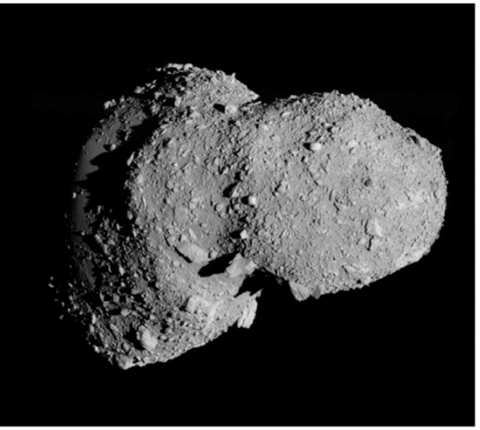
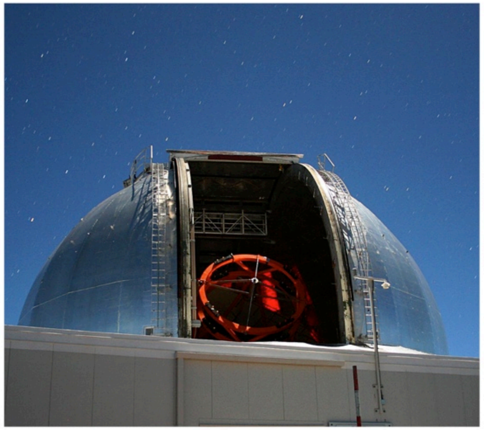
National Aeronautics and Space Administration

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

August 20, 2013

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

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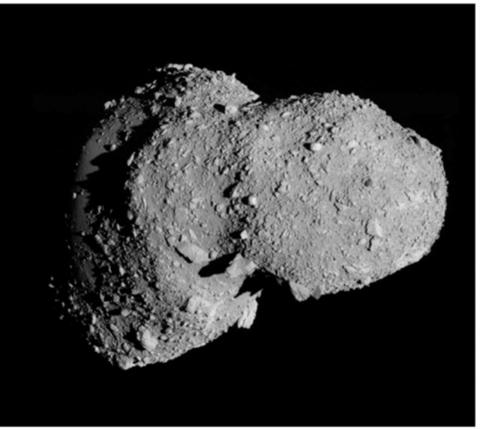
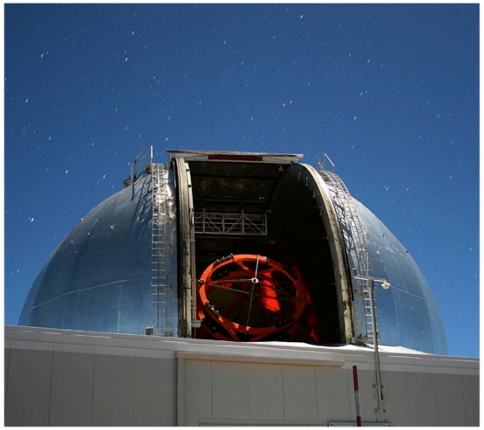
A. Introduction and Objectives

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 baseline derived from the analysis of numerous options
  - A Credible 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, we have a “valid candidate target:” 2009 BD

Asteroid Redirect Robotic Mission
What Is It?

- The proposed 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 would 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 would also enable future forays into deep space with larger payloads.
- The result would be human missions farther from Earth than ever before, and the first human missions beyond low-Earth orbit in 50 years.
- It would 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 would 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 would live on beyond the target selection for ARM and extend discovery and characterization of the current observational programs. The result would 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

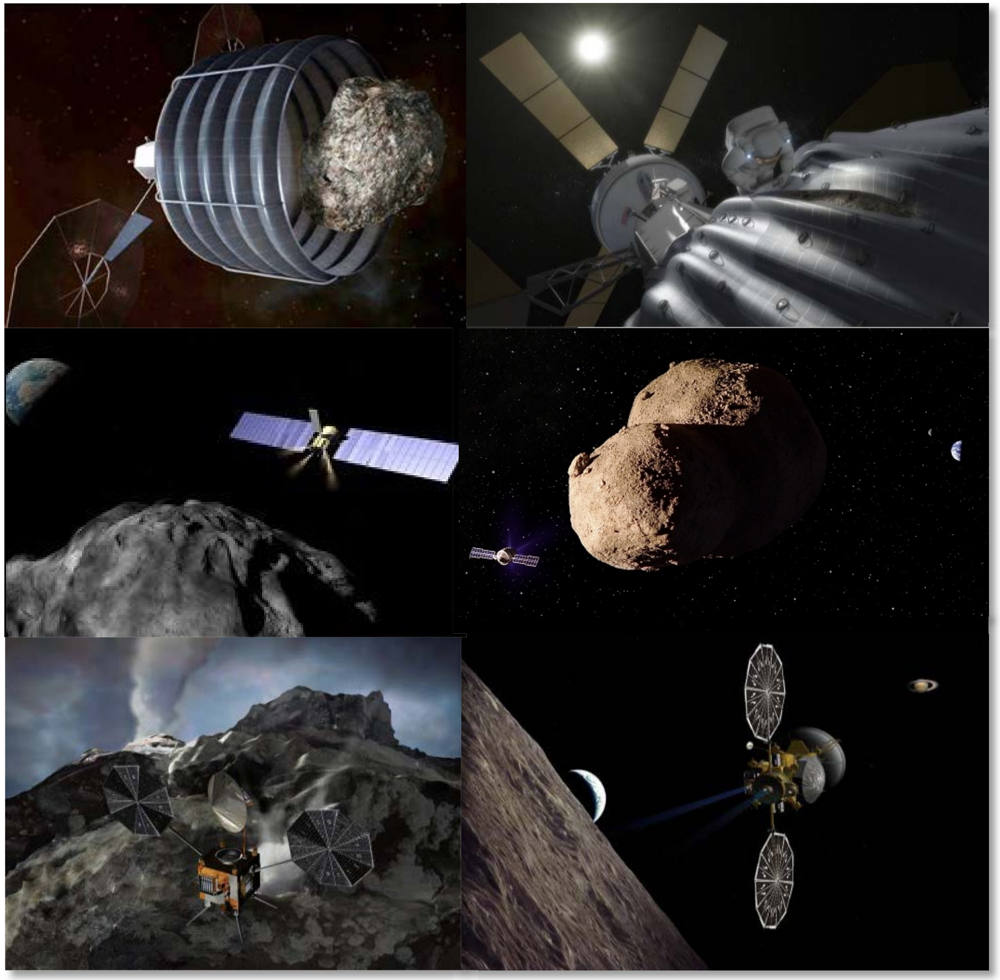
- The capture, return, and close-up inspection of the asteroid would provide insight into the ability to control and deflect a large mass with solar electric propulsion helping to inform future planetary defense measures.
- The methodologies and technologies developed to rendezvous with and capture a 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 would also provide opportunities for the commercial sector which has recently expressed interest in mining asteroids. Sampling techniques and potentially in situ resource utilization (ISRU) would path find future applications. The demonstration of high-power solar arrays and high-power electric propulsion systems would support U.S. competitiveness in the commercial satellite industry.

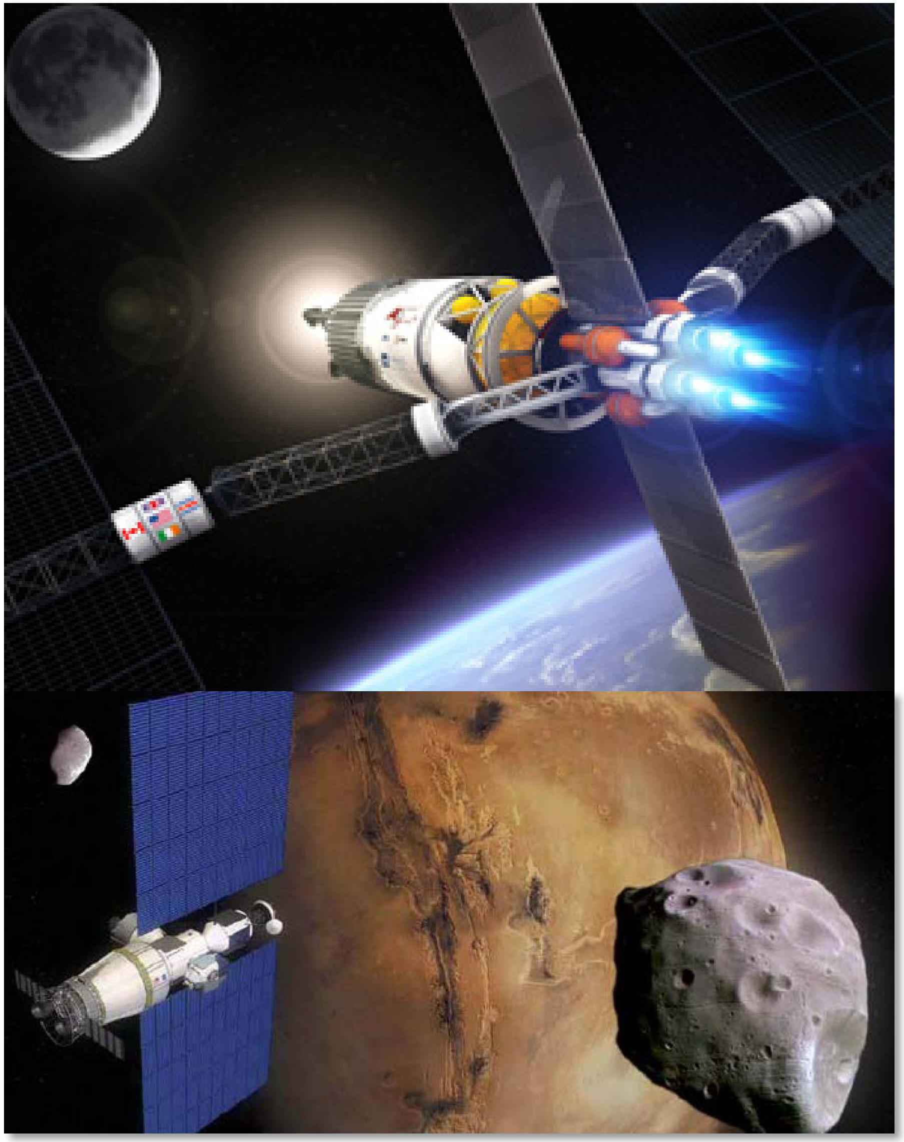
ARRV Versatility

- Study process has identified a suite of capabilities that could 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—would be 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 ARM 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).

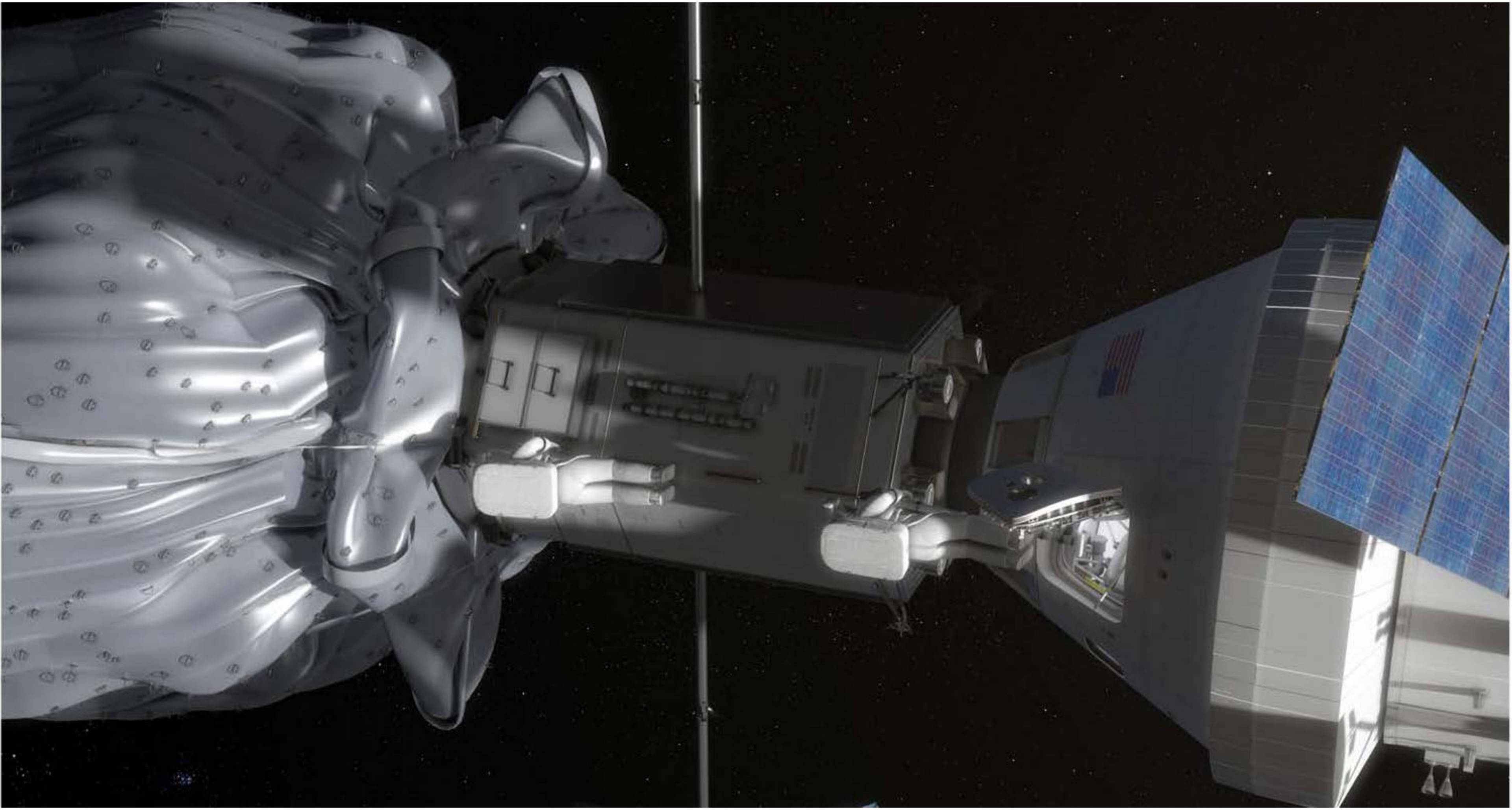
ARRM Reference Mission Features

- The Architecture, mission design and flight system would 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 would be designed to be inherently safe to planet Earth at all times
- The robotic vehicle would be crew safe but not human rated
- The mission could include 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
- Total development cost <$1B real year, with reserves—not including launch vehicle or flight operations
- Total cost, including launch vehicle and operations: ~$1.4B

