National Aeronautics and Space Administration

Asteroid Redirect Mission (ARM) Robotic Boulder Capture Option (Option B)

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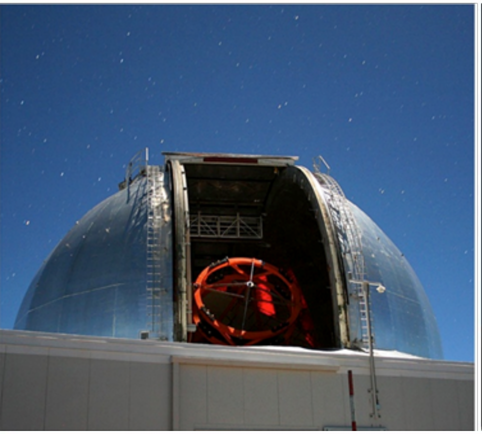
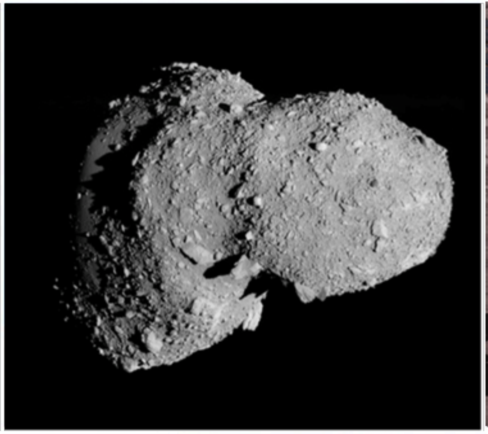
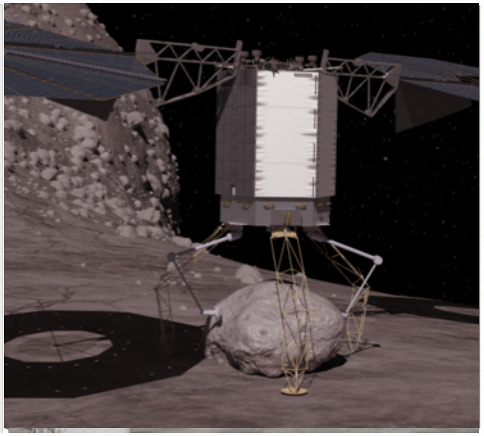
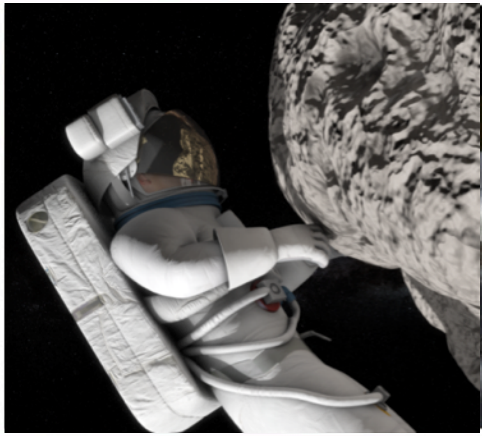





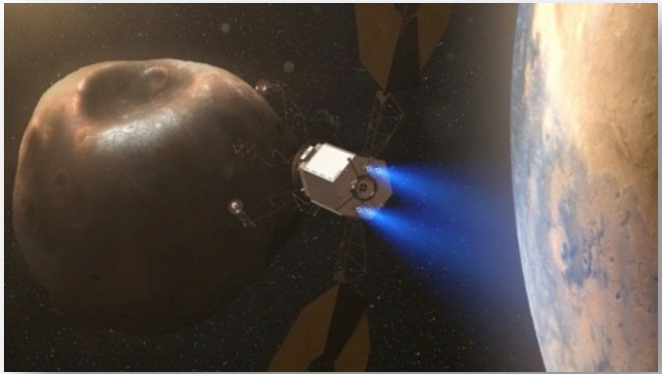
11th Meeting of the NASA Small Bodies Assessment Group – July 30, 2014

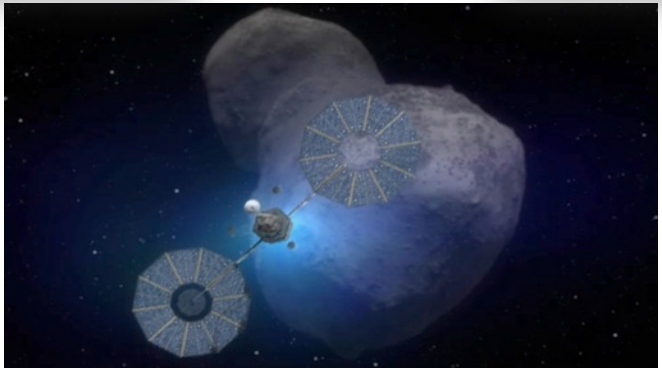
Robotic Boulder Capture Option Mission Overview

Utilizes a risk-informed design strategy to develop a mission that meets the following primary objectives.

Return a boulder from the surface of a large Near-Earth Asteroid (NEA) to a stable lunar orbit.

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





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

Image Credits:
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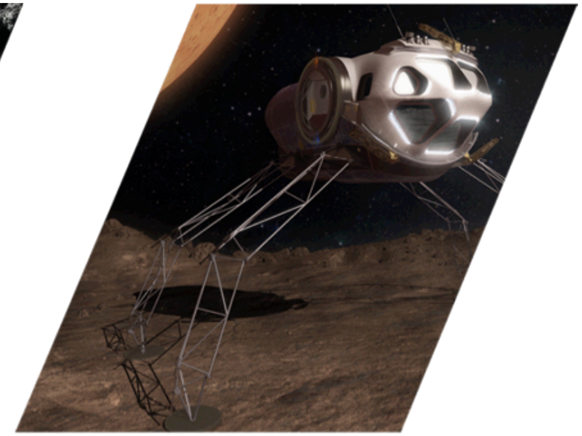
Stakeholder Benefits

Initial Human Mission

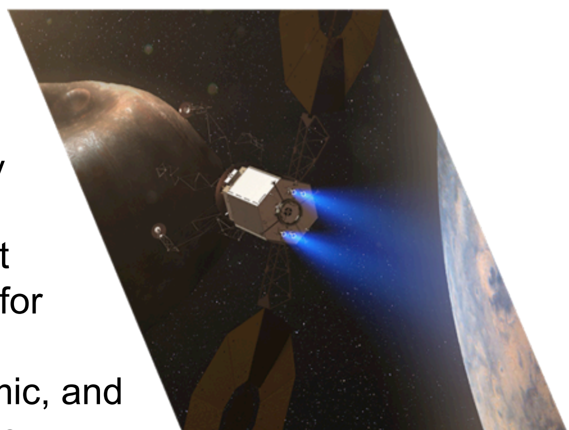
Provides a well-characterized, accessible, multi-ton boulder for astronauts to explore and return samples from, using a mission approach that is robust to programmatic uncertainties.

Mars Forward



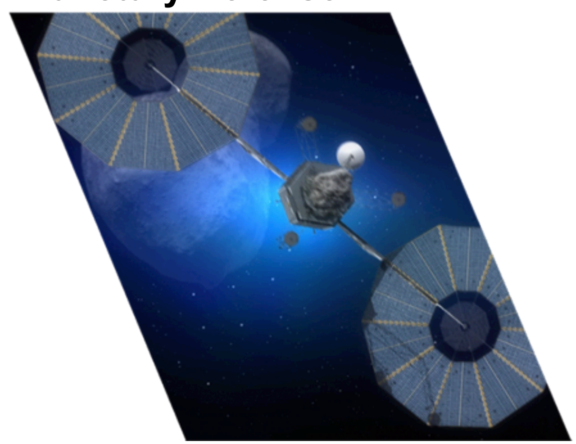
Addresses and matures multiple Mars-forward technology and operations gaps, including operations near and on the Martian moons, Phobos and Deimos.

Science & Resources



Returns a well-characterized, community-selected sample. Provides access to potentially volatile/water-rich carbonaceous target and the opportunity for hosted payloads – commercial, academic, and international partners.

Planetary Defense



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

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

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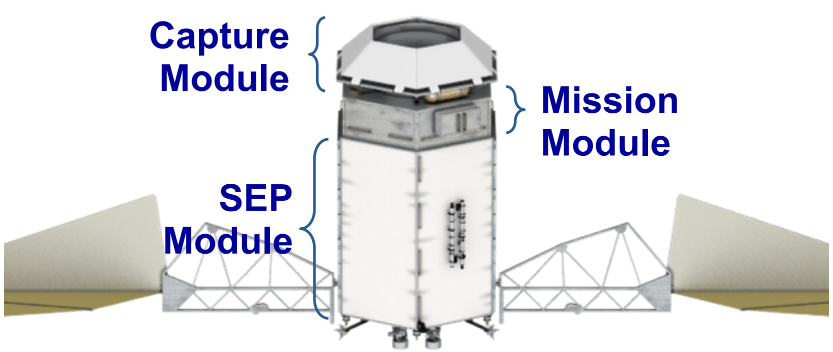
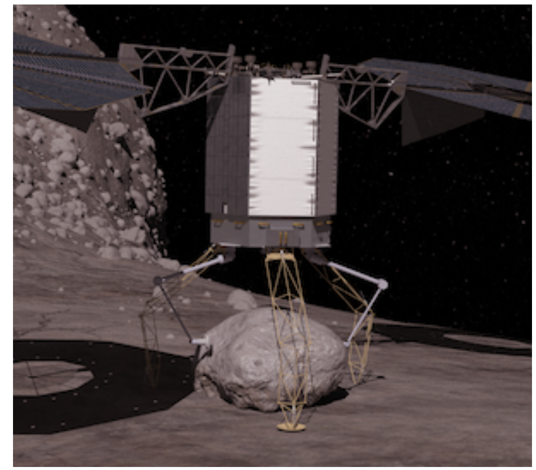
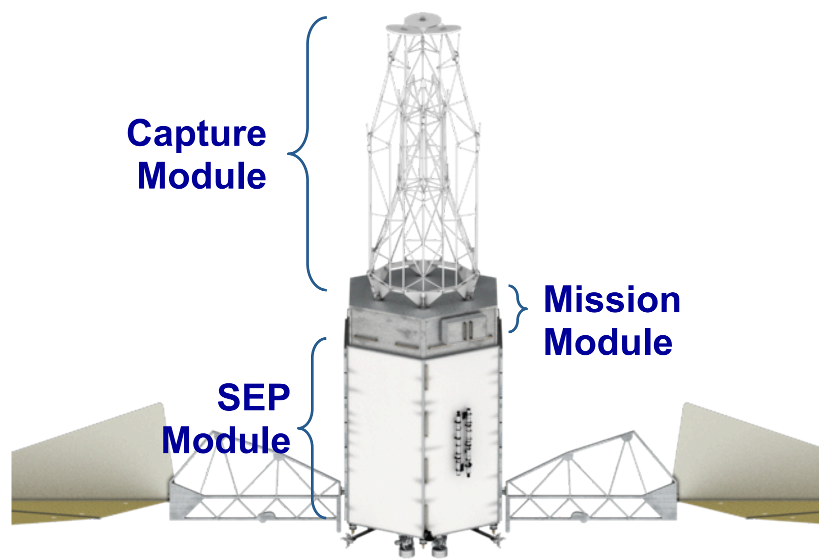
Asteroid Redirect Mission Robotic Concepts

Small Asteroid Capture



Robotic Boulder Capture





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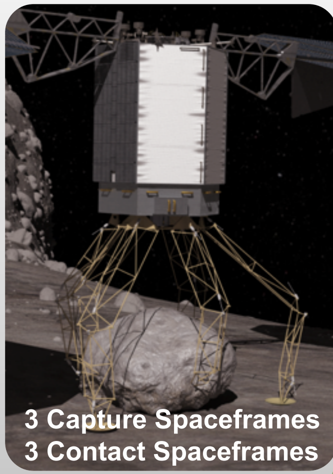
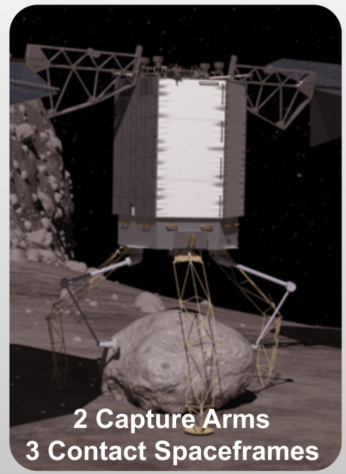
Proximity Operations and Capture System Options

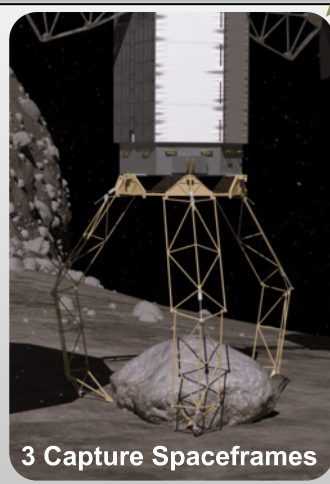
3-DOF Spaceframe | **Hybrid** | **7-DOF Arms**

