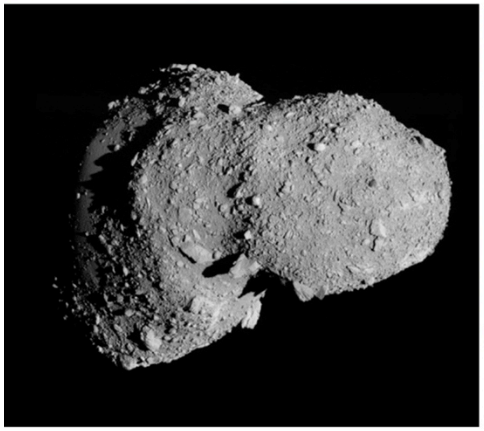
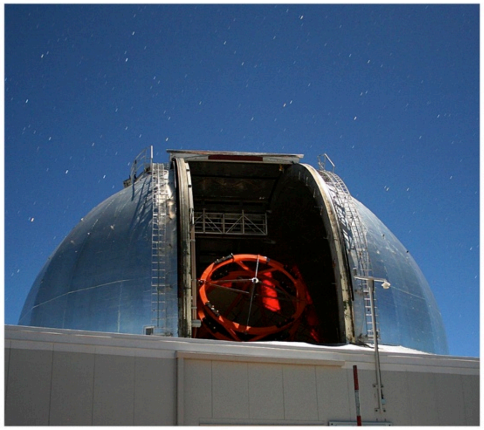
National Aeronautics and Space Administration

ARRM Reference Mission Status Briefing 12/17/13

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

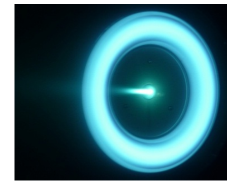



Agenda

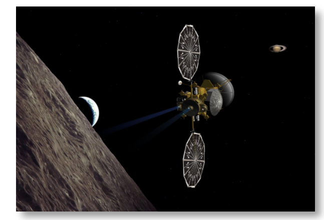
- Background: Objectives, Constraints, Highlights
- Mission Design and Launch Vehicle Options
- Flight System Baseline and SEP Module Technology
- Capture Mechanism and Proximity Operations
- Implementation Approach, Schedules and Costs

ARRM Reference Mission Objectives

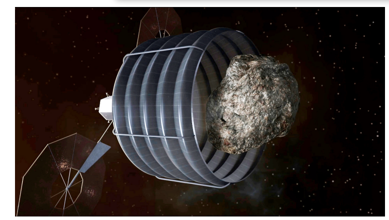
Architecture, mission design and flight system will deliver the following functionality:



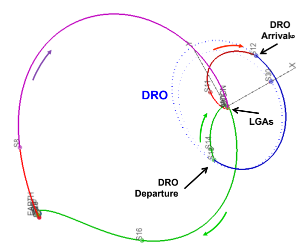
- High performance, high throughput, solar electric propulsion system with power up to 40 kW operating beyond Earth orbit



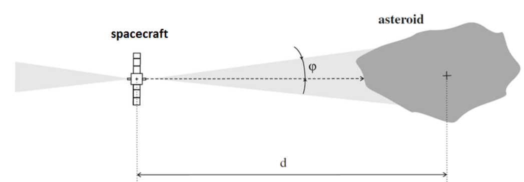
- Capability to rendezvous, characterize and operate in close proximity to an Near Earth Asteroid (NEA)



- Capability of capturing and controlling an asteroid up to the 10m class with a mass of up to 1000t



- Capability of returning a NEA, into a stable, crew accessible lunar orbit by the early-mid 2020's, and provide accommodations for a crewed mission to explore the NEA



- Ability to perform planetary defense capability demonstration(s) within mission timeline

ARRM Reference Mission Constraints

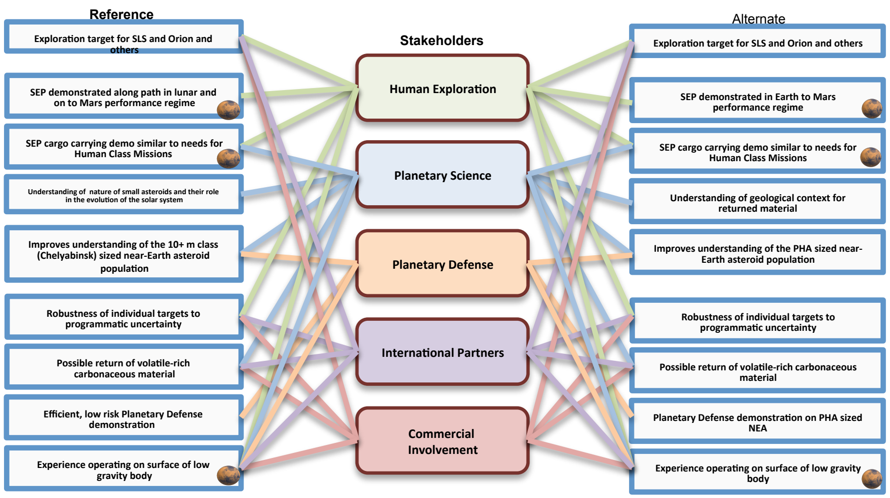
- Mission designed/operated to be inherently safe to planet Earth at all times
- Demonstrate rapid, lean, agile development under a cost driven paradigm
- Vehicle will be crew safe but not human rated
- For implementation planning evaluate launch options in 2019
- Capable of launch on SLS, Falcon Heavy, Delta IVH and Atlas 551, assumed direct launch on SLS, FH or DIVH
- Operational lifetime at least 6 years

Highlights Since MFR

- Evaluated mission options into 2019 for various launch vehicles
- Negotiated scope of TDM technology tasks to provide greatest possible alignment with ARRM needs
- Continuing development of capture system mechanism design and performance for slow and fast rotators
- Developed alternate implementation schedules with objective to use additional time to reduce risk while not driving up costs
  - MCR Feb ‘14 launch June ‘19
  - MCR Feb ‘15 launch June ’19
- Supported RFI Workshop, extensibility studies and the Robotic Concept Integration Team

Stakeholder Analysis

- Stakeholder analysis should be used for comparison of options (like risk analysis) and will be done by the RCIT
- Primary objectives should satisfy primary stakeholders NGOs and constraints
  - Administration, Congress
  - NASA
- Secondary objectives should only be included if they help, and not hurt, moving the mission forward through satisfying secondary stakeholders communities, within primary stakeholder constraints
  - Planetary Defense
  - Science
  - Commercial
  - International Partners



