National Aeronautics and Space Administration

ARRM Alternate Approach Mid-Term Status Briefing

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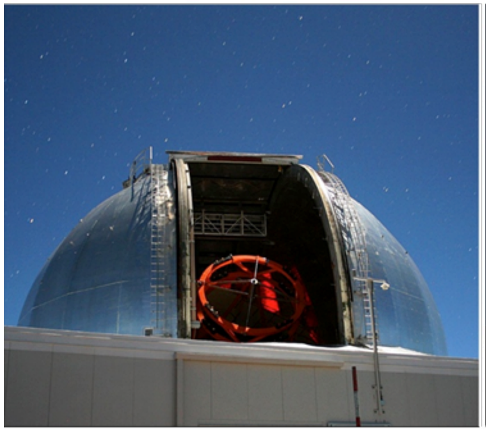
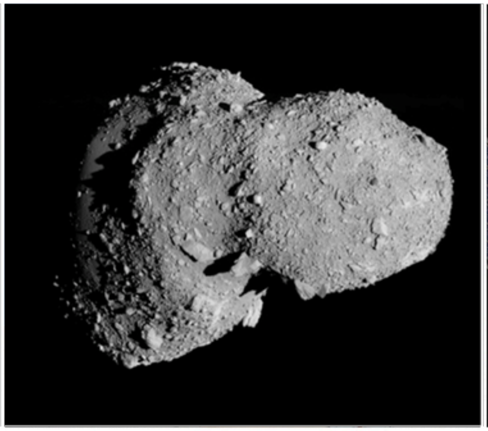
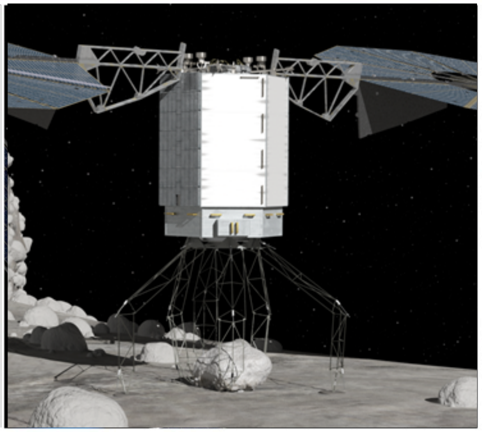
December 17, 2013


Mission Overview

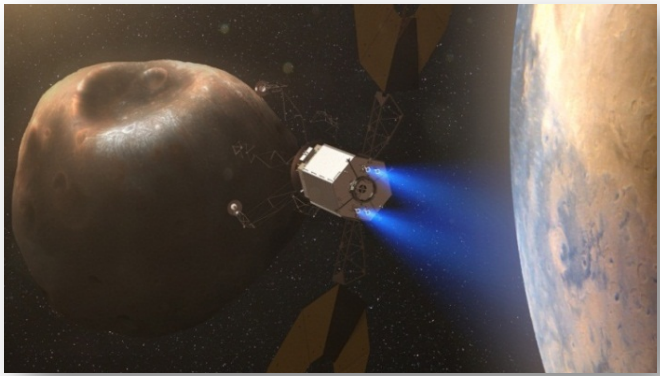
The Alternative Approach utilized a risk informed design strategy to develop a mission that meets the following primary objectives.

Returns a boulder from the surface of a large near-Earth asteroid (NEA) to a stable lunar orbit.

Alters the trajectory of an asteroid of potentially hazardous size (~100+ m diameter).

Depiction of Gravity Tractor Planetary Defense Demo

Matures key technologies and operations in human-class Mars mission environment.



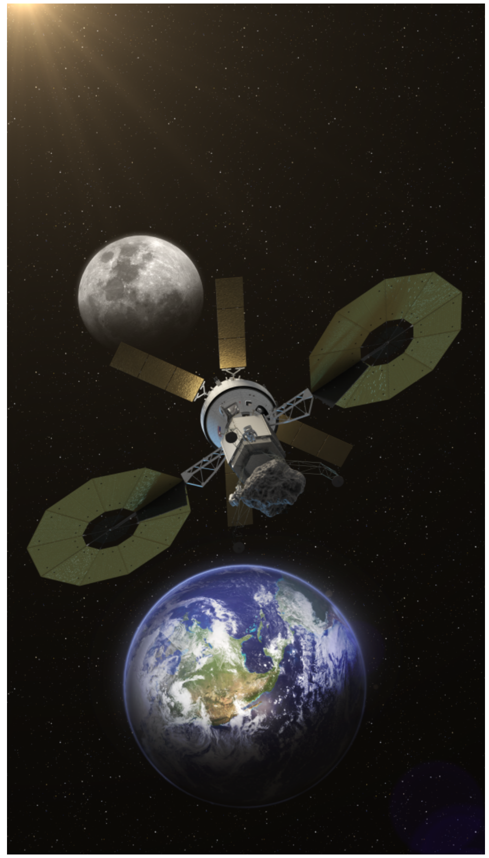
Stakeholder Benefits

Human Exploration

Addresses multiple *Mars forward* technology and operations gaps. Provides a *multi-ton sample* from a large NEA, well characterized *accessible surface.* Mission approach is *robust* to programmatic uncertainty.

Planetary Defense

Interacts with a *hazardous-size* NEA. Demonstrates one or more *deflection techniques* on a *relevant* target, including the option to test a kinetic impact approach.



Science

Returns a well characterized, *science community selected* sample with *geologic context.* Provides the potential for *hosted payloads* for further investigations.

Commercial & International Partners

Provides experience interacting with a large low-gravity body. Provides access to a *large surface area* of *potentially volatile/ water-rich* carbonaceous material and provides the potential for *hosted payloads*.

The Alternative Approach addresses the needs of a broad set of stakeholders, and leverages precursor missions and existing agency capabilities to ensure mission success.

Target Availability

- One Valid Candidate with hundreds of candidate boulders: **Itokawa**
- Two candidates may be characterized by precursors in 2018: **Bennu** (OSIRIS-REx) & **1999 JU_3** (Hayabusa 2)
- One candidate characterized by radar at ~ 6000 SNR: **2008 EV_5***
- At least two more candidates may be sufficiently characterized by radar during the next 4 years: **2011 UW_{158}, 2009 DL_{46}**

Itokawa

Earth Departure	Earth Arrival 2023	2024	2025	2026
2018	0	8	25	33
2019	0	6	19	20
2020	0	0	10	14

1999 JU_3

Earth Departure	Earth Arrival 2023	2024	2025	2026
2018	2	14	30	45
2019	0	12	27	45
2020	0	0	26	43

Bennu

Earth Departure	Earth Arrival 2023	2024	2025	2026
2018	15	28	39	45
2019	1	13	18	24
2020	0	0	11	16

2008 EV_5

Earth Departure	Earth Arrival 2023	2024	2025	2026
2018	14	40	55	64
2019	0	32	40	51
2020	0	23	43	44

All performance numbers in **metric tons (t)** and assume Falcon Heavy. More mass would be returned when using SLS.

The Alternate Approach has a robust set of tangible Potential Candidates, and for those candidates is robust to changes in launch and return dates.

