National Aeronautics and Space Administration

Asteroid Initiative Opportunities Forum

ARRM Robotic Boulder Capture Option

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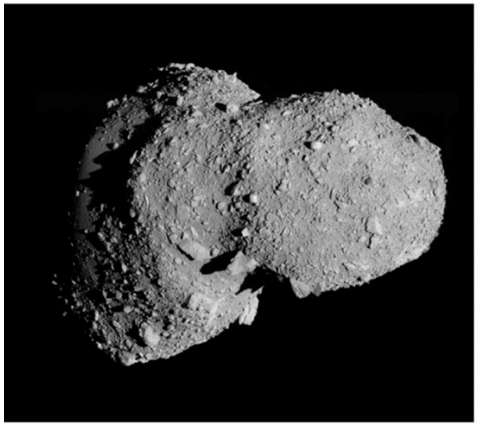
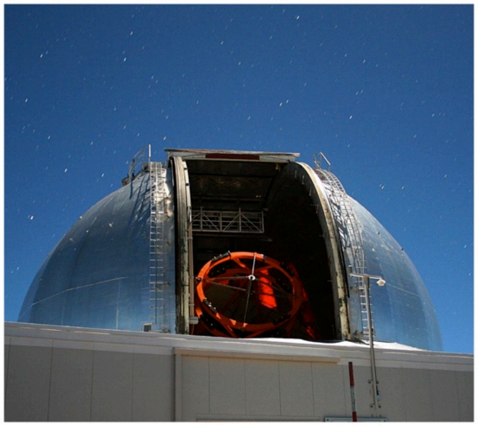
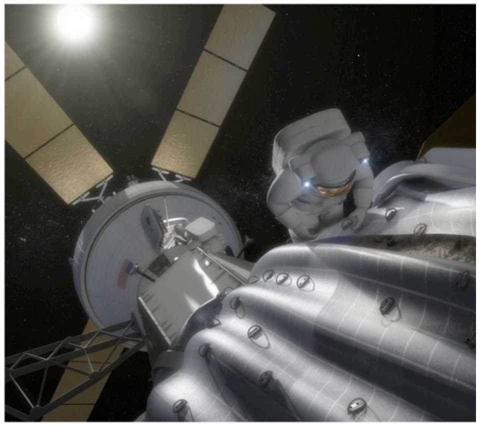
Contributing NASA Centers & Academia:

GSFC, ARC, GRC, JPL, KSC, MSFC, U. Colorado Boulder, U. Alaska Fairbanks







Abbreviations and Acronyms

ACS	Attitude Control System
ARCS	Attitude and Reaction Control System
ARCM	Asteroid Redirect Crewed Mission
ARV	Asteroid Redirect Vehicle
BC	Boulder Collection
CAD	Computer Aided Design
CCAR	Colorado Center for Astrodynamics Research
CG	Center of Gravity
DARPA	Defense Advanced Research Projects Agency
DOF	Degree(s) of Freedom
EDU	Engineering Development Unit
EGT	Enhance Gravity Tractor
EPS	Electric Propulsion System
FH	Falcon Heavy
FOV	Field of View
FOM	Figure of Merit
FREND	Front-end Robotics Enabling Near-term Demonstration
GT	Gravity Tractor
HP	Home Point
IBD	Ion Beam Deflection
I&T	Integration and Test

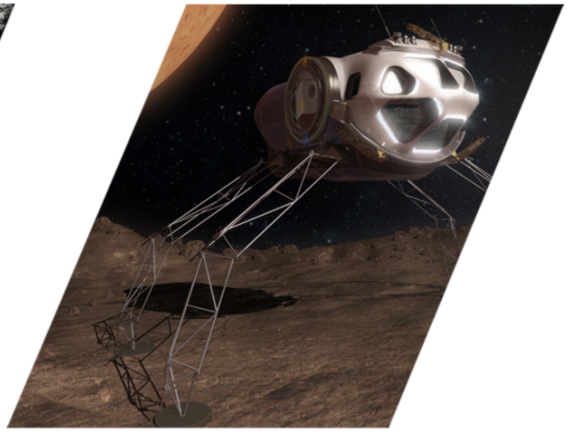
LDRO	Lunar Distant Retrograde Orbit
MFOV	Medium Field of View
NEA	Near-Earth Asteroid
NFOV	Narrow Field of View
NRE	Non-Recurring Engineering
OpNav	Optical Navigation
PHA	Potentially Hazardous Asteroid
RCS	Reaction Control System
REU	Robotics Electronics Unit
S/C	Spacecraft
SEP	Solar Electric Propulsion
SLS	Space Launch Vehicle
TRN	Terrain Relative Navigation
UAF	University of Alaska - Fairbanks
WFOV	Wide Field of View
WP	Way Point

Stakeholder Benefits

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.

Initial Human Mission

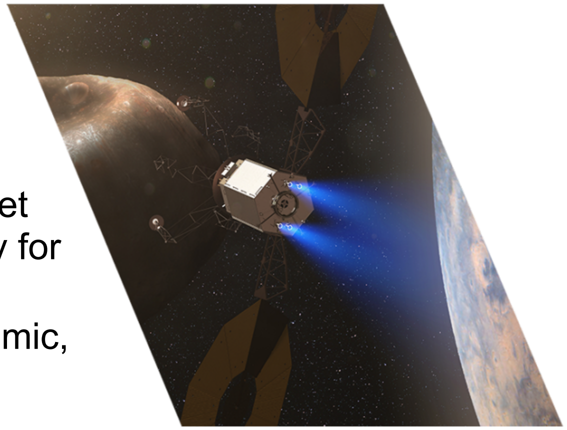
Mars Forward



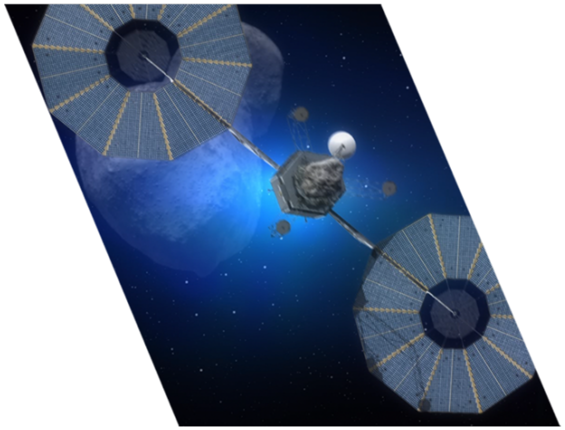
Addresses and matures multiple Mars-forward technology and operations gaps, including operations near and on the Martian moons, Phobos and Deimos.

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

Science & Resources



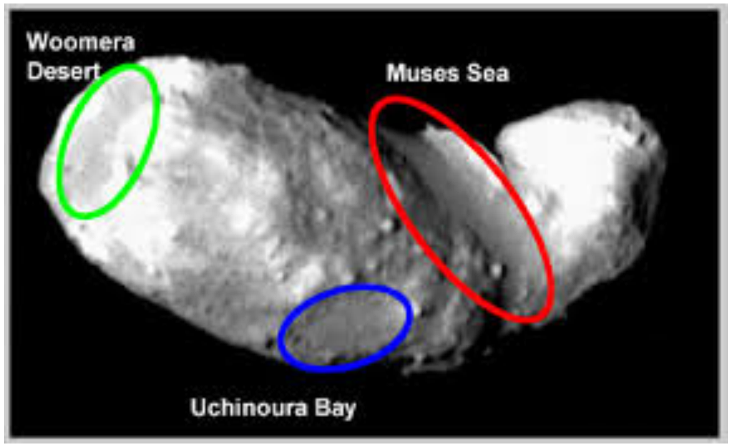
Planetary Defense

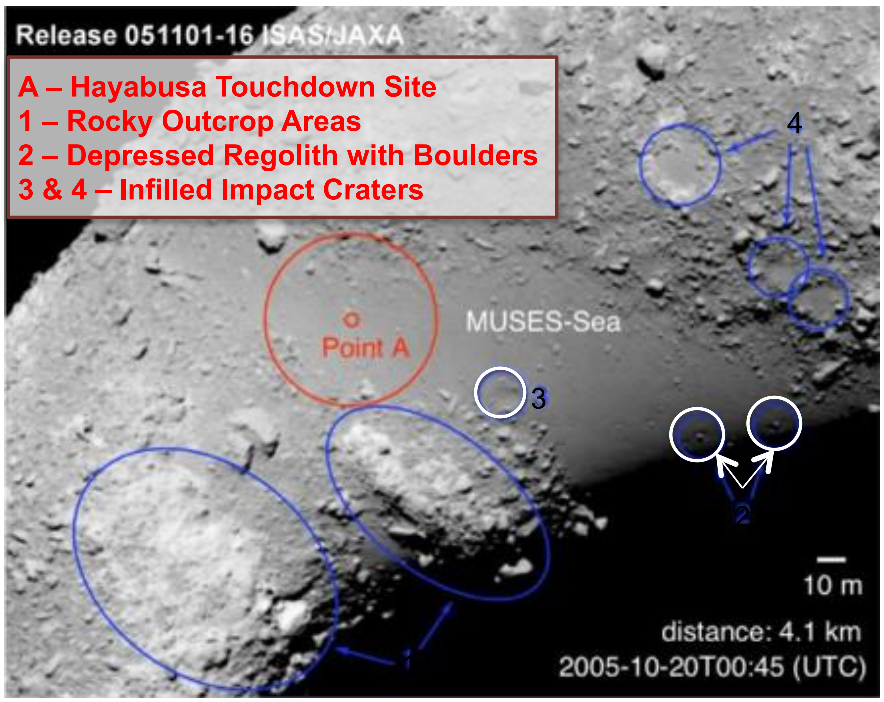


Surface interaction with a hazardous-size NEA. Demonstrates one or more deflection techniques on a relevant target, including the option to test a kinetic impact approach.

