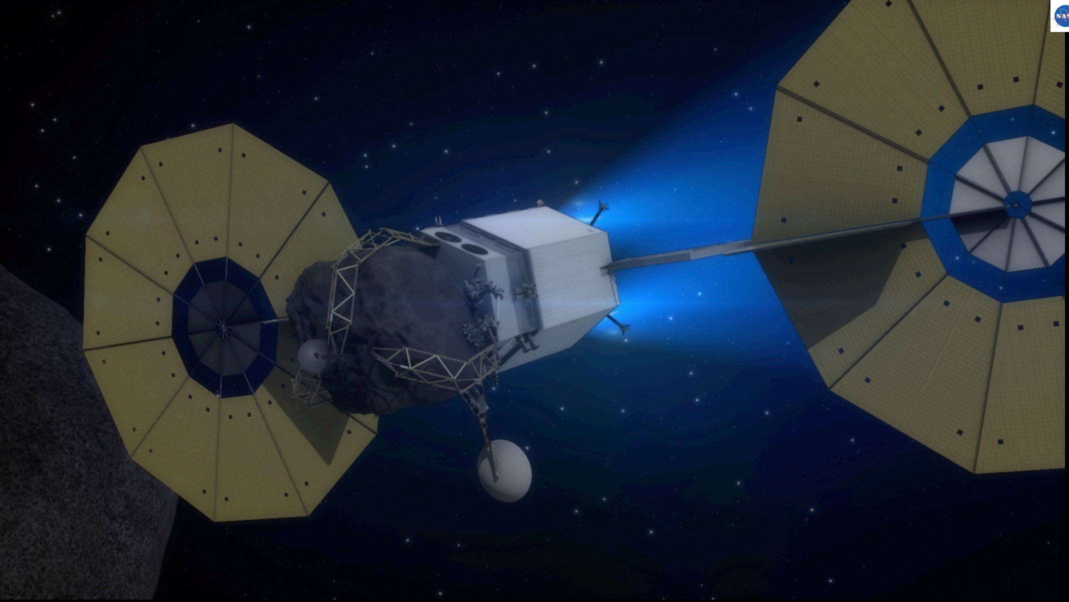

# Key Challenges in Capturing a Boulder for the Asteroid Redirect Robotic Mission

15th International Planetary Probe Workshop

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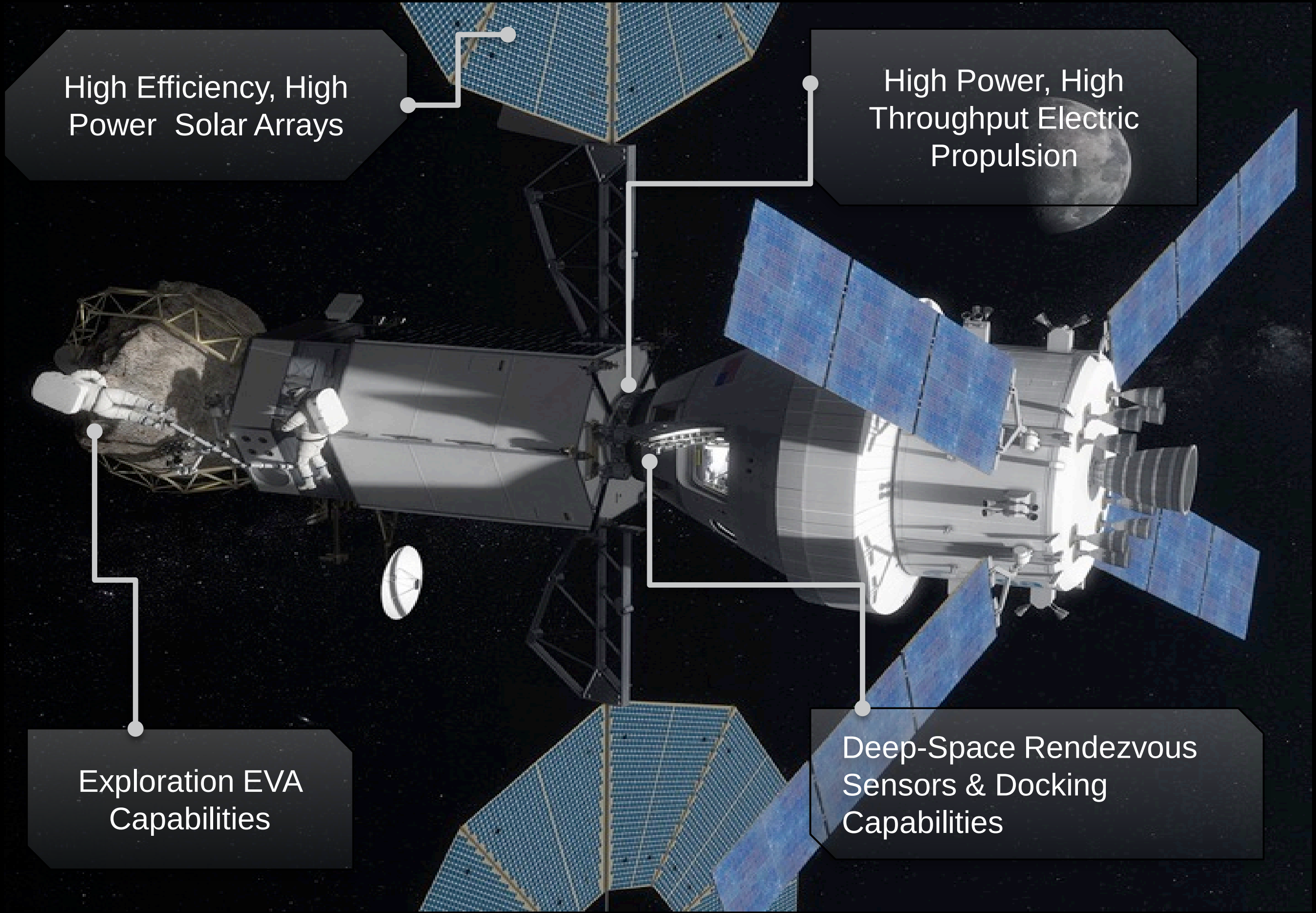
**Asteroid Redirect Robotic Mission**