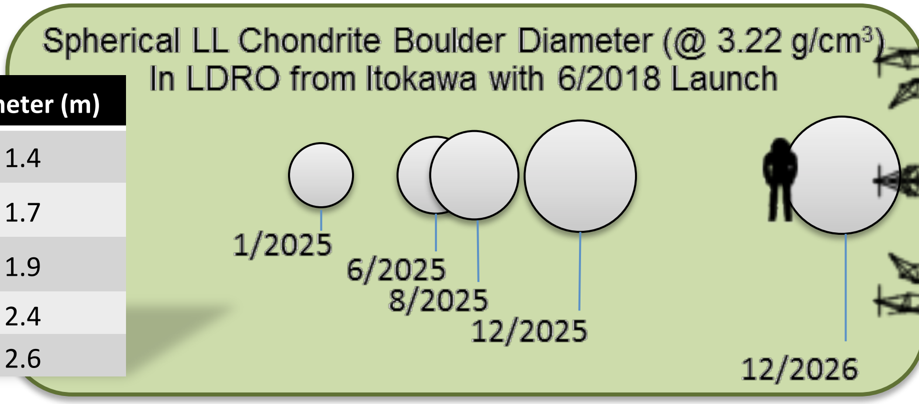
* Personal communication Michael Bush (ref. Busch et al., Icarus Volume 212, Issue 2, April 2011, Pages 649–660)

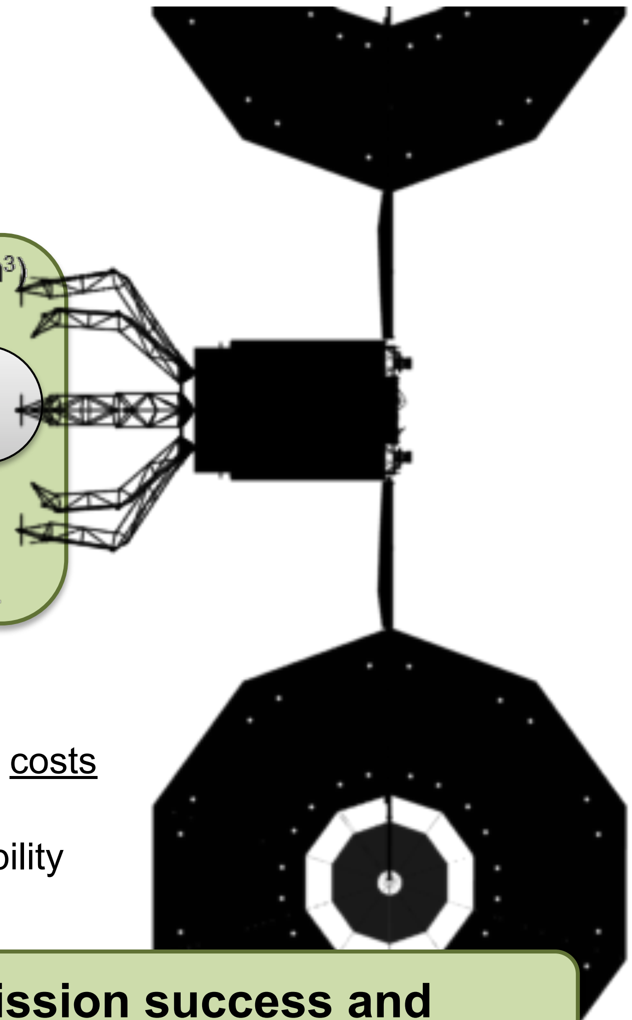
Itokawa: Point of Departure

Developed a detailed mission to Itokawa to:

- Assess options and risks associated with proximity operations.
- Understand spacecraft design requirements differences.
- Develop sufficient fidelity to inform cost & schedule estimates.

In LDRO	Mass (t)	Diameter (m)
1/2025	4.7	1.4
6/2025	7.9	1.7
8/2025	12.2	1.9
12/2025	24.7	2.4
12/2026	29.5	2.6



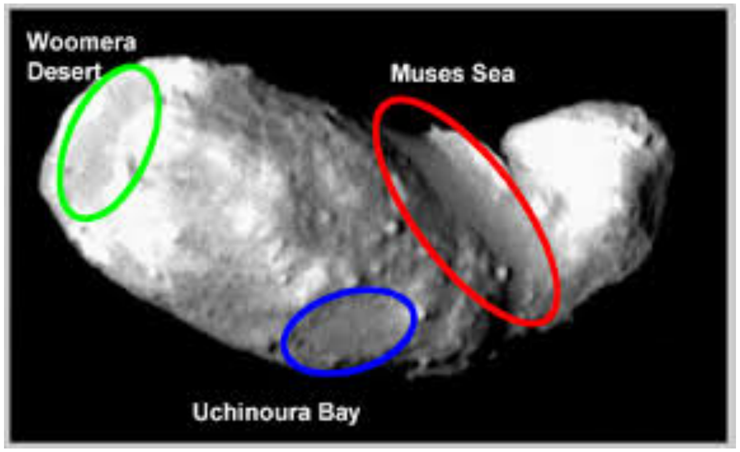


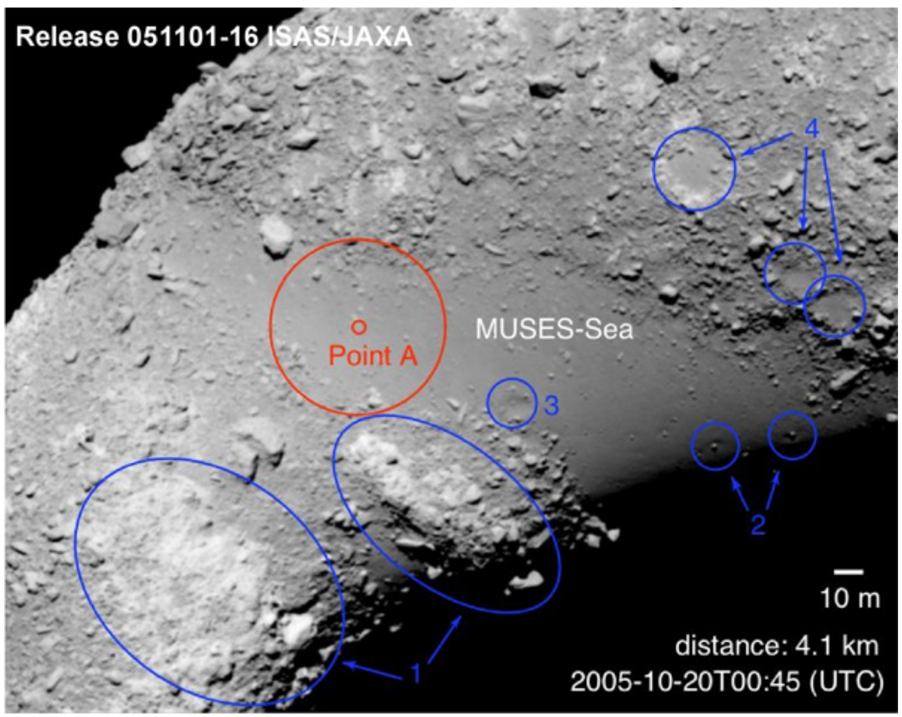
Why Itokawa?

- Meets valid candidate criteria for alternative approach.
- Leverages Hayabusa as a precursor mission to reduce mission costs and programmatic/technical risks.
- Hayabusa instrumentation has provided a high confidence in ability to find many selectable boulder targets.