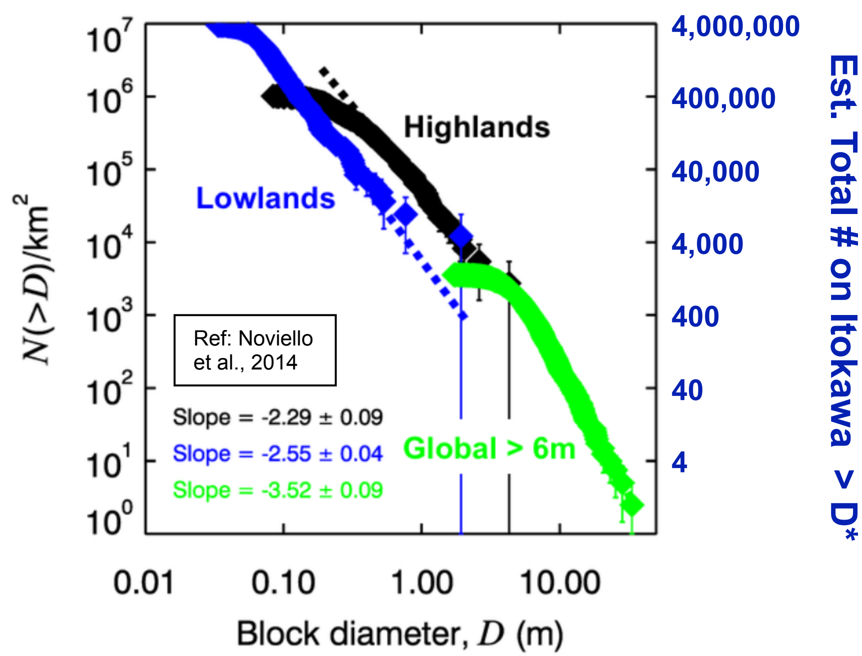
Addresses the needs of a broad set of stakeholders, and leverages precursor missions and existing agency capabilities to ensure mission success.

Itokawa's Boulder Rich Surface



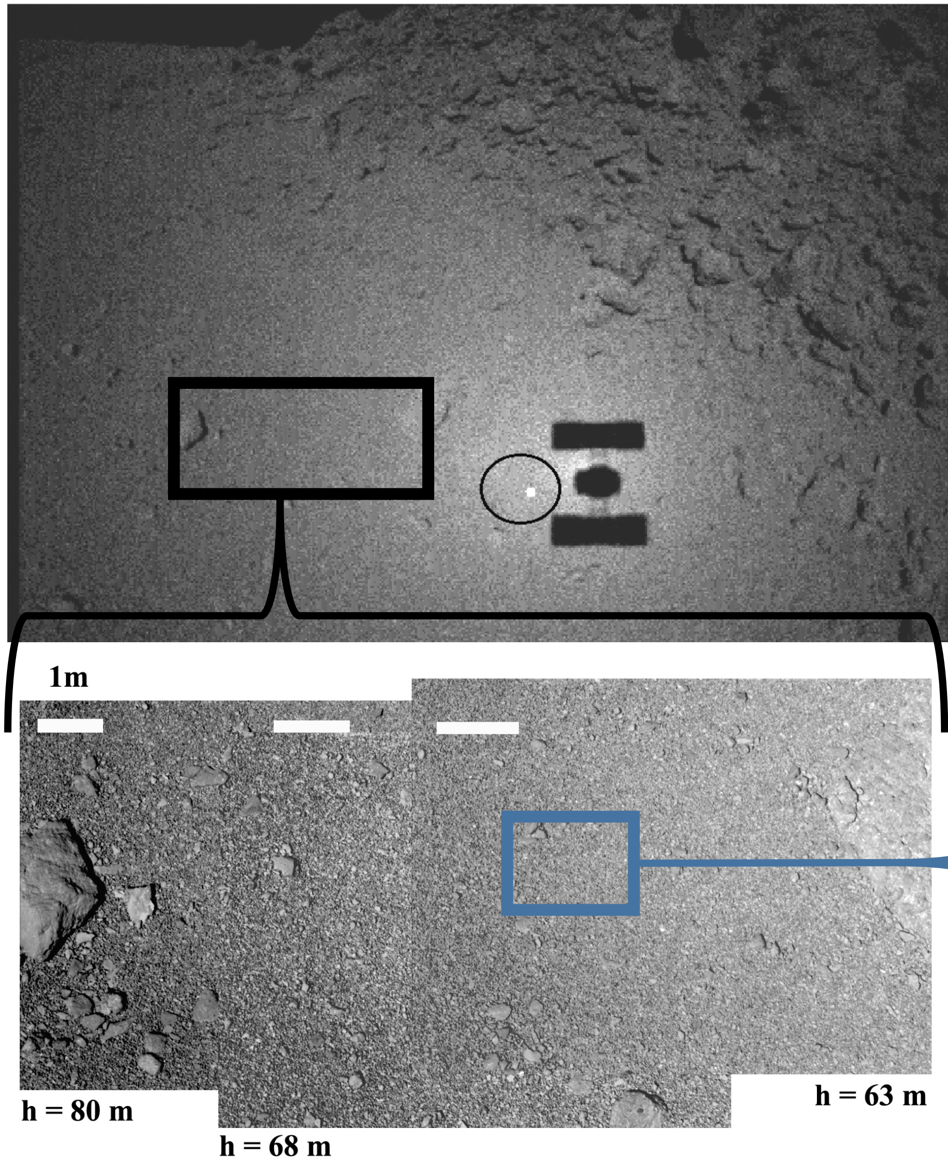


- Hayabusa mission confirmed the presence of many boulders on Itokawa's surface.
- Data from images suggest that several thousand 2 to 5 m boulders exist on Itokawa.
- ~20% of the entire asteroid's surface contains smooth areas (flat terrain with few hazards and wide access) – hundreds of boulder targets
- 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 km^2

Hayabusa Touchdown Site Approach

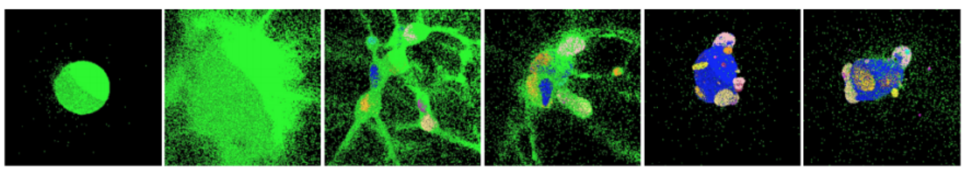


- Smooth areas have boulders sitting on a surface dominated by gravels and pebbles. Stereo image analysis indicates a high probability that some boulders are not embedded.
- Highest resolution of the images during the Hayabusa touchdown are 6 to 8 mm/pixel.
- Evidence from Hayabusa and ground-based radar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

Boulder Characteristics

- Low probability boulders will crack/crumble during collection
  - Boulders are most likely the result of a collision and reaccumulation process which means they have withstood forces much greater than the what will be seen during the collection process (< 350 N).
  - Friability of the boulder is dependent on the type of asteroid, but is expected to be sufficiently low to facilitate collection operations.
  - High resolution imagery will be obtained prior to collection to provide detailed shape model and identify any defects to ensure successful collection.

P. Michel and D. C. Richardson: Itokawa formation by reaccumulation



Material	Typical Compressive Strength	
Ordinary chondrite	6.2 - 420 MPa	900 - 61,000 psi
Concrete	20 MPa	3000 psi
Carbonaceous	0.3 - 50 MPa	44 - 7,250 psi
Charcoal Briquette	~3 MPa	440 psi

- Mass properties will be highly characterized with low uncertainty
  - Boulders are likely homogenous with a near constant density. Shape of boulder will be known (< 1 cm resolution) and mass properties estimates will be well within vehicle performance.
  - Visual inspection of boulders will provide a reasonable estimate of density compared to the parent body. Density of Itokawa material is known from Hayabusa, further reducing uncertainty in mass of boulders for that target.

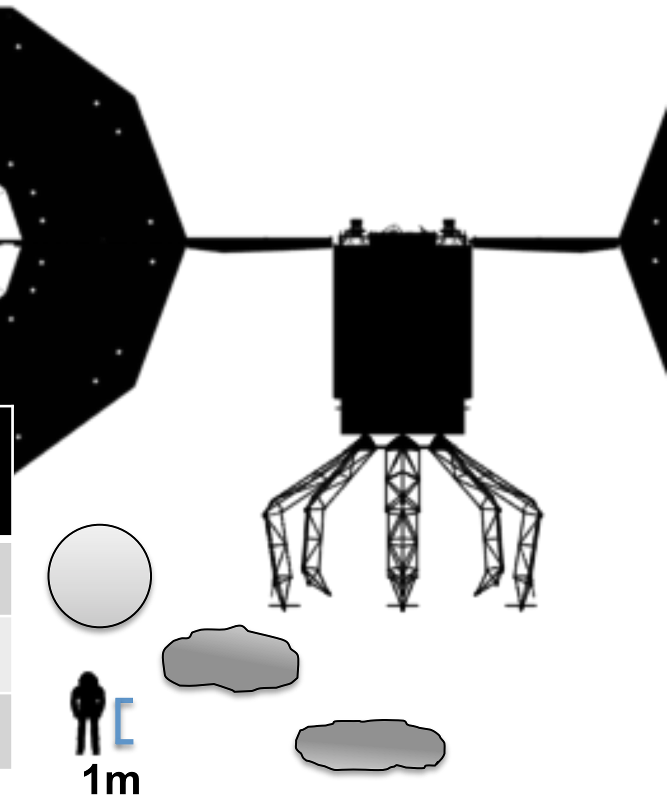
Boulder Aspect Ratio

- Spherical boulder sizes in this presentation assume represent the <u>smallest</u> maximum extent for a given mass and density. For example:
  - A 10 t carbonaceous boulder with density of 1.62 g/cm^3 has a 2.3 m spherical extent.
  - This mass and density would have a maximum extent of ~3.3 m for 3:3:1 aspect ratio.