# Asteroid Redirect Mission (ARM)




"A Capability Driven Mission"

Transporting multi-ton objects with advanced solar electric propulsion

Integrated crewed/robotic vehicle operations in deep space staging orbits

Advanced autonomous proximity operations in deep space and with a natural body

Astronaut EVA for sample selection, handling, and containment

# Robotic Segment Boulder Collection Operations Concept

Approach

2 weeks

Characterization

2 months

Boulder Collection

~5 hours per attempt, 3 attempts over 2 months

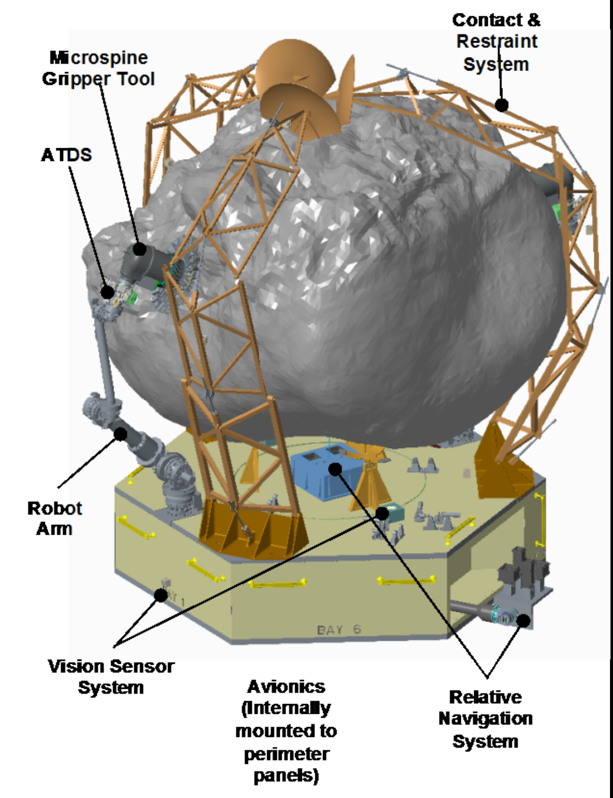
Planetary Defense Demo

5 months

# Capture Module – Capabilities and Key Challenges

Capture Module Mockup

Microspine Gripper Tool




ARM Capture Module (CAPM)

Built from capabilities under development for robotic satellite servicing and on-orbit assembly

Characterize surface of asteroid at 10 cm resolution

Autonomously land a 10 t vehicle with 50 m solar arrays to a pre-identified target with 50 cm accuracy and 10 cm/s touchdown velocity