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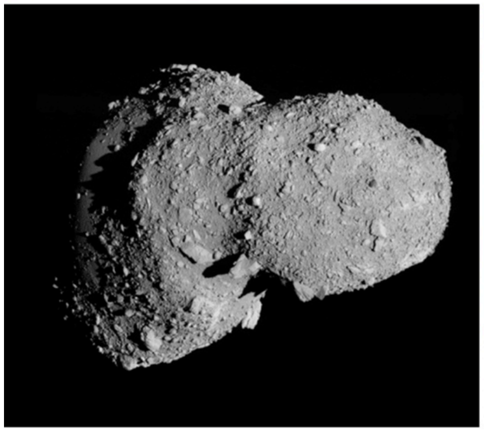
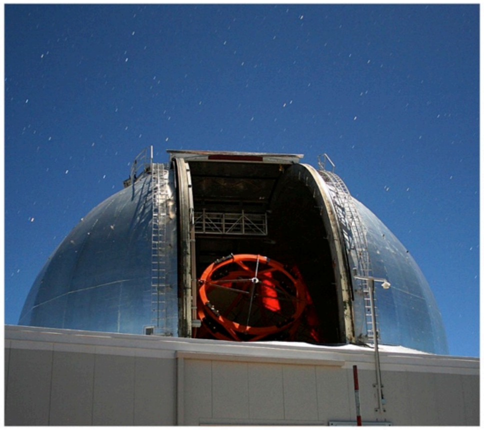
Mission Design

Nathan Strange, Mission Design Lead, JPL
Melissa McGuire, GRC

Current Reference Asteroids for Mission Design

- Each asteroid's return date is fixed & dictated by natural close approach times
- Lunar Gravity Assist (LGA) capture for smaller objects allows higher V_∞ and lower V_∞ allows capture of larger objects)
- Mid 2019 or later launches assumed for return dates in table

Asteroid	Asteroid Mass Est.	Asteroid V-infinity	Earth Return Date	Crew Accessible	Notes
2009 BD*	30-145 t	1.2 km/s	Jun 2023	Mar 2024	Area/Mass ratio estimated, rotation period > 2 hrs, Spitzer upper bound on mass
2011 MD*	50-50,000 t	1.0 km/s	Jul 2024	Aug 2025	Rotation period 0.2 hrs, possible 2009BD-like Area/Mass Spitzer opportunity in Feb. 2014
2013 EC20	4-43 t	2.6 km/s	Sept 2024	Late 2025	Discovered March 2013, Radar characterized rotation period ~ 2 min 2024 return requires DIV H or FH launch 2020 return possible with Feb 2018 launch
2008 HU4	5-40,000 t	0.5 km/s	Apr 2026	Mid 2027	Close Earth flyby in April 2016

* High-fidelity trajectory analysis performed for 2009 BD and 2011 MD

Launch Vehicle Decision Points

- Assuming launch opportunities in calendar 2019
- All current mission designs assume direct injection on a heavy lift LV
  - Use of Atlas V demos spiral out, adds ~ 1 yr to mission time, reduces return mass by ~200t, adds mission design, operations
- Desire decision on LV early enough to enable clear definition of interfaces, launch adapter and environments
  - Typically missions have decision on LV before system PDR (assuming mid-2016 for a 2019 launch
  - Can carry multiple vehicles beyond PDR but will require engagement with multiple organizations to keep parallel options viable
    - Costs and risks of keeping decision open will need to be mitigated by design, mass and reserves
    - Better to make a choice and work with uncertainties in I/F and environments than try and keep multiple L/V choices open
- Contractual lead times
  - Typical lead time for procurement of NLS contracted Atlas V is 27 months
  - Lead time for Delta IVH is TBD (likely ~36 months)
  - Lead time for Falcon Heavy is TBD
  - Lead time for SLS is likely dictated by HEOMD manifest decisions and availability of a 5 m shroud

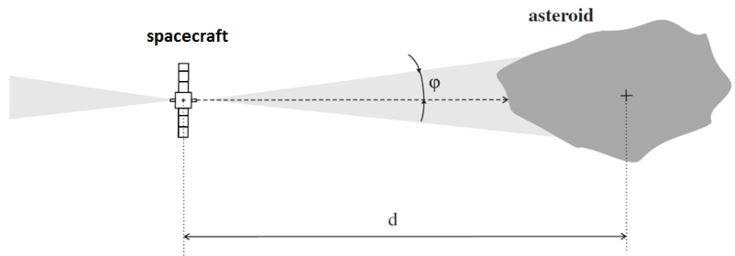
Planetary Defense Background

- Deflecting a threatening object by an Earth radii in 10 years would require a ΔV of order 1 cm/s or much less for deflecting from a keyhole.
- Deflection Strategies
  - Impulsive
    - Kinetic Impactor
    - Nuclear Explosive (ablation or disruption)
  - Gradual, Precise Deflections
    - Gravity Tractor (GT)
    - Ion Beam Deflector (IBD)
    - Laser Ablation, and other concepts
- Comparison of Deflection Strategies
  - Gradual technique can impart significant total impulse precisely which allows the asteroid trajectory to be accurately measured, but takes much more time than impulsive
  - IBD and GT would operate in situ but deflection capabilities are very slow. Unless there was a great deal of warning time, these are not really primary deflection techniques – more in the way of providing “trim maneuvers” following a more robust deflection technique like a kinetic impactor or nuclear explosion.
- Can reliably measure ΔV to an accuracy of <<0.1 mm/s

Planetary Defense Demo

- Could demonstrate either the ion beam deflector or gravity tractor approaches on a small or large asteroid
- Could be done with minimal impact to the reference mission
  - No design changes
  - Mission design changes depending on the size of the object
- IBD/GT relative performance on a small NEA
  - IBD, <500 t (like 2009 BD) could impart: 1 mm/s in < 1 hour
  - GT, <500 t (like 2009 BD) could impart: 1 mm/s in < 30 hours
- IBD/GT relative performance on a large NEA
  - IBD, at Itokawa, could impart: 0.1 mm/s in ~50 days
  - Enhanced GT, on Itokawa, w/ 10 t boulder, could impart: 0.1 mm/s in ~130 days