Contact NEA





Hover



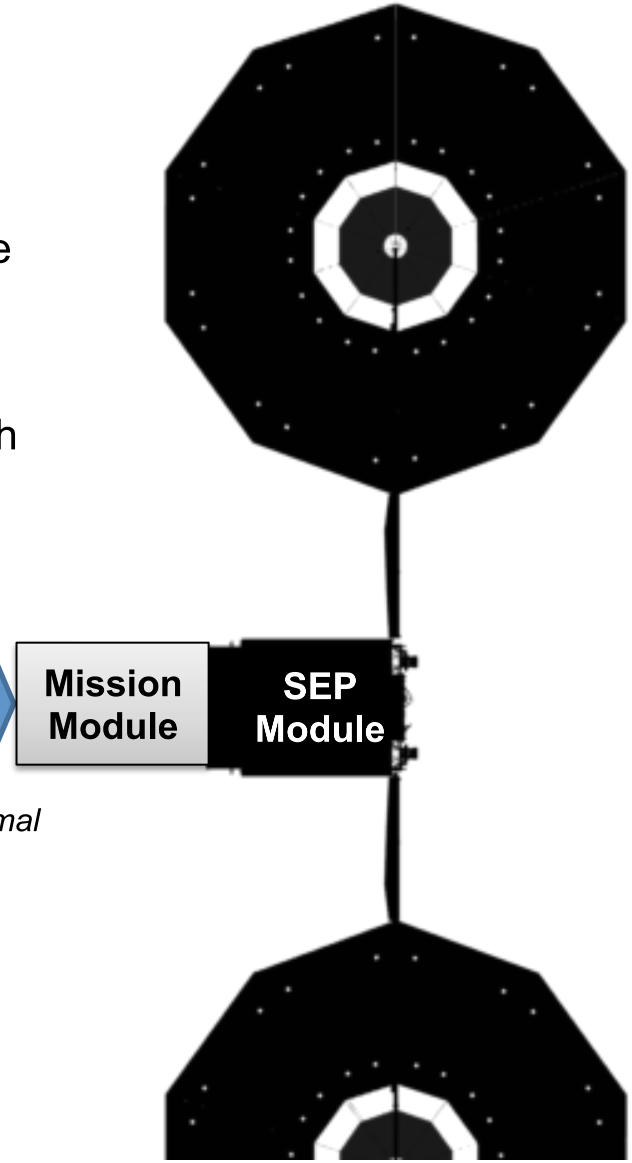
3 options assessed

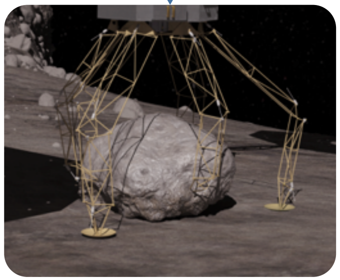
DOF = Degree of Freedom

Image Credits: NASA/AMA, Inc.

Modular Spacecraft Approach

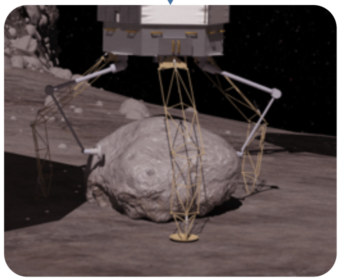
- Allows integration and functional testing of entire Capture Module (mechanism, avionics, sensors, software) prior to system integration.
- Streamlines the interface between the Capture Module and the Mission Module, but increases management and systems engineering.
- Promotes reuse of SEP Module & Mission Module designs with minimal changes as the Capture Module contains the majority of the mission-specific hardware.





Spaceframe

7-DOF Arms



Hybrid

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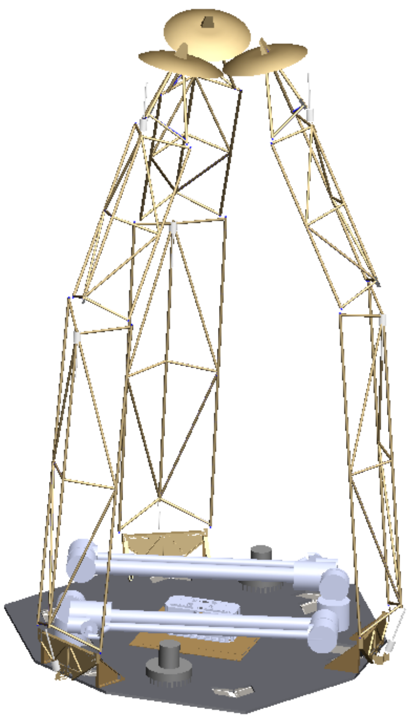
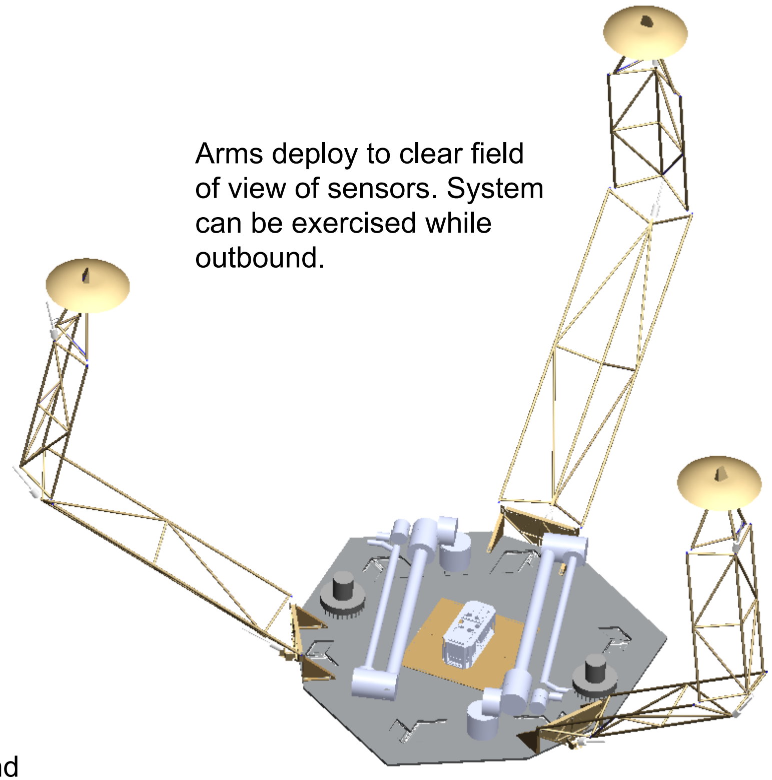
Hybrid Option Design

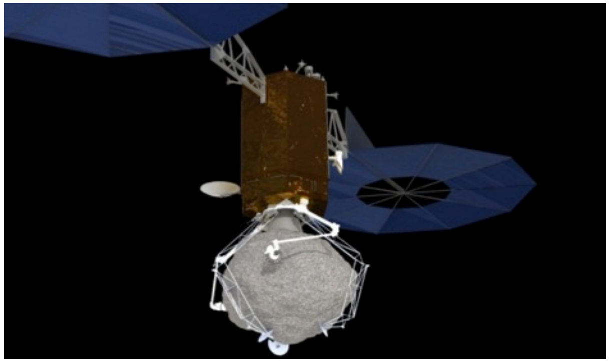
- 7-DOF Arms and microspine grippers are built and tested in parallel to Spaceframe contact arms
- Assembles as single module for integration with the S/C bus



Contact Arms pinned at pads and 7-DOF arms pinned to deck for launch.



Arms deploy to clear field of view of sensors. System can be exercised while outbound.



Contact Arms with Sample Collectors and boulder constraint after capture.

Testing of microspine gripper prototype

Hybrid capture system optimizes functionality and maximizes extensibility of concept.

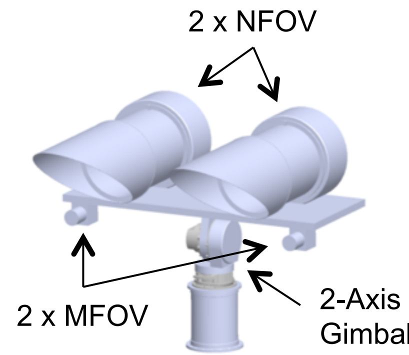
Image/Video Credits: NASA

Sensor Selection

Sensor Suite

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

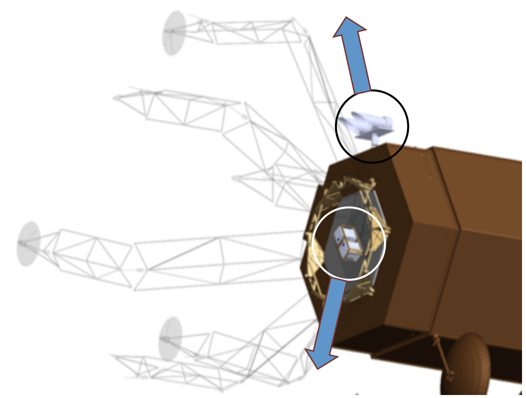
The use of multiple redundant systems enable identification and characterization of thousands of boulders in the returnable mass range, long-/close-range navigation, and execution of autonomous capture ops.



Extensibility Benefits

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

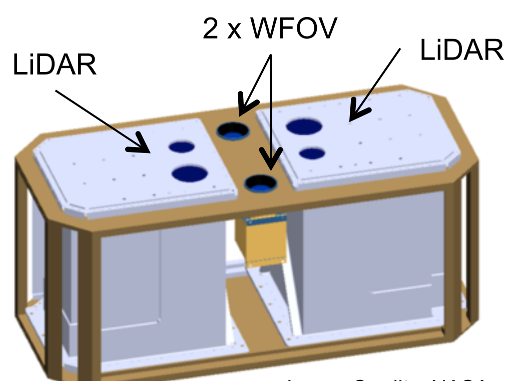
Long characterization and imaging phases collect data to meet mission needs and provides value for science, public engagement, and future exploration activities.



Ground Penetrating Radar

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

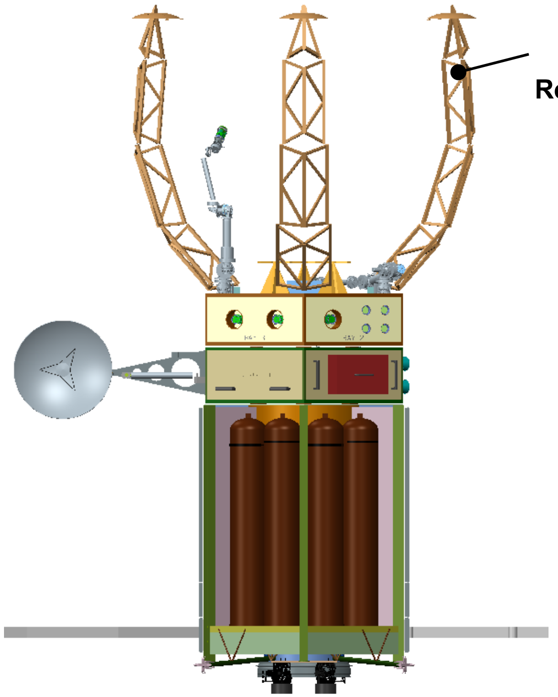
Ideal Mission of Opportunity



FOV = Field of View

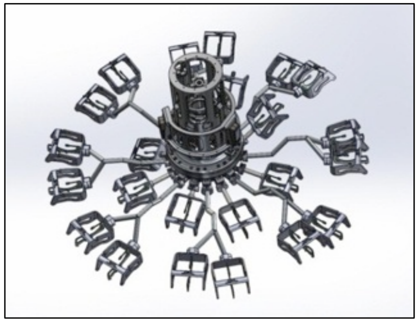
Image Credits: NASA

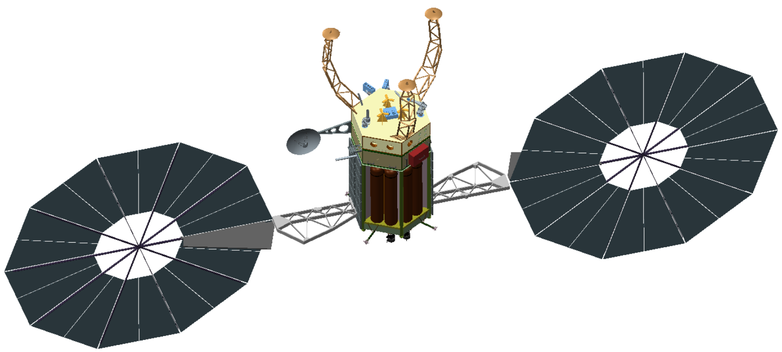
Updated Option B Hybrid Approach Configuration