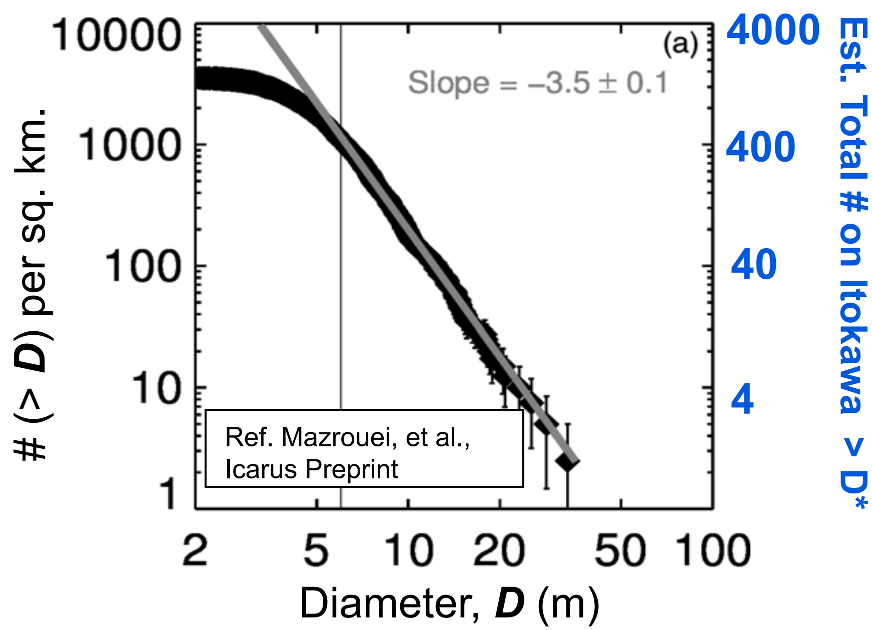
Alternative Approach has ability to increase mission success and robustness by targeting well-characterized asteroids and to accommodate uncertain programmatic schedules by tailoring the return mass.

Boulder Rich Surface



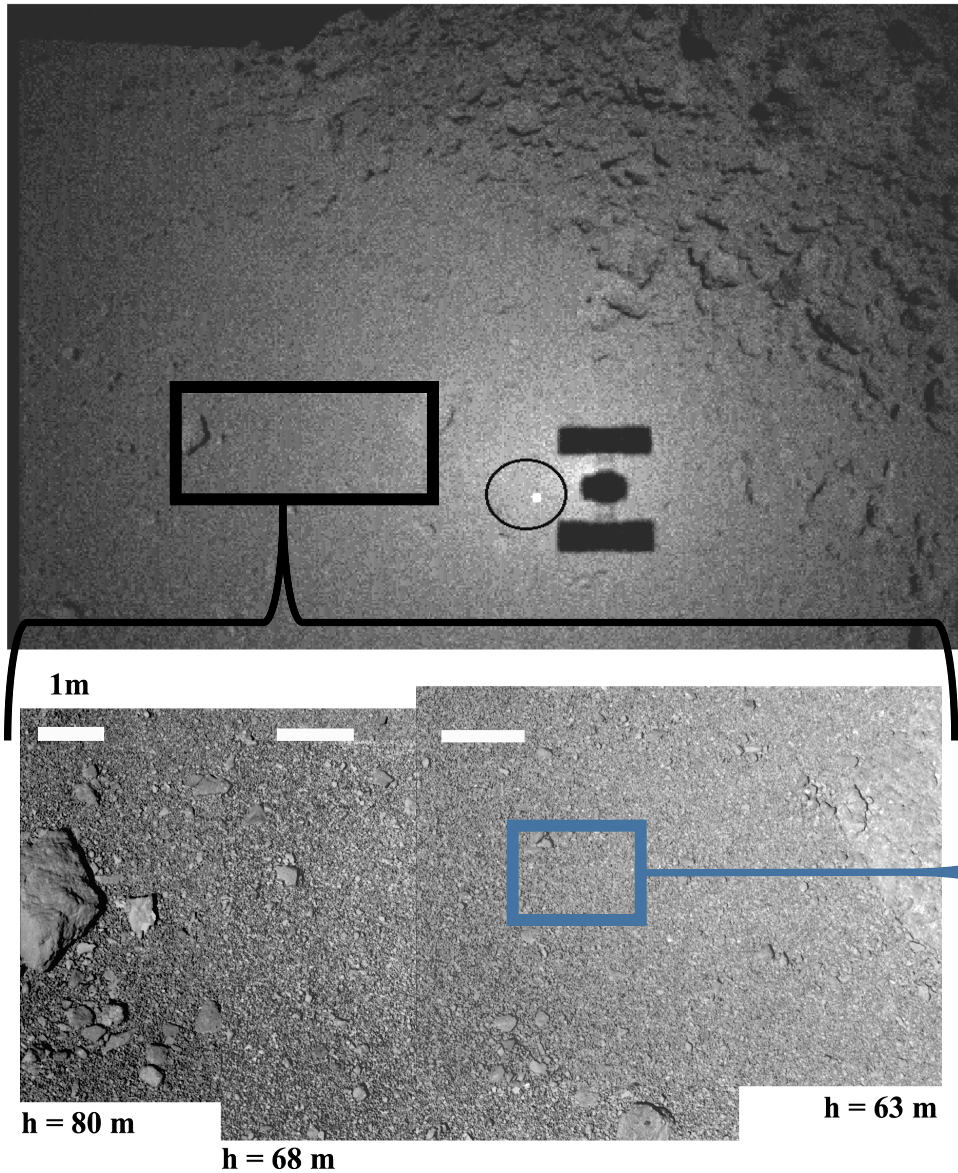


- Hayabusa mission confirmed the presence of many boulders on Itokawa's surface.
- Data from images suggest that **several thousand 2 to 5 m boulders exist** on Itokawa.
- ~20% of the entire asteroid's surface contains smooth areas (flat terrain with few hazards and wide access) – hundreds of boulder targets
- The largest area of smooth terrain (MUSES-Sea) is ~60 m across at its widest point.



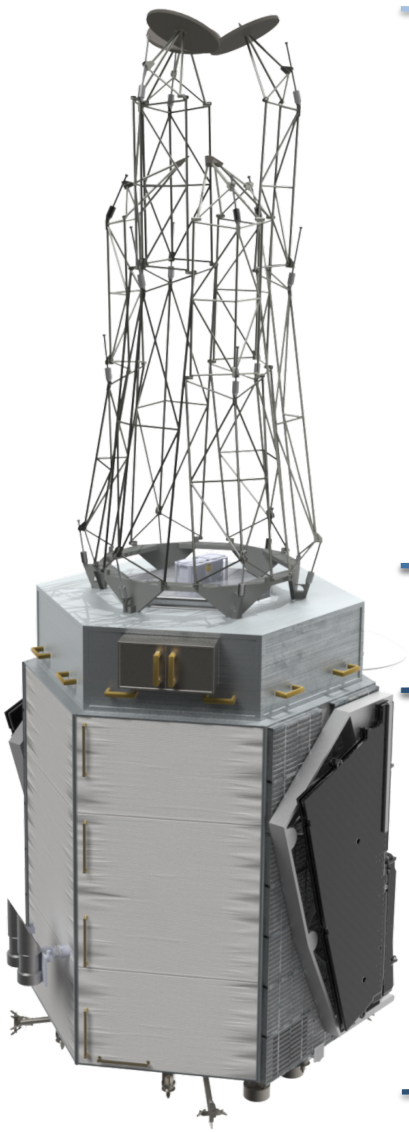
* Added axis based on Itokawa surface area of 0.4011 km^2

Hayabusa Touchdown Site Approach



- Smooth areas have boulders sitting on a surface dominated by gravels and pebbles. Stereo image analysis indicates a high probability that some boulders are not embedded.
- Highest resolution of the images during the Hayabusa touchdown are 6 to 8 mm/pixel.
- Evidence from Hayabusa and ground-based radar suggests that boulders may be relatively common on near-Earth asteroids (e.g., Bennu and 2005 YU55).
- This evidence is supported by theoretical and laboratory analysis of asteroid rubble pile formation and impact processes.