Ion Beam Deflector



Asteroid size-independent planetary defense demo

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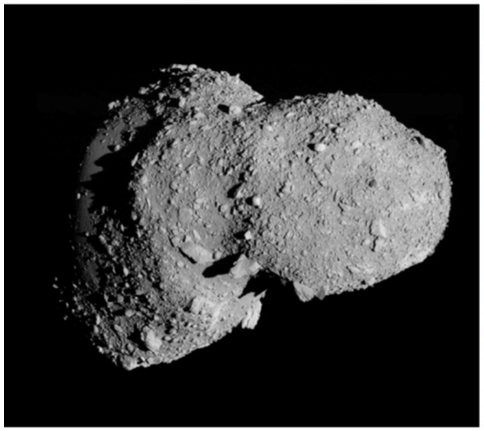
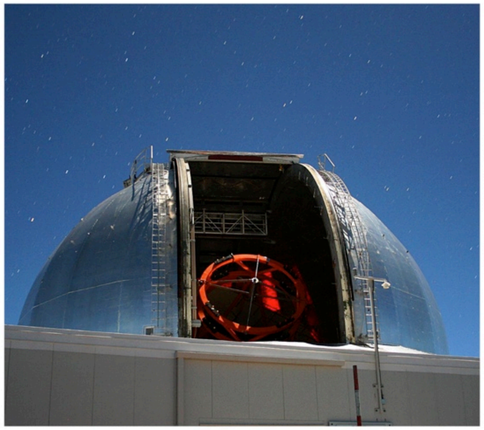
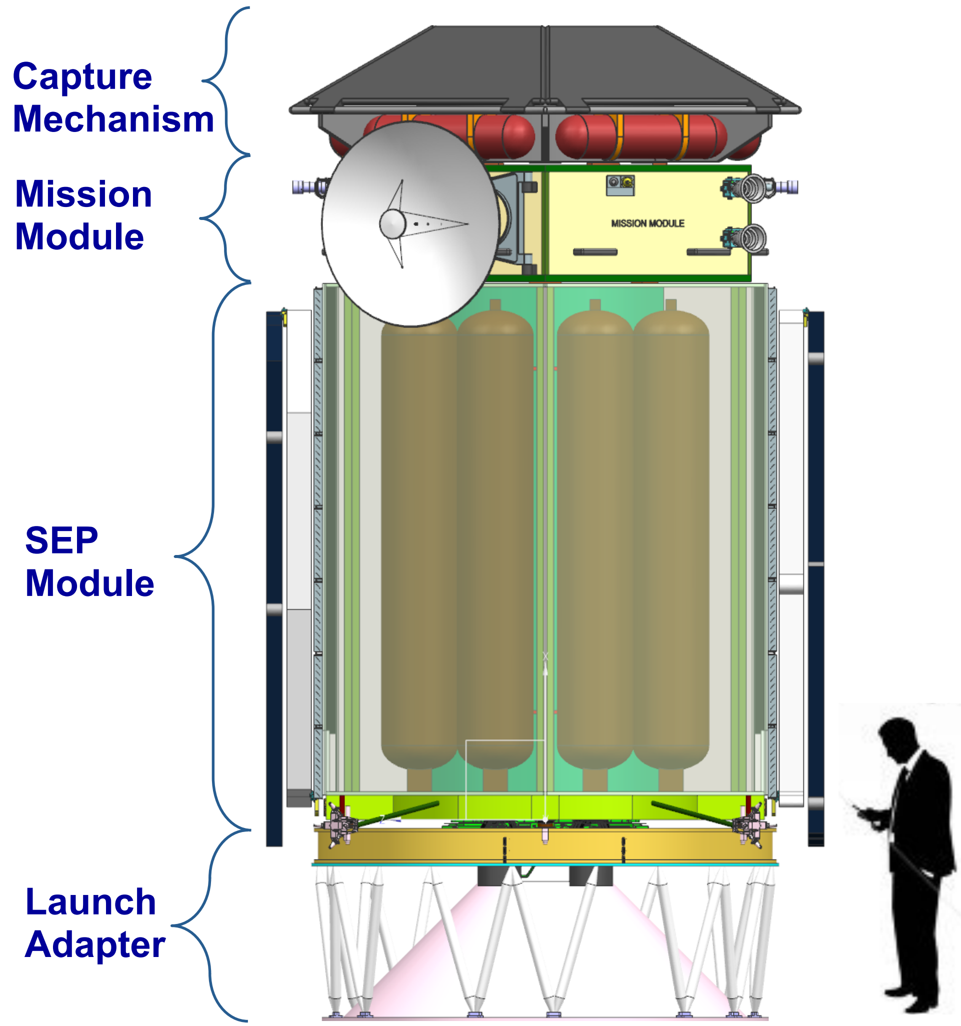
Asteroid Redirect Robotic Mission Mission and Flight System Baseline

John Brophy, ARRM Chief Engineer, JPL
Mike Barrett, SEPM Lead, GRC
Hoppy Price (JPL), Kurt Hack (GRC), Dave Manzella (GRC)

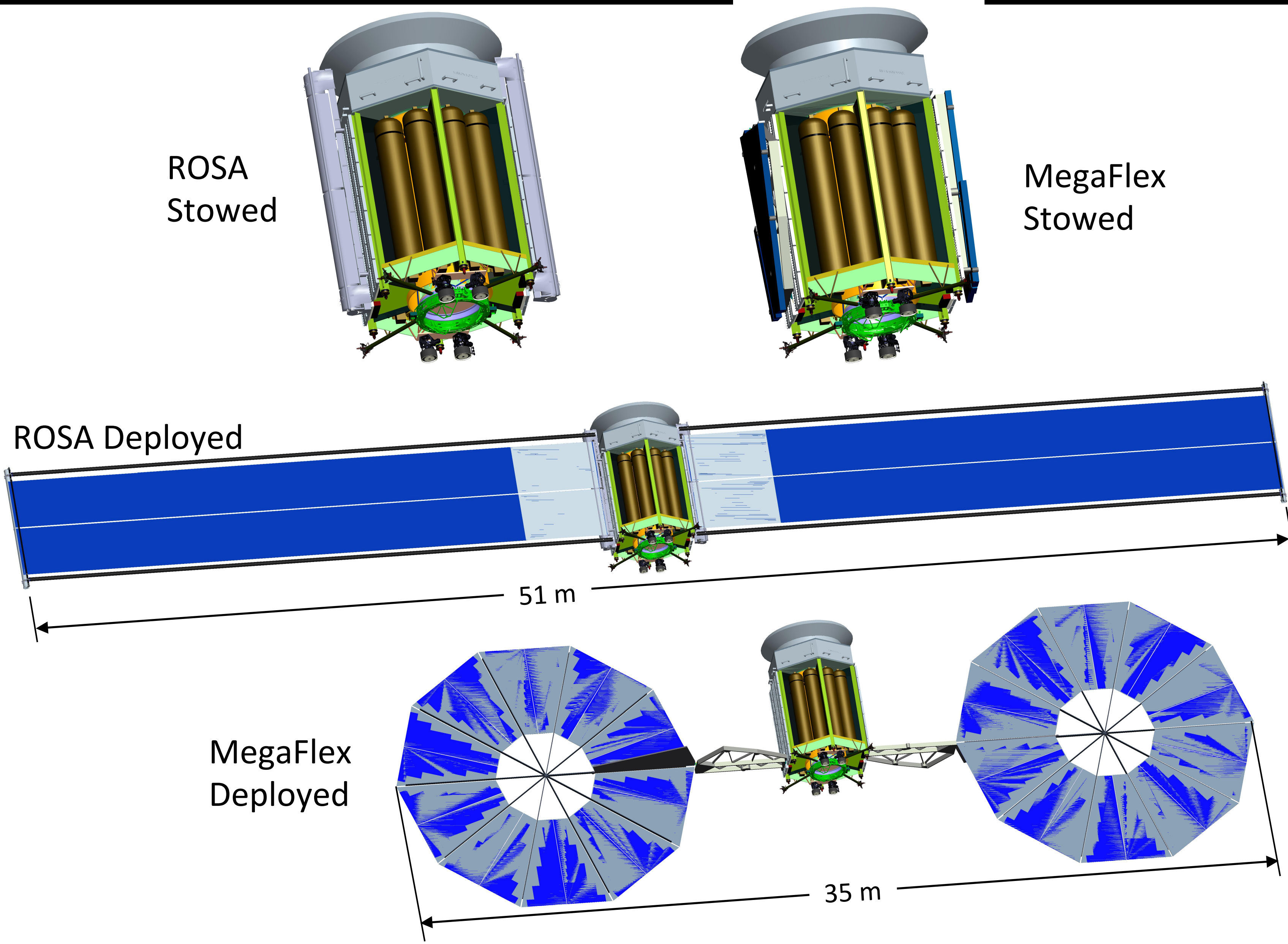



Mission and Flight System Summary

- 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 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



