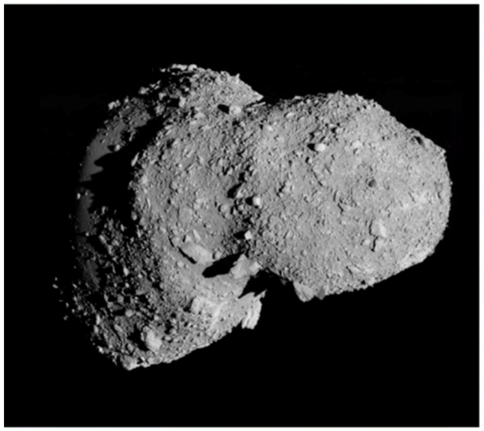
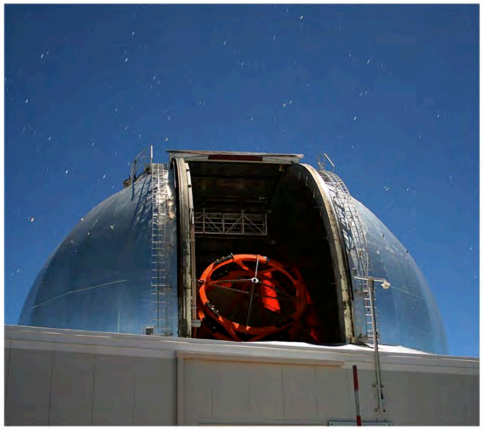
G. ARRM Reference Implementation