Spherical boulders represent the minimum possible size extent for a given mass and density.

Aspect Ratio	Mass (t)	Volume (m^3)	Maximum Extent (m)
1:1:1	10	6.14	**2.3**
2:2:1	10	6.14	**2.9**
3:3:1	10	6.14	**3.3**

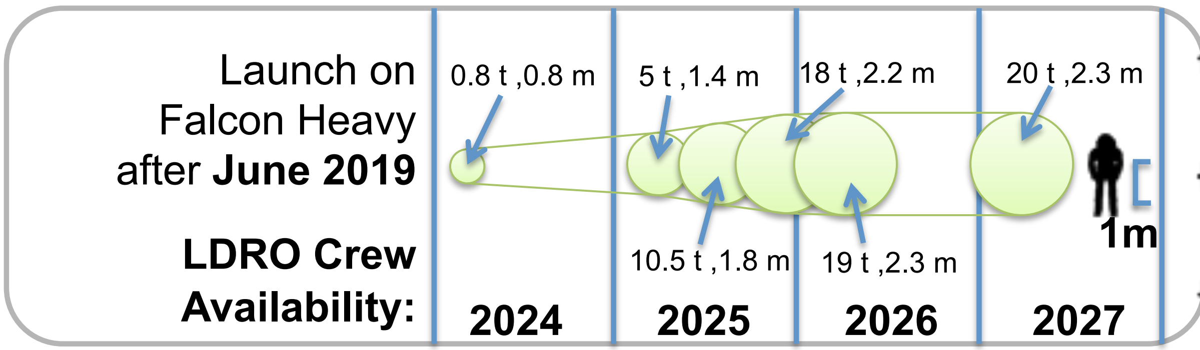
Assumes carbonaceous material with density = 1.62 g/cm^3



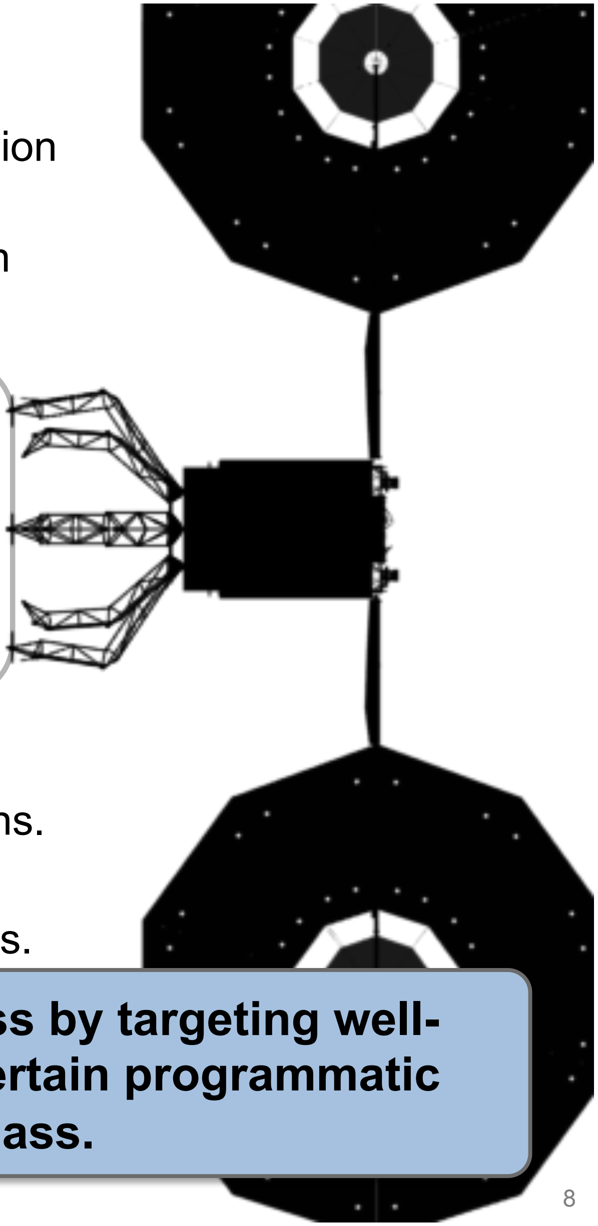
Itokawa: Case Study

Why Itokawa?

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



Size assumes spherical shape



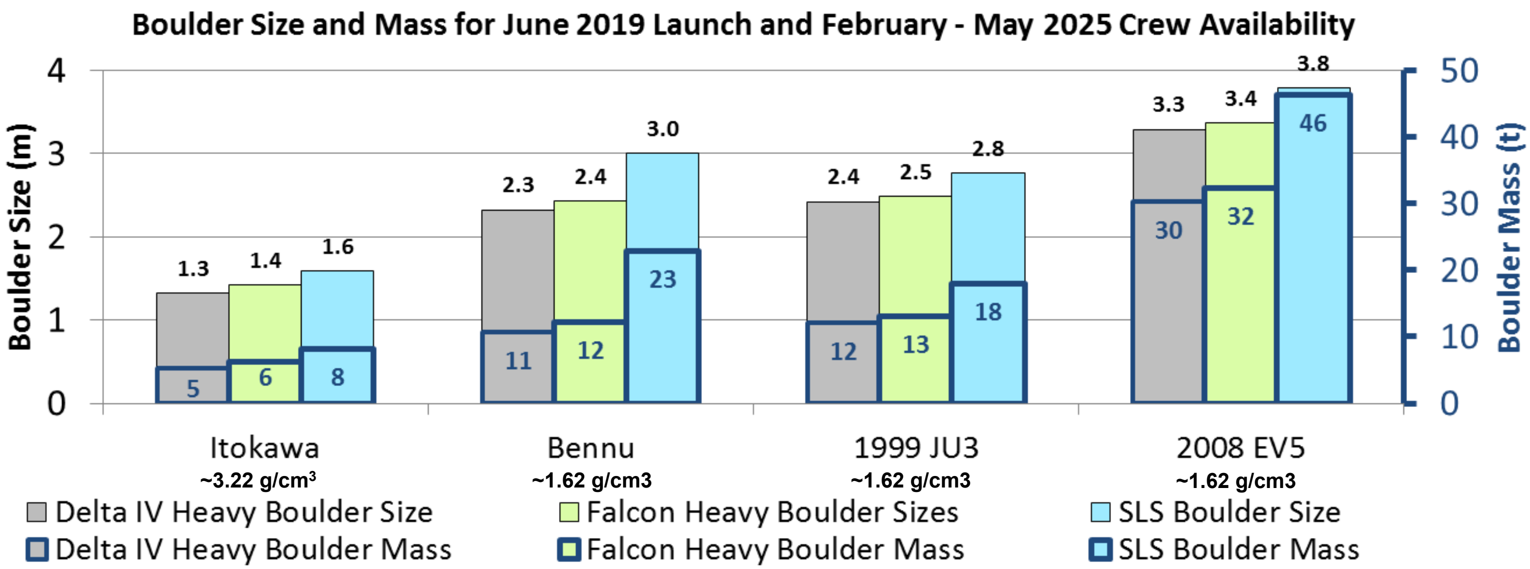
Developed a detailed mission to Itokawa to:

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

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

Target Availability and Boulder Size and Mass

- 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}**



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)