Flight System Configurations



FY14 Full-year CR SEP TDM Scope

FY14 Plan Under Full-year CR	
Solar Array	• Completion of SAS Phase I (both contracts)
Thruster	• Thruster acquisition preparation • In-house design, build & test of technology unit
PPU	• PPU acquisition preparation • In-house design, build & test of technology unit
Propellant Tank	• Plan for tank development and certification
SEP Mission Study	• Study-level support of ARRM team • Continuation of SEP TDM effort • Project Office Support

Augmentations to provide more direct application to flight:
Thruster: materials specifications (magnetic, boron-nitride), high temp magnets, thermal modeling with plasma power, cathodes, mechanical design for flight (loads, fasteners, manufacturability)
PPU: dual stage PPU using parts with path to flight (e.g. SiC MOSFETs)

Ref: C. Taylor for MG OMB Presentation, Sep 2013

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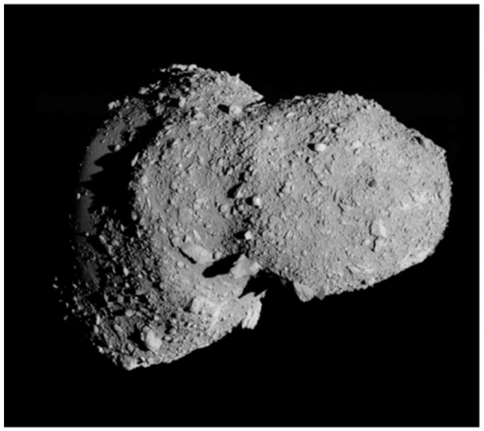
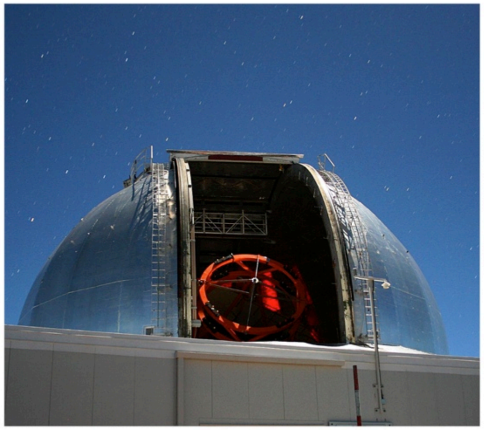
Capture Mechanism and Proximity Operations

Miguel San Martin, G&C Lead, JPL

Brian Wilcox, Capture Mechanism Lead, JPL

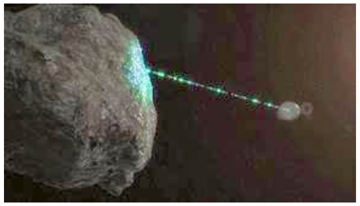




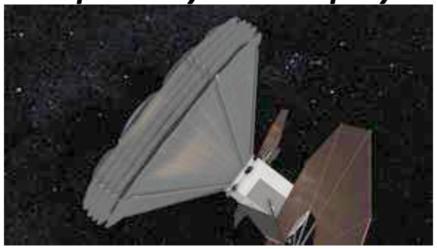
Rendezvous and Proximity Operations Phases

Orbit Refinement and Rendezvous
(Radio and Optical)

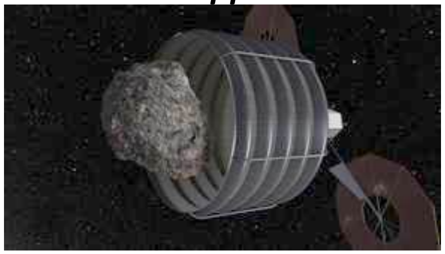
Characterization



Pre-Capture
Capture System Deploy



Final Approach



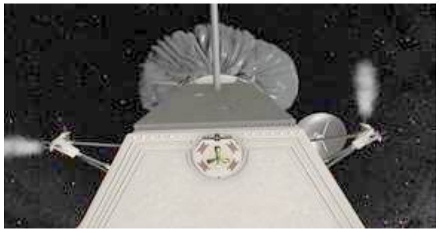
Attitude Control Disabled

Capture
Mechanical Capture

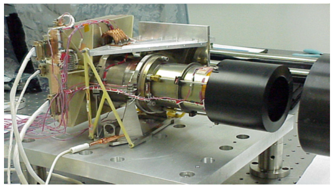
Capture Bag Retraction

Attitude Control Enabled

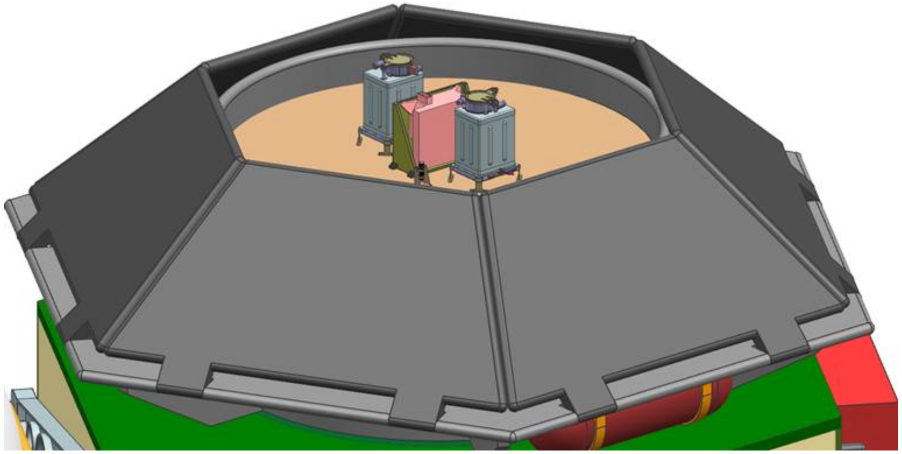
Characterize, Spin down, and Detumble

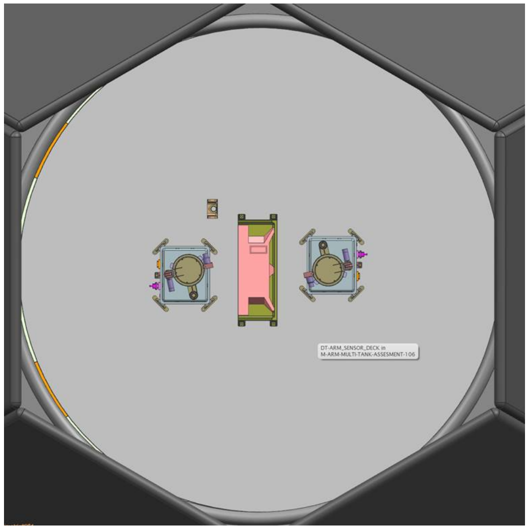


Asteroid Rendezvous & ProxOps Instruments



- Minimum Instrument suite to minimize cost is consistent with AR&D study conclusions
  - Narrow Angle Camera (NAC) used for both optical navigation and, at asteroid range > 2km: for mapping, generating shape model (including rotation/dynamics and inertia properties)
  - Scanning LIDARs (2): for mapping, updating shape model and closed loop control
  - Wide angle cameras (e.g. RocketCams) for additional information and outreach (could be HD quality)
- Deep Space Network (DSN) Doppler and Range measurements for asteroid mass estimation