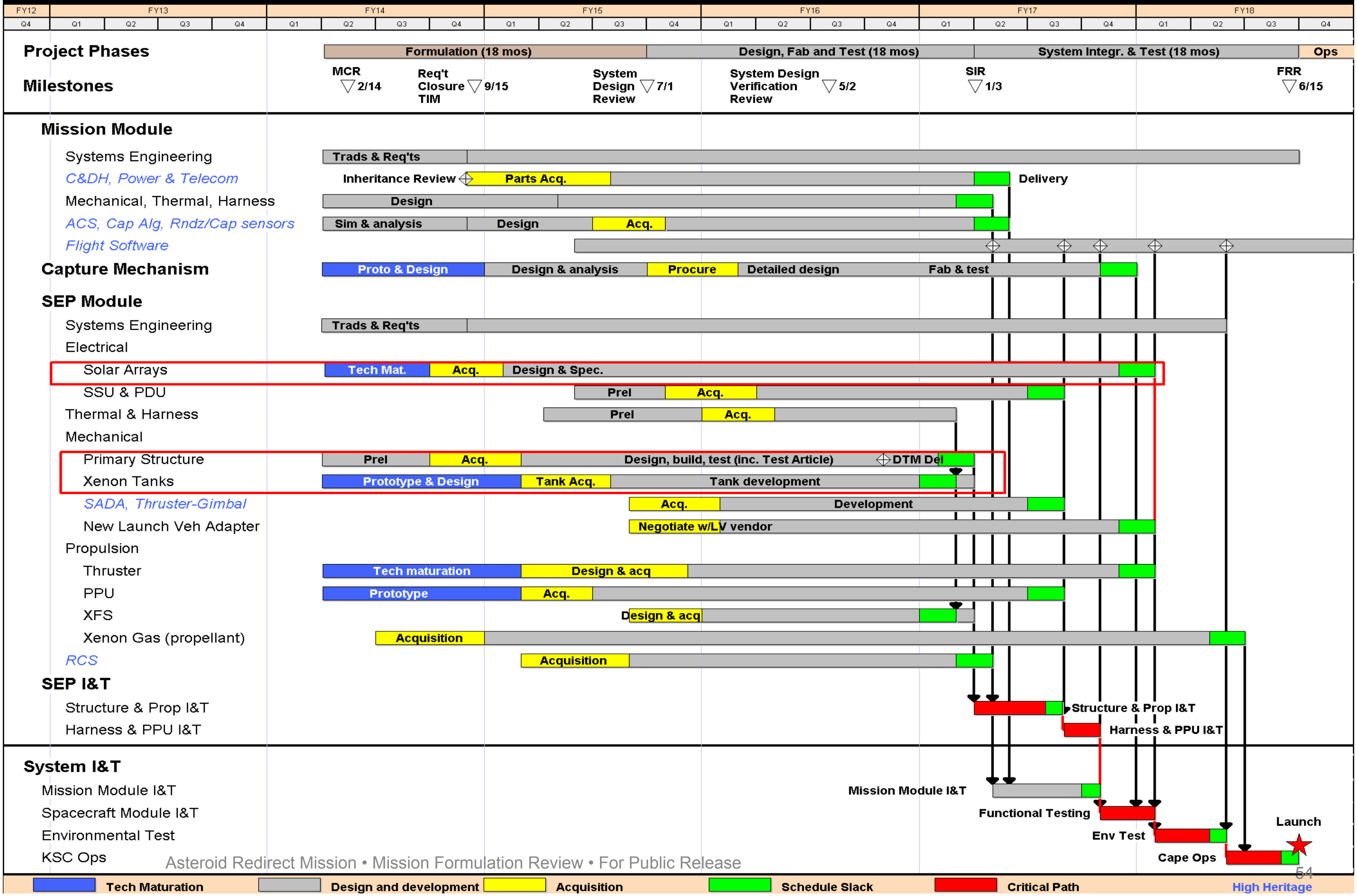
Implementation Executive Summary

- This study has developed an integrated technical and programmatic ARRM system architecture and conceptual design that meets stakeholder objectives and constraints
- Concept is based on a technology demonstration mission approach within a cost driven paradigm using a rapid, lean, agile implementation approach
- Architecture provides flexibility in the launch vehicle choice (SLS, Falcon Heavy or Atlas V), with specific launch date being dependent on the choice of the return target
- Reference schedules are complete and credible with reasonable margins for as early as a mid-2018 launch
- Project implementation options have been explored and a cost effective approach, yielding a current best estimate within constraints, has been developed

Reference Mission Schedule

- Assumptions and features
  - Authority to proceed: January 2014
  - Launch readiness date: June 2018
  - FY14 funding requested/planned
  - Appropriate system-level schedule margins included (and funded)
- Schedule features to meet timeline:
  - Parallel developments of modules
  - Short procurement initiation cycles (working with the institutions)
  - Early focus on critical path risks (e.g. structure and solar array)
  - Enabled by existing investments and heritage (e.g. technology, avionics, SW)
- Launch date most likely driven by programmatics (funding profile) and availability of launch vehicle, but SEP and target choices provide flexibility
  - Choice of final target can be made within months of the launch

Study Results:
Reference Mission Development Schedule – June '18 Launch



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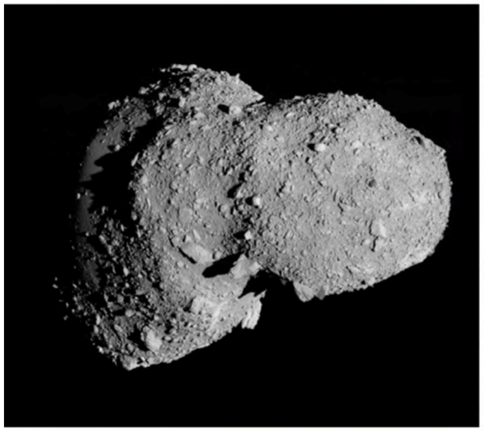
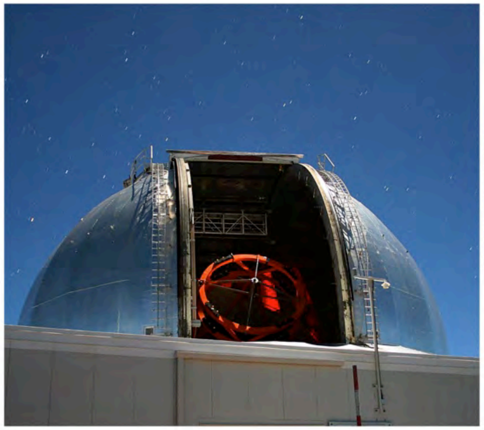
H. Conclusions

Conclusions

- **Objectives of the MFR have been met**
  - ARRM reference concept has been shown to be technically and programmatically feasible, within provided objectives and constraints, at reasonable confidence, and acceptable risk
  - Architecture and design elements are versatile for a range of missions and targets
- Solar Electric Propulsion (SEP) technology options have been evaluated and a credible baseline has been established that can provide the capability and flexibility needed to return a NEA to lunar orbit by 2021-2026
- Flight system options have been evaluated and a credible baseline has been established that meets functional objectives
- An inflatable capture system concept has been developed that is viable, testable and can capture a wide range of spinning/tumbling NEAs with acceptable risk
- 2009 BD is a "valid candidate target." Possible certification for selection pending Spitzer observations in October 2013.
  - This candidate target is low risk for capture and detumble/despin.
  - Choosing a mission target early will reduce external concerns about mission readiness and reduce overall mission risk and cost

Conclusions (continued)

- The ARRM mission can:
  - Demonstrate high-power solar electric propulsion that will support near-term human exploration missions beyond low-Earth orbit, enable new robotic planetary science missions, and is extensible to the systems required to improve the affordability of human exploration missions to Mars.
  - Provide a unique target destination for SLS/Orion in translunar space that will result in astronauts traveling farther from Earth than ever before, leaving low-Earth orbit for the first time in 50 years, and coming in contact with only the second celestial object in human history.
  - Significantly enhance our knowledge of the near-Earth object population and it’s potential threats to Earth.