Flight System



Capture System (New)

Mission Module (Modified)

SEP Module (Unmodified)

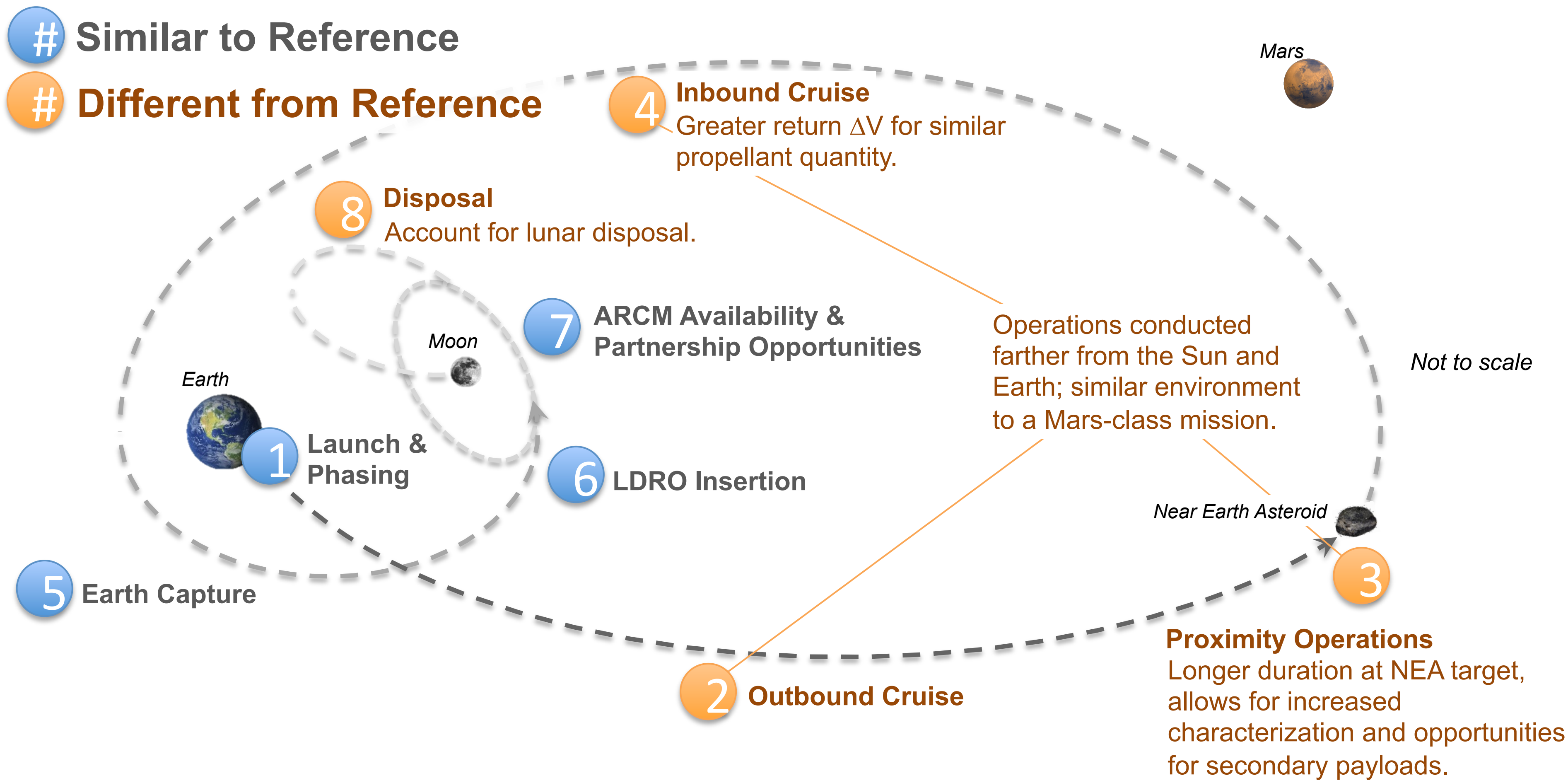
Minimal modifications required from the Reference Approach's Mission and SEP Module designs.

Potential Mission Module Changes

- Modified communications system to accommodate larger Earth distances and to provide critical event coverage for entire boulder capture operations.
- Avionics additions to allow for autonomous optical navigation and boulder collection, and to accommodate storage of increased asteroid characterization data.

- Potential removal of sun shade depending on minimum distance to sun.

Mission Design



The Alternate Approach demonstrates SEP and operations in an environment similar to a human-class Mars mission, and has increased opportunities for characterization and secondary payloads.

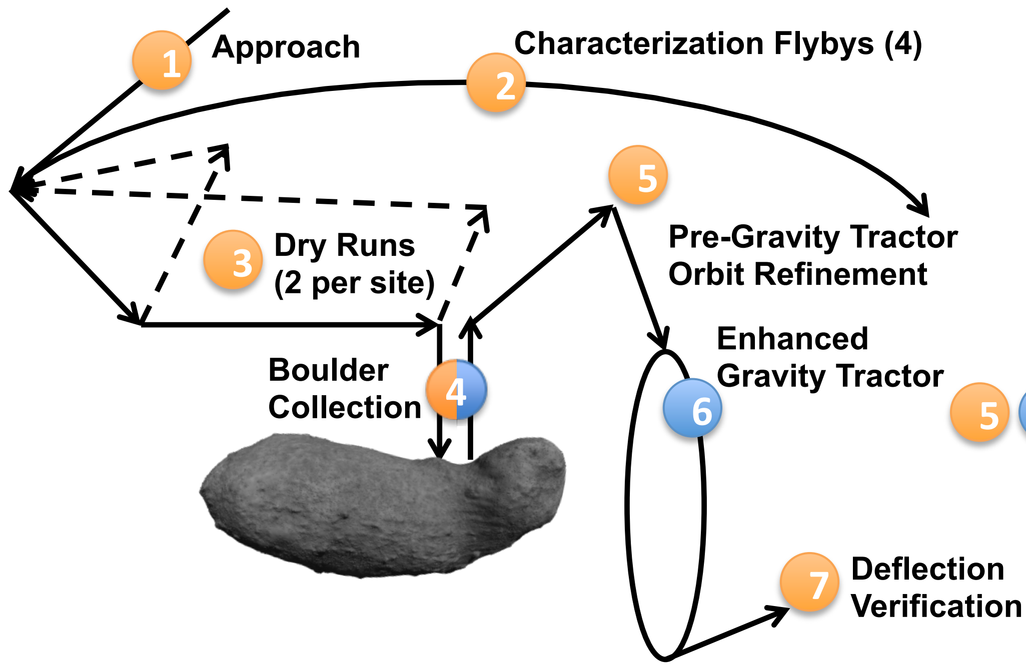
Proximity Operations Overview

Proximity Operations Timeline (400 days)

1	2	3	4	Reserve (3 & 4)	5	6	Reserve (6) & Wait	7	Margin

Operations heritage to prior robotic missions

Mission unique operations



1 2 Approach, Flybys, & Characterization: 37 days to verify and refine shape, spin, and gravity models, and obtain ~cm imagery for majority of the surface.

3 Dry Runs: 2 dry runs at up to 3 sites refine local gravity, provide sub-cm imagery, and verify navigation performance.

4 Boulder Collection: Reserving for up to 5 boulder collection attempts provides contingency against surface and boulder anomalies.

5 6 7 Enhanced GT Demonstration: 260 days allows for operations and proper Earth-Itokawa alignment to verify deflection.

6 Enhanced Gravity Tractor (EGT): 180 days reserved for EGT operations, 60 days required for measurable deflection.

Operations Margin: In addition to conservative operations profile, 19 days of unencumbered operations schedule reserve is provided in mission plan.

Even with the Alternate Approach's proximity operations having a high heritage, a conservative operations strategy has been implemented.