The Vision



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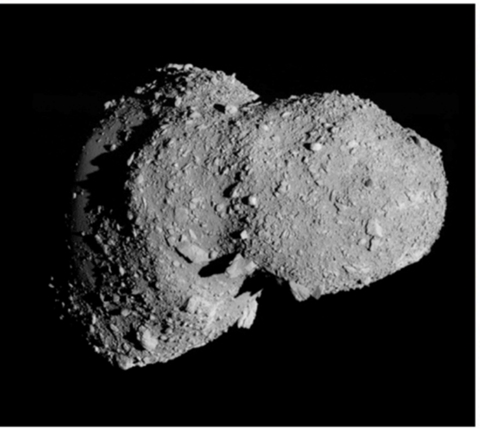
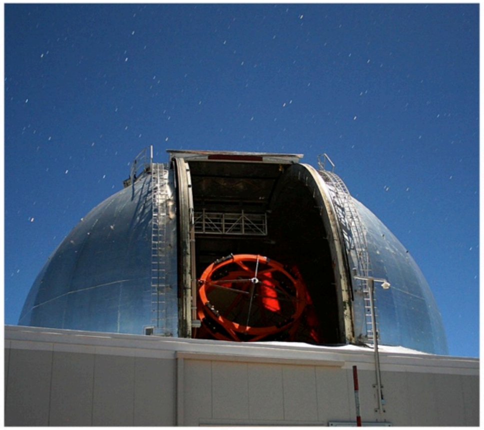
B. Observation Campaign

Paul Chodas, NASA NEO Program Office

With assistance from: Lindley Johnson (HQ), Robert Jedicke and Eva Schunova (U. of Hawaii), Bob Gershman, Mike Hicks, Steve Chesley, Don Yeomans (JPL)





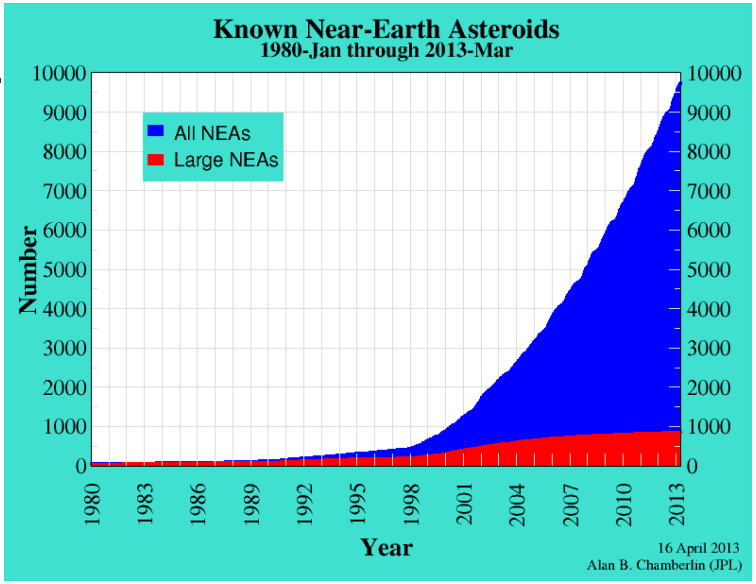
Executive Summary

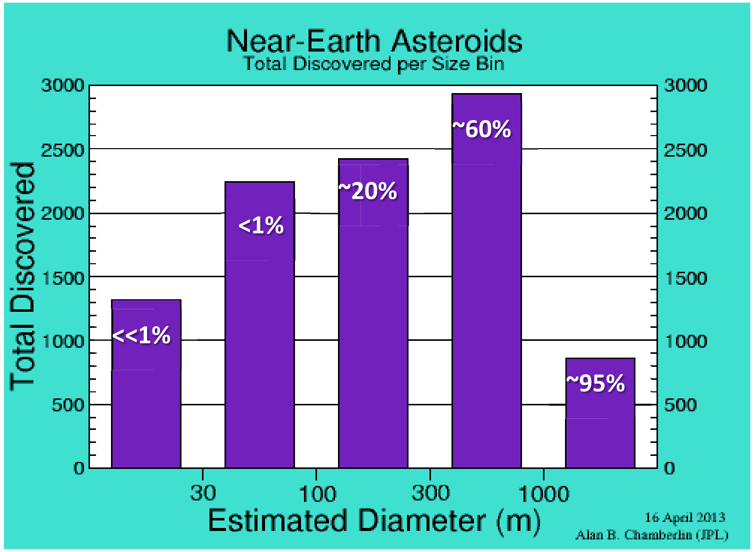
- Current population models suggest that there are a large number of good ARRM candidate targets. Current surveys are finding 2 to 3 per year. There are currently 4 known candidates that can be adequately characterized (2009 BD, 2011 MD, 2013 EC20, 2008 HU4).
- Discovery of good candidates is challenging, but the rate can be increased to at least 5 per year via near-term enhancements to current survey assets, as well as additional assets that can be online by 2015.
- Enhancing surveys to find more ARRM candidates also increases their capabilities for finding potentially hazardous asteroids in general.
- The discovery process alone is not sufficient to identify good candidates: physical characterization of the size, mass, and spin state is also needed. This can be accomplished using existing assets.
- Radar is a key characterization asset for ARRM candidates.
- Rapid response is critical for physical characterization of newly discovered ARRM candidates. The process has been successfully exercised for a small candidate asteroid.

Numbers of Near-Earth Asteroids (NEAs)

- 99% of Near-Earth Objects are asteroids (NEAs).
- Current number of known NEAs: ~10,000, discovered at a rate of ~1000 per year.
- Since 1998, NASA's NEO Observation Program has led the international NEO discovery and characterization effort; this responsibility should continue in the search for smaller asteroids.
- 95% of 1-km and larger NEAs have been found; the completion percentage drops for smaller asteroids because the population increases exponentially as size decreases.
- Numbers for 10-m-class NEAs:

Estimated population:	~100,000,000
Number currently known:	~380
Estimated number that meet ARRM orbital criteria:	~15,000
Number currently known:	14



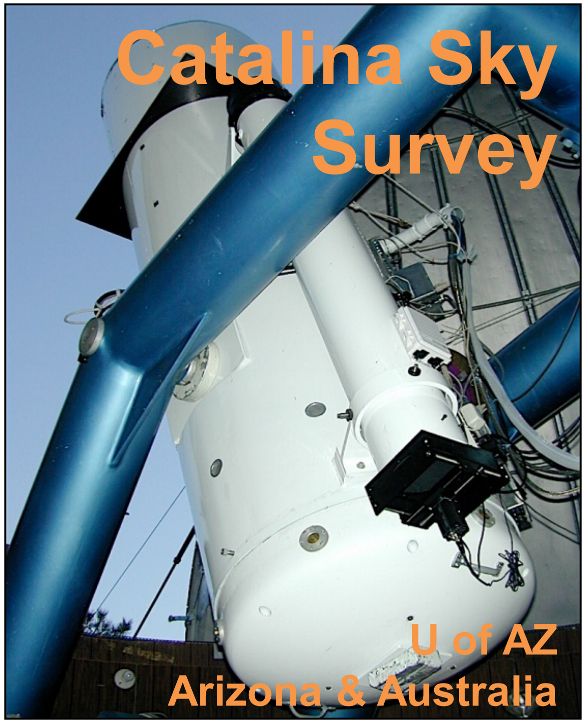


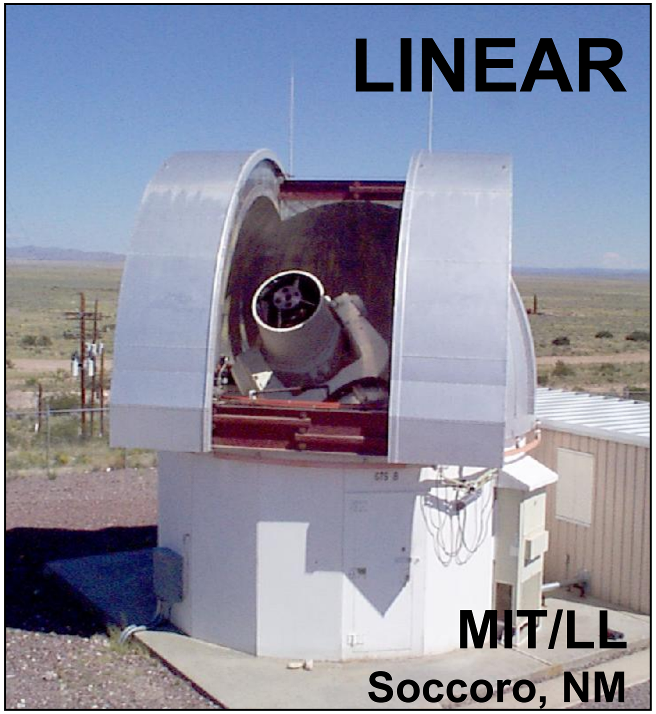
NEO Observations Program

- US component to International Spaceguard Survey effort has provided 98% of new detections of NEOs since 1998.
- Began with NASA commitment to House Committee on Science in May, 1998 to find at least 90% of 1-km NEOs.
  - Averaged ~$4M/year Research funding 2002-2010
- NASA Authorization Act of 2005 provided additional direction:

  "...plan, develop, and implement a Near-Earth Object Survey program to detect, track, catalogue, and characterize the physical characteristics of near-Earth objects equal to or greater than 140 meters in diameter in order to assess the threat of such near-Earth objects to the Earth. It shall be the goal of the Survey program to achieve 90 percent completion of its near-Earth object catalogue within 15 years [by 2020].
- Current Program Objective: Discover ≥ 90% of NEOs larger than 140 meters in size as soon as possible.
  - Starting with FY2012, now has $20.5M/year

NASA's NEO Search Programs: Current Systems



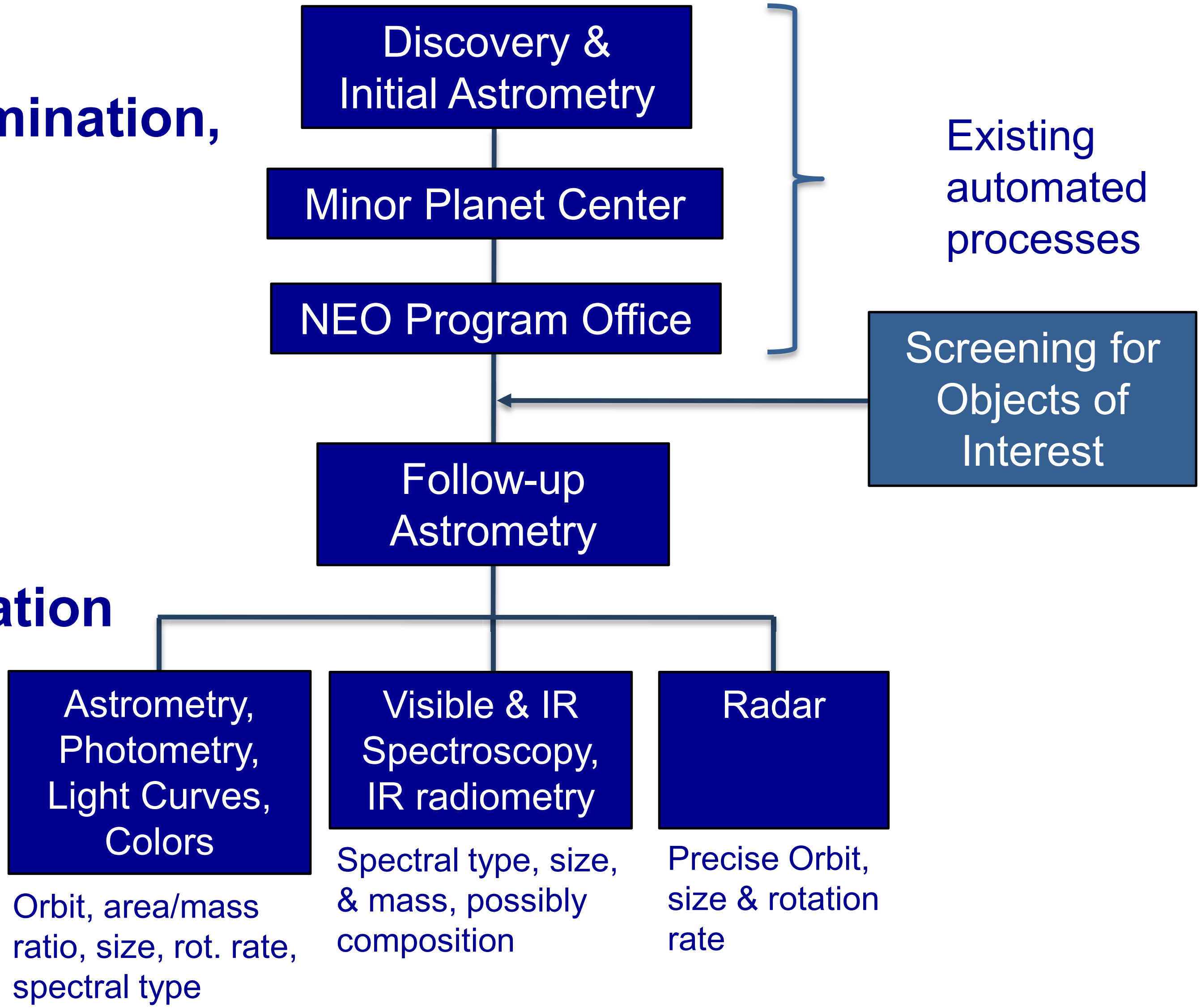


- Currently, most Near-Earth Asteroid discoveries are made by:
  Catalina Sky Survey (60%), Pan-STARRS-1 (30%), and LINEAR (3%).
- Enhancements and new surveys can come online in the next 2 years. Some will require additional funding.
- These enhancements will increase capabilities to find hazardous asteroids as well as ARRM candidate targets.