Key Characteristics of Asteroid for Capture

Composition/ Strength

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

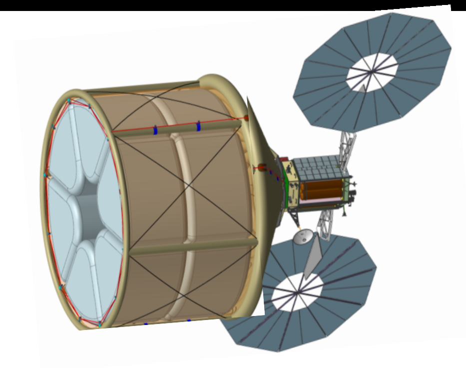
Spin State

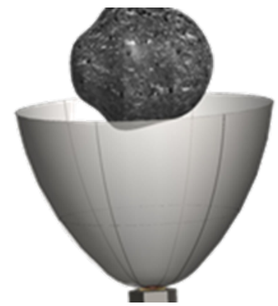
- Slow (<<1RPM), Simple Spin
- Slow (<<1RPM), Tumbling
- Fast (~>1RPM), Simple Spin
- Fast (~>1RPM), Tumbling

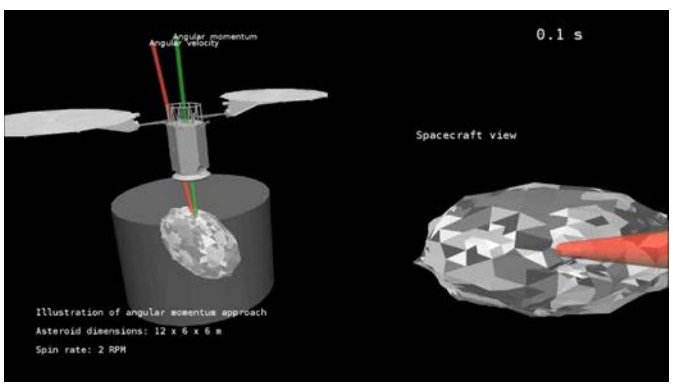
- For capture, the primary concerns are composition/strength and spin state
- So far all candidate targets are slow rotators.
- Capture system and capture process is much simpler for all asteroids except the few that may be fast tumblers
- For fast rotators have developed a passive control approach that limits forces on the spacecraft/solar arrays to <0.1 g peak

Capture Mechanism Concept Status

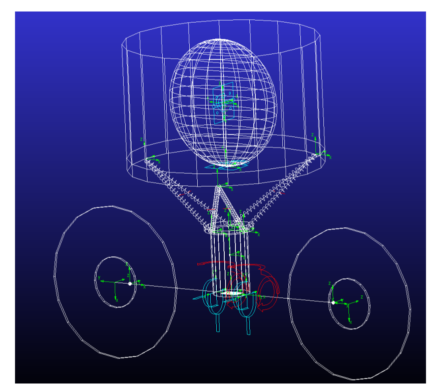
- Capture bag designed to capture/control worst case rubble pile, using inflatable exoskeleton forming a cylindrical barrel and conical section, current bag diameter is 15 m to capture irregular 10 m NEA but actual size will depend on target (can be smaller or larger)
- Design is evolving based on discussions with potential vendors about materials, manufacturability and costs.
- RFI inputs provide other options for capturing slow rotators that will be studied in coming months



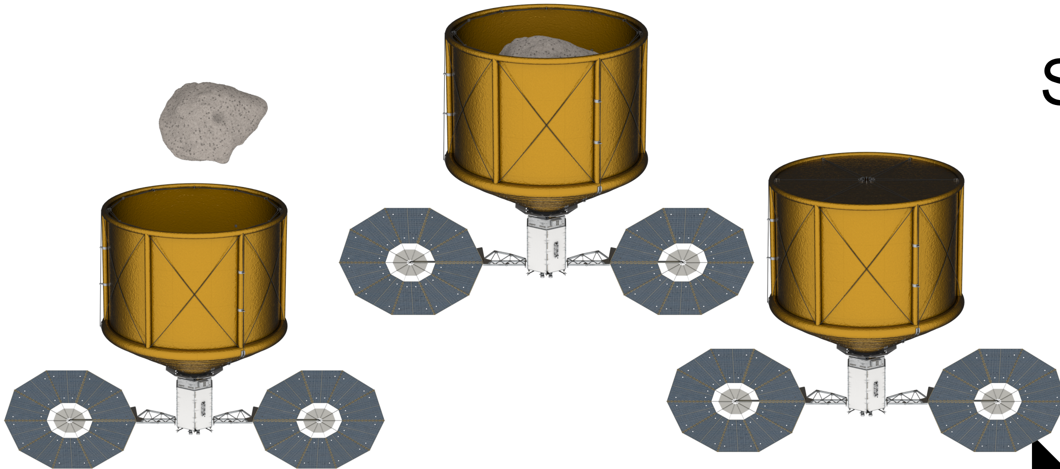




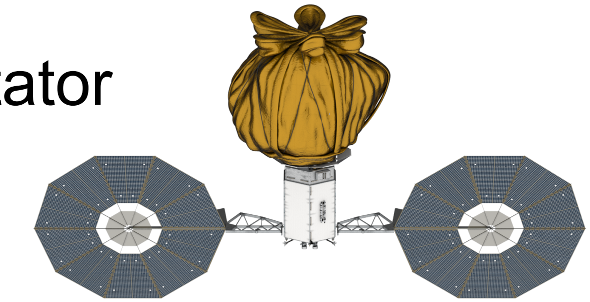
- Performed two independent dynamics analyses to assure robust system for capture at slow and fast rotation states while limiting forces on S/C.
- Monte Carlo analyses show good performance over wide range of asteroid size and mass properties



Slow and Fast Rotator Capture Sequence



Slow Rotator

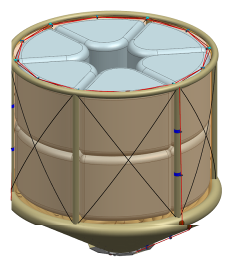


Winch closed bag

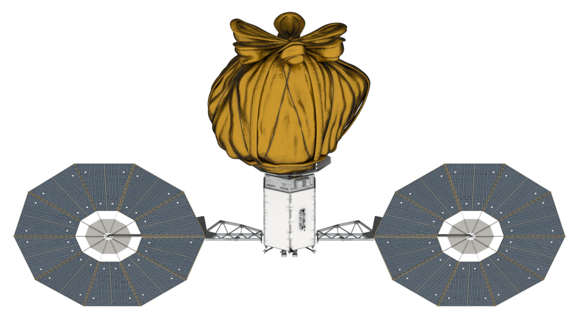
Fly S/C to position bag over asteroid, close diaphragm over top