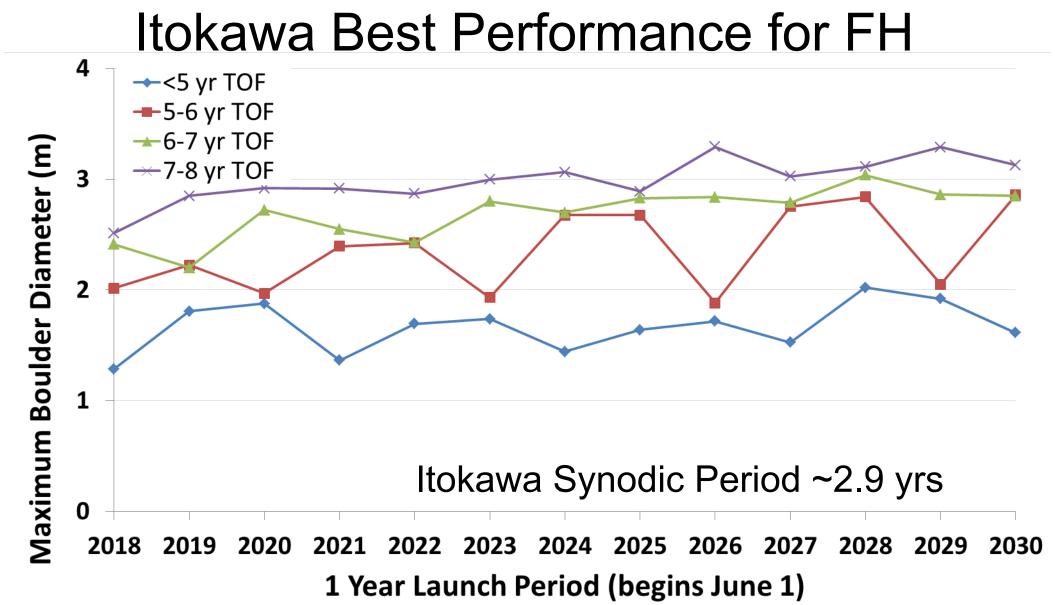
Returnable Boulder Size Trends

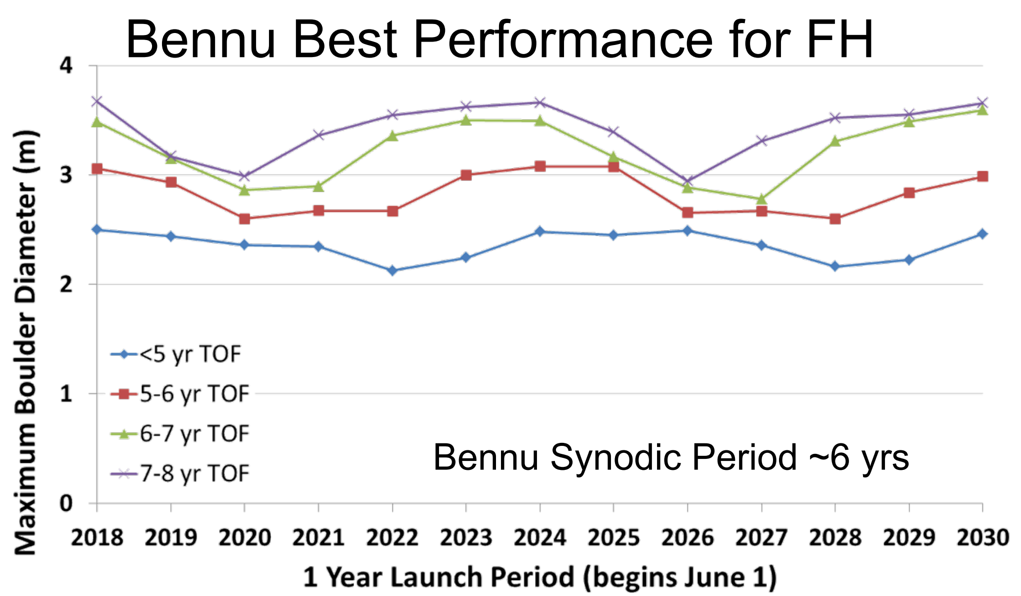
Missions with duration >5 years can launch any year and return a ~2+ meter boulder from Itokawa or Bennu providing mission robustness to schedule changes.

Similar performance expected for:

1999 JU_3 synodic period ~4.3

2008 EV_5 synodic period ~15.7





Mission Profile Comparison – Candidate Targets

Phase/Activity	Itokawa Mid 2025		Itokawa Late 2025		1999 JU3 2025		Bennu 2024		2008 EV5 2024	
	Date/Dur	Xenon Use	Date/Dur	Xenon Use	Date/Dur	Xenon Use	Date/Dur	Xenon Use	Date/Dur	Xenon Use
Launch	**June 20, 2019**		**June 17,2019**		**Sept. 6, 2019**		**June 1, 2019**		**July 28, 2019**	
Outbound Leg	2.2 years	4,020 kg	2.2 years	4,080 kg	1.6 years	2,400 kg	2 years	3,740 kg	2 years	3,120 kg
Asteroid Rendez & Prox Ops										
Arrival	**Sept. 11, 2021**		**Aug. 17, 2021**		**March 24, 2021**		**June 6, 2021**		**June 3, 2021**	
Characterization & Capture	51 days		55 days		51 days		55 days		55 days	
Capture Phase Margin	18 days		51 days		18 days		51 days		51 days	
Planetary Defense Demo	262 days	170 kg	262 days	170 kg	273 days	TBD kg	285 days	TBD kg	TBD days	TBD kg
Proximity Operations Margin	69 days	30 kg	69 days	30 kg	69 days	30 kg	69 days	30 kg	69 days	30 kg
Departure	**Oct. 16, 2022**		**Sept. 21, 2022**		**May 28, 2022**		**July 11, 2022**		**July 8, 2022**	
Inbound Leg	2.5 years	1830 kg	2.8 years	1,750 kg	2.7 years	4,720 kg	1.5 years	3240 kg	1.5 years	3,960 kg
Earth-Moon System DRO Insertion	August, 2025	70 kg (TBR)	November, 2025	70 kg (TBR)	May , 2025	70 kg (TBR)	May, 2023	70 kg (TBR)	May, 2023	70 kg (TBR)
Earliest ARCM Availability	**Aug-Sept. 2025**		**Nov. -Dec. 2025**		**May-June 2025**		**May-June 2024**		**May-June 2024**	
Assumes Heavy Lift Launch Vehicle (Falcon Heavy)	**Xe used: 6,230 kg** SEP Operating Time: TBD days **Boulder Return Mass: 11 t** (1.8 m spherical, 2.3 m max extent @ 2:2:1 Aspect Ratio)		**Xe used: 6,200 kg** SEP Operating Time: TBD days **Boulder Return Mass: 18 t** (2.2 m spherical, 2.8 m max extent @ 2:2:1 Aspect Ratio)		**Xe used: 7,500 kg** SEP Operating Time: TBD days **Boulder Return Mass: 10 t** (2.5 m spherical, 3.1 m max extent @ 2:2:1 Aspect Ratio)		**Xe used: 7,360 kg** SEP Operating Time: TBD days **Boulder Return Mass: 6 t** (1.9 m spherical, 2.4 m max extent @ 2:2:1 Aspect Ratio)		**Xe used: 7,500 kg** SEP Operating Time: TBD days **Boulder Return Mass: 13 t** (2.5 m spherical, 3.1 m max extent @ 2:2:1 Aspect Ratio)	

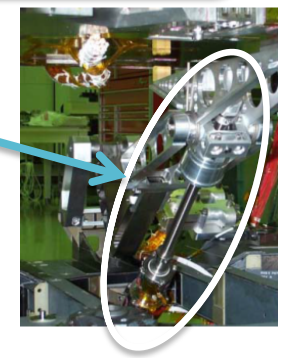
Spaceframe Concept

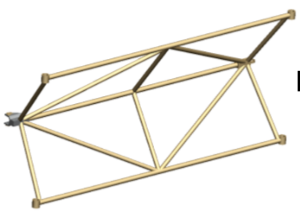
Spaceframe capture system employs simple, repetitive design with only 42 unique machined parts and no new technology.

Operations use planned routines with fault tolerance for boulder acquisition and asteroid contact.

- Not robot arms, more like a large three-finger gripper
- Each arm is three trusses of same design
  - Different lengths for Capture and Contact arms.
  - No end effectors.
- 1 actuator model used throughout
- Each joint identical in size, number of bearings, and number of fasteners

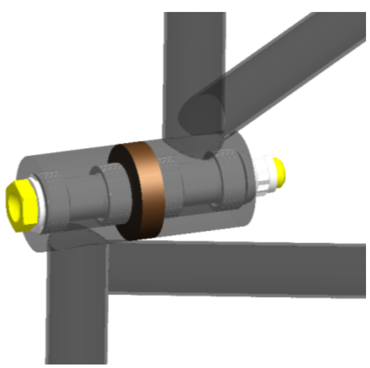
Heritage actuators that performed Mars Exploration Rover standup operation.
See backup for detail

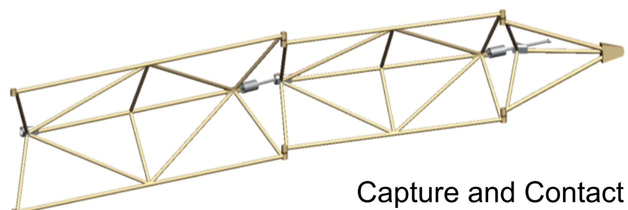




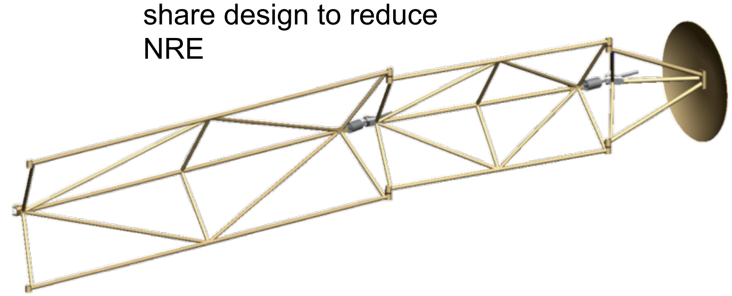
Example Truss

Example Joint





Capture and Contact Arms share design to reduce NRE



7-DOF Heritage

Prior Investments by NASA and Collaborating Agencies

Ranger
First use of robot control of "hazardous" payload; leveraged by Robonaut and Restore

FLT QUAL 1995 - today

Mars Exploration Rover Arm
First demo of flex harness to send signals down a robot arm; leveraged by FREND/ Phoenix, Mars, and Restore arms

FLOWN 2004 - today

DARPA FREND/Phoenix
First demo of autonomous capture; leveraged by Restore

FLT QUAL 2007 - today

CSA Dextre
First demo of teleoperated servicing in space; leveraged by Restore

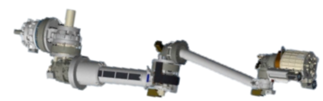
FLOWN 2008 - today

Robonaut
First demo of Orocos as a space robotic software framework; leveraged by Phoenix and Restore

FLOWN (Pressurized) 1999 - today

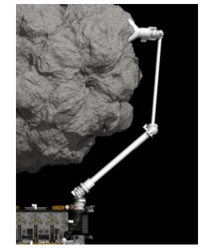
Mars Science Lab Arm
First demo of force sensing on Mars

FLOWN 2012 - today



NASA Servicing Arm
Leverages previous NASA & DARPA investments in motional control approach, robotic software frameworks, flex harnesses, force-torque sensor, joint design, & flight ops experience; majority of design directly applicable to ARRM.

DEVELOPMENT SINCE 2010 Engineering unit ready 2015



Asteroid Retrieval Robotic Mission Arm
Autonomous capture of non-cooperative deep space small body; direct descendent of Restore and DARPA FREND/Phoenix arms.