Discovery & Characterization Processes

Discovery, Orbit Determination, Rough Size Estimation

Physical Characterization



Characteristics of ARRM Target Candidates

$V_{infinity}$ is the velocity of the asteroid relative to the Earth during an encounter, with the acceleration due to the Earth's gravity removed.

	Characteristic	Reference Value
Orbital	Orbit: $V_{infinity}$ relative to Earth	< 2 km/s desired; upper bound ~2.6 km/s
Orbital	Orbit: Natural approach to Earth	Orbit-to-orbit distance < ~3 million miles Natural approach to Earth in early 2020s
Physical	Size and Aspect Ratio	Estimated mean size: 7 to 10 m Upper limit on maximum dimension: ~14 m Aspect ratio < 2:1
Physical	Mass	<1,000 metric tons (Upper bound decreases as $V_{infinity}$ increases)
Physical	Spin Rate	< 2 rpm
Physical	Spectral Class	Known Type preferred, but not required (C-type with hydrated minerals desired)

Current List of Potential ARRM Candidates

	Name	Estimated Size (m)	V_∞ (km/s)	Earth Approach Date	Maximum Returnable Mass (t)†
	Good retrieval trajectories found				
	2007 UN12	3 - 14	1.2	9/15/2020	490
	2008 EA9	5 - 22	1.9	11/15/2020	130
	2013 EC20	2 - 4	2.6	3/15/2021	120
	2010 UE51	4 - 17	1.2	10/15/2022	130
Current ARRM baseline	2009 BD	4 - 8	0.7	6/26/2023	590
	2011 MD	5 - 18	0.9	8/10/2024	690
KISS baseline	2008 HU4	4 - 18	0.5	3/27/2026	1600
	Good retrieval trajectories may be possible				
	2010 XU10	6 - 25	2.5	10/22/2021	TBD
	2012 WR10	4 - 15	2.6	12/6/2021	TBD
	2011 BQ50	4 - 17	2.6	11/4/2022	TBD
	2011 PN1	6 - 24	n/a	6/30/2023	TBD
	2005 QP87	5 - 22	1.5	3/1/2024	TBD
	2010 AN61	7 - 30	2.6	6/10/2025	TBD
	2013 GH66	5 - 18	2.0	4/15/2025	TBD

*1 AU = 93,000,000 miles; †Assumes Falcon Heavy launch vehicle and launch dates no earlier than 2017.

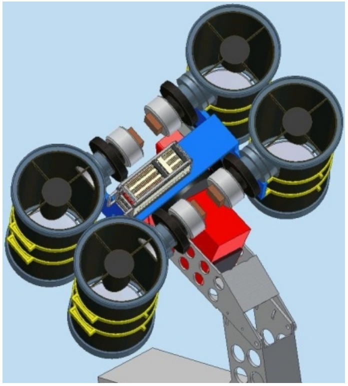
- 14 known asteroids meet the rough size and orbit criteria for ARRM.
- But, most were not physically characterized after discovery.
- These potential candidates are being discovered at a rate of **2-3 per year**.
- **There is no reason to expect this discovery rate to decrease.**
- 4 candidates on this list can be at least partially characterized:
  2009 BD, 2011 MD, 2013 EC20 and 2008 HU4.

Primary Enhancements for ARRM Candidate Discovery

- **NEO Time on DARPA Space Surveillance Telescope**
  - Large 3.6m telescope, first light: Feb 2011, now in testing.
  - Eventual operations by AFSPC for DoD Space Situational Awareness.
  - Testing of NEO detection capability: Sep 2013.

- **Enhancing Pan-STARRS 1, Completing Pan-STARRS 2**
  - Increase NEO search time to 100% on PS1: Early 2014.
  - Complete PS2 (improved copy of PS1): Late 2014.
  - Simulations suggest the ARRM candidate discovery rate for PS2 alone at 100% will be ~5 per year.

- **Accelerated Completion of ATLAS**
  - Set of small telescopes with extremely wide fields of view covering the entire night sky every night, but not as deeply.
  - Final design selection soon. Completion: Early 2015.
  - Simulations suggest the ARRM candidate discovery rate for ATLAS will be ~10 per year.



Summary on Future Discovery Rate of ARRM Candidates

- The ARRM candidate discovery rate will almost certainly **increase** due to enhancements to existing surveys and new surveys coming online.
- Several asteroid survey enhancements are already in process and funded by the NEOO Program. Some could be accelerated with additional funding.
- A conservative projection, based on study of enhancements, is that the discovery rate will increase to **at least 5 per year**.
- Search for ARRM candidates will continue until final selection.
- With at least another 3-4 years to accumulate discoveries, at least **15 more candidates are expected**.
- With rapid post-discovery characterization capabilities in place, there will be better opportunities to physically characterize future ARRM discoveries.
- Enhancing surveys to find more ARRM candidates also increases their capabilities for finding potentially hazardous asteroids in general.

Physical Characterization of ARRM Candidates

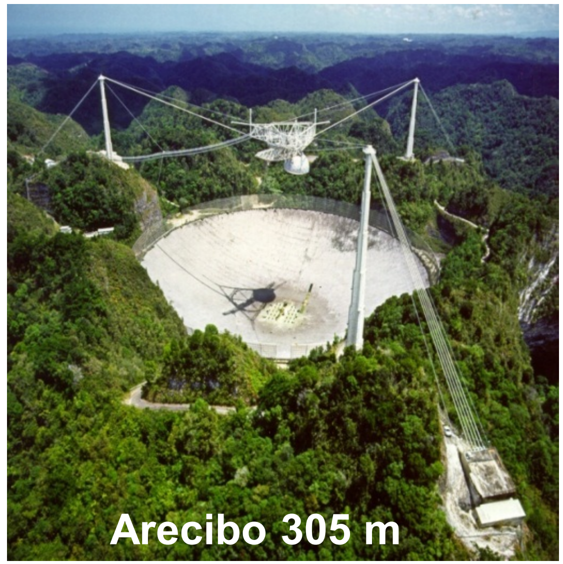
- **Radar** is essential for obtaining an accurate estimate of size and shape to within ~2 m, as well as rotation state.
- Ground-based and space-based **IR** measurements are important for estimating albedo and spectral class, and from these an approximate density can be inferred.
- **Light curves** are important to estimate shape and rotation state.
- **Long-arc high-precision astrometry** is important for determining the area-to-mass ratio.
- Mass is estimated from size and shape using an inferred or assumed density, and it should be constrained by the estimate of the area-to-mass ratio. Even so, mass may only be known to within a factor of 3 or 4.
- Final ARRM target selection may depend largely on how the estimated upper bound on the mass of each candidate compares with the return mass capability for that candidate.

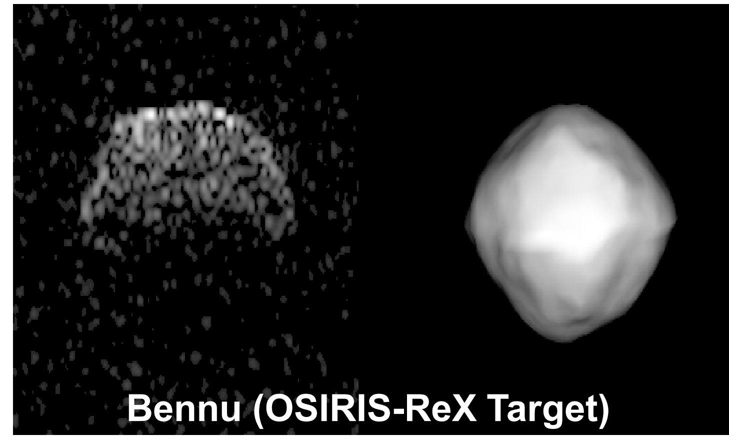
Assumed albedo ρ = 0.04

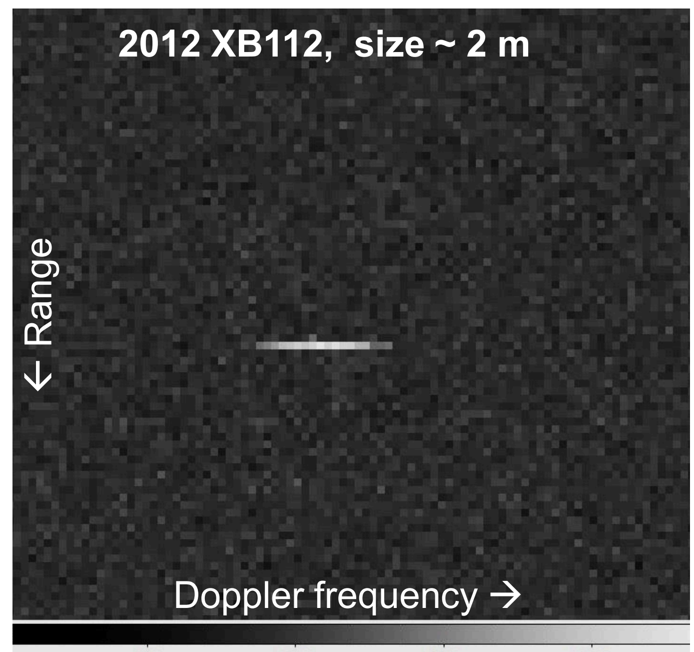
Assumed albedo ρ = 0.34

Radar Observations of NEOs


Goldstone 70 m


Arecibo 305 m


Bennu (OSIRIS-ReX Target)



2012 XB112, size ~ 2 m

- These are complementary capabilities.
- Currently, 70-80 NEOs are observed with radar every year.
- A 10-m-class ARRM candidate must pass within ~5 lunar distances to be detected; ~80% of the 14 known candidates could have been detected.
- Radar observations can provide:
  - Size and shape to within ~2 meters.
  - High precision range/Doppler orbit data.
  - Spin rate, surface density and roughness.

Infrared Characterization of NEOs

NASA InfraRed Telescope Facility (IRTF)

- Dedicated Planetary Science Observatory
- Characterization of Comets and Asteroids
- Spectroscopy and Thermal Signatures
- On-call for Rapid Response on Discoveries

Spitzer Infrared Space Telescope

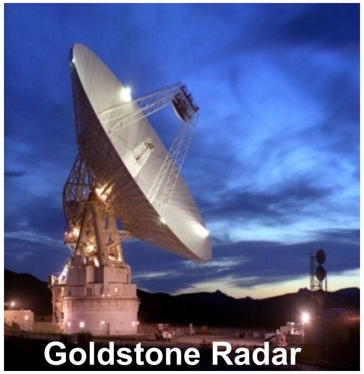
- Orbit about Sun, ~176 million km from Earth
- In extended Warm-phase mission
- Characterization of Comets and Asteroids
- Thermal Signatures, Albedo/Sizes of NEOs
- Longer time needed for scheduling

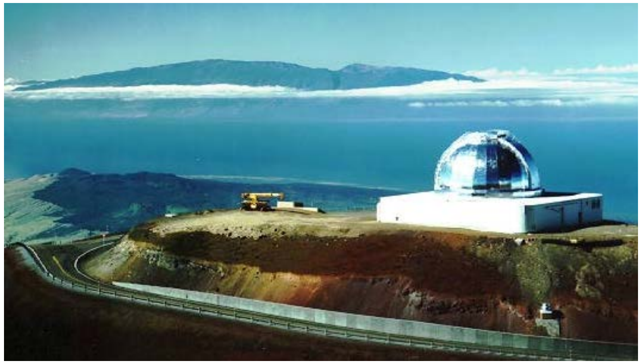
ARM Candidate Characterization Process

- **Rapid response** after discovery is essential while the asteroid is within range of characterization assets, since the asteroid will not likely be any closer for many years.
- Need rapid response for **radar** observation at Goldstone and/or Arecibo. The Goldstone interrupt response process especially needs to be streamlined.
- **Follow-up astrometry** from the observing community is essential for characterization.
- Request interrupt observations from **IRTF** and other large-aperture assets that can provide thermal IR data for faint objects. (This may require additional interagency agreements for target-of-opportunity observing time.)
- Obtain high precision astrometry, photometry and light curve measurements from geographically dispersed observatories (e.g. Palomar, Keck, European Southern Observatory in Chile).
- Solicit support from smaller telescopes, including amateurs, to provide quick follow-up astrometry and photometry.