Inflate inner bags for quick capture, winch closed bag

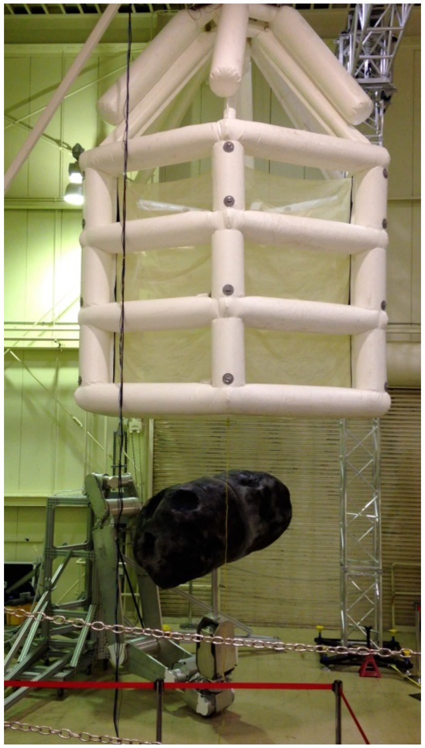
- For slow rotator (<0.1 rpm): approach, envelop, close top and winch bag down onto S/C, re-establish full attitude control
- For fast rotator (>0.1 rpm): approach, envelop, match rotation state about combined spin vector, close top, inflate pie shaped inner bags for rapid capture, despin NEA using RCS system, winch closed bag to S/C, re-establish full attitude control



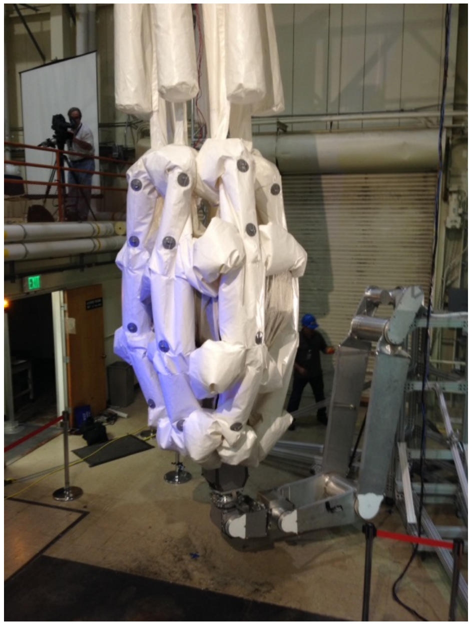
Fast Rotator



Capture Mechanism Concept Status (cont.)



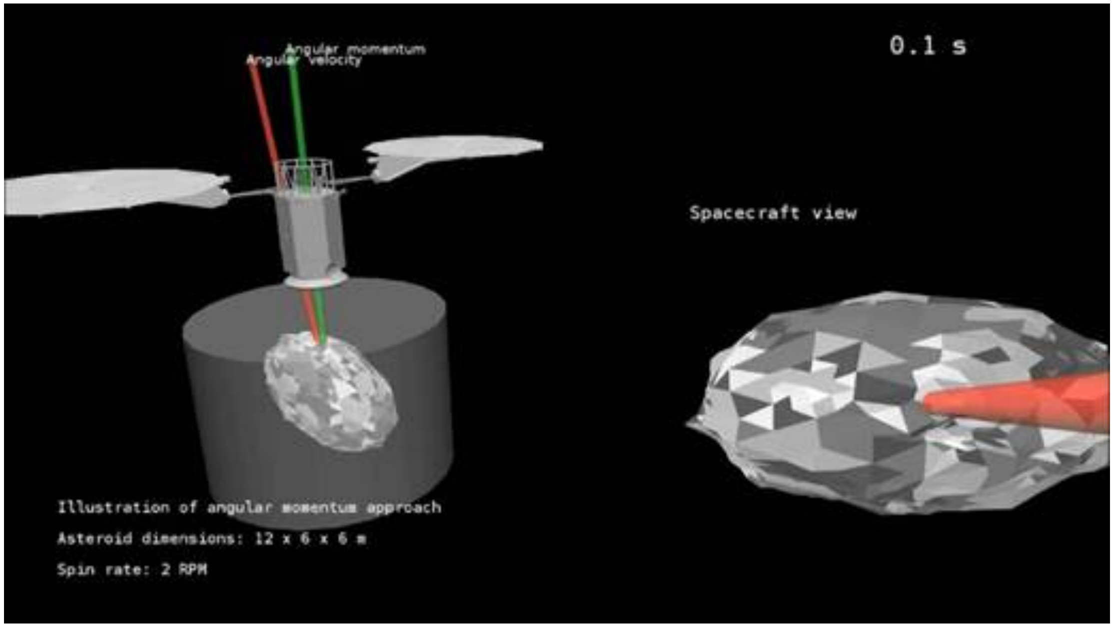
- Built first generation 1/5 scale testbed
  - To help characterize stiffness and damping, forces on the bag, and general control of the bag and fabric
  - Images show capture sequence demo in facility at JPL



- Upgrades to system to include more flight-like configuration and materials, including pie-shaped inner bags for fast rotation capture, planned for spring 2014 if funding available.

Passive Capture, Matched Instantaneous Spin Vector

- Asteroid inertial and spin properties determined by observation and state accurately projected into the future by many minutes to hours
- Asteroid instantaneous spin vector circulates around angular momentum vector
- Spinning S/C approaches along projected instantaneous spin vector and grabs when vector matches S/C location to minimize bag scuffing