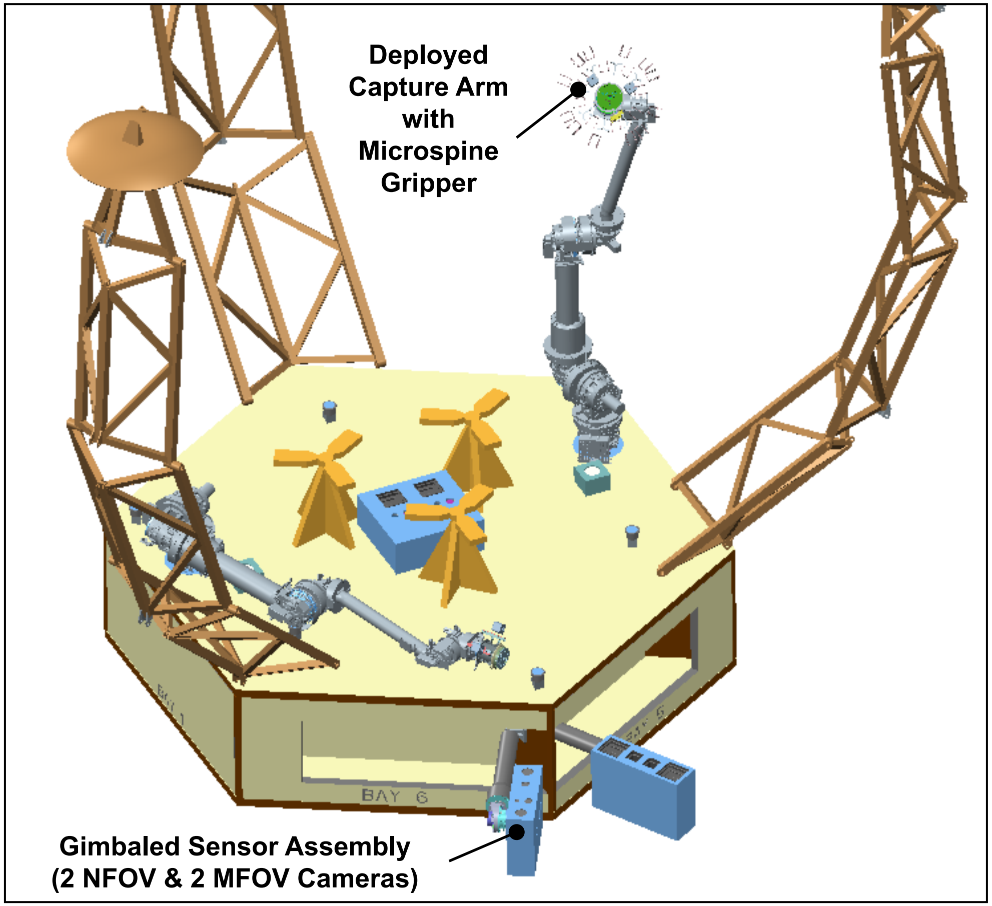


4-Segment Contact and
Restraint Subsystem (CRS)

Microspine Gripper
Version 2.0

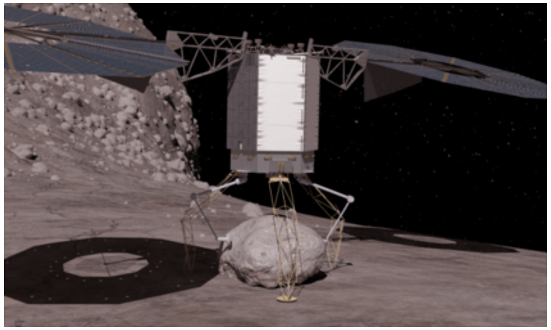






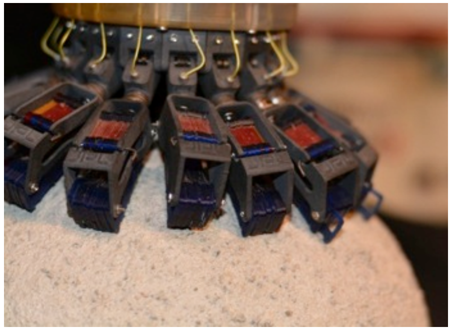
Images at Different Scales

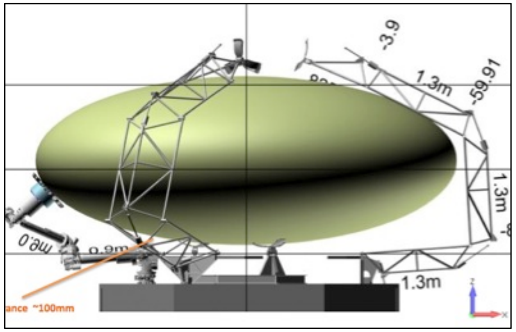
Option B Development and Risk Reduction

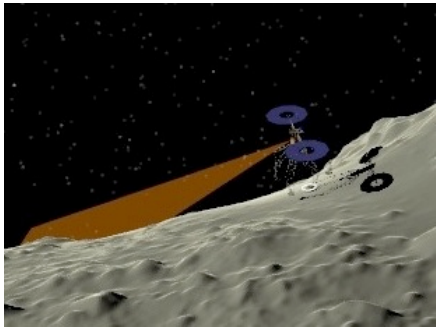


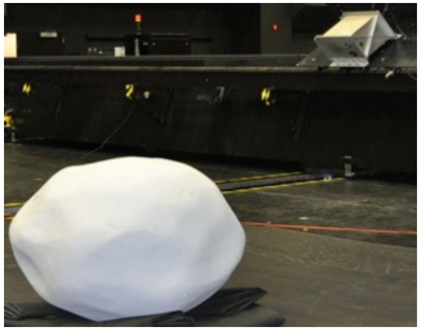
Option-B Capture System Risk Reduction Testing

- Four major activities to reduce engineering and technology development risks for the hybrid approach this year
- Tests scheduled to complete prior to December down-select









Capture Arm & Gripper

- ***Full scale testing of Microspine gripper and 7-DOF robotic arm***
- Initial boulder material sensitivity study 6/11
- Optimized Microspine 2.0 peer review held 6/25
- Microspine 2.0 fab started
- 2.0 testing August-October

Contact/Restraint "Legs"

- ***Full scale 2-D flat-floor testing of descent contact, ascent, & boulder restraint***
- CRS design geometry studies completed 6/1
- Peer review held 6/24
- Fab started, complete Aug.
- Restraint testing in Fall
- Ascent testing in Fall

Closed-Loop Sims

- ***6-DOF simulations of descent, surface operations, & ascent***
- Open-loop simulations of descent trajectories completed 5/28
- Initial closed-loop testing started 6/3
- ADAMS analysis of landing/ascent ongoing

Relative Navigation

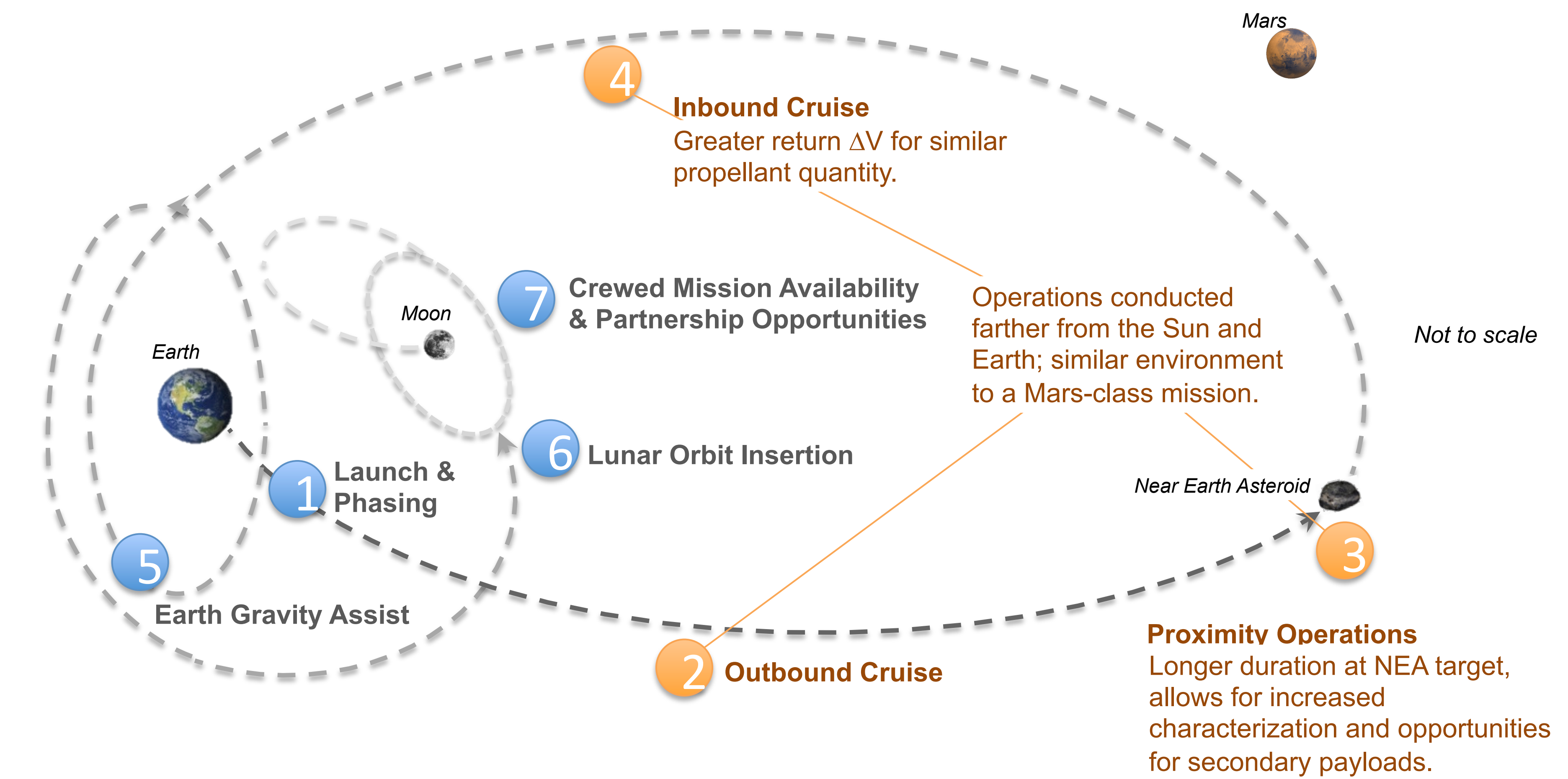
- ***Sensor and algorithm testing to validate relative-nav approach***
- Completed imaging of boulder mockup with Lidar sensor 6/6
- Data in process of being run through navigation algorithms in July-August

Image Credits: NASA/AMA, Inc.

Mission Design

Similar for Both Options

Different for Robotic Boulder Capture Option



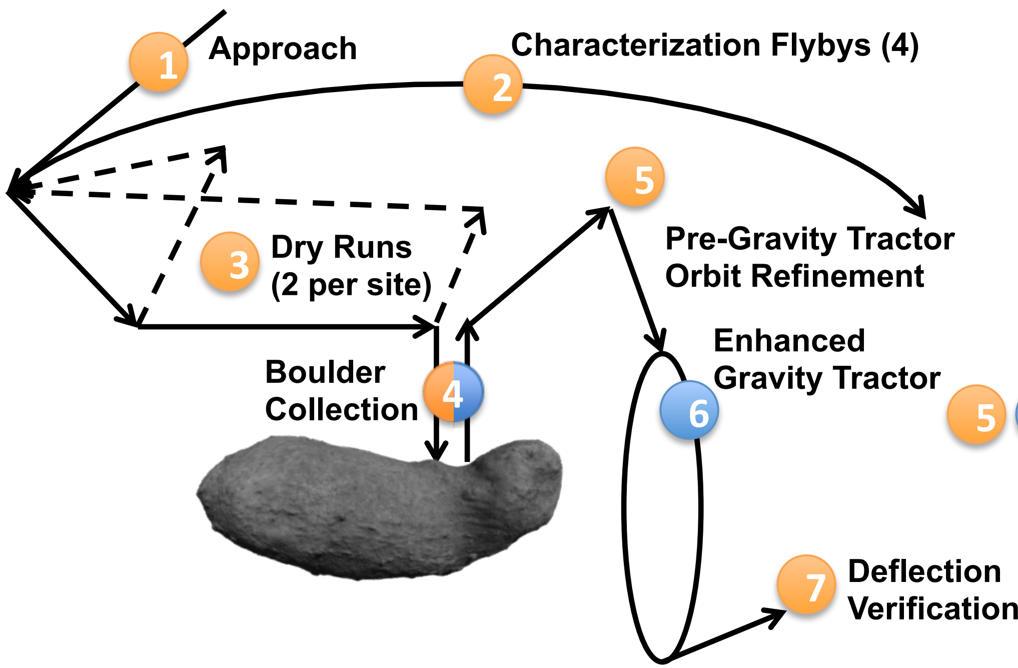
Proximity Operations Overview

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:** 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:** 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.