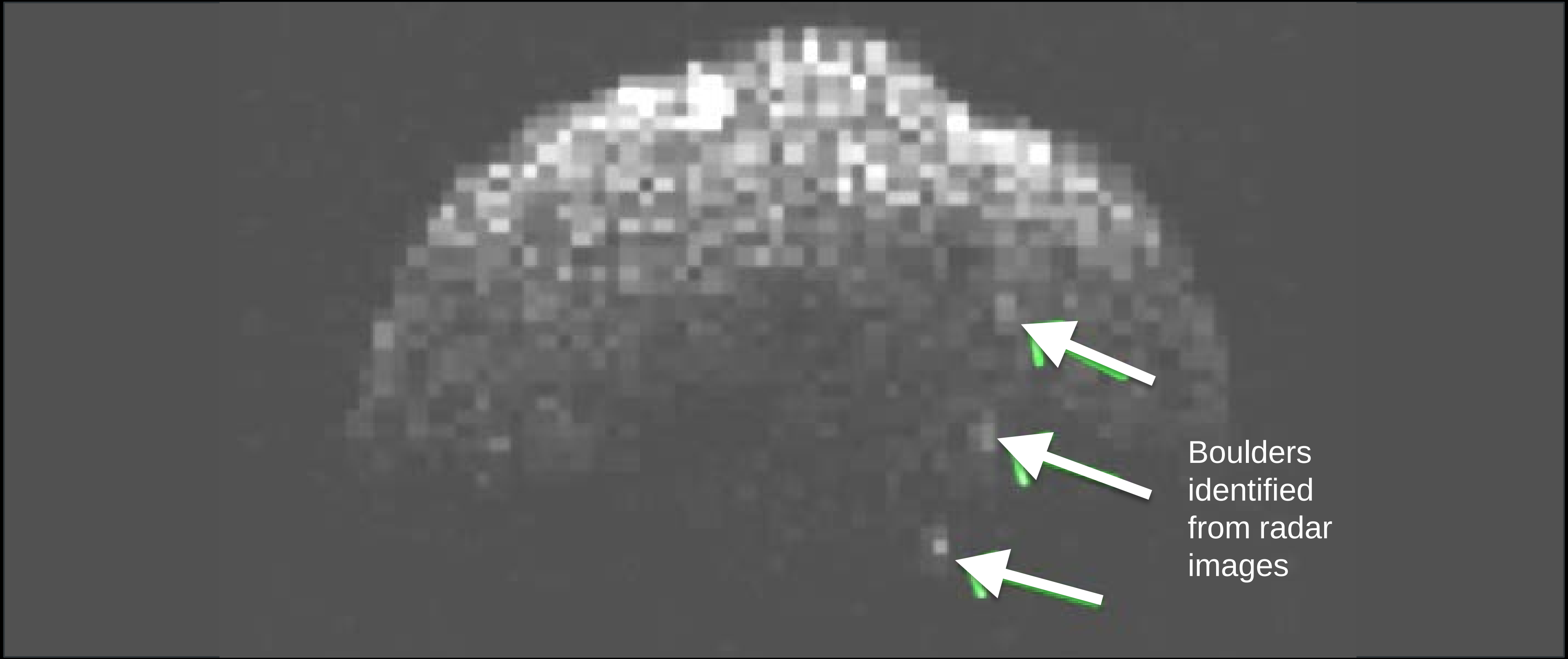
Autonomously grasp and anchor to natural rock surface

Autonomously extract the boulder breaking attachment / cohesion to surface

Autonomously depart asteroid

Defend the planet

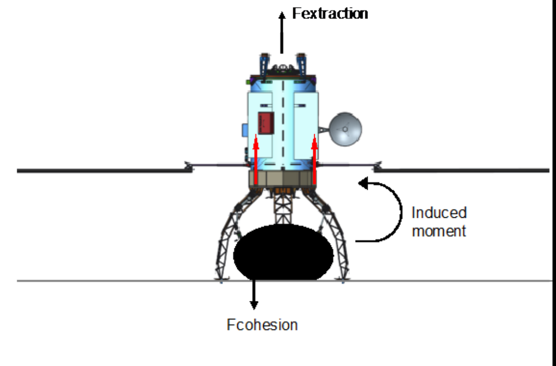
# Reference Target 2008 $EV_5$



# Key Mission Challenges – Technical and Programmatic

Significant uncertainty in understanding of C-type asteroid properties, including the quantity, accessibility, strength, and surface cohesion of boulders

Evolution in mission objectives from original capability-driven 2-3 m boulder estimate, to a Level-1 requirement for returning a 6 m boulder