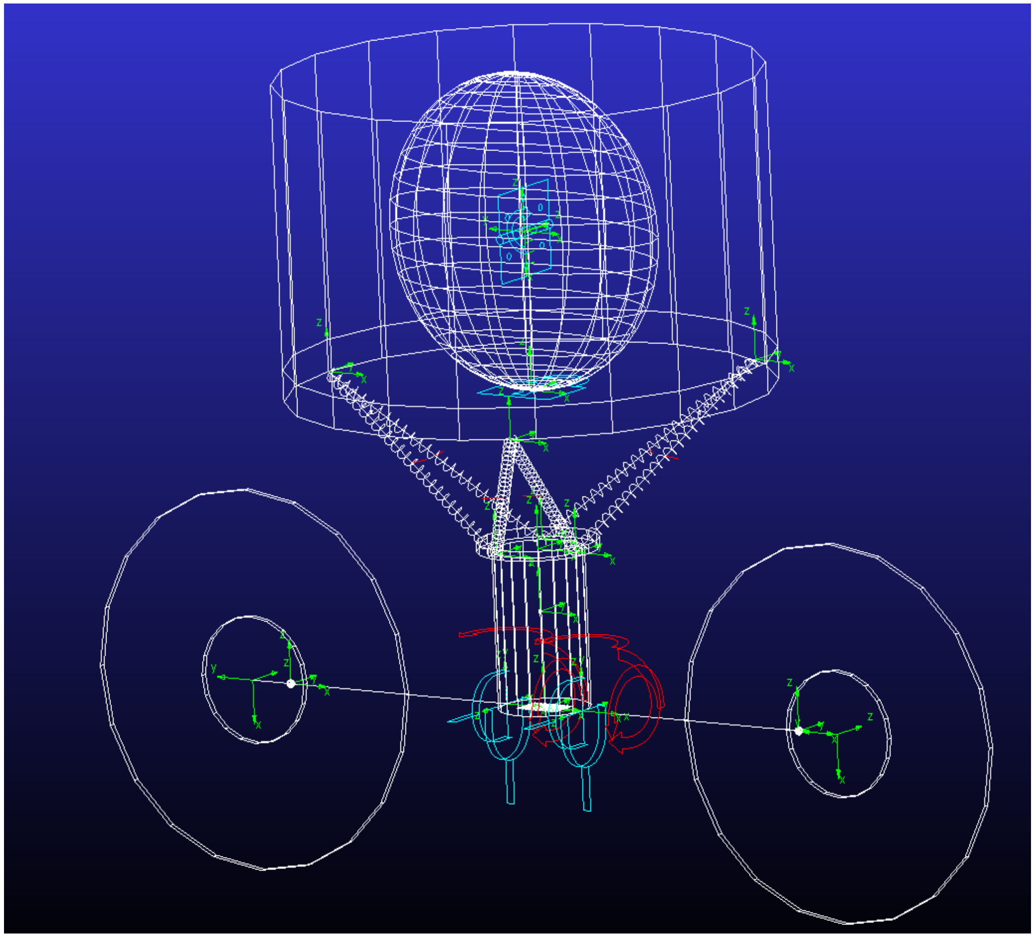


Passive Capture, Unmatched Transverse Spin

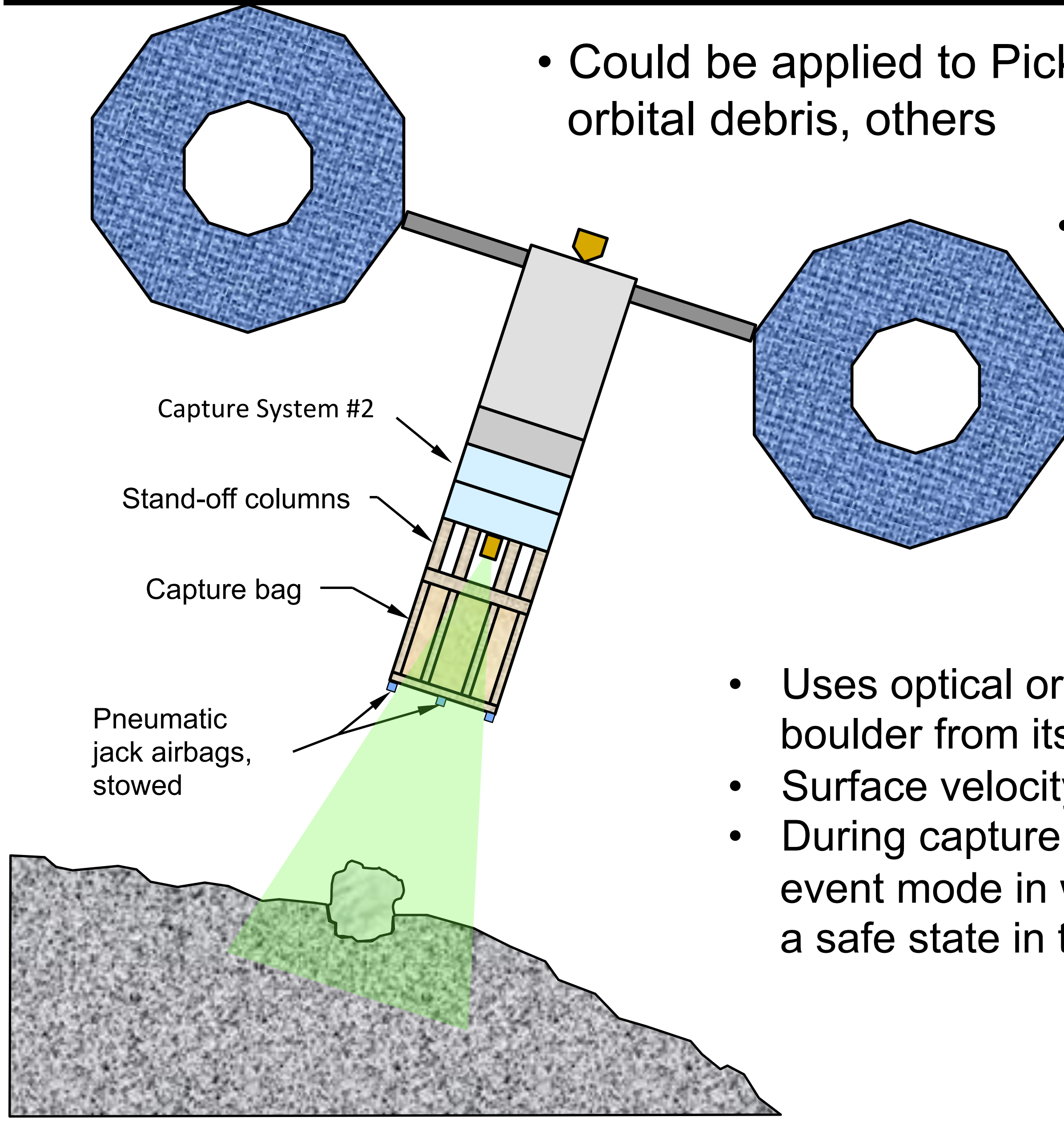
- ADAMS model with assumed <u>soft</u> spring/ damper characteristics for capture airbags and torroidal cone modeled as a Stewart Platform

- Softness of capture extends over ~45 degrees of rotation

- Time history shows moment force limit at hinge of solar array is met at worst case transverse rate of 2 rpm