NEO Characterization Enhancements

Radar (Goldstone and Arecibo)
- Increase time for NEO observations.
- Streamline Rapid Response capabilities.





NASA InfraRed Telescope Facility (IRTF)
- Increase On-call for Rapid Response.
- Improve Instrumentation for Spectroscopy and Thermal Signatures.

Reactivate NEOWISE
- ~3 year warm phase dedicated to NEO Search/Characterization data collection.

Observation Campaign Summary

- Simulations suggest there are thousands of suitable ARRM candidate targets; the challenge is to find them.
- Candidates are currently being discovered at the rate of 2-3 per year.
- With several survey enhancements in process, and new surveys coming online within the next 2 years, the ARRM candidate discovery rate should increase to at least 5 per year.
- Discovery enhancements will add capability to find hazardous asteroids as well as ARRM candidate targets.
- Rapid response after discovery is critical for physical characterization of ARRM candidates. The process has already been successfully exercised for a difficult-to-characterize candidate.
- Goldstone and Arecibo radars are key characterization assets for ARRM candidates because they provide accurate estimates of size and rotation state.
- Other major assets for characterization are available. Interagency agreements for target-of-opportunity observing time from important non-NASA facilities (eg. Subaru) can be negotiated.

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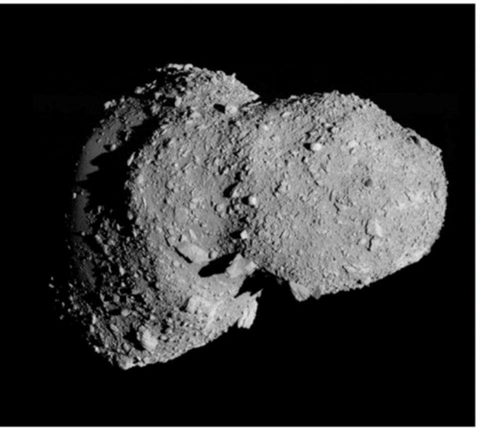
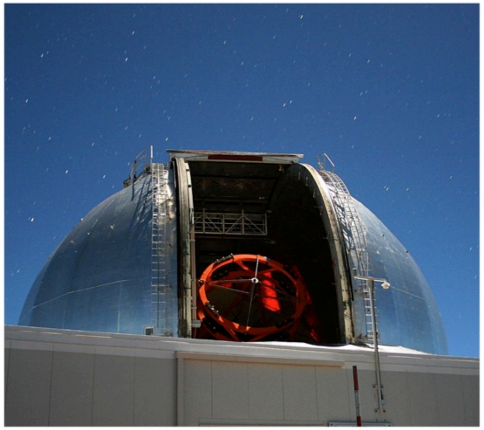
C. Mission Design

Mission Design Executive Summary

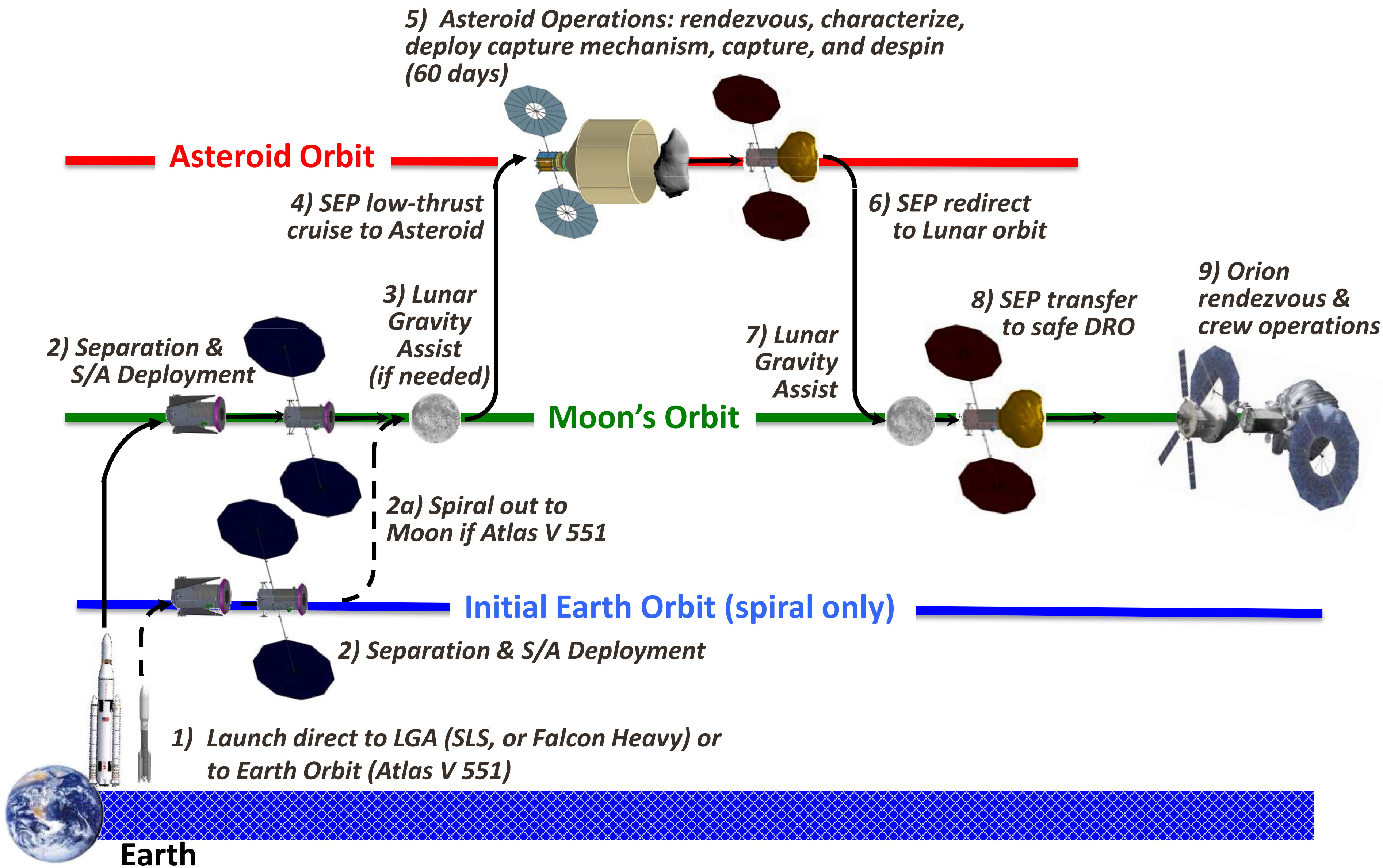
- The ARRV concept mission design trade space consists of the following areas
  - Target asteroid: mass, trajectory, natural return date and velocity
  - Launch date
  - Propellant mass (Xe)
  - Specific impulse (Isp) of the electric propulsion system
  - Power to the electric propulsion system
  - Launch 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 could be returned without increasing the natural risk of Earth impact and would 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

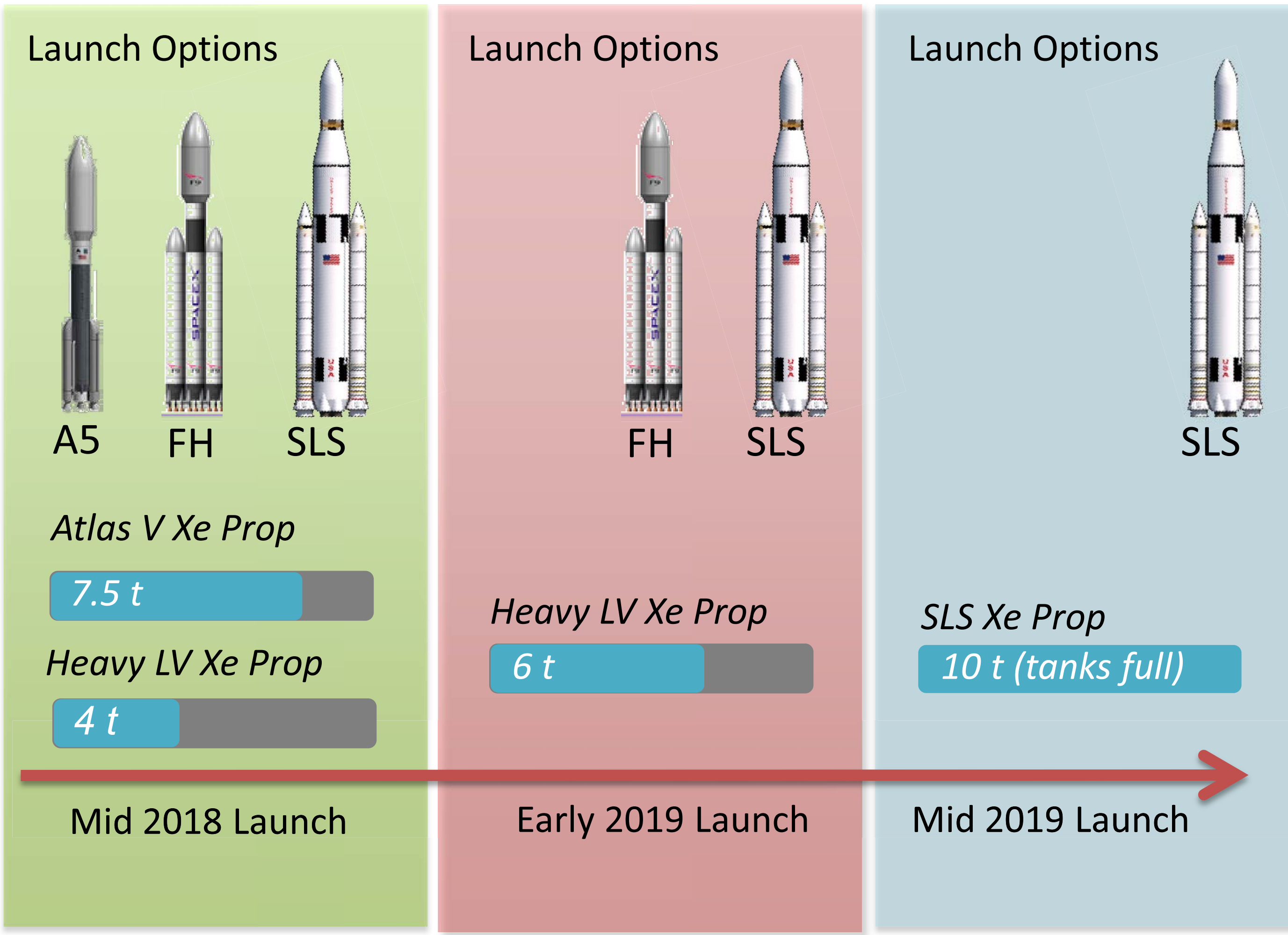
Asteroid	Asteroid Mass Est.	Asteroid V-infinity	Natural Return Date	Crew Accessible Date	Notes	Valid Candidate Target?
2013 EC20	4-50 t max return: 120 t	2.6 km/s	Mar 2020	Mar 2021	Discovered March 2013, can be observed again in Aug. 2013 rotation period ~ 2 min	**Yes, but needs Jan 2018 Launch**
2009 BD	30-325 t max return: 590 t	1.2 km/s	Jun 2023	May 2024	Area/Mass ratio estimated, rotation period > 2 hrs, 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 period 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**

Concept Mission Overview



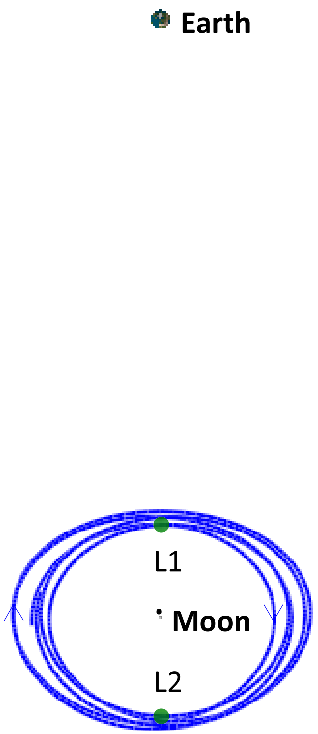
Design Resilience to Launch Date for 2009 BD