2018

Leverages ~$90 M In prior investments

1995	2004	2007	2008	2011	2012	2015	*2018*

Microspine Development

TRL 5 Concentric Ring Microspine Gripper Refinement

- Designing to grip curved or flat surfaces
- Flight materials incorporated
- 2 DOF control >1000 microspines
- Grips through .01 m of dust/regolith
- Repeatable100s of times
- Est. maximum grip strength of ~400 N normal and ~300 N tangent to rock (~10 Nm twist)
- 0.5 m diameter, <4 kg mass

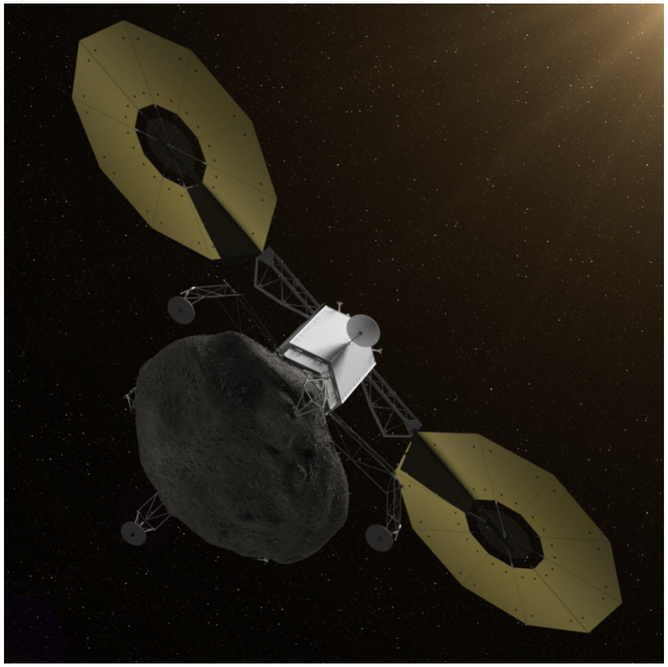
Continue testing with GSFC 7-DOF robot in 6-DOF micro-g simulation environment

- Boulder material & shape variations
- Position and alignment errors
- Arm compliance control
- Vehicle GN&C interaction
- Surface contract and hover ops

Scalability to Boulder and Asteroid Targets

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

7-DOF reaching past mid-plane of 4 m boulder



7-DOF arms can accommodate 10 m boulders if not required to reach past mid-plane of boulder

Spaceframe arms can be lengthened for 10 m boulders; Contact Arms can be used for additional constraint

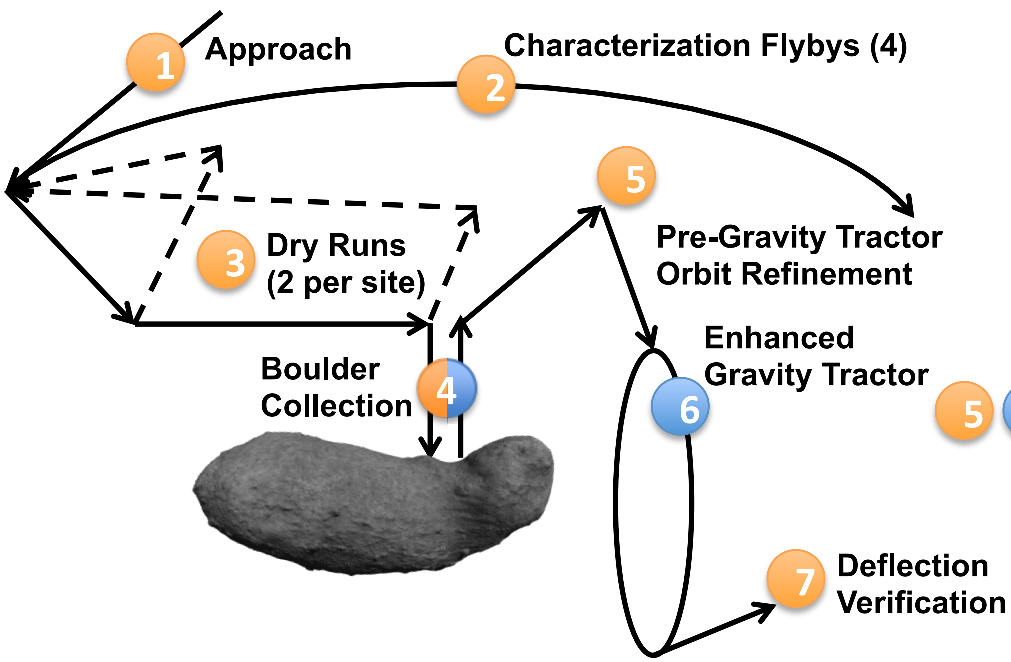
Proximity Operations Overview

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.

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

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.

Legend:
- Orange: **Operations heritage to prior robotic missions**
- Blue: **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

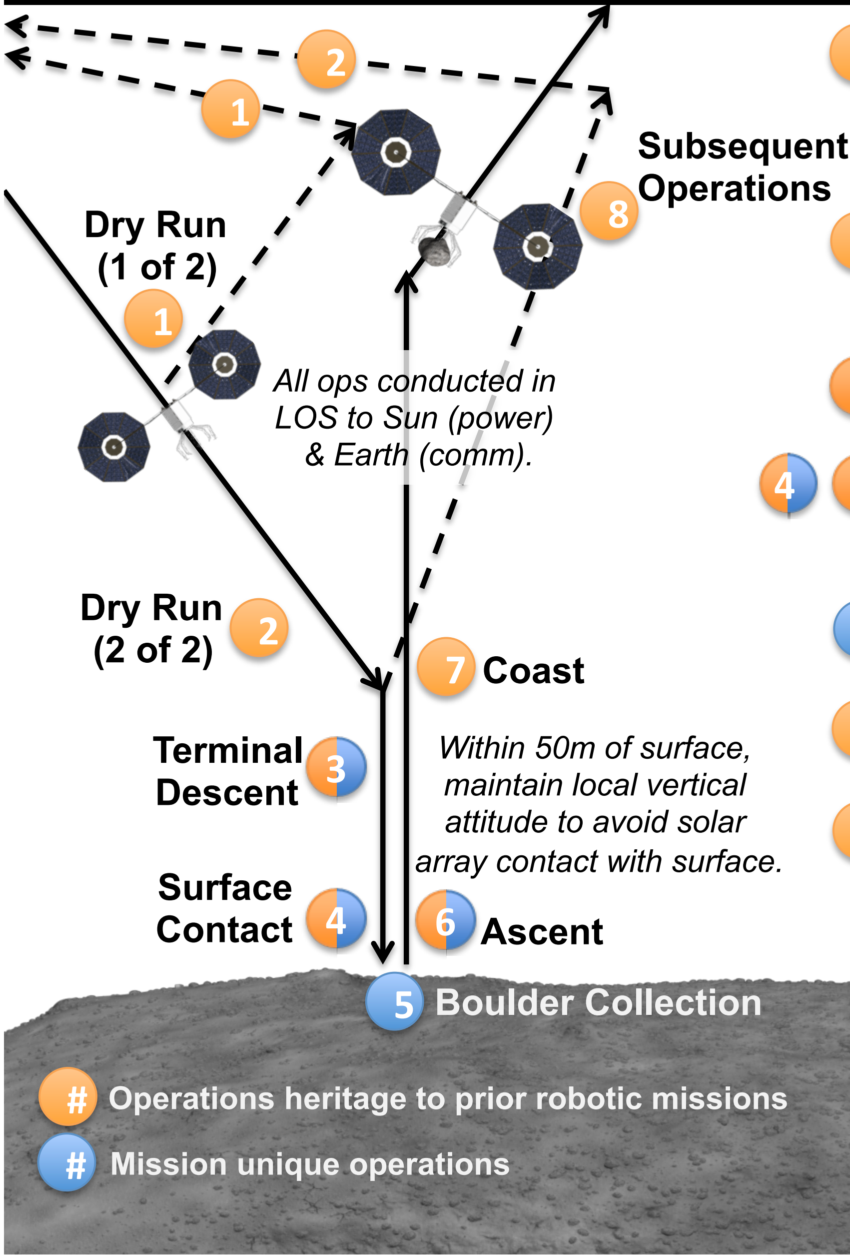
Approach (~2 weeks)	4 Fly-bys (~4 weeks)	Addt. Imaging (1 week)	2 Fly-bys (2 weeks)	Addt. Imaging (>2 weeks)
• ***Acquire images to build / refine shape model (many more images than Itokawa case)***	• Refine shape model • ***Select potential landmarks*** • Image landmarks at high resolution • ***Identify 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 (orange)

Mission unique operations (blue)

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.