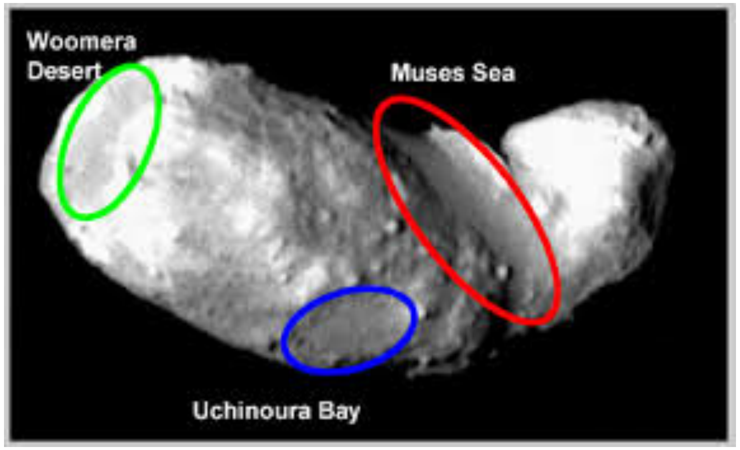
Operations Margin: In addition to conservative operations profile, reserve is provided in mission plan.

Proximity operations having a high heritage, along with a conservative operations strategy.

Robotic Boulder Capture Mission Overview

Animation Credit: NASA/AMA, Inc.

Itokawa's Boulder Rich Surface



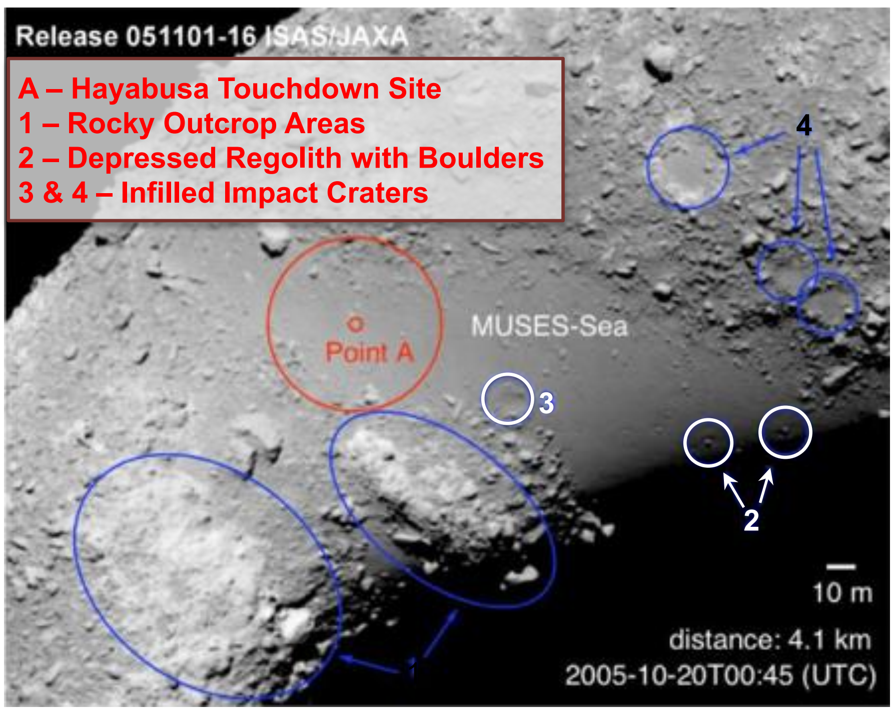
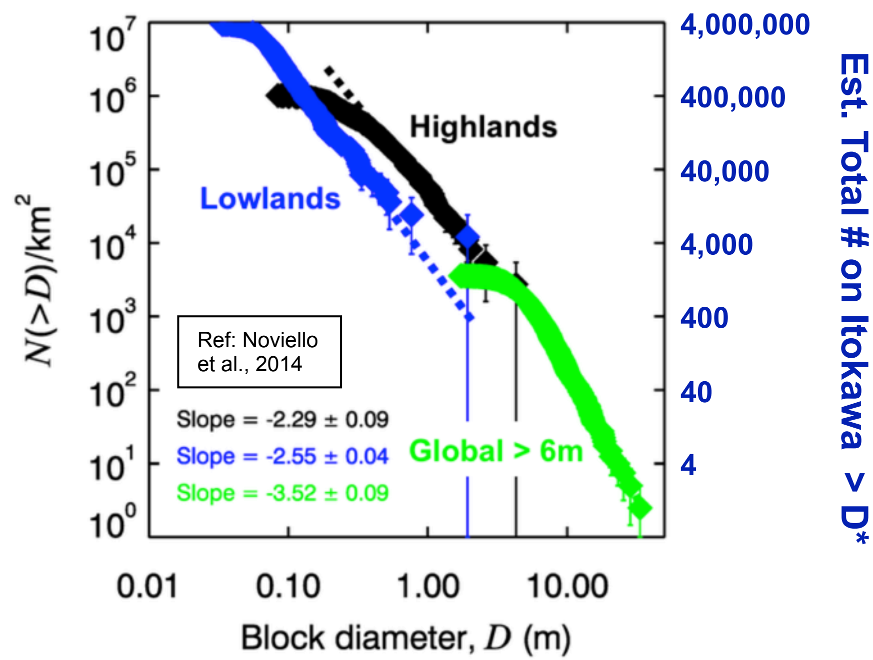


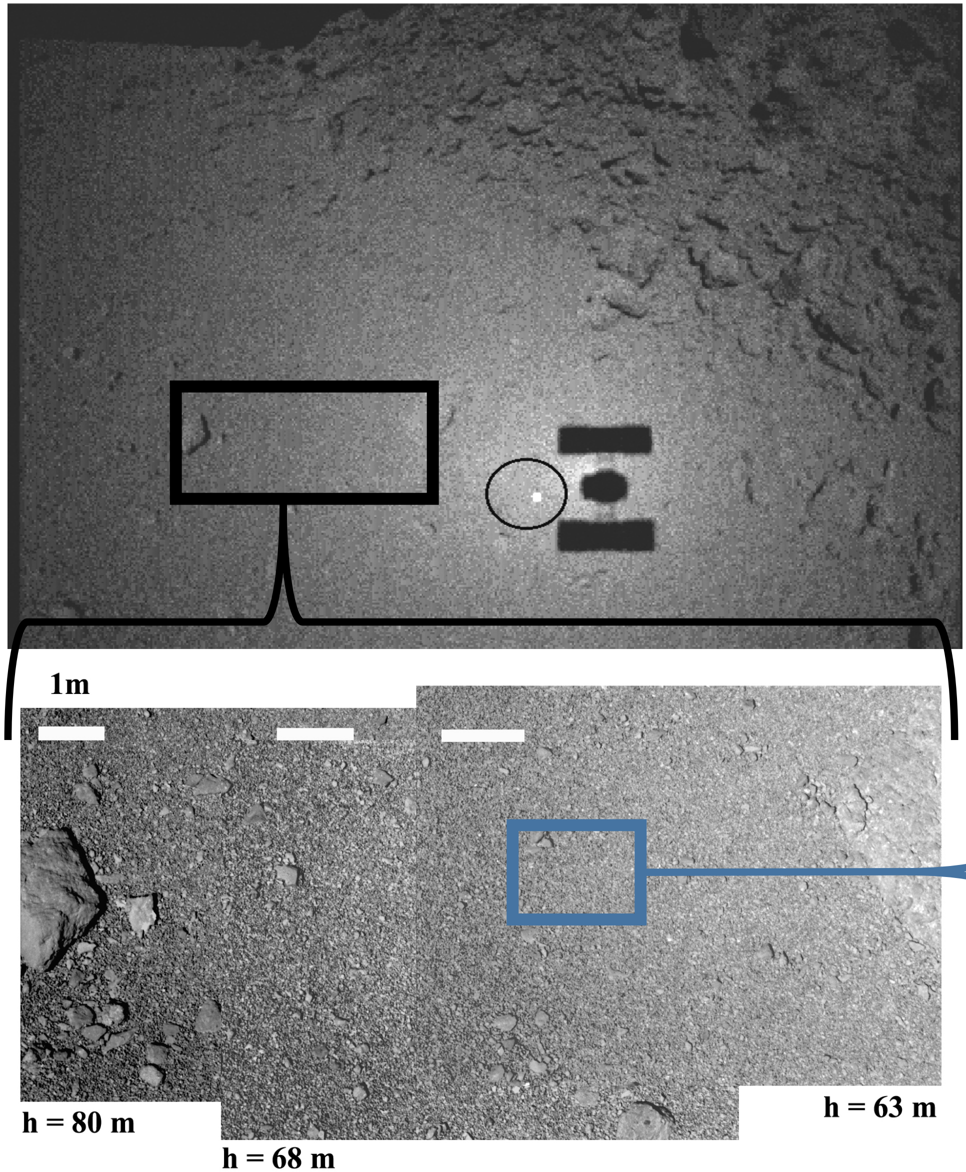
Image Credits: JAXA

- 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
- Boulders are believed to be generated by impacts and appear to be common on NEAs.



* Added axis based on Itokawa surface area of 0.4011 km²

Hayabusa Touchdown Site Approach

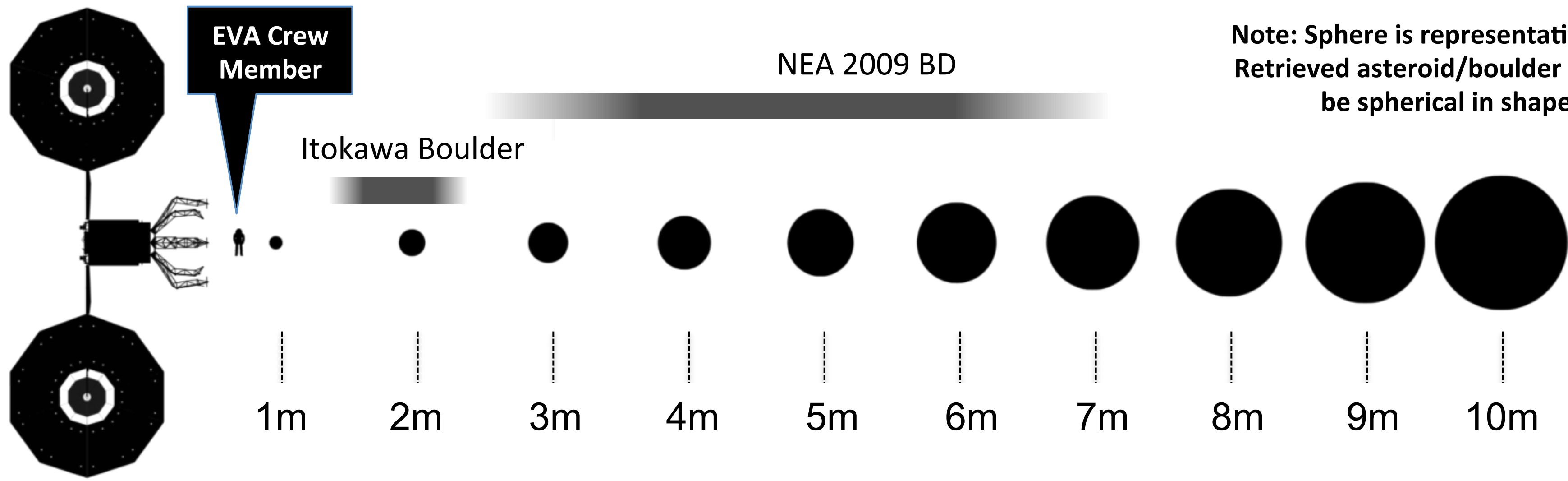


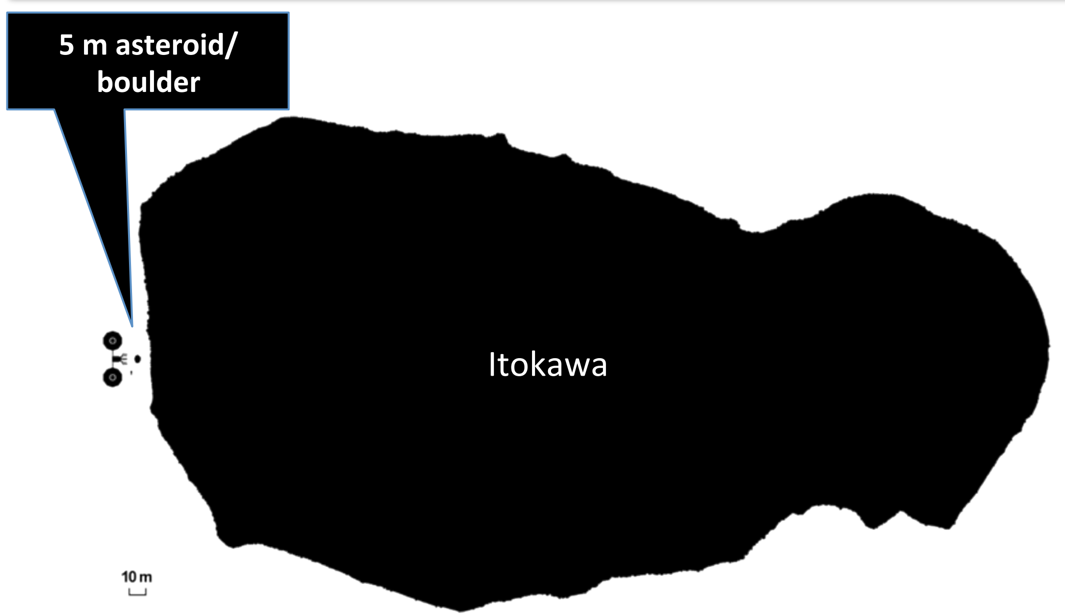
- Smooth areas have boulders sitting on a surface dominated by gravels and pebbles. Stereo image analysis indicates a high probability that some boulders are not embedded.
- Highest resolution of the images during the Hayabusa touchdown are 6 to 8 mm/pixel.
- Evidence from Hayabusa and ground-based radar 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.