2009 BD Mission Options (assuming 325 t asteroid)

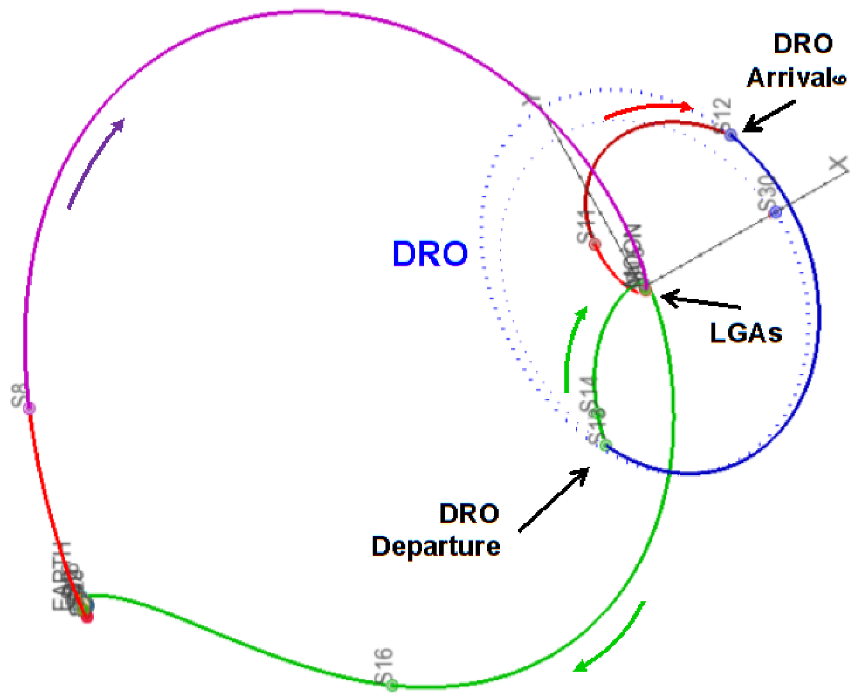


Lunar Asteroid Safe Storage Orbit (LASSO)

- 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

Lunar DRO in Earth-Moon Rotating Frame

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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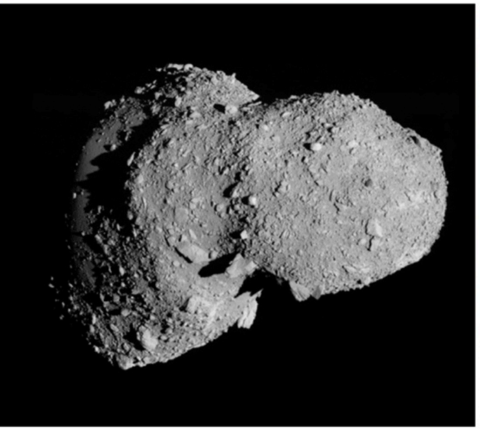
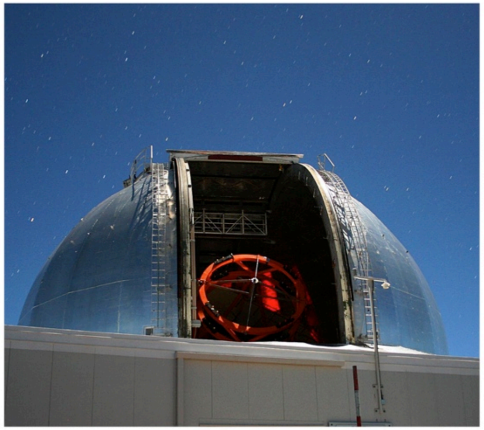
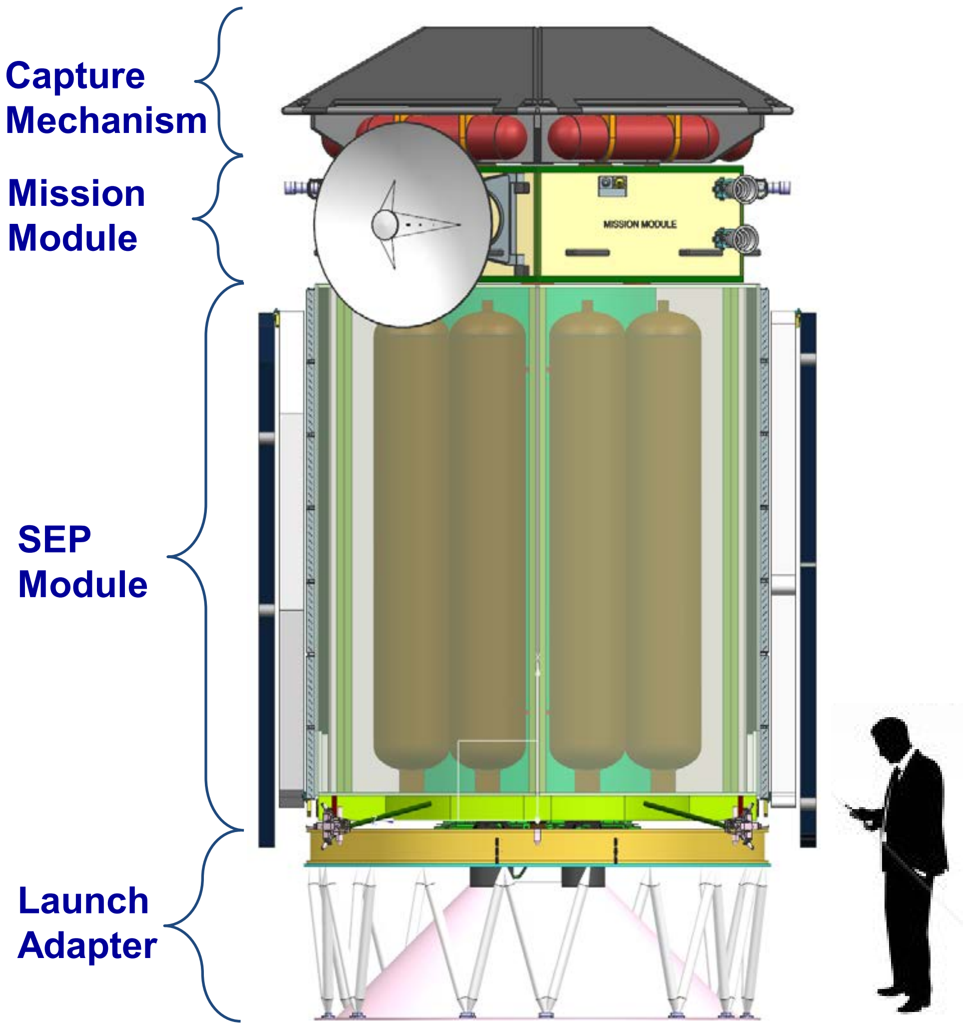
D. Mission and Flight System Baseline





Mission and Flight System Executive Summary

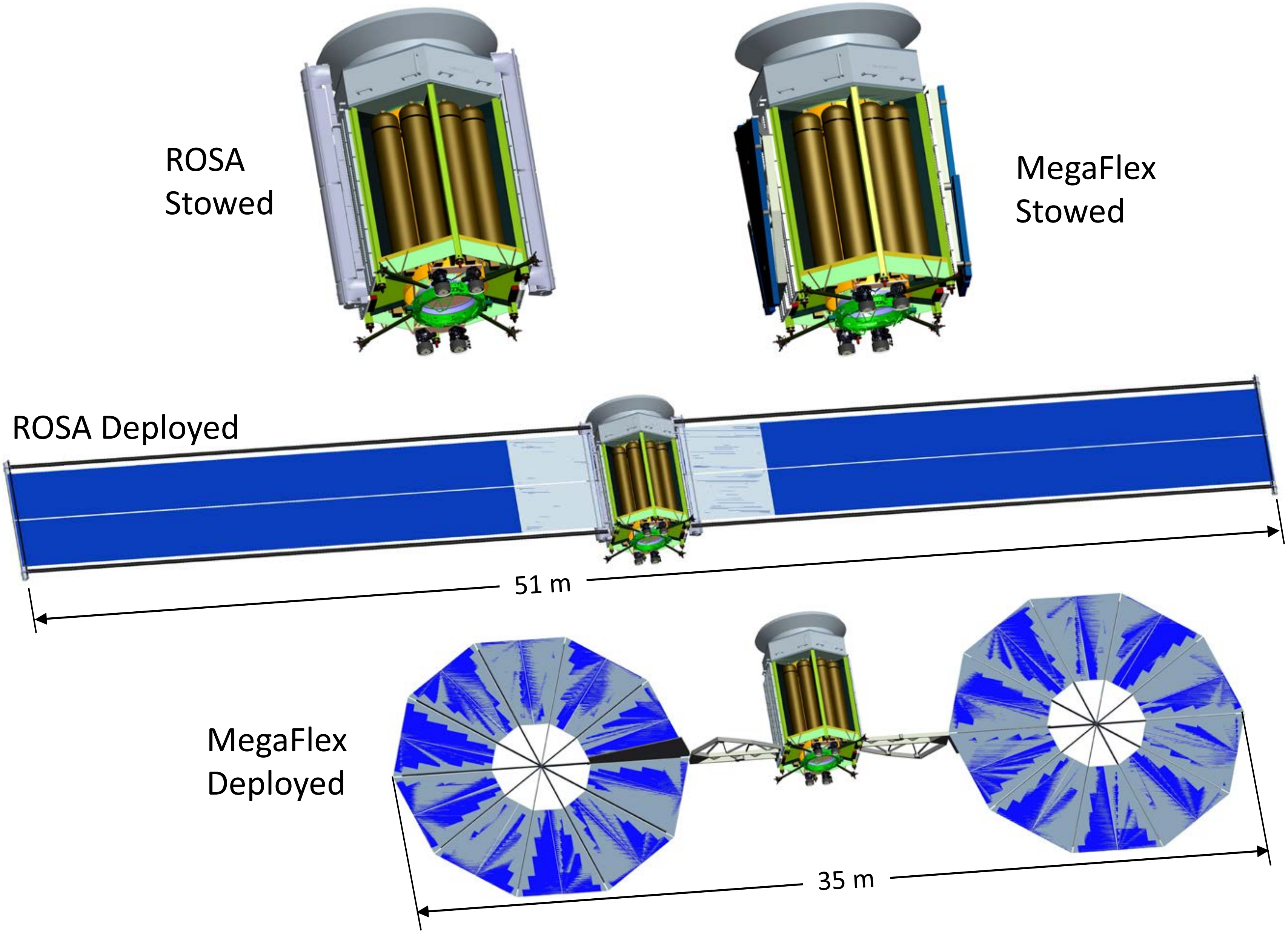
- Key Driving Objective:
  - Minimize the cost and technology development risk for an asteroid redirect mission with extensibility to future missions
- Balanced risk across major elements
  - Asteroid discovery and characterization
  - Transportation technology development
  - Proximity operations time
  - 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	EP system power: 40 kW; 50-kW BOL solar array EP specific impulse: ~3000 s Accommodate up to 10,000 kg of xenon Proximity operations schedule Capture Mechanism sizing
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	
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



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

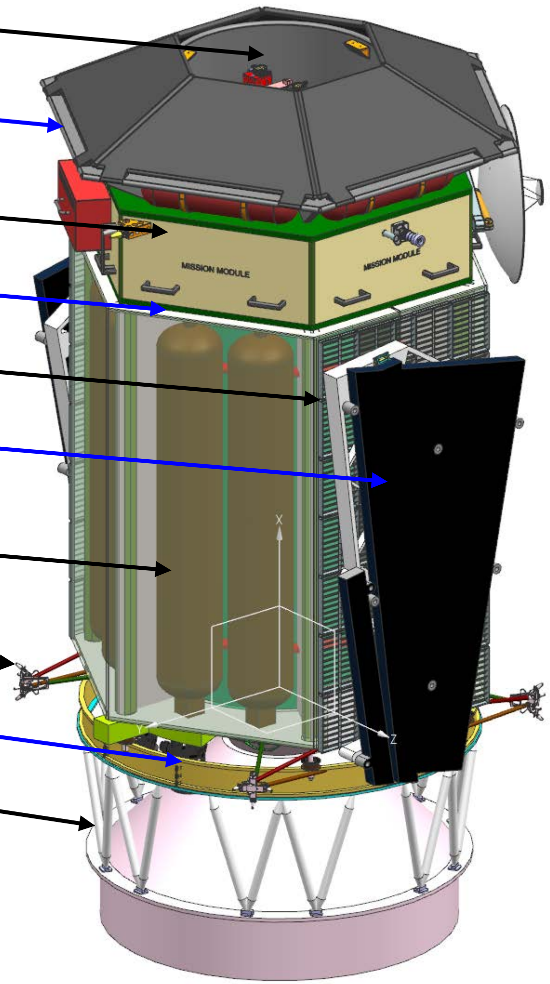
Compatible with either STMD solar array at 50 kW BOL

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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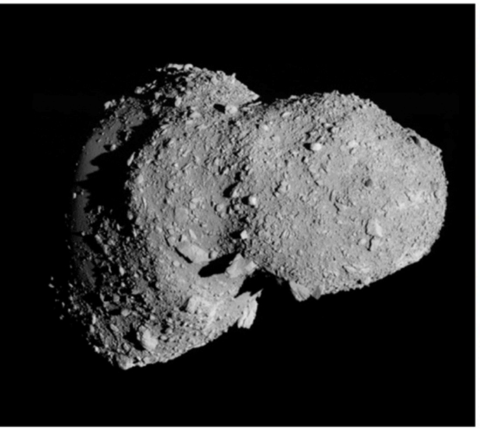
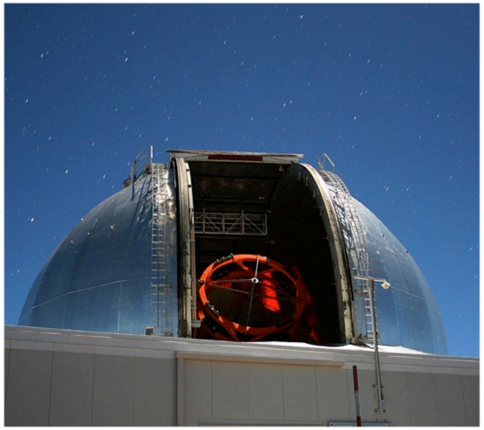
E. Solar Electric Propulsion (SEP) Module