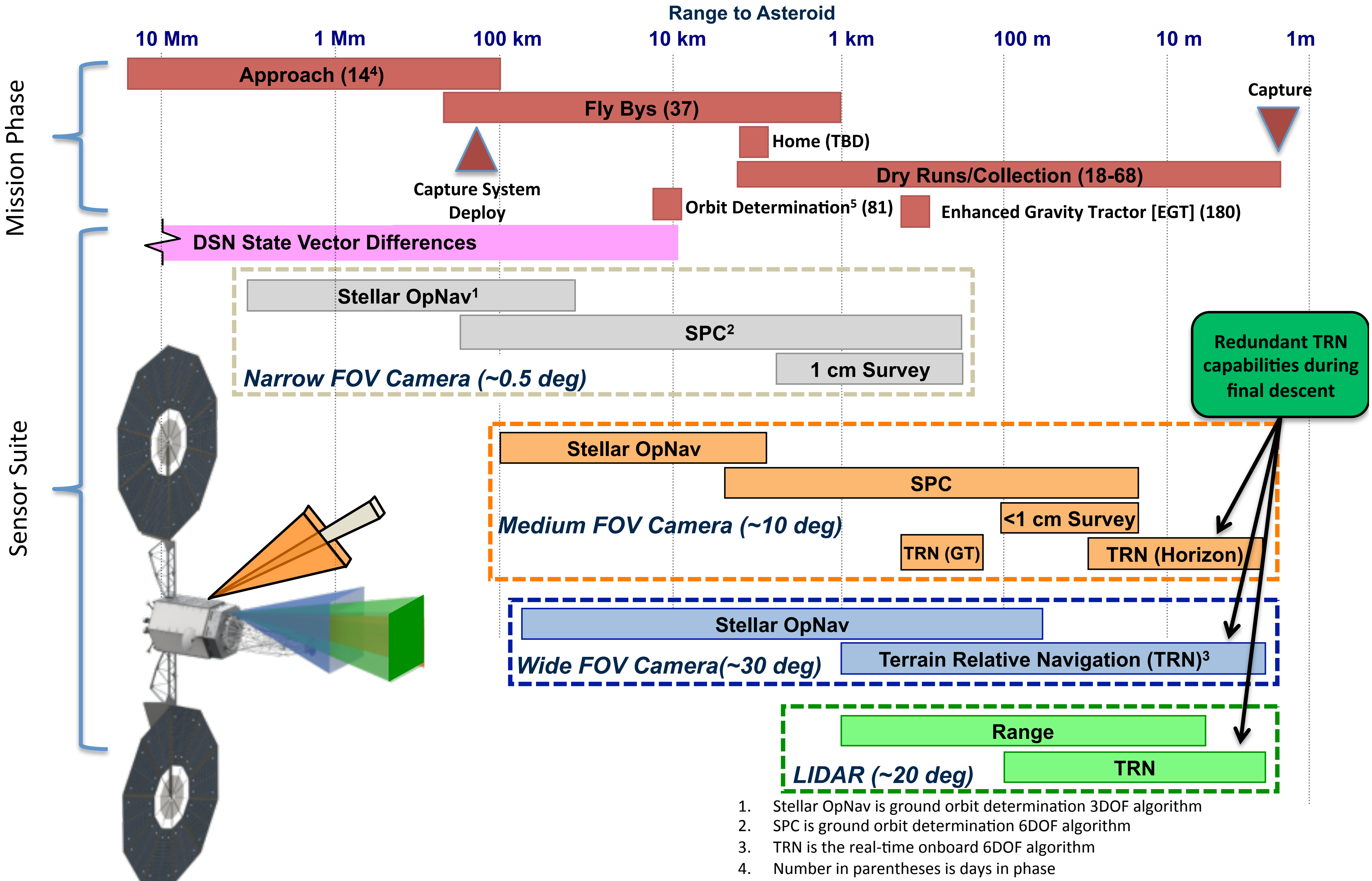
Conservative, high-heritage operations mitigate risks during boulder collection operations to increase probability of successful boulder capture.

Summary of NEA Targets Analyzed

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

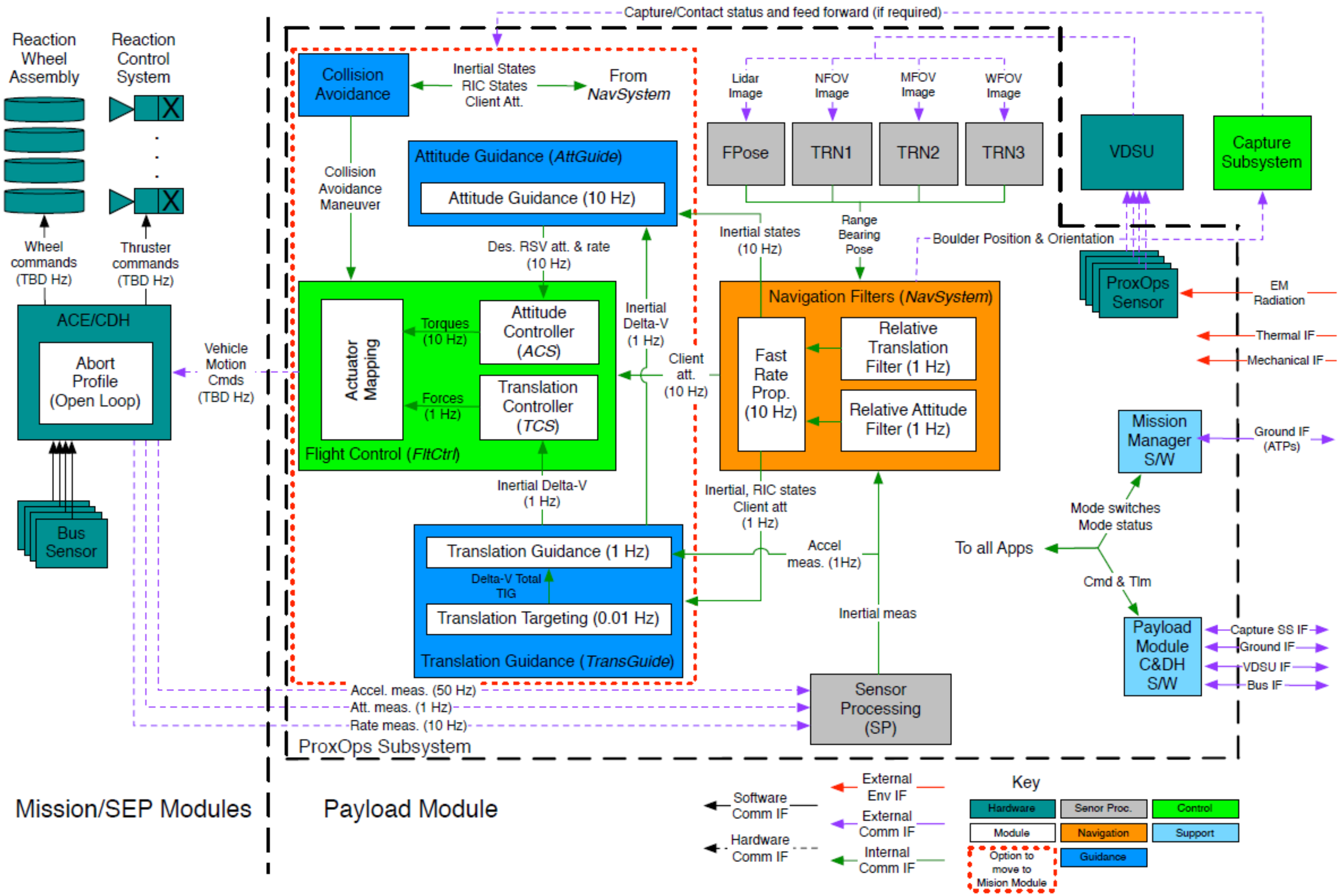
	Itokawa	Bennu	1999 JU_3	2008 EV_5
Mass	3.15×10^{11} kg	7.79×10^{10} kg	1.55×10^{12} kg	1.05×10^{11} kg
Dimensions	535 x 294 x 309 m	Mean Dia.: 492 m	Eff. Dia.: 870 m	420 x 410 x 390 m
Rotation Period	12.132 hours	4.297 hours	7.627 hours	3.725 hours
50 m Sun Angle	45 degrees	60 degrees	37.5 degrees	60 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

Sensor Operations Description



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

S/W Block Diagram



ARV Sensor Suite

Sensor Type	Purpose	Phase	FOV (deg)	Res.	Focal Length (mm)	F#	Aperture (cm)	urad/ pixel	Pixel Size (um)
Narrow FOV Camera (x2)	Star field OpNav up to 125km, detailed survey	App., Char.	0.5	1024	762.72	3.81	20	8.52	6.5
Medium FOV Camera (x2)	Star field OpNav up to 4km	Char., Home	10	1024	38.04	0.95	4	170.44	6.5
Wide FOV Camera (x2)	SPC-based OpNav and TRN sub 8km	Char., BC	35	2592	9.04	4.52	0.2	235.67	2.2
Eng. Cams (x5)	Provide general situational awareness	BC	35	NTSC	TBD	TBD	TBD	NA	NA

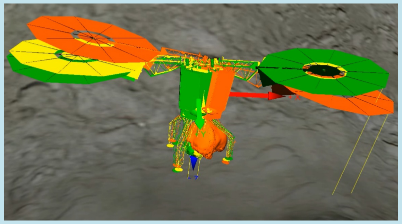
Sensor Type	Purpose	Phase	FOV/ FOR (deg)	Res.	Voxel Accuracy	Laser Power
Lidar (x2)	ICP-based TRN sub 200m	BC	NA	TBD	TBD	TBD

Proximity Operations Analysis

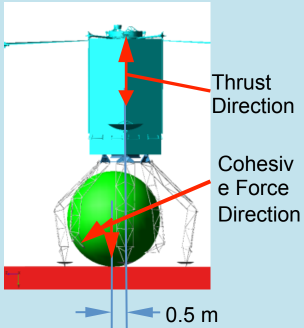
Multiple analysis tools from government, industry, and academia are being used to understand the details of the proximity operations. Results have yet to find any show stoppers.

Descent / Ascent Dynamics

LaRC/AMA developed attitude control simulation



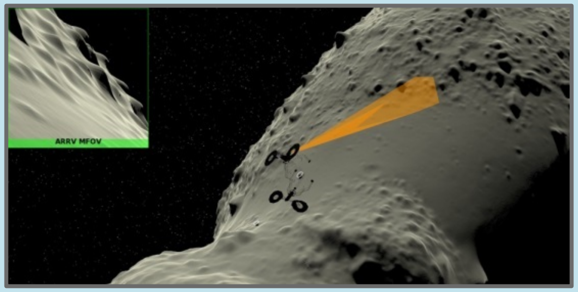
ADAMS multi-body dynamics simulation



Results show *sufficient control authority and array tip clearance* with margin over expected boulder masses with worst case c.g. offset, surface cohesion, and push off.