Capture Bag and Inflatables Are Scalable

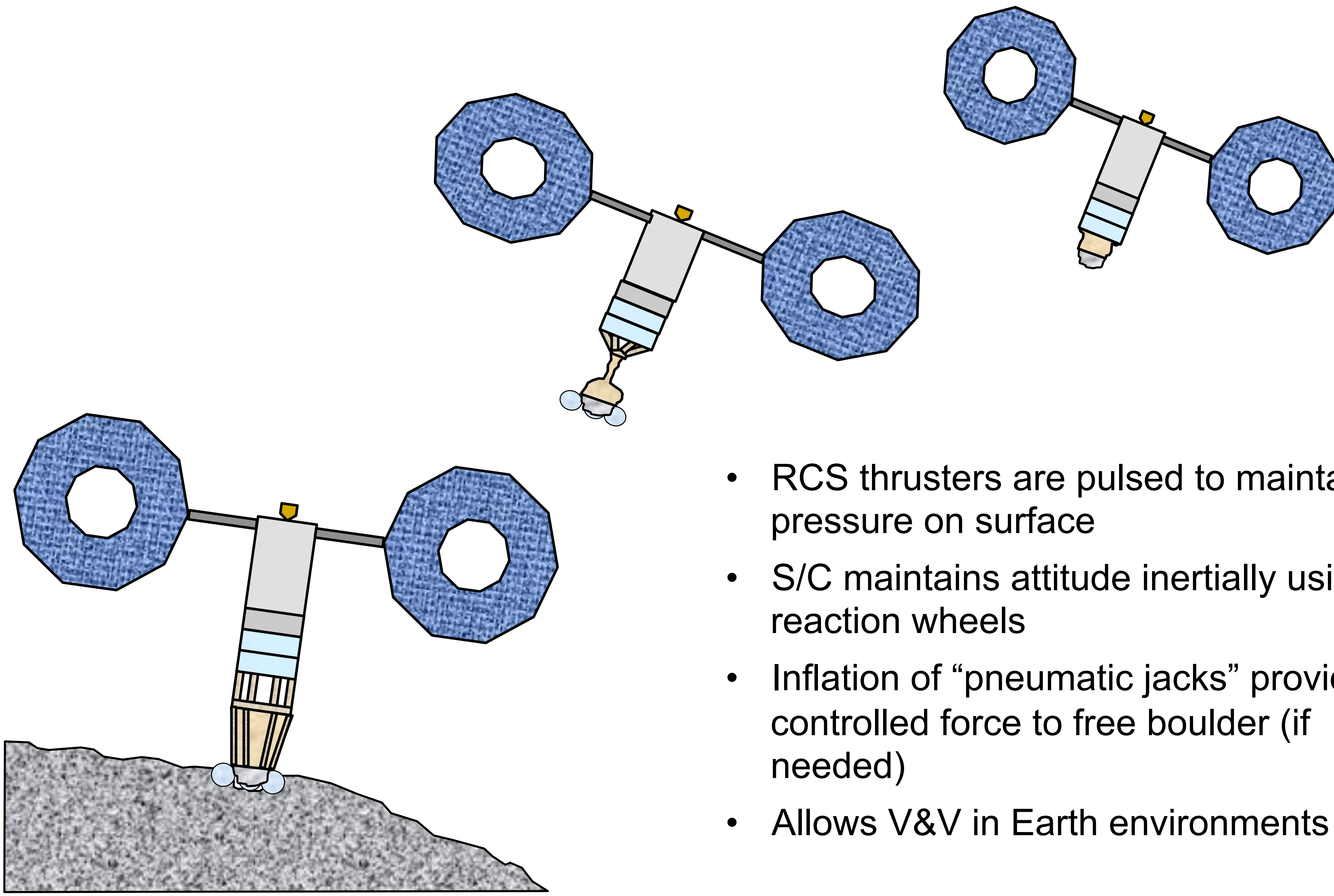


- Could be applied to Pick-Up-Boulder (PUB), orbital debris, others

- Assumptions for PUB:
  - Boulder is partially imbedded
  - Boulder is ~ 2m
  - Boulder may not be structurally strong and could break apart at any time.

- Uses optical or LIDAR discrimination of the boulder from its surroundings
- Surface velocity precisely matched by the ARV
- During capture, system operates in a critical event mode in which the S/C control will assure a safe state in the face of most faults.

Boulder Capture and Fly-Away



- RCS thrusters are pulsed to maintain pressure on surface
- S/C maintains attitude inertially using reaction wheels
- Inflation of "pneumatic jacks" provides controlled force to free boulder (if needed)
- Allows V&V in Earth environments

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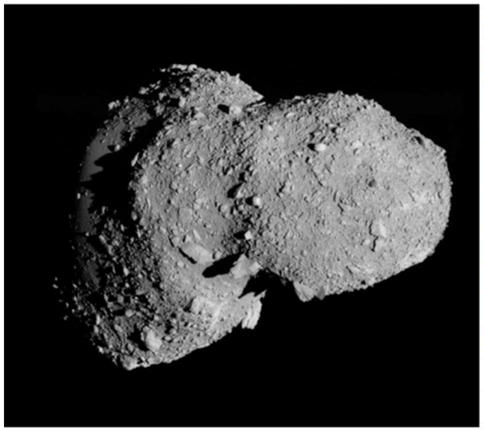
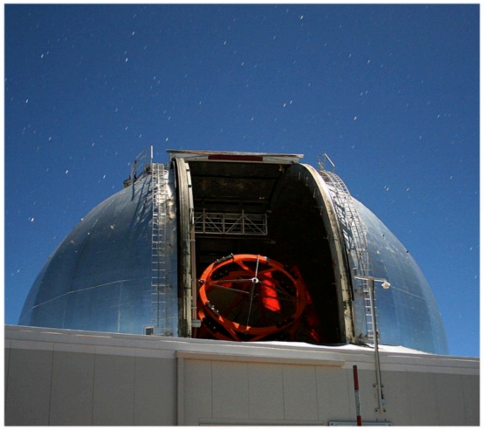
ARRM Reference Implementation and Schedule Options

Brian Muirhead, ARRM Study Lead, JPL

Rick Manella, ARRM Deputy Study Lead, GRC





MFR Reference Mission Schedule Basis

- MFR assumptions and features
  - MCR : February, 2014
  - Launch readiness date (LRD): 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
  - Final choice of target could be made within months of the launch, assuming all equivalent from a capture and mission design point of view.

MFR Key Implementation Assumptions

- 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

Two Options for LRD June 2019

- ARRM reference implementation (LRD June 2018)

ATP
Jan. 2014

Launch
June 2018

- Two options for LRD June 2019

Option 1

ATP
Jan. 2014

Launch
June 2019

1. *Mitigate the schedule risk (critical path items) using one additional year*
2. *Flatten the NOA profile*

Option 2

ATP
Jan. 2015

Launch
June 2019

1. *Mitigate the schedule risk using early tech. maturation (FY14)*
2. *Reduce Life Cycle Cost (not including FY14 funding)*

For both options, minimize the overall Life Cycle Cost increase.

Forward Work and Risk Reduction Items

- System design, system engineering and mission design:
  - Continue to assess/refine candidates delivery performance
  - Evaluate specifics for GNC sensors, specifically LIDARs
  - Update proximity operations MBSE model
  - Evaluate feasibility and impacts of ARV changes for extensibility
  - Evaluate specific cost reduction opportunities (e.g. contributions/ partnerships)
  - Implementation planning
- SEPM:
  - Augment SEP technology efforts (specifically thruster and PPU) if funding available to get more direct path to flight-HW
  - Continue structure and tanks design and conduct loads/environments analyses
- Capture system:
  - Upgrade capture system testbed and analyses, including HW in the loop simulations
  - Engage industry (including RFI inputs), possibly through a BAA, on slow spin capture systems