Sensor Suite

Sensor Suite

- **Narrow FOV Camera**
- **Medium FOV Camera**
- **Wide FOV Camera**
- **3D LIDAR**
- **Situational Awareness Cameras**

Enables identification and characterization of thousands of boulders in the returnable mass range, long-/close-range navigation, and execution of autonomous capture ops.

Extensibility Benefits

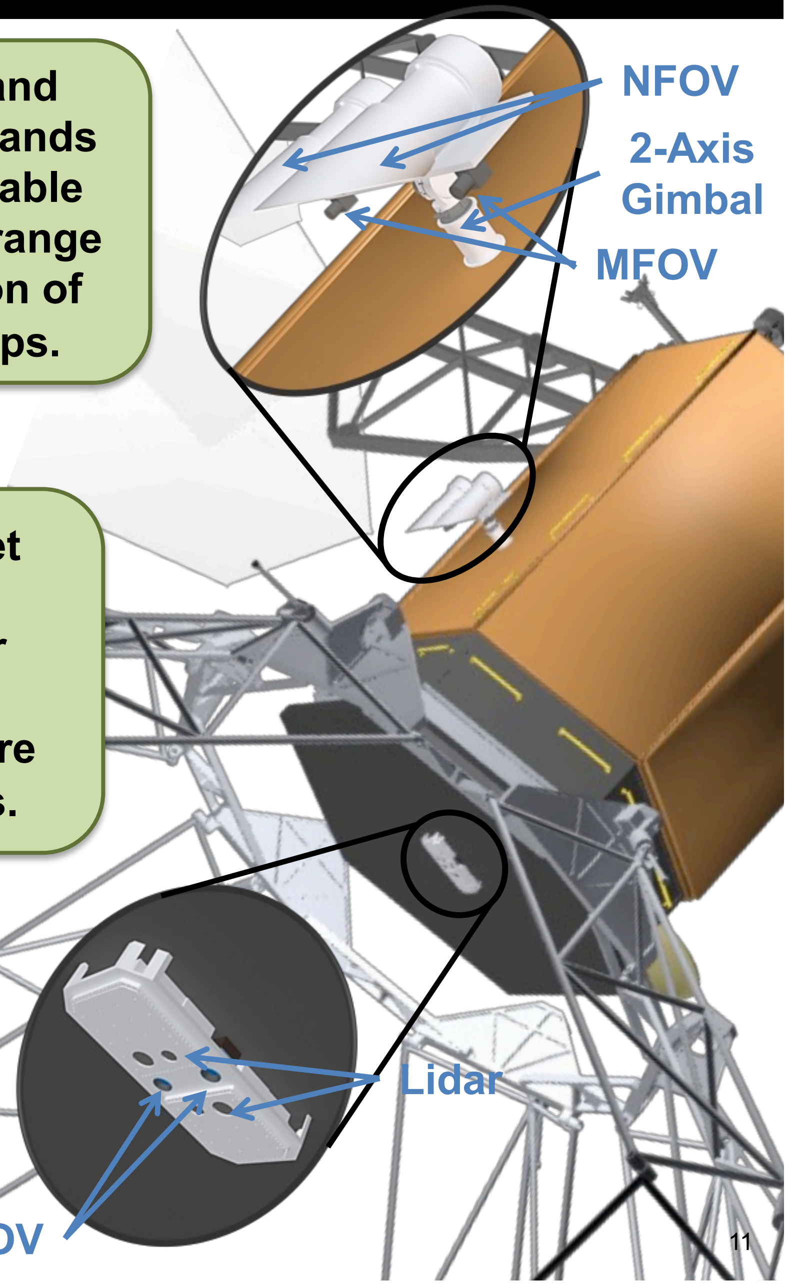
- Validation of optical nav techniques (Exploration).
- Video of ops for Exploration, Public Engagement, Science.
- Enhanced surface coverage, detailed internal structure (Science, Exploration).

Data collected to meet mission needs has extensibility value for science, public engagement, and future exploration activities.

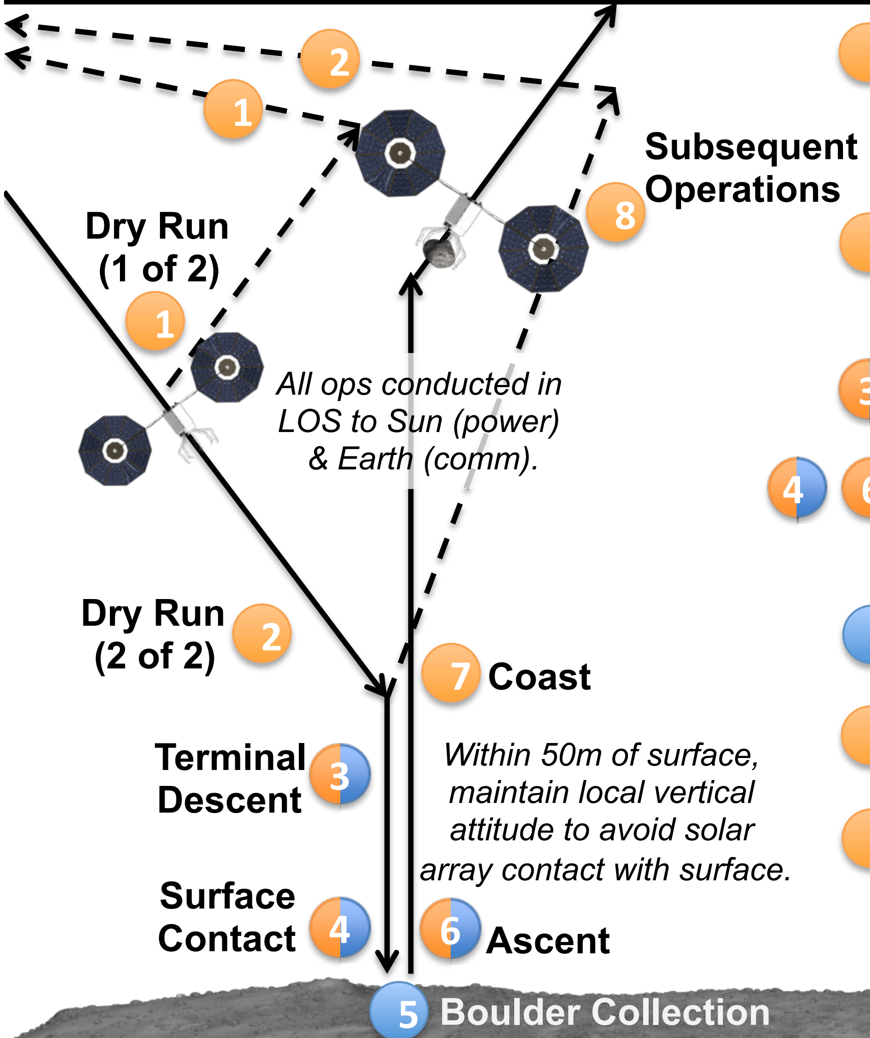
Ground Penetrating Radar

- Not required to characterize boulders.
- Provides further risk reduction through sub-surface imaging.
- Has extensibility value to both science and exploration.

Ideal Mission of Opportunity



Boulder Collection



1. **Dry Run (1 of 2):** *Refine local gravity* and increase *boulder characterization* while in *passively safe* trajectory. Sufficient time allocated between dry runs to downlink data, process data, and update spacecraft.
2. **Dry Run (2 of 2):** System verifies *closed-loop* Terrain Relative Navigation acquisition of landmarks for descent navigation by while in *passively safe* trajectory.
3. **Terminal Descent:** No nominal thrusting toward asteroid to *limit debris*.