Characterization and Navigation

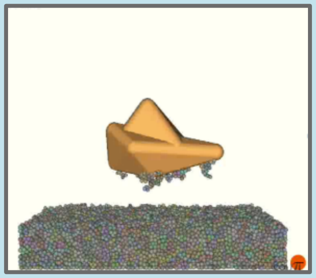
GSFC Freespace engineering visualization environment



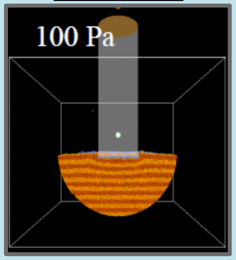
Simulation shows *sensor resolution* over time, total *surface coverage* by resolution, *terrain relative navigation* imagery, and sensor *gimbal requirements*.

Surface Interaction

UAF CouPi for boulder extraction forces

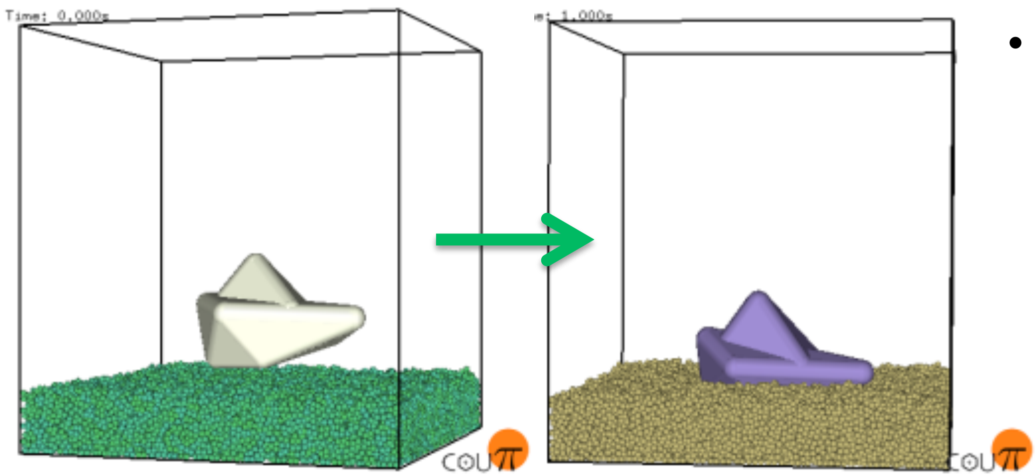


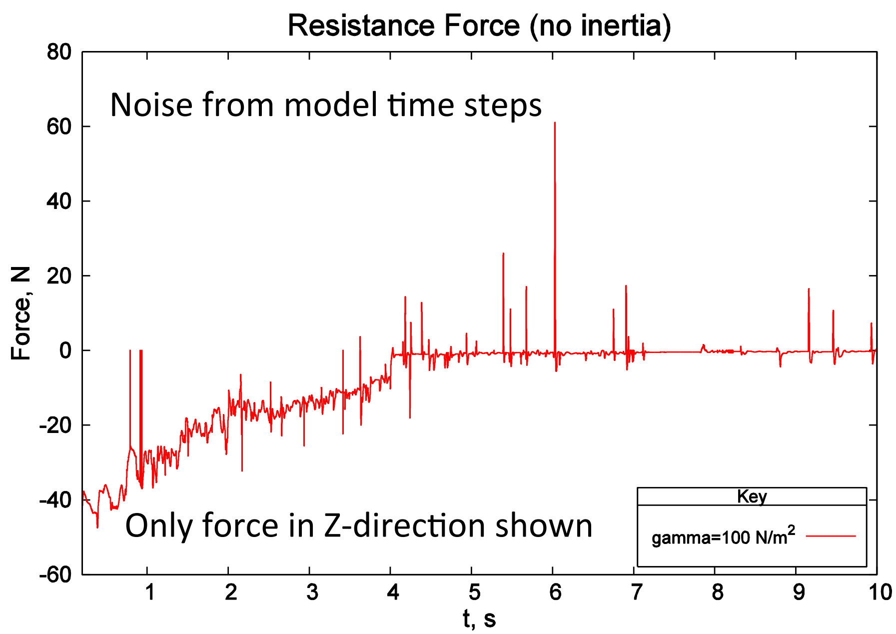
CCAR developed surface interaction simulation



Results show that for the full expected range of surface cohesions, *boulder separation force* will be dominated by inertia and surface will provide adequate *stability during contact*.

Collection Force Results

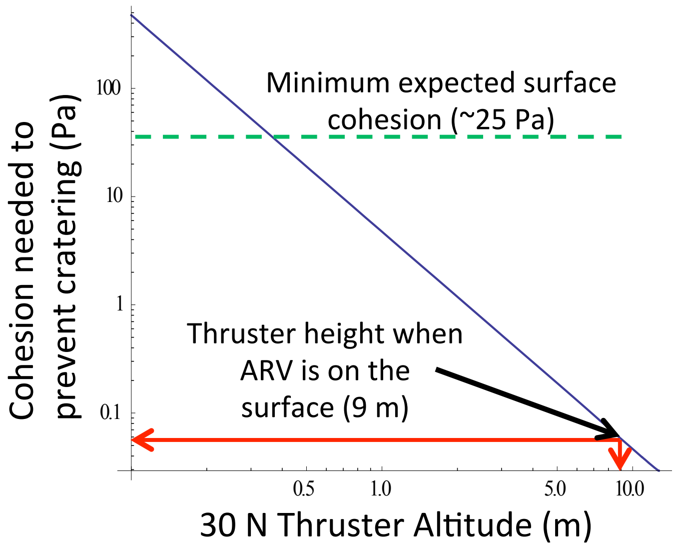


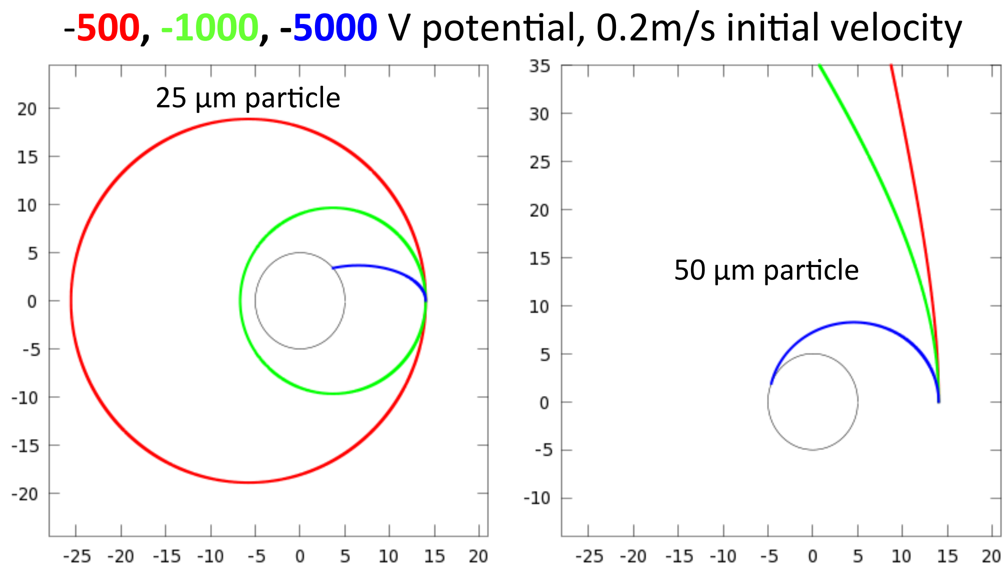


- Example Case
  - Boulder Diameter: 3 m
  - Boulder Mass: 6,974 kg
  - Surface Energy: 100 J/m^2 (~3,000 Pa cohesion, max seen for lunar regolith and much more than expected on NEAs)
  - Particle Diameter: 0.05 m
  - Constant acceleration to 0.2 m/s over 4 seconds
  - Boulder sitting on surface
- Maximum cohesion resistance force ~50 N
- Inertia dominates ~ 350 N
  - Acceleration can be reduced to reduce inertia
- *This model is still in development. Further work will look at adjusting time-steps and particle sizes to refine results.*

Surface Pluming

Preliminary analysis shows debris creation expected to be minimal with low probability for ARV impact.





Preliminary Debris Creation Analysis

- Conducted by KSC Swamp Works
- Minimum expected surface cohesion is ~1,000 times the maximum cohesion that would allow cratering
- If debris is liberated from the surface it will most likely be <1 mm in diameter and likely to be cleared by solar radiation pressure within hours or days
- Any liberated particles would expected to exceed escape velocity and be pushed away from ARV since all vertical thrusters are canted