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 mission scenarios close using <3000 s Isp
  - ARRM thruster is directly extensible to commercial and other NASA missions

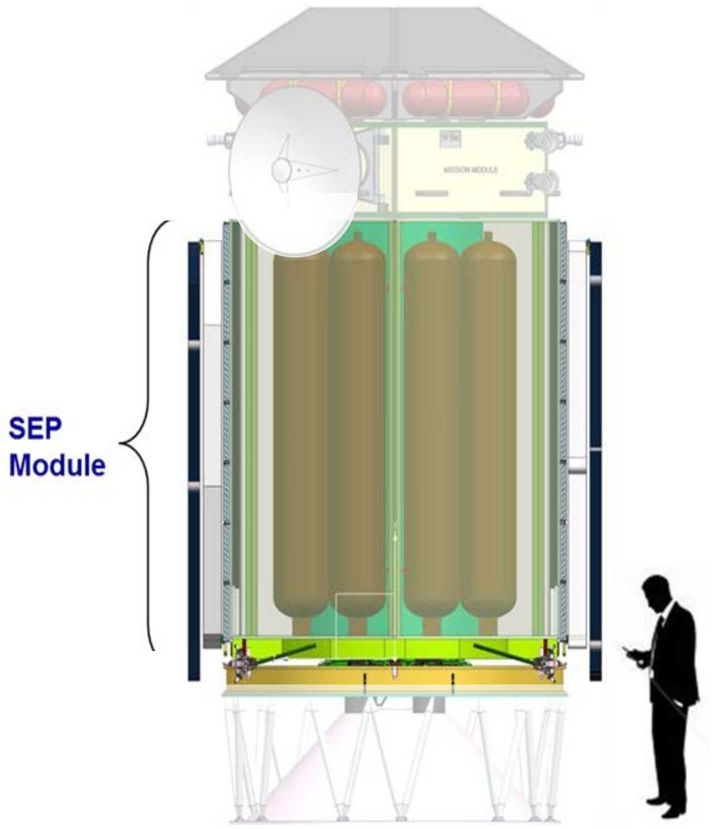
SEP Module Overview

Module-level Design Drivers and Constraints

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

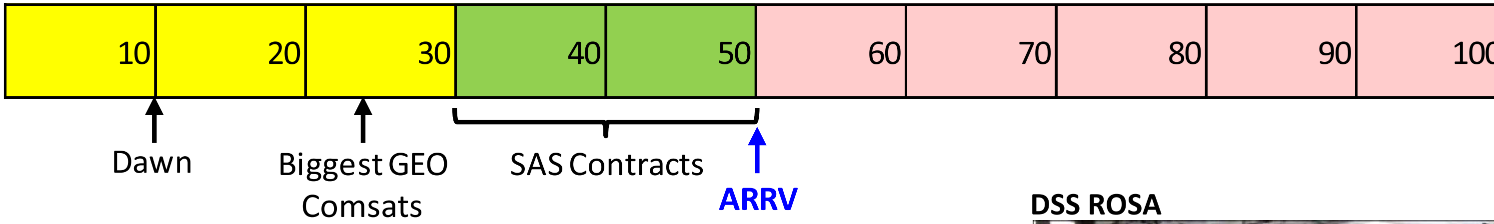
Module Subsystems

- 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



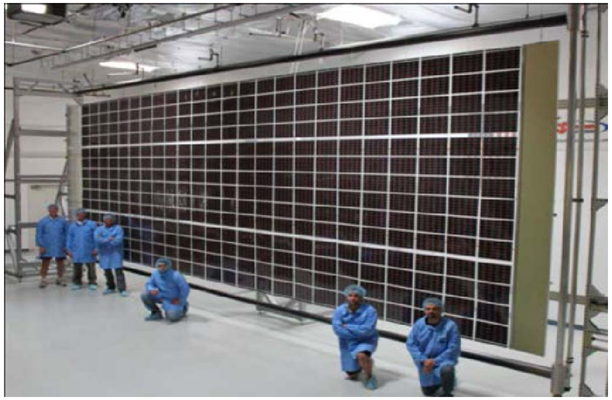
Power Subsystem

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
  - MegaFlex or ROSA 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

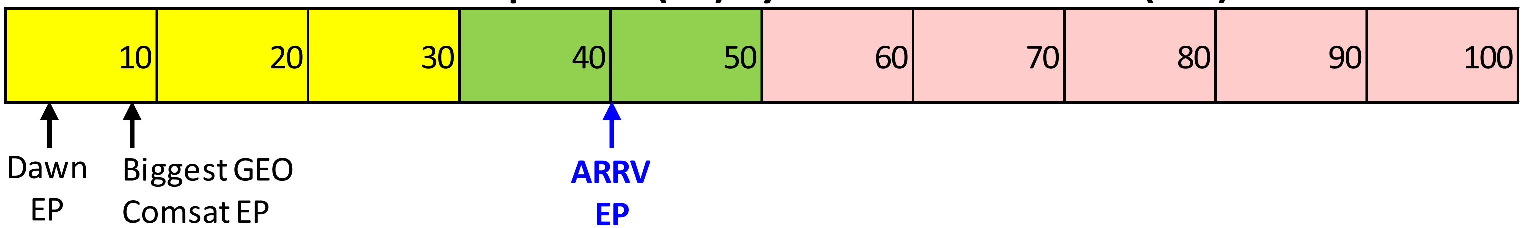
DSS ROSA



ATK MegaFlex “Gorelet”

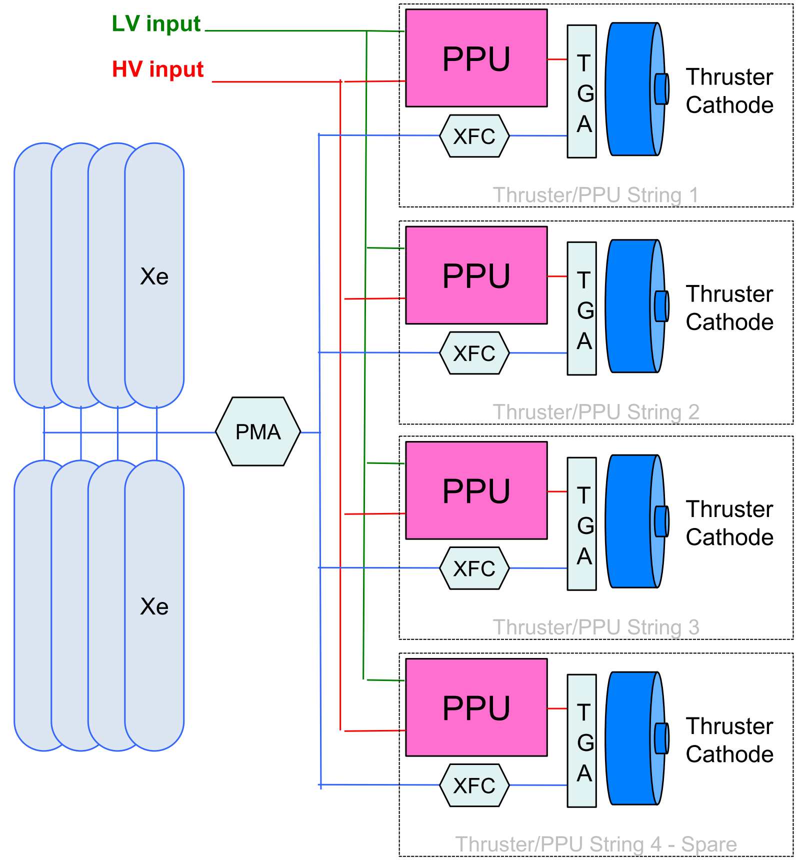
Ion Propulsion Subsystem: Overview

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

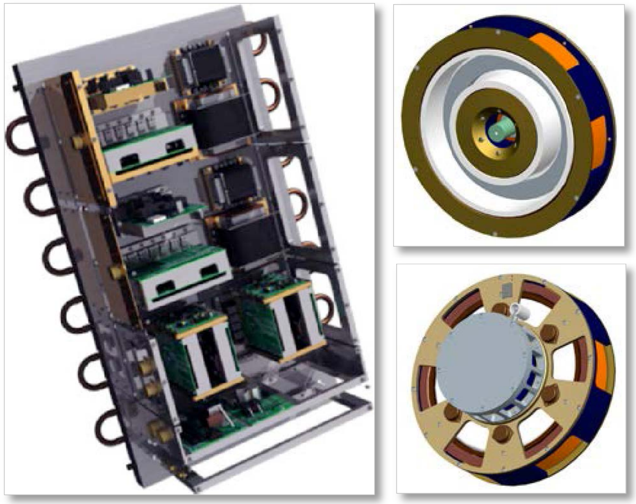
- Basic design characteristics
  - Three 13.3 kW thruster/PPU strings + 1 spare
  - Leverages high-Isp, long-life Hall investments



Ion Propulsion Subsystem: Uses STMD Developments

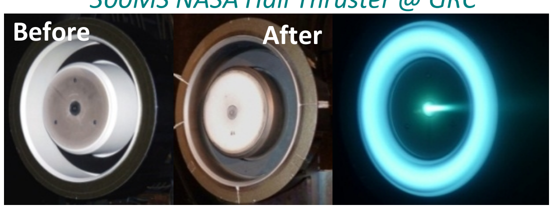
STMD enabled ARM by addressing PPU & Hall thruster technology risks

Hall Thruster & PPU development currently underway

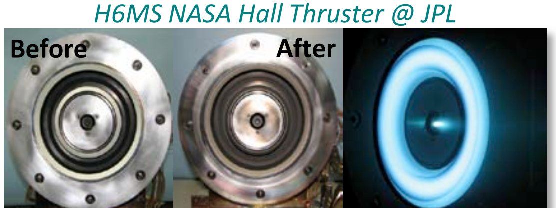


Erosion testing addressed propellant throughput risk

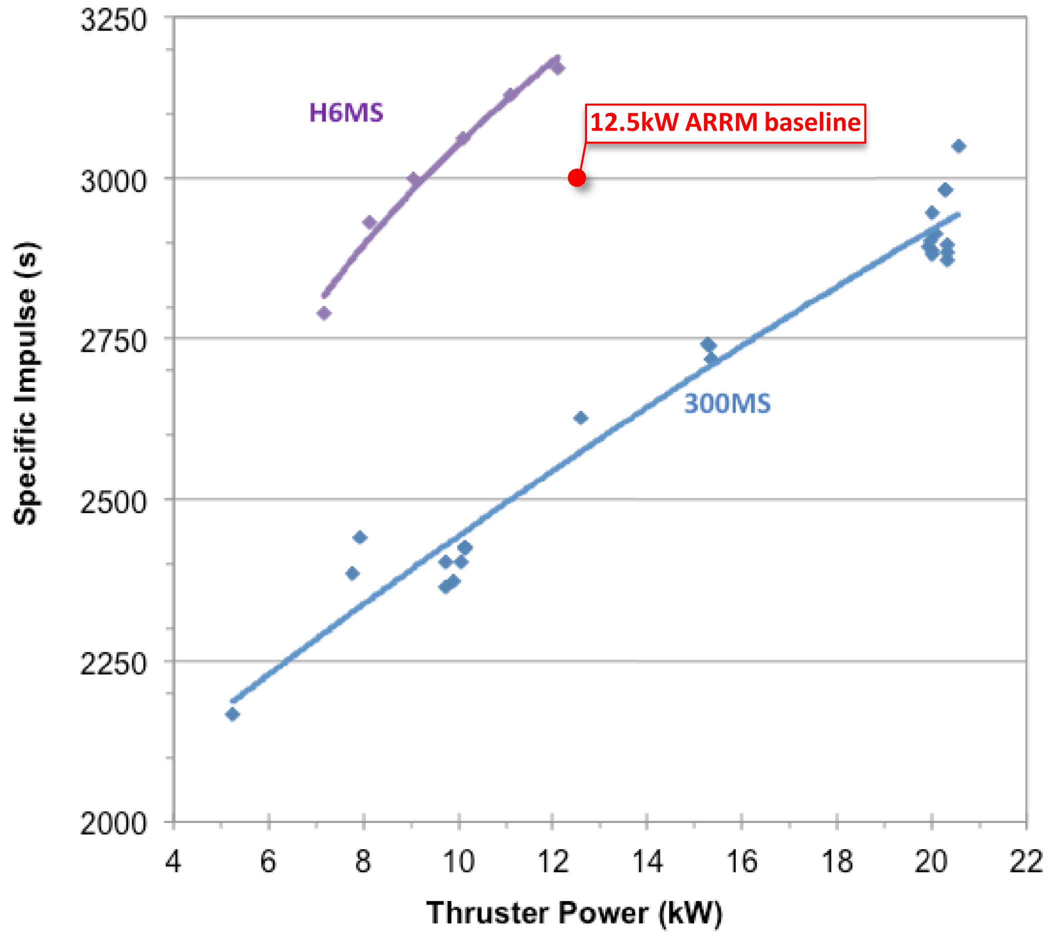
300MS NASA Hall Thruster @ GRC



H6MS NASA Hall Thruster @ JPL



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



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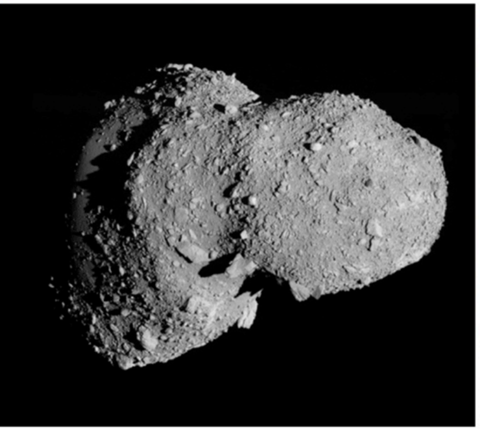
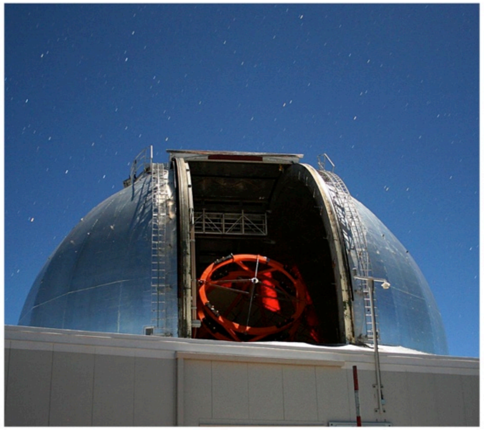
F. Rendezvous and Proximity Operations