Image Credits: JAXA

Size Comparisons

Note: Sphere is representative only. Retrieved asteroid/boulder will not be spherical in shape





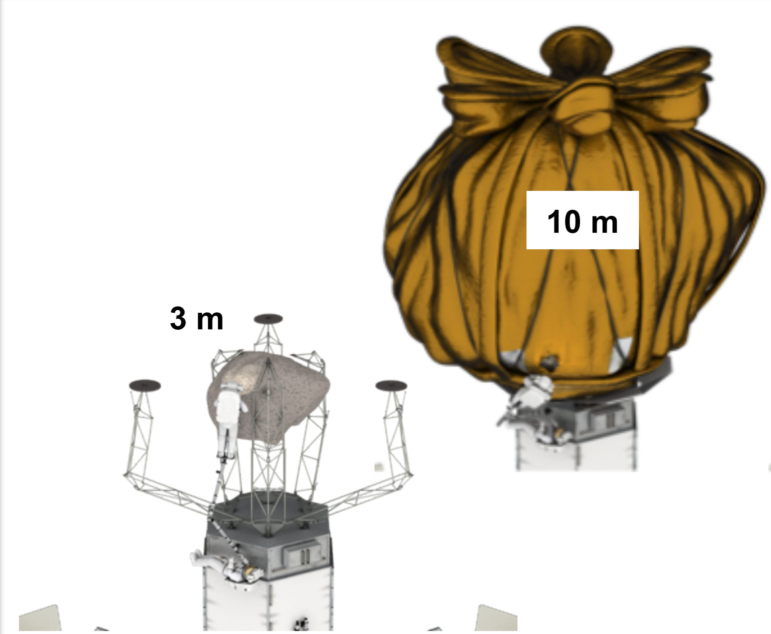


Image Credits:
NASA/AMA, Inc.

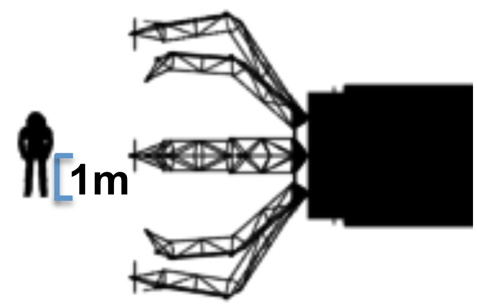
Boulder Mass and Size and Density

NEA Type

Mass (t)	Metallic 5.2 g/cm^3	Stony 3.22 g/cm^3	Carbonaceous 1.62 g/cm^3
1	0.7 m	0.8 m	1.1 m
10	1.5 m	1.8 m	2.3 m
20	1.9 m	2.3 m	2.9 m
30	2.2 m	2.6 m	3.3 m
40	2.5 m	2.9 m	3.6 m
50	2.6 m	3.1 m	3.9 m

Note: Assumes spherical extent

Observed size is a key characteristic of the object returned.



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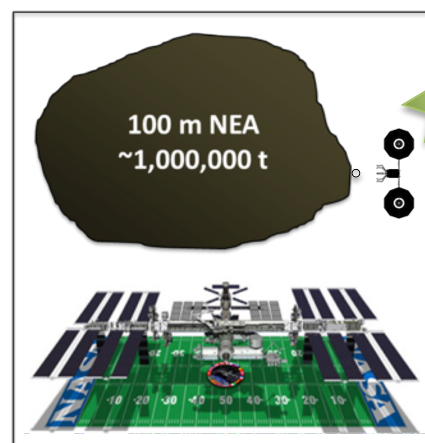
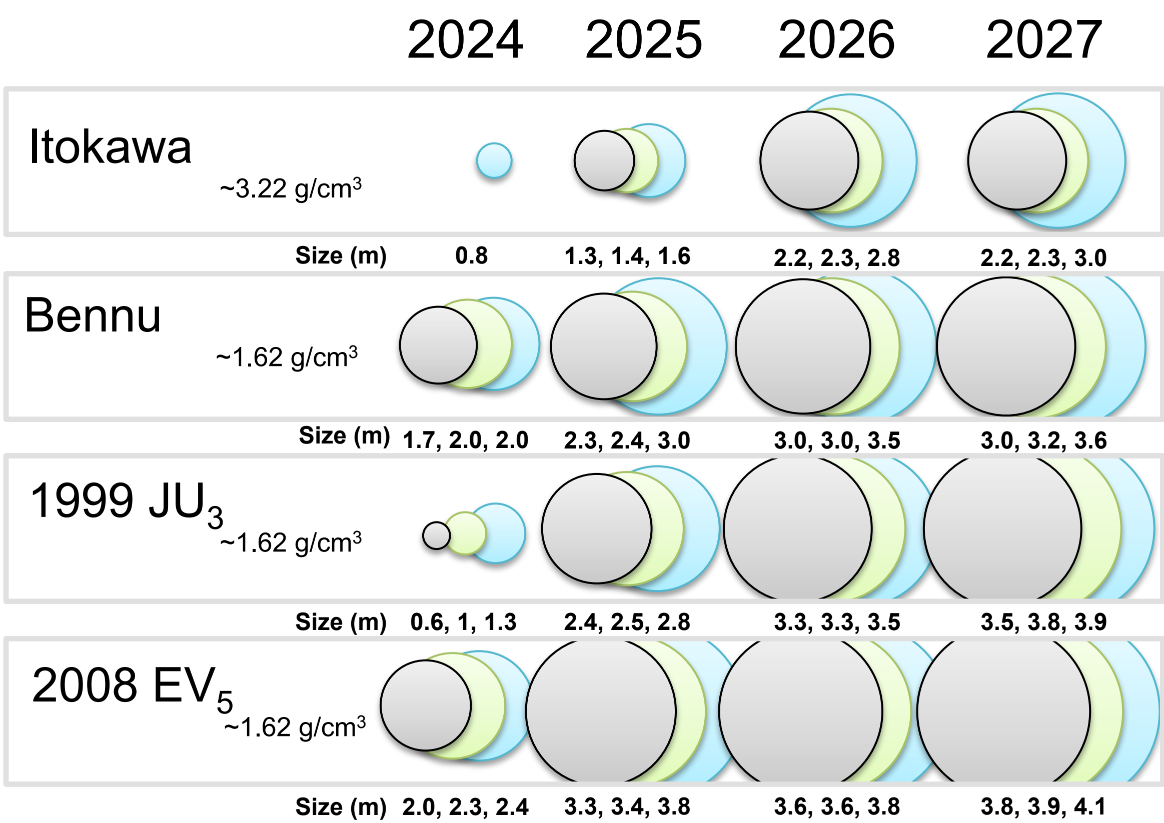
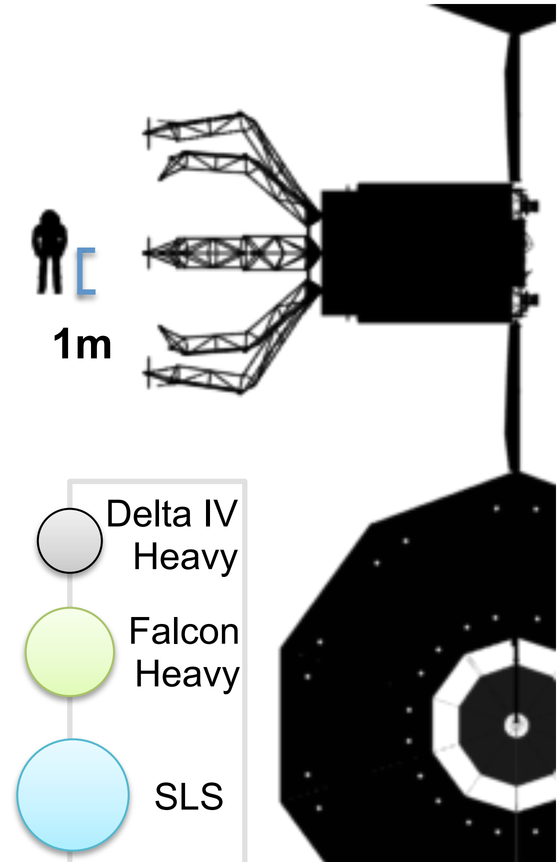


Candidate Target Boulder Return Sizes

Launch no earlier than June 2019

Crew Availability in stable LDRO in February - May of:





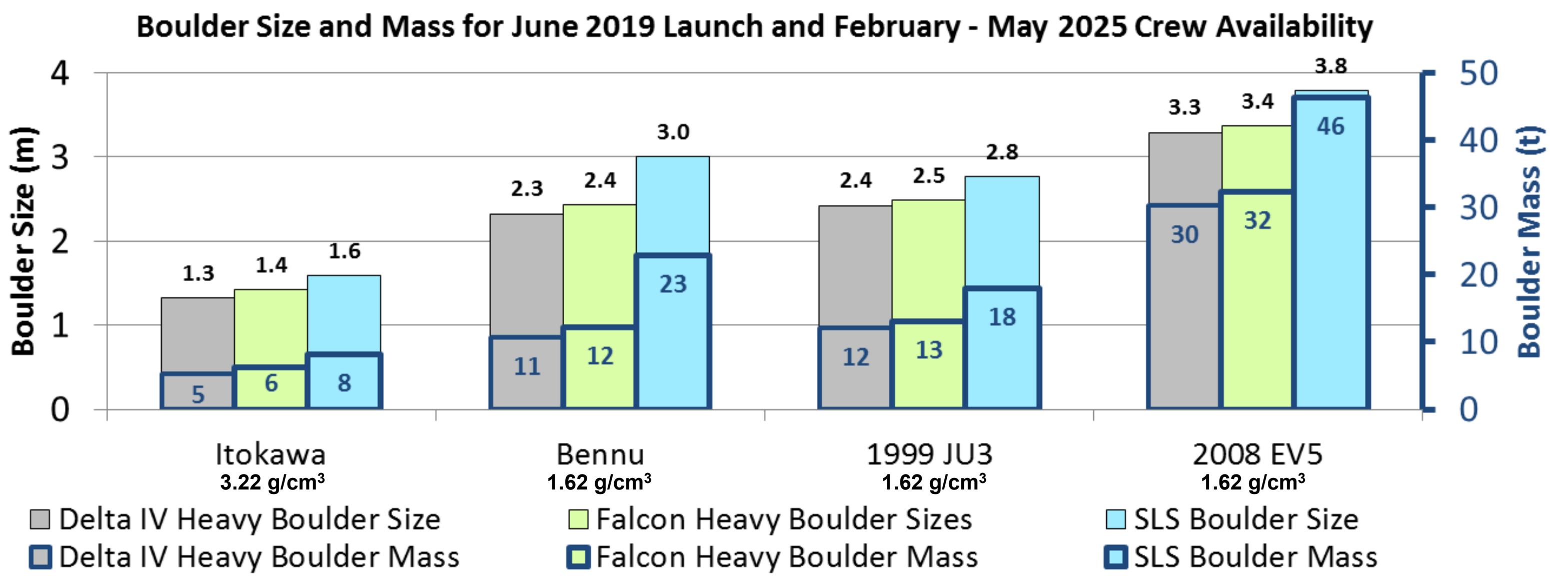
Note: Atlas V 551 performance not assessed.

Image Credit: NASA/AMA, Inc.

Robotic Boulder Capture Option has a set of candidates that are robust to changes in return dates.