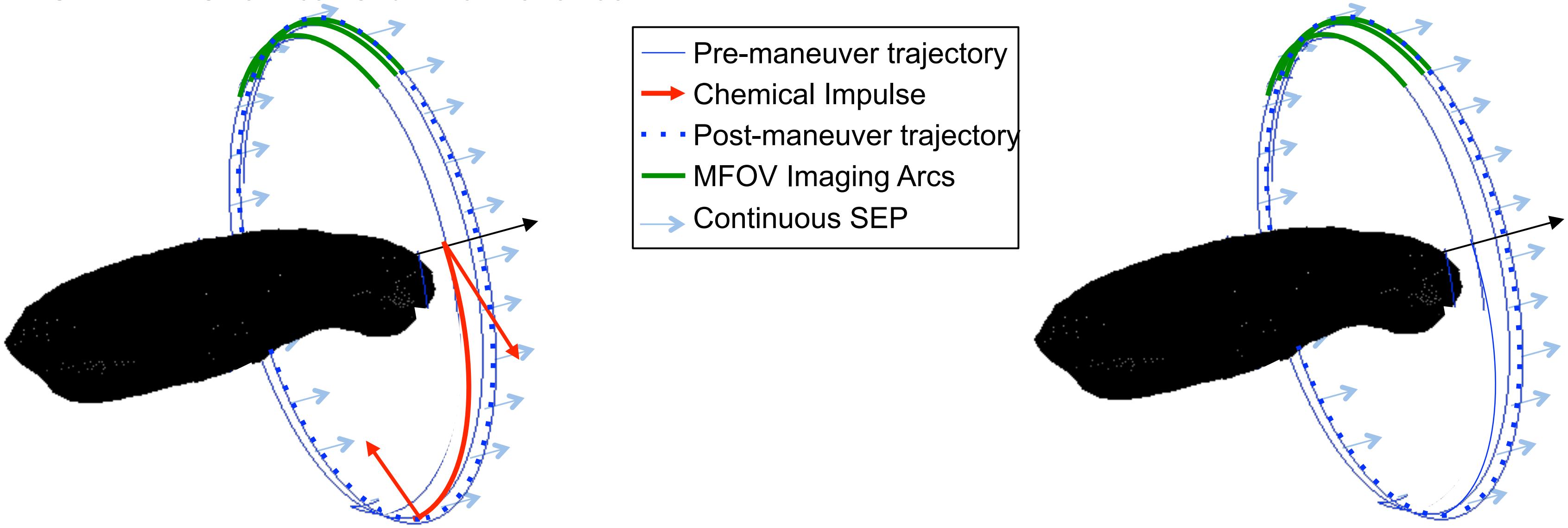
Preliminary Electrostatic Analysis

- Conducted by GSFC
- Particles that have highest change of being liberated from the surface would require > 1,000 V potential difference in order to be attracted back to the ARV
- Maximum expected potential difference ~100 V

Gravity Tractor Halo Orbit – Two Control Options

SEP with Chemical Orbit Maintenance

SEP Only

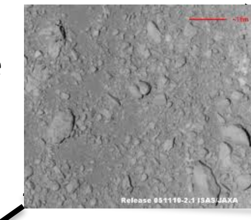


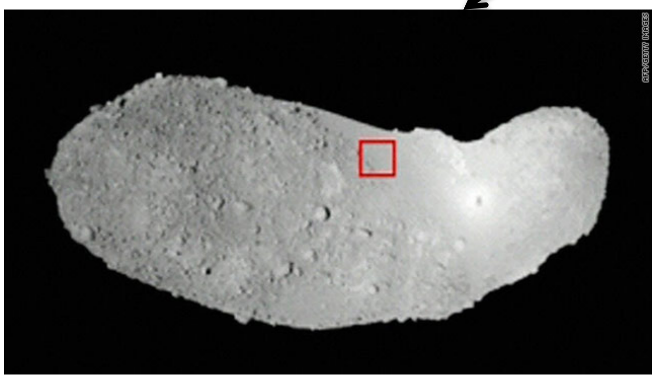
Enhanced Gravity Tractor (EGT) operations utilizing halo orbit are safe and effective.

- Continuous SEP used for counteracting NEA gravitational force and solar radiation pressure.
- Chemical impulses can be used to maintain halo orbit and account for navigation and control errors as well as un-modeled perturbations.
- SEP Thrusters are thrusting at away from the NEA at all times and can throttle up upon any anomaly detection to push ARV to a safe distance from the NEA.
- 4 RCS thrusters are also pointed away from the NEA at all times and can be used as backup to SEP for escape to safe orbit.

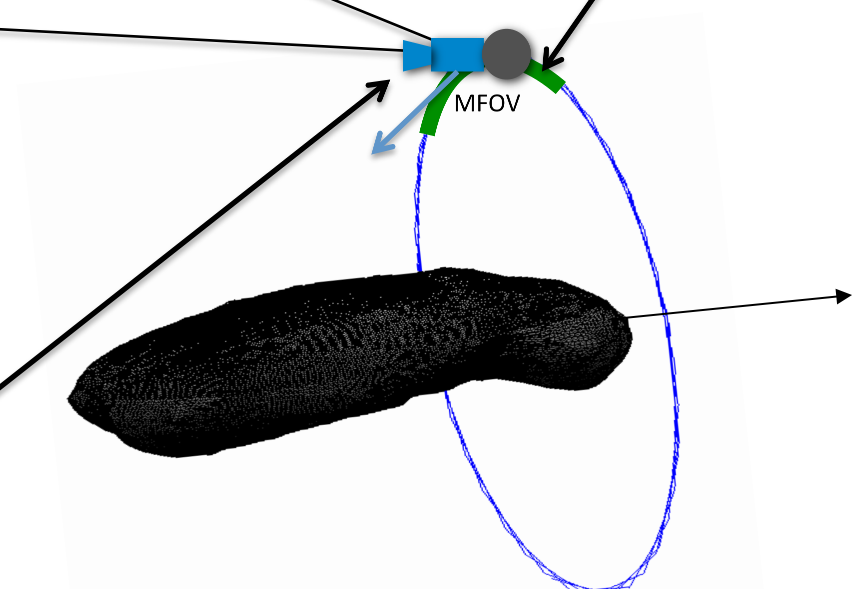
Gravity Tractor Optical Navigation Operations

Map image to determine spacecraft state relative to asteroid





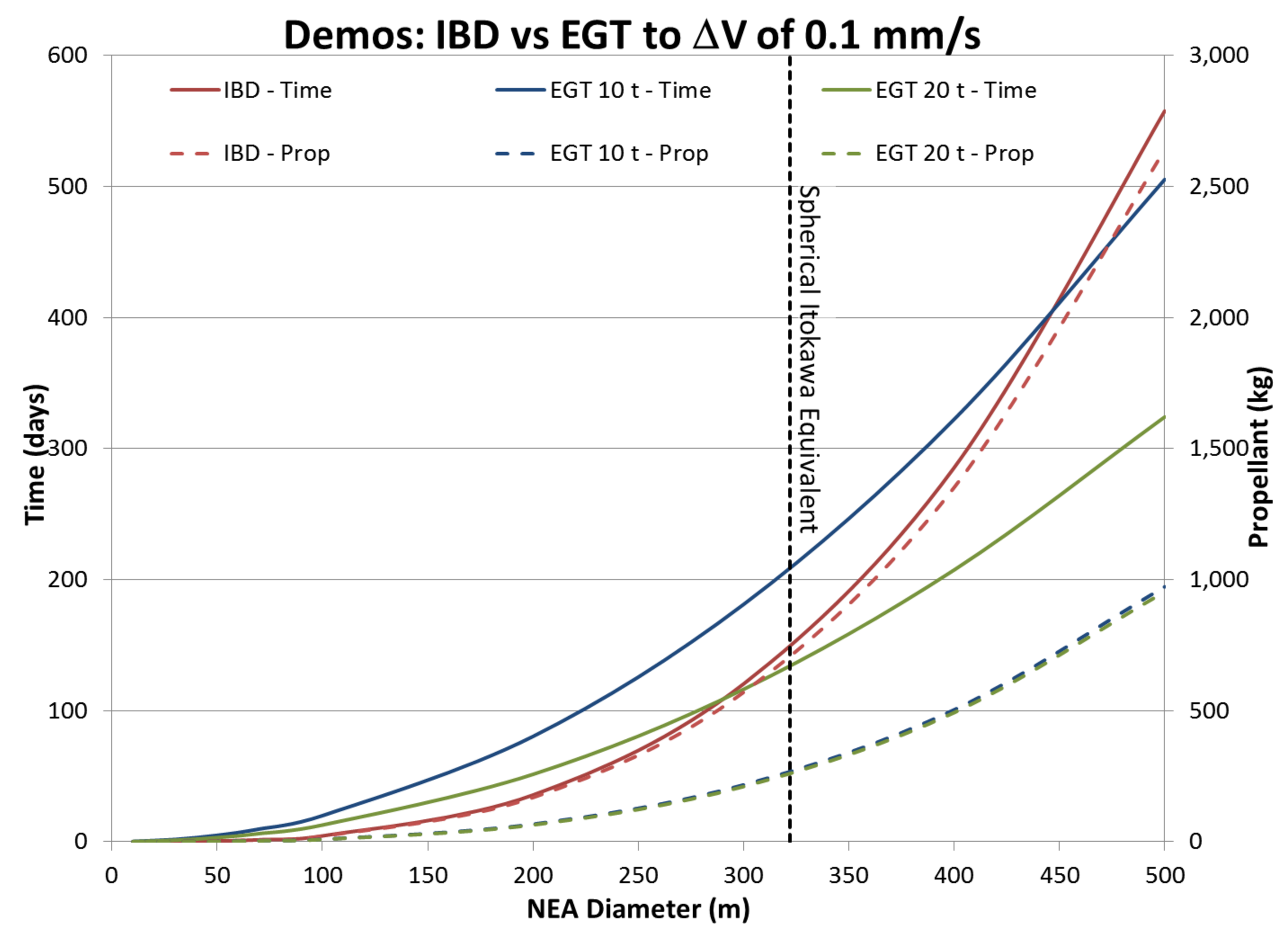
One imaging arc per orbit. Orbit has ~12 hour period -> 2 imaging arcs per day.



Receive DSN/ DDOR updates once per day

One imaging arc per orbit (~12 hours) provides more than sufficient on-board processing and anomaly resolution. Combined with once daily ground support, there is high confidence in the ARV's ability to determine and maintain orbit.

Planetary Defense Demonstration Options



Note: Assumes 30 degree plume half-angle for EGT

EGT was chosen over IBD

- Utilizes collected boulder mass inherent in mission concept
- Uses ~1/2 the propellant of IBD (~300 kg vs. ~600 kg for Itokawa)
- For larger NEAs, EGT requires less time than IBD for a similar deflection
- EGT does not risk xenon contamination of the surface
- EGT utilizes simplified operations requiring maintaining constant safe distance with adequate optical navigation imagery
- IBD demonstration requires multiple close approaches

EGT was chosen over IBD for applicability to larger NEAs, propellant savings, and simplified operations. Other demonstrations could also be included by have not been fully analyzed.