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

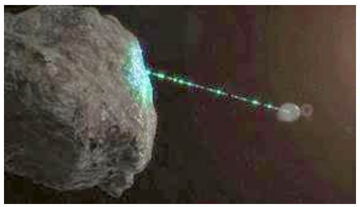
- Sensor suite that accommodates all phases of the process has been defined

- 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
  - GSFC Satellite Servicing Capabilities Office (SSCO) is joining the ARRM team to apply their 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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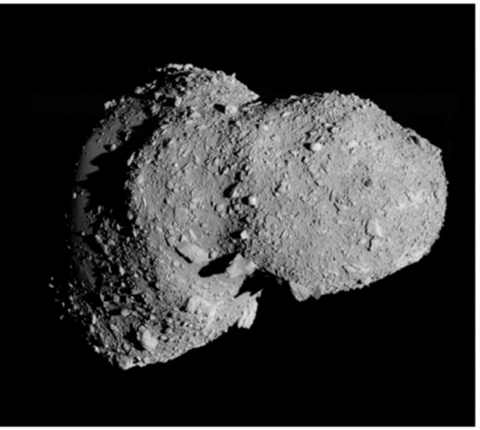
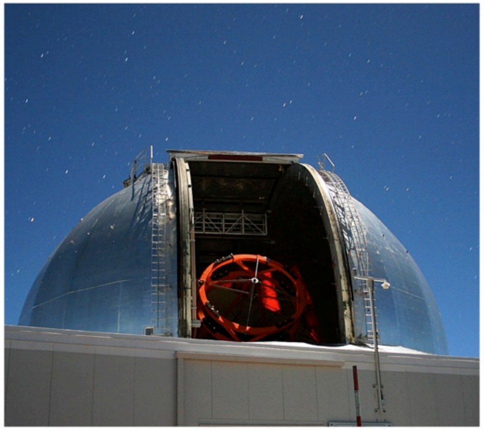
G. Capture Mechanism and Capture Process