4, 6 **Surface Contact/Ascent:** Contact arms allow *controlled contact/ascent*, provide stability, and limit debris. Thrusters provide attitude control and contingency ascent.

5. **Boulder Collection:** *Conservative* 120 minutes reserved, nominal ops estimated at 30 minutes.
7. **Coast:** Slow drift escape provides time to *establish mass properties* of the combined spacecraft/boulder system.
8. **Subsequent Operations:** As appropriate, transition to performing gravity tractor or subsequent capture attempt.

\# Operations heritage to prior robotic missions

\# Mission unique operations

Conservative, high-heritage operations mitigate risks during boulder collection operations to increase probability of successful boulder capture.

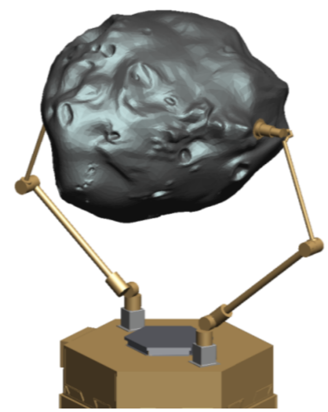
Capture System Trades

Performed an exploration of the tradespace:

- Hover vs. contact
- Degrees of freedom
- Single vs. multiple spacecraft
- Nets, bags, arms, clamshells, harpoons
- End effector type (microspines, claws, grippers)
- # of capture arms
- # of contact arms

Downselected to two capture systems that:

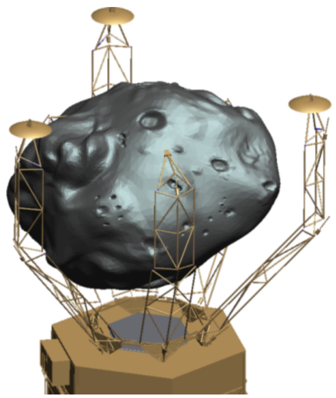
- Allow acquisition of up to a 70 t boulder autonomously
- Effectively constrain boulders during post-capture ops
- Facilitate crew operations at the boulder
- Support multiple capture attempts and boulder release



Cradle not shown.

<u>Hover-Mode Concept</u>:
7-DOF Arm Capture System

Two arm, high degree of freedom system that performs capture from hover. Modified from existing FREND / Phoenix / Restore arm.



Assumed for PoD mission operations

<u>Contact-Mode Concept</u>:
Spaceframe Capture System

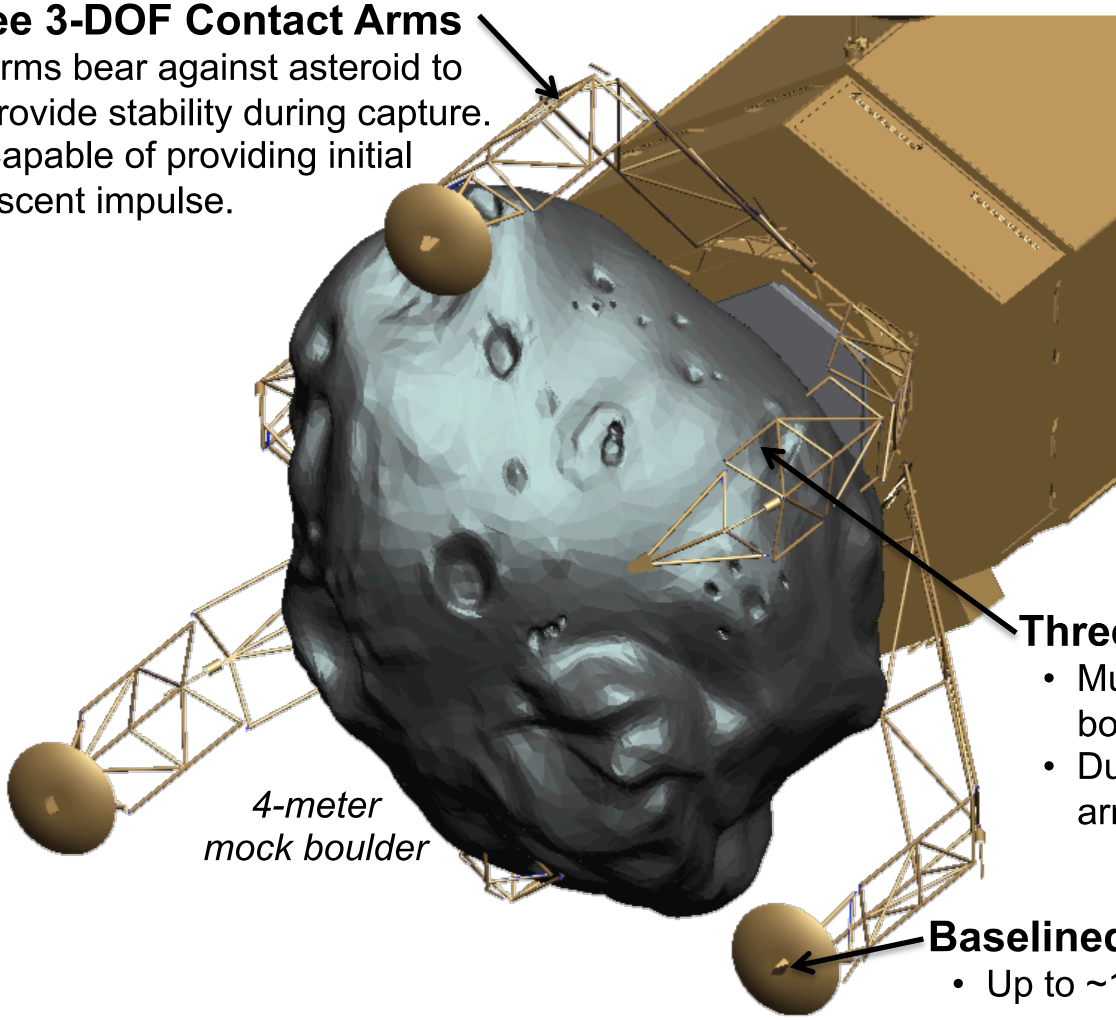
Spaceframe system with 3x 3-DOF Capture Arms and 3x 3-DOF Contact Arms. New development that leverages a simple design and heritage components.

Currently assessing both capture systems in hover and contact modes within the context of the entire mission to determine which best meets the concept's technical and programmatic needs.

Spaceframe Capture System

Leverages a simple design and heritage components to reduce costs and programmatic risks.

Three 3-DOF Contact Arms
- Arms bear against asteroid to provide stability during capture.
- Capable of providing initial ascent impulse.



Design & Test
- Common, MER-heritage hardware used across contact and capture arms to simplify design and reduce testing requirements.
- Full-scale testable in 1-G.

Controls
- Leverages control hardware and software from 7-DOF capture system concept investments to reduce costs.

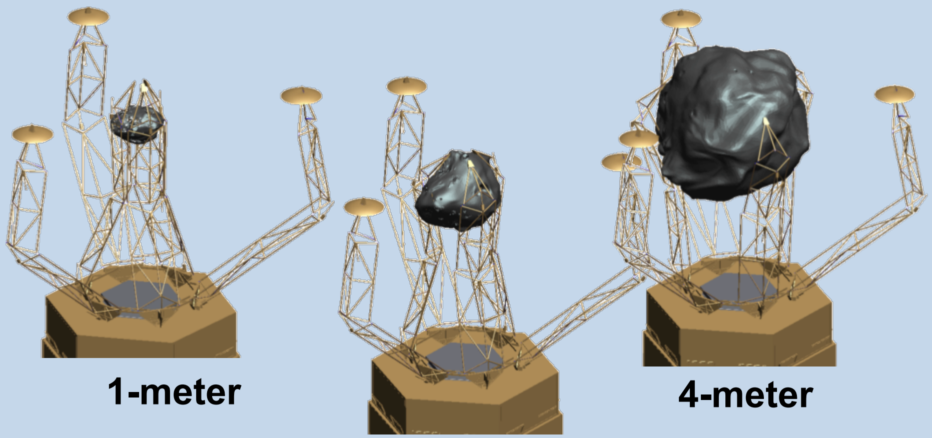
Three 3-DOF Capture Arms
- Multiple contact points to stabilize boulder.
- During capture, forces balanced across arms to minimize s/c attitude disturbance.