Target Availability and Boulder Size and Mass

- One Valid Candidate with hundreds of candidate boulders: **Itokawa**
- Two candidates planned to 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$_{46}$**

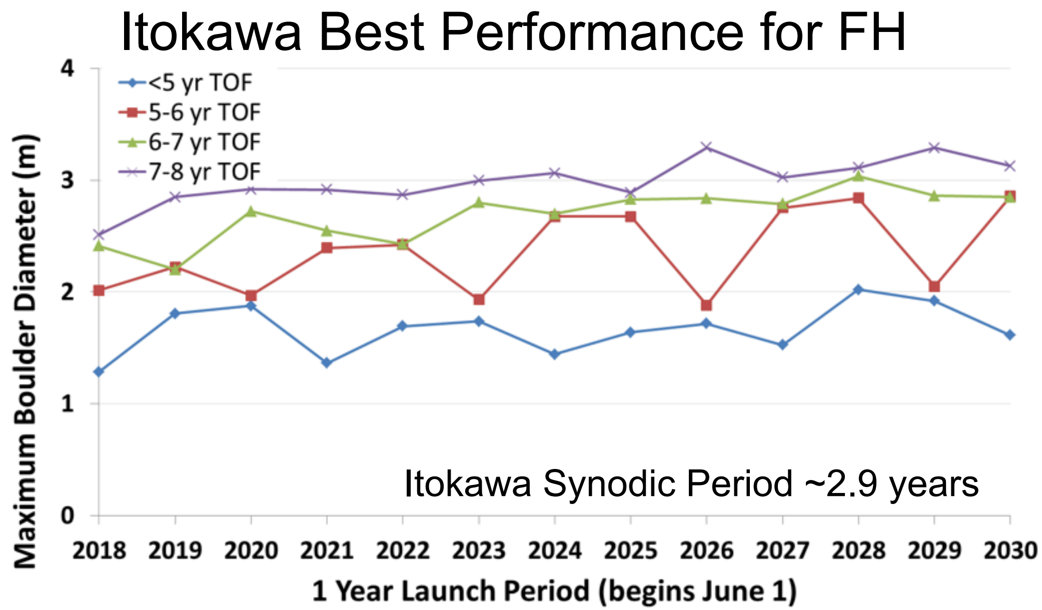


Spherical maximum returnable boulder size ranges from 1.5 m to 4 m enabling a large range of boulder size for retrieval.

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

Returnable Boulder Size Trends

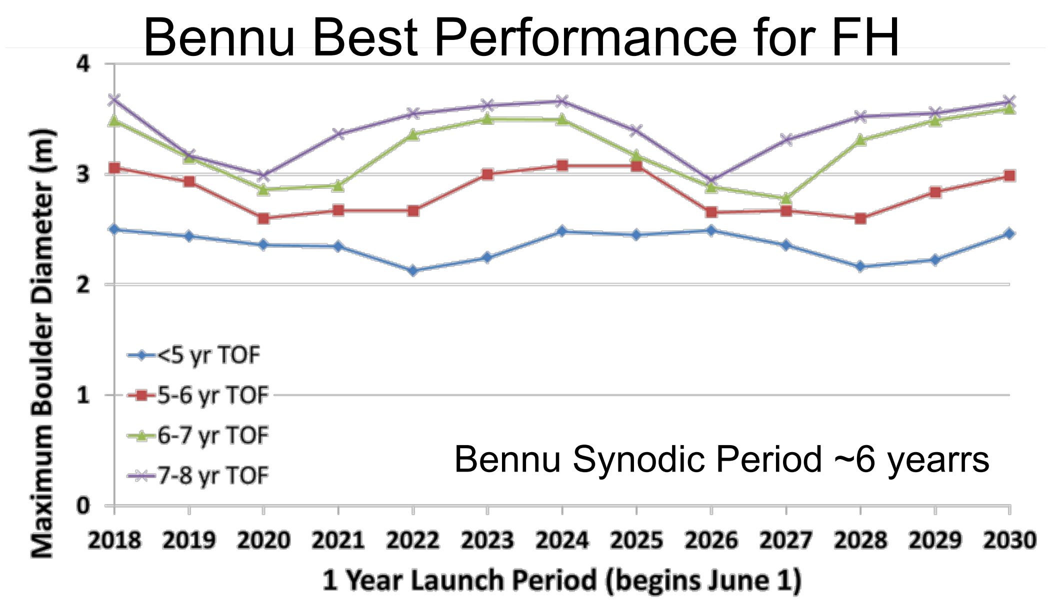
Missions with duration >5 years can launch any year and return a ~2+ meter boulder from Itokawa or Bennu providing mission robustness to schedule changes.



Similar performance for:

1999 JU_3 synodic period ~4.3 years

2008 EV_5 synodic period ~15.7 years



FH = Falcon Heavy

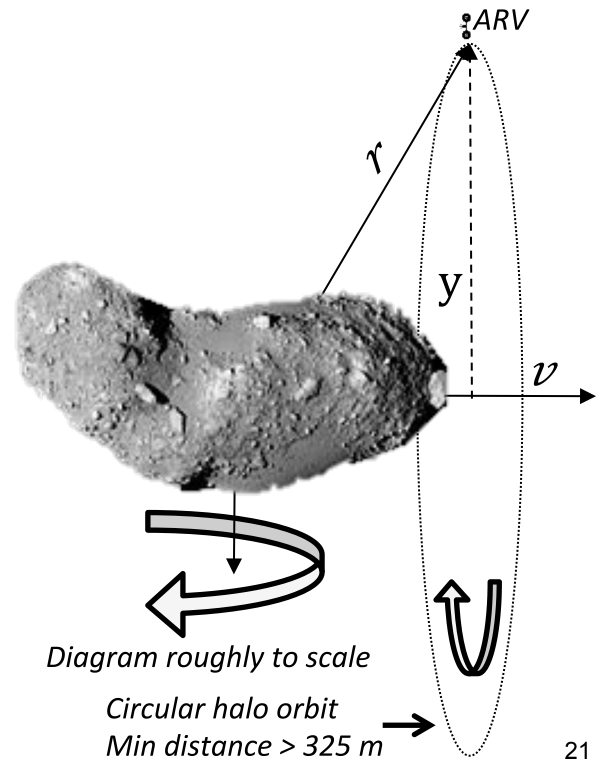
Planetary Defense Demonstration at a Larger NEA

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

Selected Enhanced Gravity Tractor for Itokawa Case Study

- 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.

Focus is on demonstrating the applicability of Enhanced Gravity Tractor on potentially-hazardous-size NEA.



Enhanced Gravity Tractor Concept of Operations for Itokawa

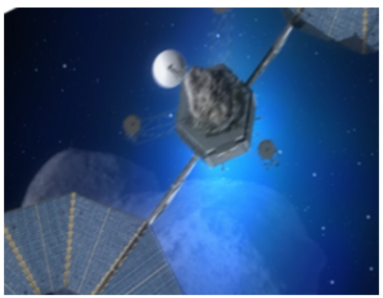
- Phase 1: Fly in close formation with the asteroid with collected boulder (60 days required for measurable deflection with 120 days of reserve performance).
- Phase 2: Wait for orbital alignment to become favorable to allow measurement of deflection beyond 3-σ uncertainty (~8 months from start of Phase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

Image Credit: NASA/JAXA

Objectives and Extensibility

Planetary Defense

Small Asteroid Capture	Robotic Boulder Capture
• ARM prox ops, autonomous ops, characterization & algorithms applicable • Slow Push/Pull techniques implemented with small development costs (IBD & GT)	
• Techniques verifiable much more quickly on a <10 m NEA	• More relevant on hazardous-size NEA • Opportunity for kinetic impactor



Science, Commercial and Resource Use

Small Asteroid Capture	Robotic Boulder Capture
• Applicability of high power SEP, ARM engineering instruments • Potential to host "target of opportunity" payloads	
• Opportunity to learn about < 10 m asteroids; ~1:10 are C-type	• Better opportunity to return desired material (if C-type) w/geologic context

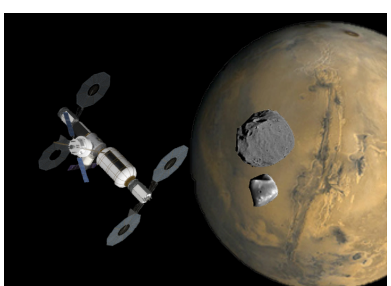


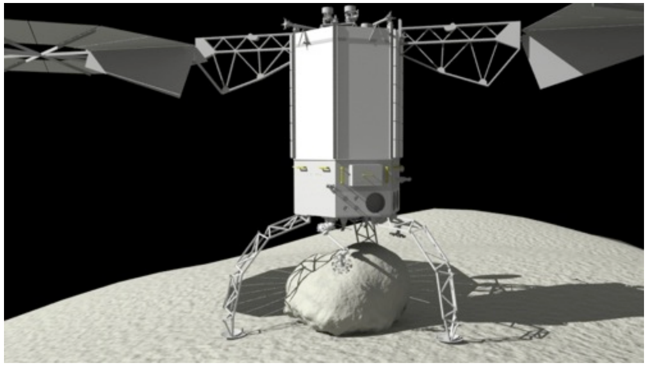
Image Credits: NASA

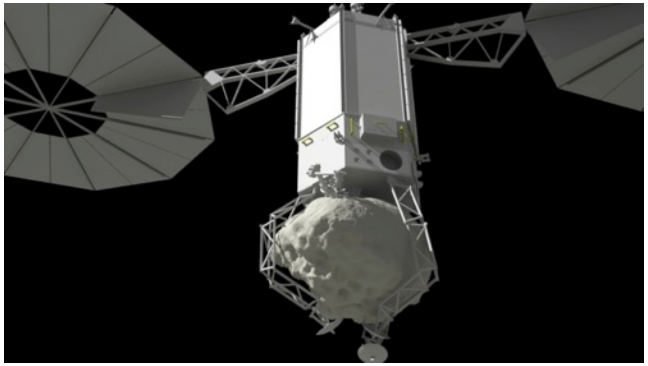
Extensibility

Small Asteroid Capture	Robotic Boulder Capture
• In-space SEP and prox ops w/uncooperative target provides broad opportunities (human exploration, science, commercial) • Supports Exploration Roadmap with partnership opportunities – **Mars Forward**	
• Inflatable technology uses • Ion Beam Deflection for orbital debris	• Near surface ops; remote manipulator and gripper applicability

Additional Science Opportunities with Option B

- Sampling of regolith around target boulder.
- Ability to host and deploy free-flyers or surface rovers/hoppers.
- Additional scientific instrumentation for in-situ or remote observation of a large NEA – partnerships for secondary payloads including NASA Broad Agency Announcement (BAA) selections.
- Potential robotic arm sample collection (e.g., drilling, coring, surface sample collection, and caching).
- Advanced SEP technologies, instrumentation, and low-gravity body autonomous operations will help enable more capable future robotic missions, including exploration of Phobos and Deimos and boulder retrieval.





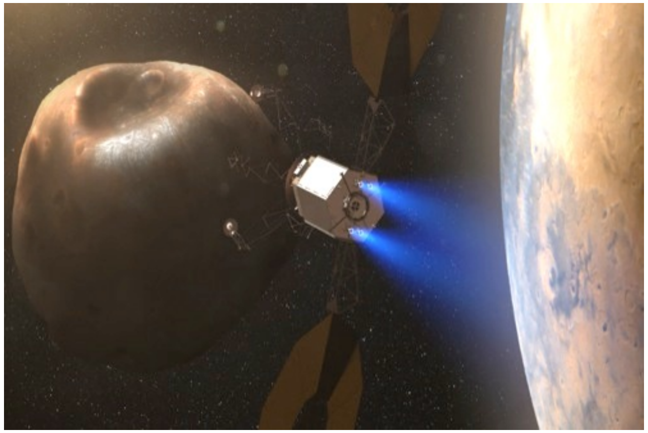


Image Credits: NASA/AMA, Inc.

Closing Remarks

The robotic boulder capture option addresses the needs of a broad set of stakeholders, and leverages precursor missions and existing agency capabilities to ensure mission success.