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

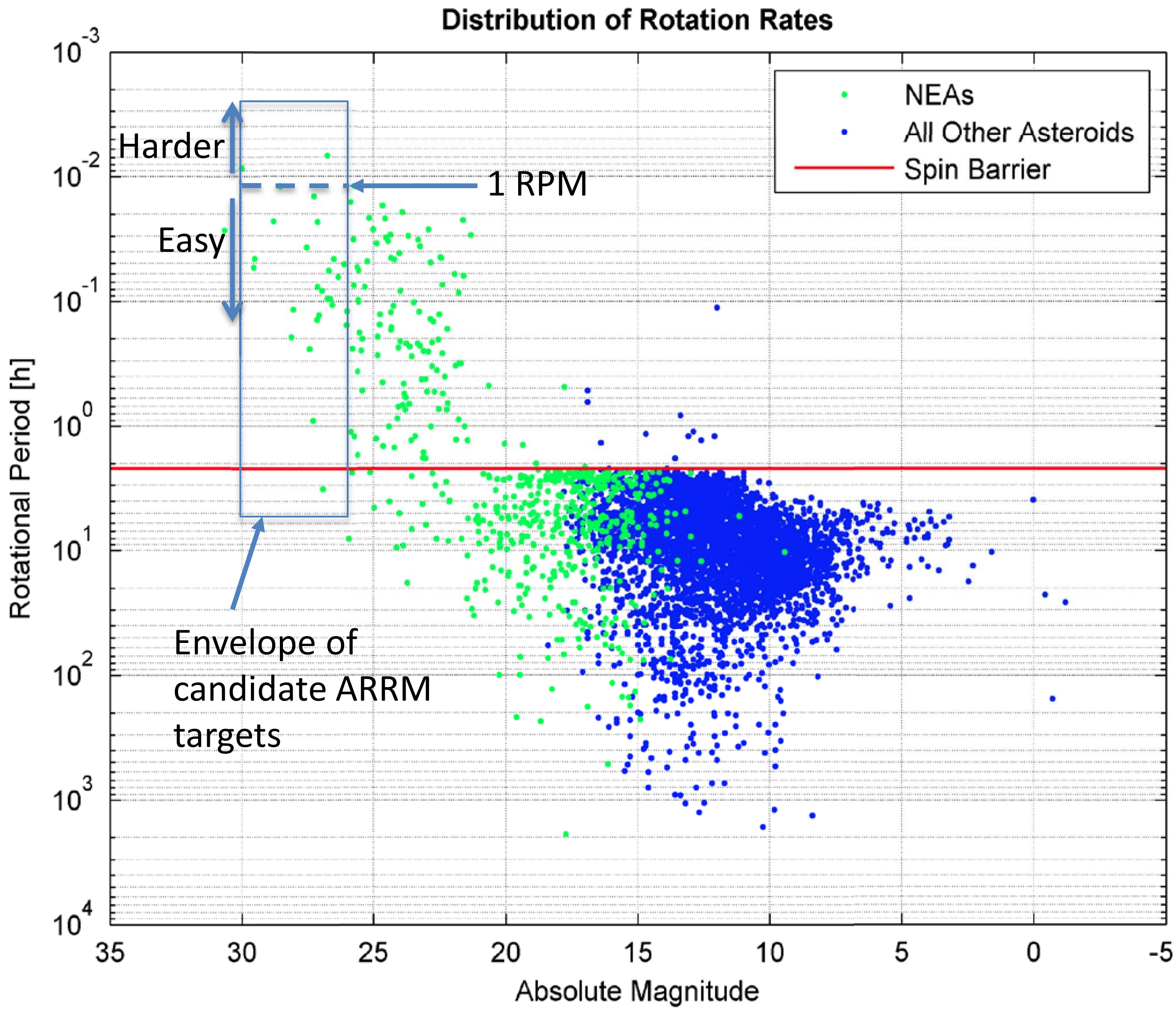
Spin State

- Slow (<<1RPM), 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

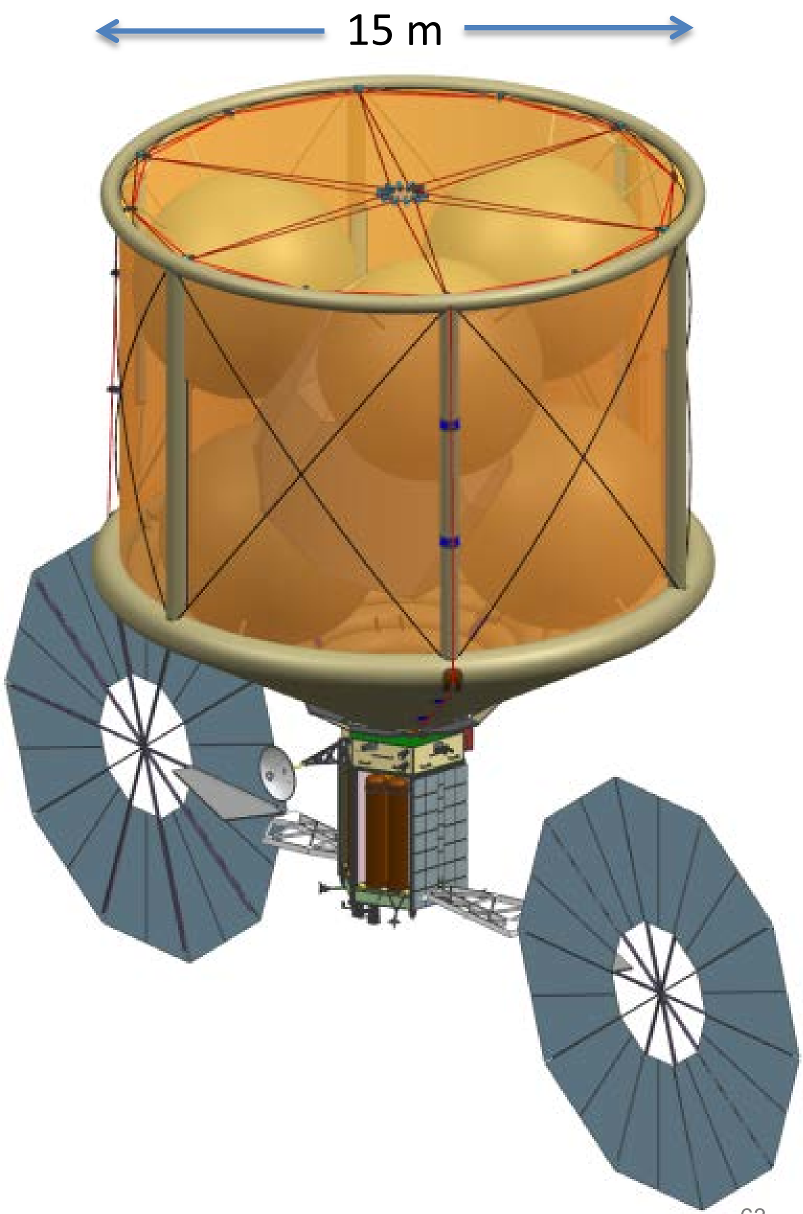
Spin Periods of Near-Earth Asteroids

- 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

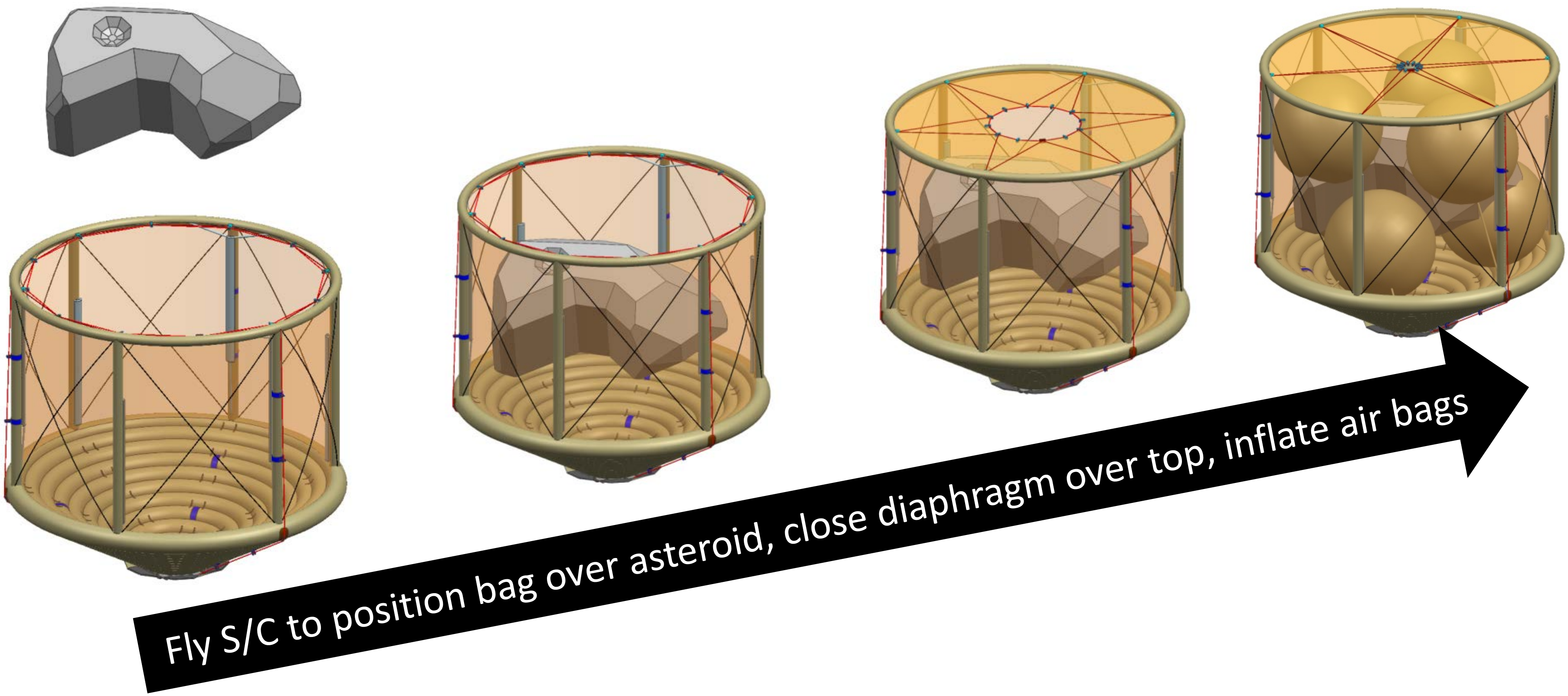


Capture Mechanism Concept

- 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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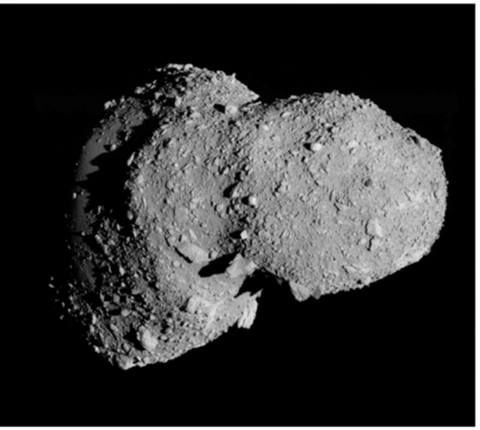
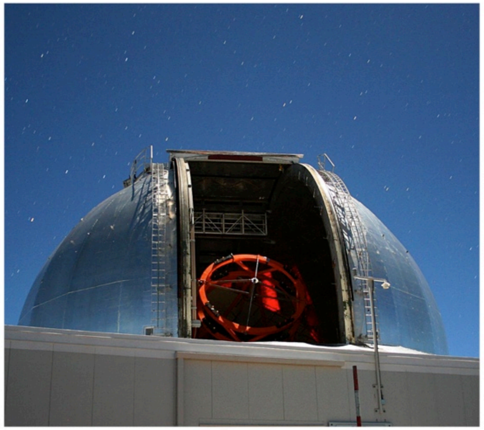
H. ARRM Reference Implementation, Schedule, and Cost

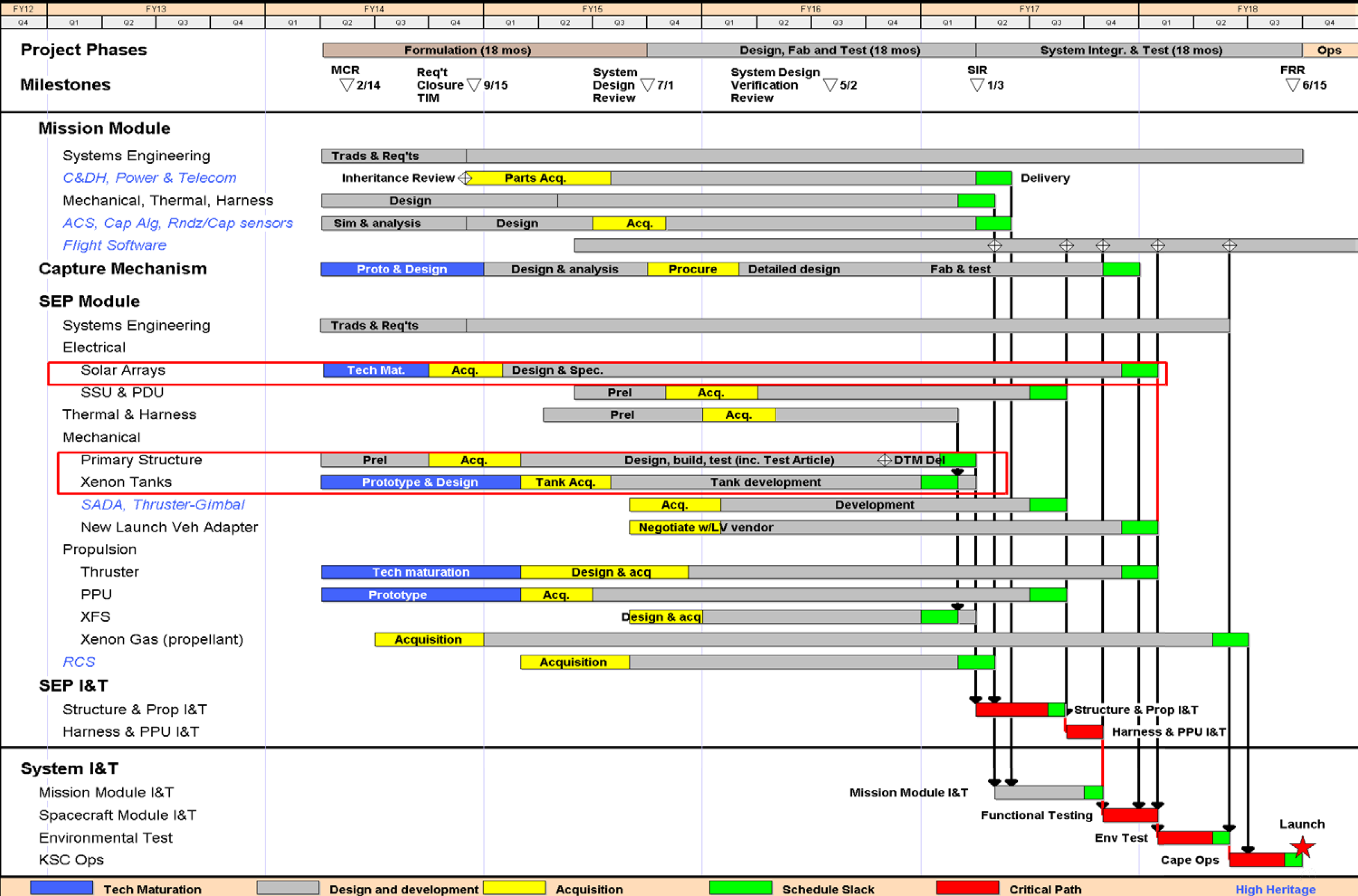
Implementation Executive Summary

- 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 per President's budget request
  - 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

Reference Mission Development Schedule
June '18 Launch



Key Assumptions

- This CBE is based on the following assumptions:
  - Lean, innovative, technology demonstration mission approach
  - Single HQ program POC providing direction and funding
  - To meet reference project schedule need requested NOA funding profile
  - No termination liability (as directed by Steering Committee)
  - Mission module designed within the capability of the JPL heritage (MSL, SMAP) build-to-print Reference Bus
  - Observation Campaign costs not included (at Steering Comm. direction), SE workforce to interface to Observation Campaign included
  - Cost for the crewed mission interface and HW integration included, based on current understanding of the scope
    - All crew I/F HW assumed to be GFE
    - Cost for the crew interface integration included
  - It is recommended that HQ carries additional UFE to cover uncertainties beyond this CBE

NOA CBE Cost Estimate

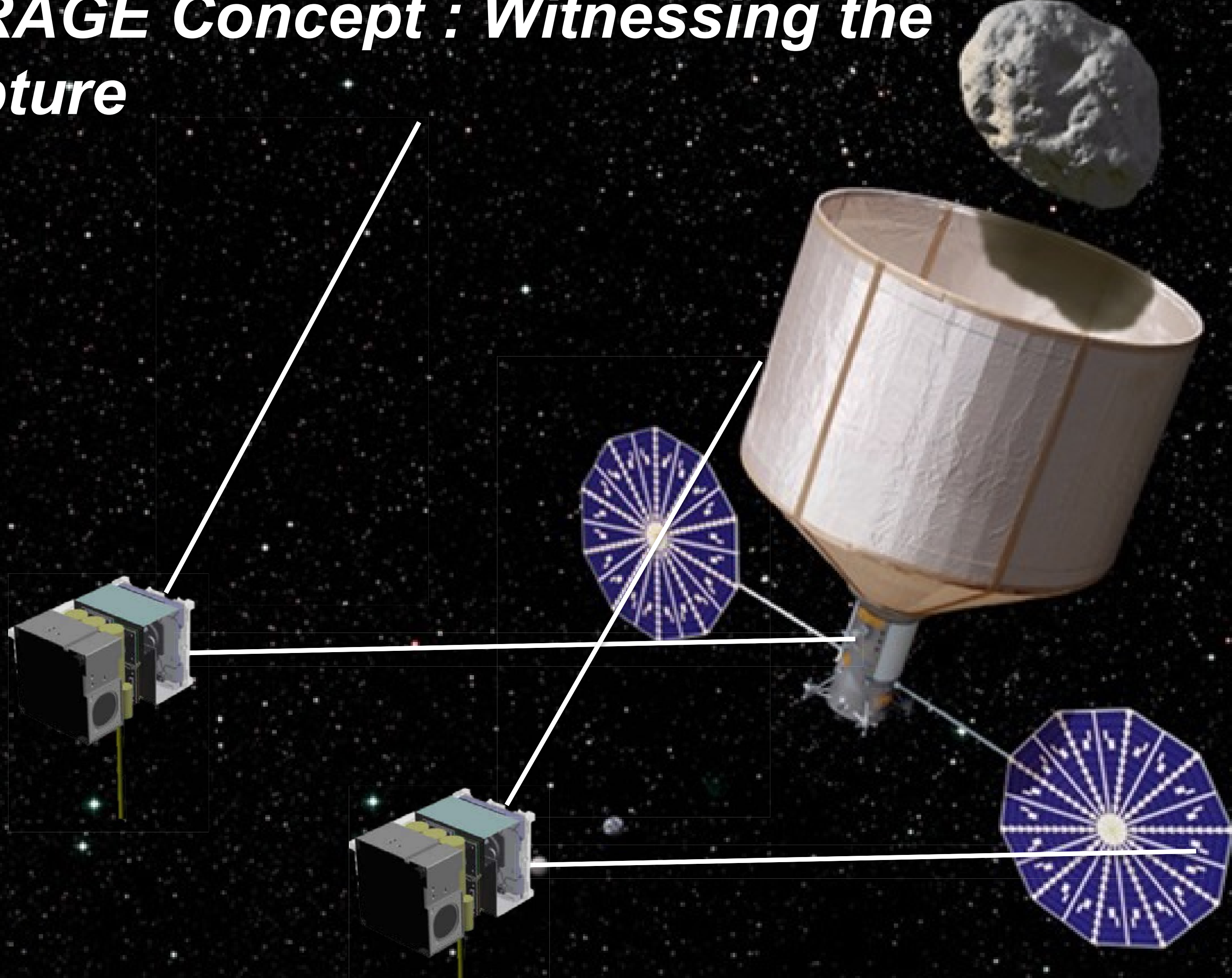
- **June, 2018 launch NOA CBE: $990M (RY$)**
  (rounded to nearest $5M)
  - **Does not include the launch services or mission operations costs**

- **December, 2018 launch NOA CBE: $1070M (RY$)**
  (rounded to nearest $5M)
  - **Does not include the launch services or mission operations costs**

Potential Technical Cost/Scope Changes

- Potential Partnerships and/or Cost/Scope Reductions
  - Potential partnership, co-development and contribution opportunities include:
    - Cubesats for secondary observations/experiments
    - Capture/characterization sensors
    - Capture mechanism elements
    - GNC sensors: star trackers, gyros, etc.
    - RCS system
    - Launch vehicle adapter
    - Co-manifests
  - Parallel build with Mars 2020, potential significant savings in fabrication, testing and analysis of electronics
  - Flight hardware spares from other missions
  - Negotiate an optimum procurement approach for Xe gas
- Potential Cost/Scope Increases
  - Mission that launches on Atlas 551 that requires a spiral-out design (upper in solar array, mission design and operations)

MIRAGE Concept : Witnessing the capture



Demonstrate CubeSat technologies for deep space imaging from a unique vantage point

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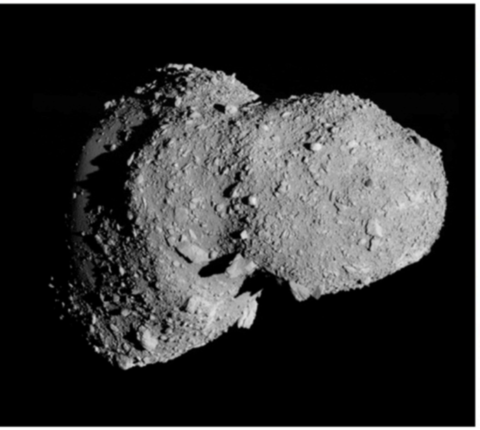
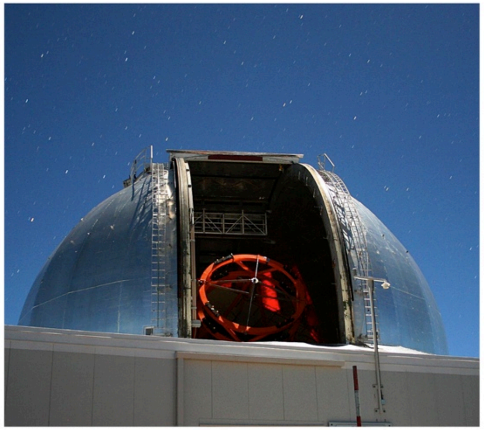
I. Conclusions

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 could 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 would meet functional objectives
- An inflatable capture system concept has been developed that would be viable, testable and could 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 would 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 would support near-term human exploration missions beyond low-Earth orbit, enable new robotic planetary science missions, and would be 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 would 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 its potential threats to Earth.