Baselined Contingency Sample Collectors
- Up to ~1 kg capacity per contact pad.

Scalability to Boulder and Asteroid Targets

Spaceframe Capture System Design

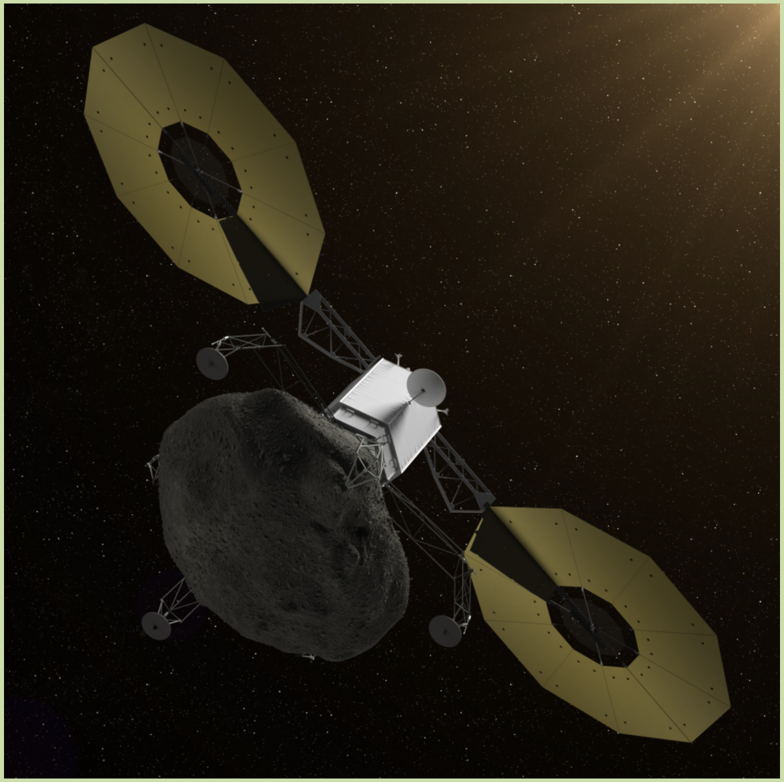
Accommodates 1 to 4 meters boulders.



(Itokawa-class: 2018 to 2024)

For a given asteroid target, arms can be sized to accommodate a wide range of boulder sizes, providing hundreds of potential boulder targets.

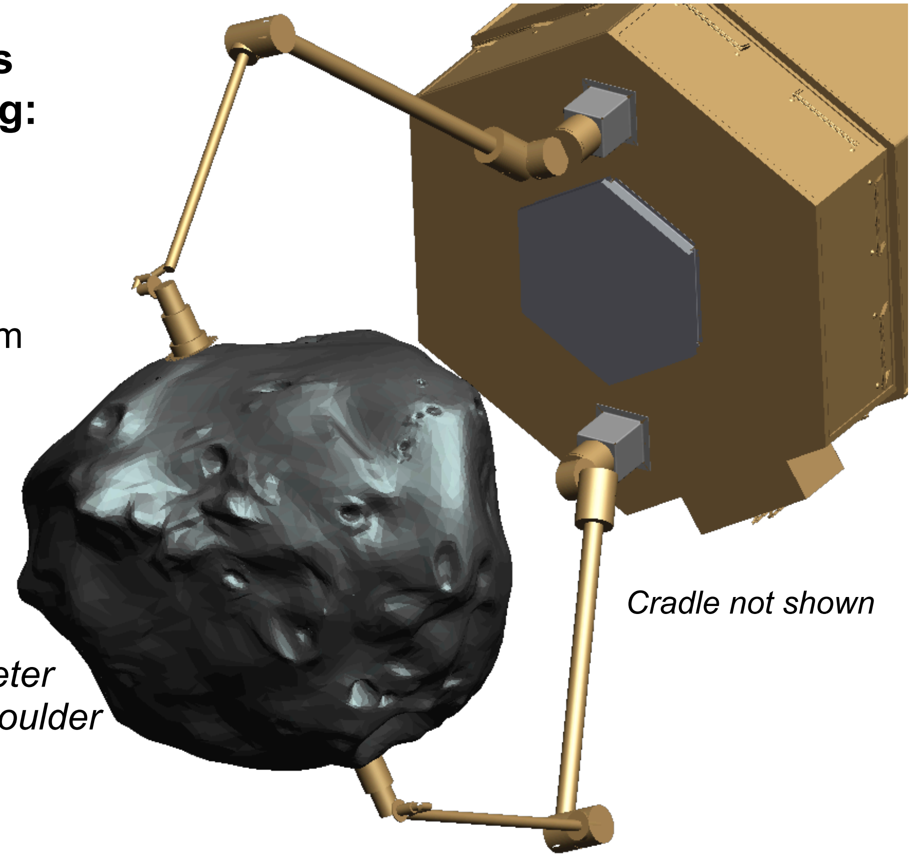
Capture System designs can be scaled to accommodate up to at least 10 m (~1000 t) boulders, allowing the flight unit to be tailored to handle the maximum mass returnable from an asteroid target.

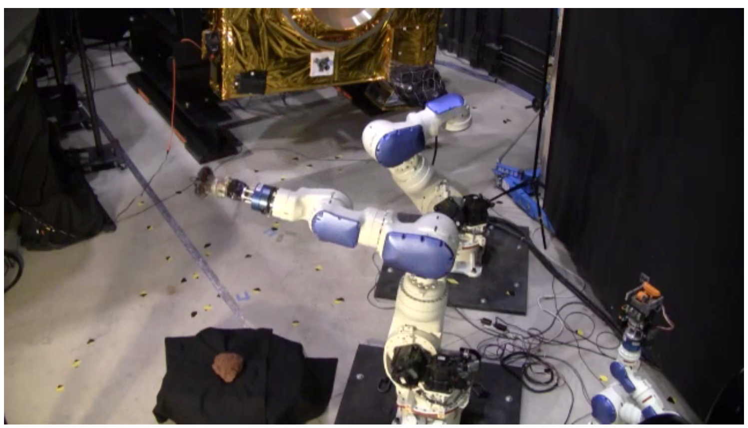


7-DOF Arms Capture System

Advanced flight-certified 7-DOF robotic arms and associated electronics design leveraging:

- Deep-space flight qualification heritage from Mars Exploration Program rovers
- GEO flight-qualified arm developed for DARPA's FREND program (satellite repositioning)
- Arm being developed for DARPA's Phoenix program (satellite harvest/reuse)
- Goddard maturing technology for >5 year life GEO satellite servicing





Video Credit: WVU / JPL / GSFC

Microspine picking up 5 kg rock, 12/3/2013

Note: 5 kg rock in 1 g is equivalent to a ~500 t rock on Itokawa

Microspine gripper end effectors :

- Opportunistically catch on pits, ledges, and slopes on the surface of a rock
- Move independently of neighboring spines
- Load share through mechanical compliance
- A hierarchical solution conforms at multiple length scales (millimeter, centimeter and decimeter scales).