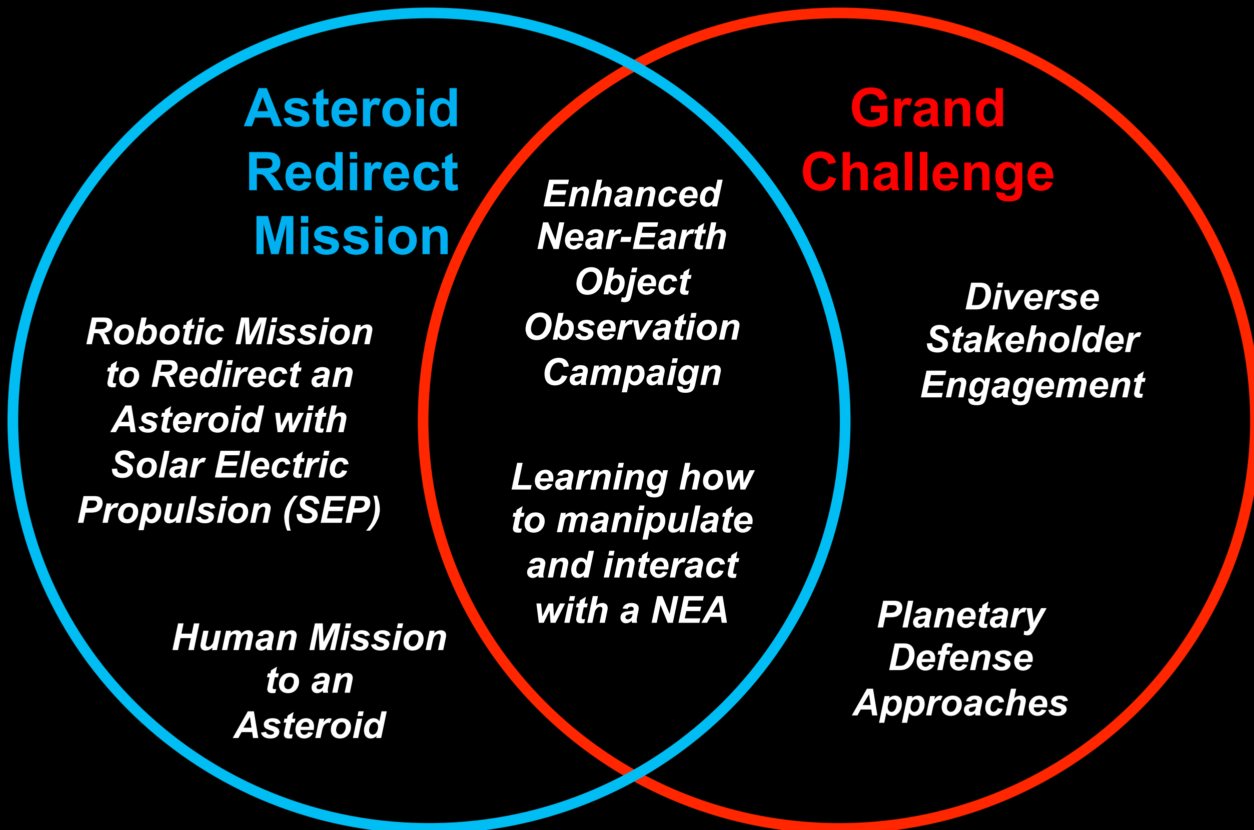
- **Mars-Forward Human Exploration and Extensibility**
- **Planetary Defense on Hazardous-size NEA**
- **Science with Community Collaboration**
- **Commercial & International Opportunities**

Thank you for your time and attention.

Image Credit: NASA/AMA, Inc.

Backup

NASA’s Asteroid Initiative



Grand Challenge Statement

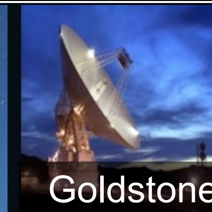
“Find all asteroid threats to human populations and know what to do about them”

(Announced June 18, 2013)

Asteroid Redirect Mission: Three Main Segments

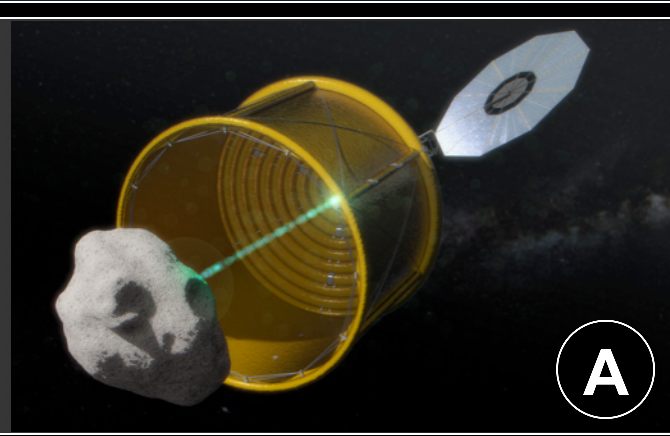
IDENTIFY

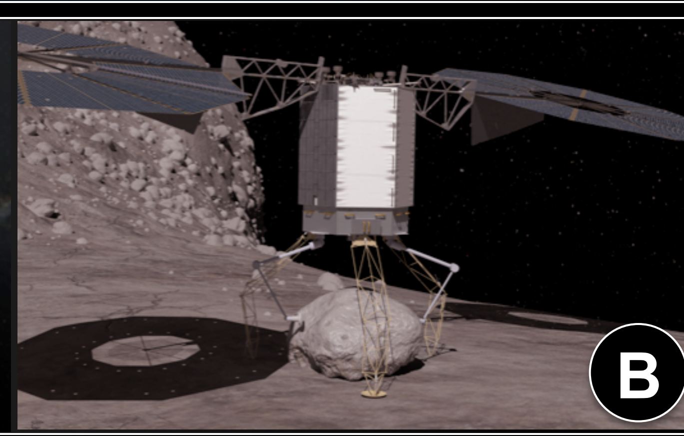
Ground and space based assets detect and characterize potential target asteroids



REDIRECT

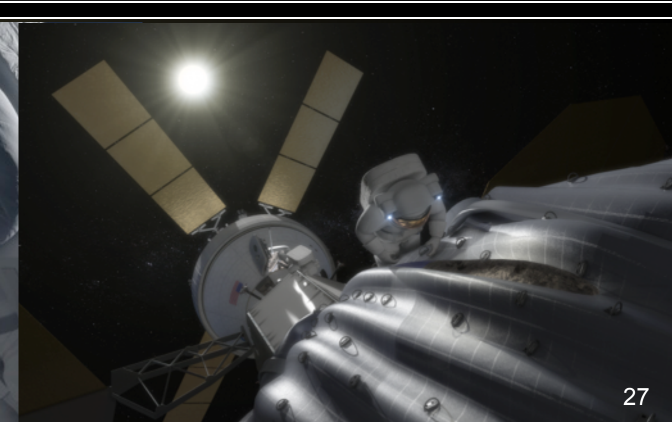
Solar electric propulsion (SEP) based robotic capture system redirects asteroid to cis-lunar space (two options)



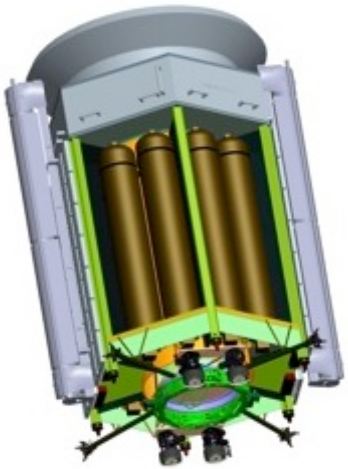


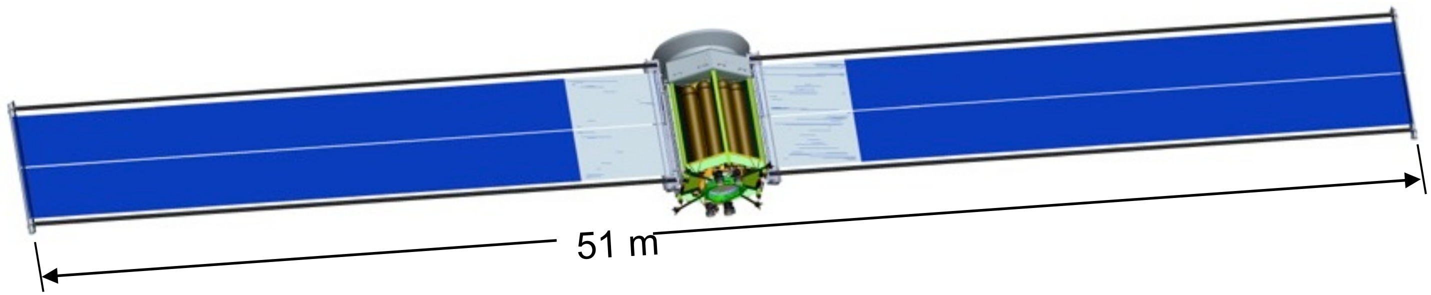
EXPLORE

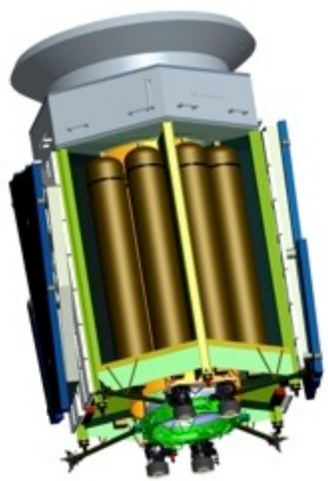
Crews launch aboard SLS rocket, travel to redirected asteroid in Orion spacecraft to rendezvous with redirected asteroid – explore, study, sample return to Earth



Representative Asteroid Redirect Vehicle (ARV) Configurations with Solar Arrays Deployed







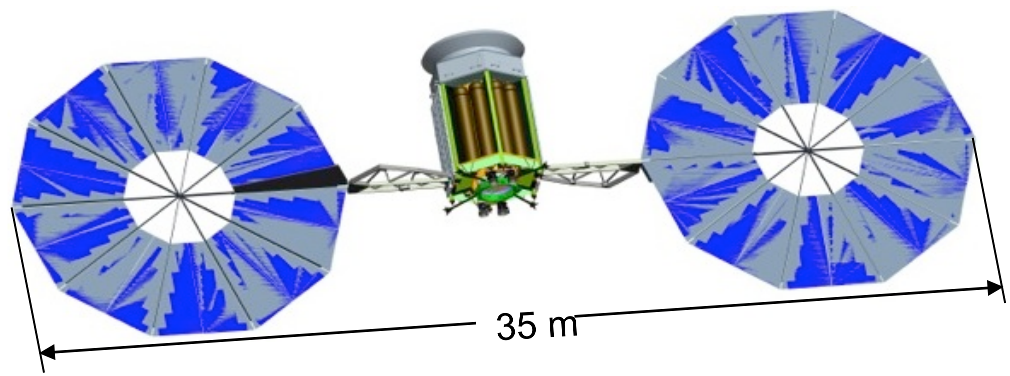
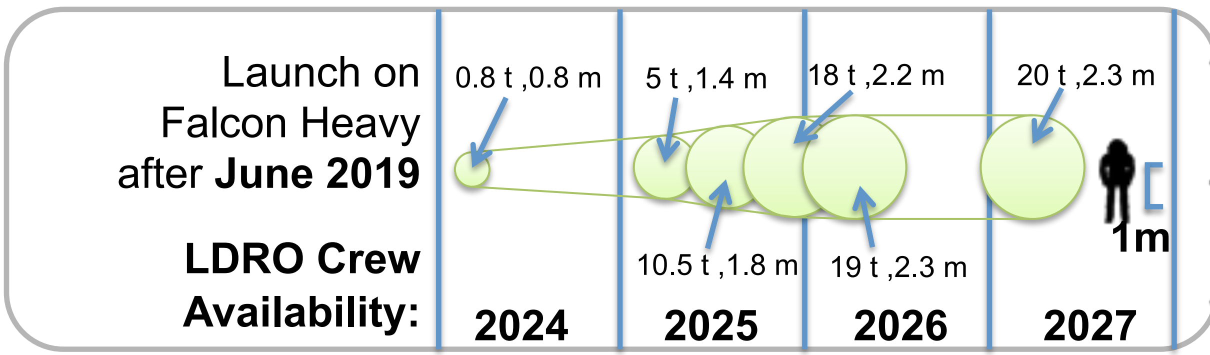


Image Credits: NASA/JPL

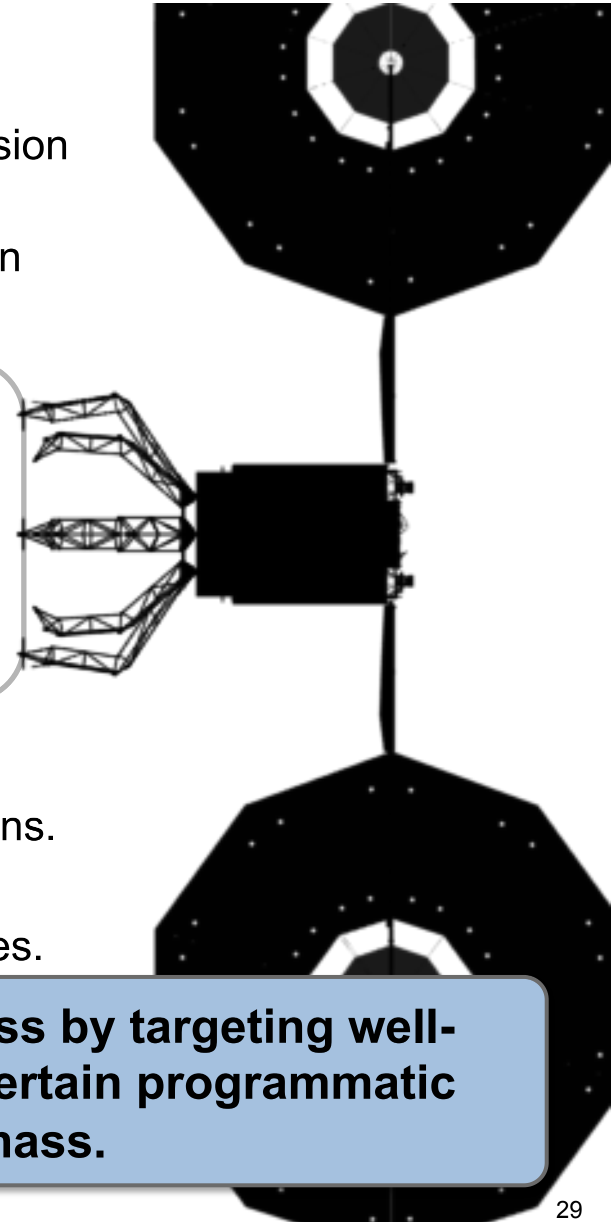
Itokawa: Case Study

Why Itokawa?

- Meets valid candidate criteria.
- 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.



Size assumes spherical shape



Developed a detailed mission to Itokawa to:

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

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

Mission Timeline

Day 0 | Day 14 | Day 51

1. Approach (14 Days)

1,000 km to 100 km. Refine shape model, acquire landmarks, and update spin state.

2. Characterization (37 days)

Four fly-bys (~7.5 days each) with a week reserved for processing and gathering additional images as needed

3-4. Dry-Runs and Boulder Collection (18 days)

Dry-Runs (x2): ~5.3 days each. ~6 hours to complete dry-run with 5 days of coast in-between for downlink and processing.

Boulder Collection Attempt: ~7.4 days with ~0.5 day for collection and 7 days for ascent and coast to allow for downlink and processing

Day 69 | Day 120

3-4. Contingency Dry-Run and Boulder Collection Attempts (51 days)

Reserve for complete dry-run sequences at two additional sites and four additional boulder collection attempts between the three sites to protect against failed collection due to boulder properties, system anomalies or other contingencies.

5. Orbit Determination (21 Days)

Hold for precise orbit determination prior to gravity tractor demonstration.

Day 141 | Day 231 | Day 360 | Day 381 | Day 400

6. Gravity Tractor (90 Days)

Maintain orbit for at least 90 days. Resources reserved for 180 days.

6. Hold for Alignment (129 days)

Hold for to allow deflection to propagate and to achieve favorable orbital alignment for deflection verification.

7. Deflection Verification (21 Days)

Hold for precise orbit determination to verify orbit deflection.

Margin (19 days)

Unused margin in the 400 day stay-time allocation.

Operations heritage to prior robotic missions

Mission unique operations

NEA Target Approach and Characterization

- Additional timeline will be required to build a detailed shape model for targets not visited by a precursor
  - Need a range of solar phase angles, at all longitudes of the body, and multiple resolutions starting ~2 million km out
- Landmark and potential boulders identification will take place during initial fly-bys

Itokawa (previously visited NEA) Timeline

Approach (~2 weeks)	4 Fly-bys (~4 weeks)	Addt. Imaging (1 week)
• Refine shape model • Refine ephemeris • Update spin state	• Refine gravity model • Landmark imaging • Target boulder imaging	• Process fly-by data • Boulder prioritization

4 extra weeks of characterization required for targets without precursor.

Previously Unvisited NEA Timeline

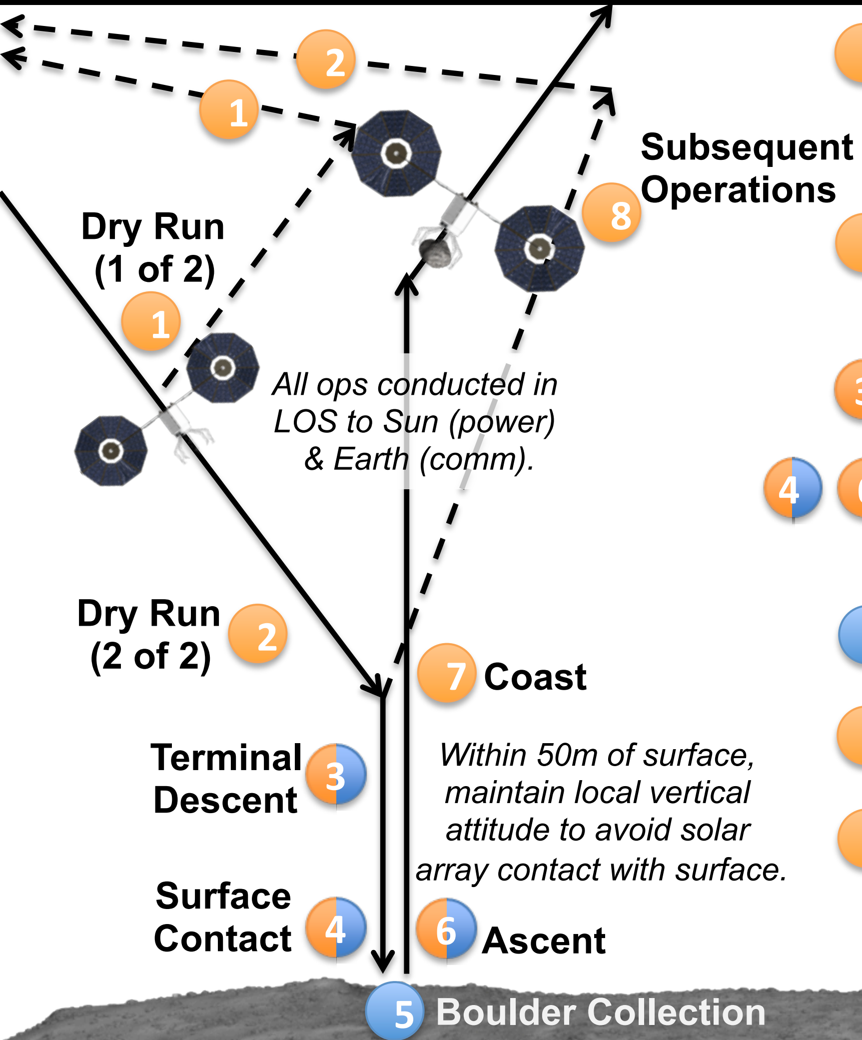
Approach (~2 weeks)	4 Fly-bys (~4 weeks)	Addt. Imaging (1 week)	2 Fly-bys (2 weeks)	Addt. Imaging (>2 weeks)
• ***Acquire images to build / refine shape model (many more images than Itokawa case)***	• Refine shape model • ***Select potential landmarks*** • Image landmarks at high resolution • ***Identify potential boulder targets*** • ***Build gravity model***	• ***Process shape model data*** • ***Identify landmarks*** • ***Plan final fly-bys***	• Final boulder imaging • Further refine shape model • Refine Gravity model	• Process fly-by data • Boulder prioritization • Determine landmarks to be used during collection

* ***Bold & italic: Additional tasks for previously unvisited NEA***

Operations heritage to prior robotic missions

Mission unique operations

Boulder Collection



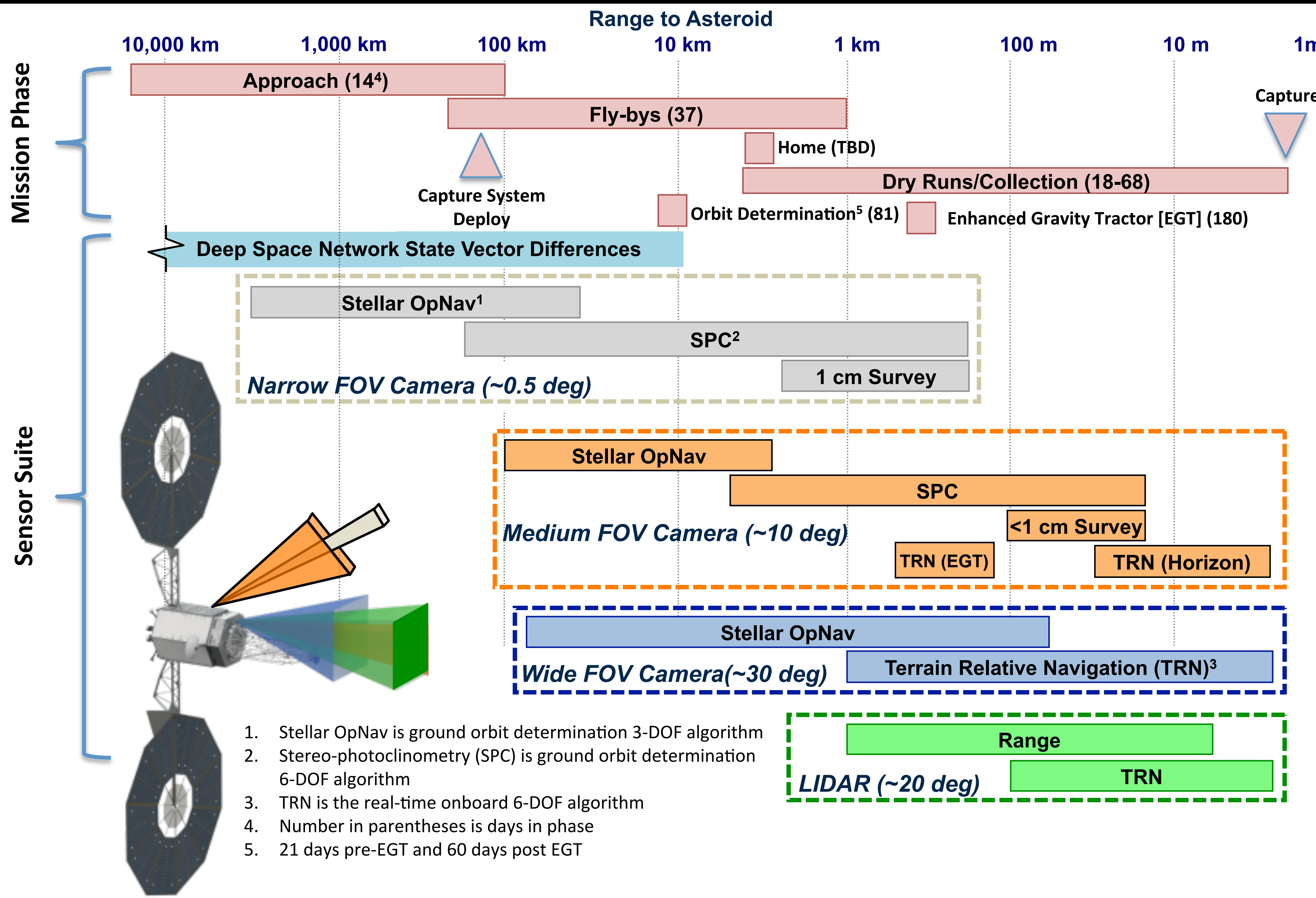
- **1 Dry Run (1 of 2):** *Refine local gravity* and increase *boulder characterization* while in *passively safe* trajectory. Sufficient time allocated between dry runs to downlink data, process data, and update spacecraft.
- **2 Dry Run (2 of 2):** System verifies *closed-loop* Terrain Relative Navigation 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.

Sensor Operations Description



1. Stellar OpNav is ground orbit determination 3-DOF algorithm
2. Stereo-photoclinometry (SPC) is ground orbit determination 6-DOF algorithm
3. TRN is the real-time onboard 6-DOF algorithm
4. Number in parentheses is days in phase
5. 21 days pre-EGT and 60 days post EGT

Summary of NEA Targets Analyzed

Configuration and operations are robust to a wide range of NEA sizes, masses, and rotation rates beyond Itokawa.

	Itokawa	Bennu	1999 JU_3	2008 EV_5
Mass	3.51×10^{10} kg	7.79×10^{10} kg	1.55×10^{12} kg	1.05×10^{11} kg
Dimensions	535 x 294 x 209 m	Mean Dia.: 492 m	Eff. Dia.: 870 m	420 x 410 x 390 m
Rotation Period	12.132 hours	4.297 hours	7.627 hours	3.725 hours
50 m Sun Angle	45 degrees	60 degrees	37.5 degrees	60 degrees
Contact Sun Angle	30 degrees	15 degrees	15 degrees	15 degrees
Dry-Run 1 Dur.	5.25 days	5.13 days	5.25 days	5.13 days
Dry-Run 2 Dur.	5.28 days	5.26 days	5.28 days	5.26 days
20 m Descent Dur.	12.73 min	11.37 min	4.51 min	7.96 min
Contact Velocity from 20 m	5.237 cm/s	5.861 cm/s	14.788 cm/s	8.371 cm/s