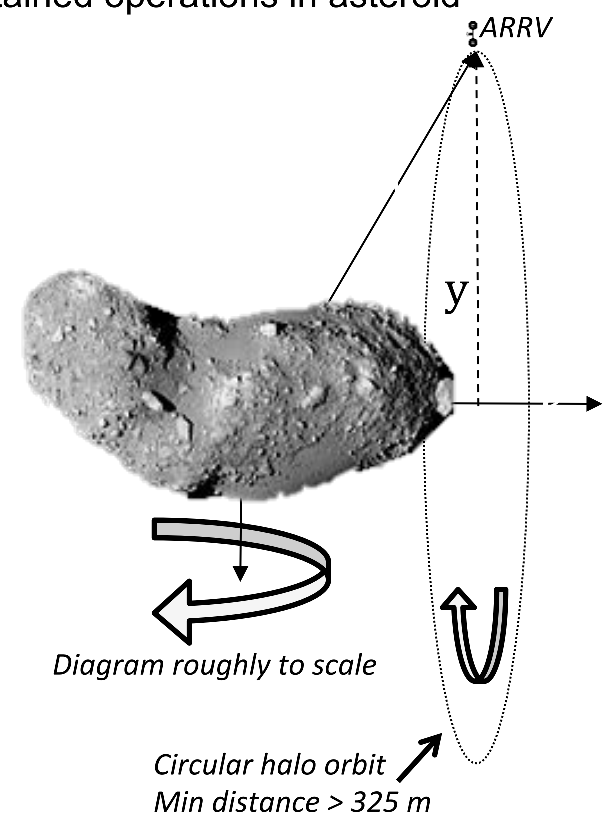
Planetary Defense Demonstration

Planetary Defense Options	Alternate Capable?
Kinetic Impactor	✓
Enhanced Gravity Tractor (EGT)	✓
Gravity Tractor	✓
Ion Beam Deflection (IBD)	✓

Selected Enhanced Gravity Tractor for PoD

- Relevant to potentially-hazardous-size NEAs: efficiency increases as boulder and NEA masses increase.
- Leverages collected boulder mass.
- Allows spacecraft to maintain safe, constant distance from NEA.
- Demonstrates sustained operations in asteroid proximity.

Alternate Approach demonstrates applicability of Enhanced Gravity Tractor on potentially-hazardous-size NEA (i.e. Itokawa). Currently comparing EGT and IBD.

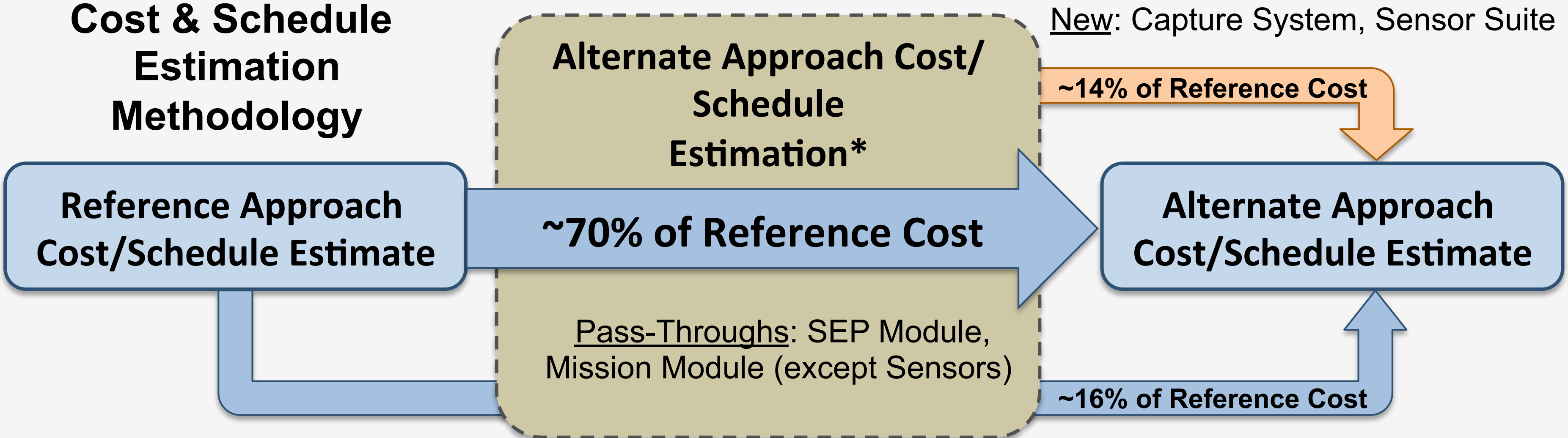


PoD Enhanced Gravity Tractor Concept of Operations

- Phase 1: Fly in close formation with the asteroid with collected boulder (60 days required for measurable deflection with 120 days of reserve performance).
- Phase 2: Wait for orbital alignment to become favorable to allow measurement of deflection beyond 3-σ uncertainty (~8 months from start of Phase 1).

Cost & Schedule Status

Cost & Schedule Estimation Methodology



Scaled: Project Management, Systems Engineering, Mission Assurance, Project I&T, Mission Design, Mission/Ground Ops

To ensure apples-to-apples comparison, the Alternative Approach team has used cost & estimate assumptions consistent with the Reference Approach.

Significant differences (e.g. >5%) in the concepts' costs will only occur if there are substantial differences (e.g. >36%) in the concepts' capture system and sensor suite costs.

Will deliver cost/schedule estimates.

Estimates will be delivered with a cost assessment led by Michael Soots (JSC)

Forward Plans

- Complete initial cost and schedule estimates and support independent JSC cost assessment
- Refine return mass estimates for launch, return and time on target for candidate targets and perform power level trades for candidate targets
- Further refinement of capture system designs and proximity operations to enable down-select
  - Further assess system performance at identified candidate targets including assessment of closed-loop autonomous navigation
  - Additional simulation of initial surface contact with contact arms and energy attenuation
  - Additional simulation of initial surface contact with capture arms and boulder interaction
  - Further assess scripted autonomous operations for boulder acquisition
  - Further assess ascent phase control and mass properties variability
  - Additional demonstration of capture system subscale models
  - Further develop capture system test plan
- Comparison of planetary defense options and applicability to actual Earth-threatening objects
  - Additional simulation of enhanced gravity tractor operations and assessment of ion beam deflection
  - Additional radio science studies for candidate targets
- Continued Robot Concept Integration Team (RCIT) Support
  - Concept comparisons, Figures of Merit (FOM) assessment, and risk evaluations
  - JSC Engineering independent capture system and proximity operations assessment

Closing Remarks

A robust, risk informed mission design to ensure objective satisfaction.

The Alternate Approach offers broad Stakeholder benefits.

Robust Target Set

- Primary target with precursor (Itokawa)
- Hundreds of accessible boulder targets
- Multiple NEAs with planned precursors (Bennu and 1999 JU_3) and/or radar characterization

Robust to Programmatic Uncertainties

- Viable multi-ton return mass over a wide range of departure and return dates
- Ability to adjust target boulder during mission

High Probability to Return a Boulder and Spacecraft Safety

- Heritage operations
- Extensive characterization phase
- Multiple collection attempts and release capability
- Low NEA spin rate (revs per day vs. per min)

Human Exploration

- Multiple Mars forward technology and operations
- Exploration target
- Robust to programmatic uncertainty

Planetary Defense

- Measurable deflection of a *hazardous-sized NEA*
- Multiple techniques on a relevant target, including option to test a kinetic impact approach

Science

- Sample that is well characterized with geologic context; selectable by science community
- Potential for hosted payloads

Commercial & International Partners

- Potentially volatile/water -rich carbonaceous material
- Potential for hosted payloads