Key forces and moments during extraction

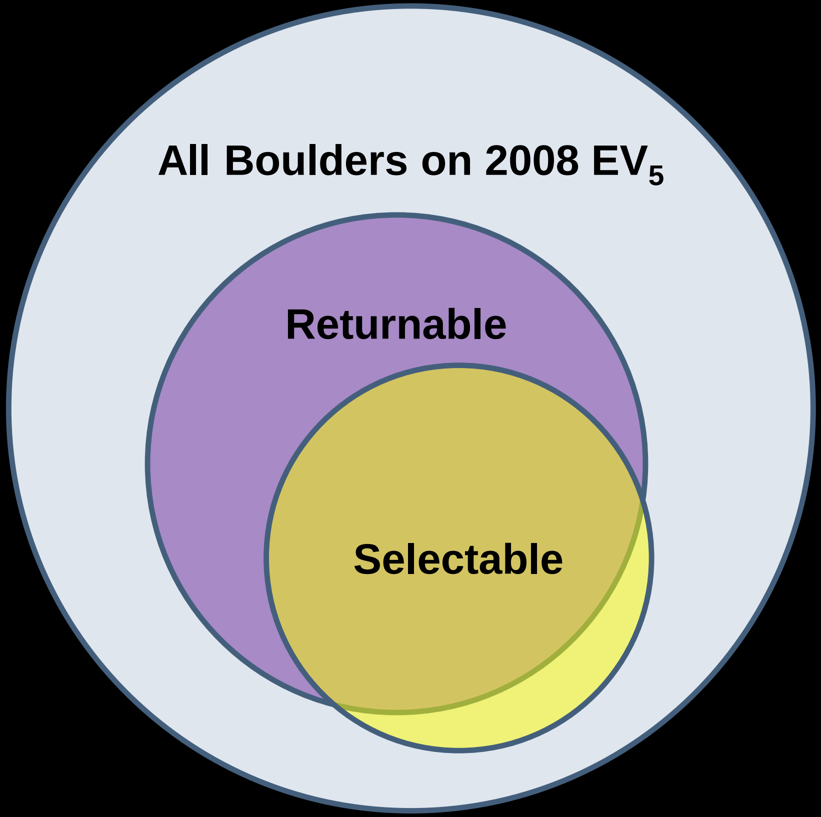
$$F_{\text{cohesion for 6m boulder}} = A_{\text{worst case surface in contact}} * P_{\text{worst case cohesion}}$$

$$\sim= 6000 \text{ N}$$

$$F_{\text{extraction}} = 2*F_{\text{cohesion}} = 12000 \text{ N}$$

Classical calculation of required extraction capability given 6 m requirement

# Mission Performance Monte Carlo Analysis




We need to analyze the probability of success – that we *find, extract,* and *return* a boulder of the required size

Simple Monte Carlo analysis would estimate by iteratively evaluating a randomly selecting boulder. However this is not correct because the mission will get to select the boulder to extract

When we model selection, we need to take into account uncertainty in knowledge, and the conservatism of the operations team – won't select a boulder unless there is a high confidence we will be successful. Thus *selectable* not a proper subset of *returnable*

$$P_{\text{success}} = P(\textit{Returnable} \mid \textit{Selectable}) * P_{\text{one selectable}}$$

$$\text{where } P_{\text{one selectable}} = [1-(1-P_{\text{selectable}})]^{\text{number of boulders}}$$

Probability of success formulation

# Mission Performance Scorecard

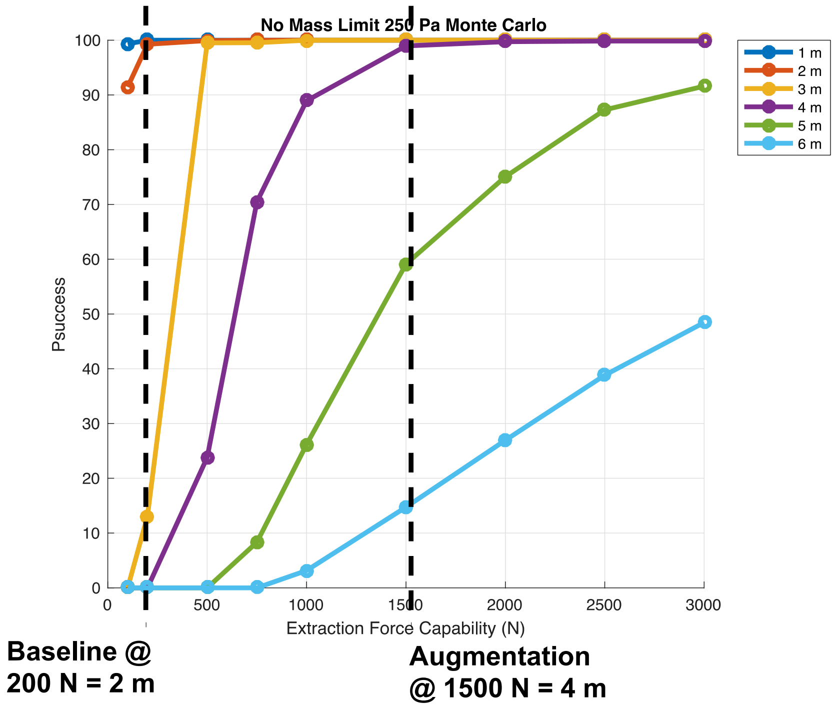
<table>
<tr><th rowspan="2">Boulder Size</th><th colspan="4">100 N</th><th colspan="4">200 N</th><th colspan="4">500 N</th><th colspan="4">1500 N</th></tr>
<tr><th>CI</th><th>CM</th><th>CK</th><th>CR</th><th>CI</th><th>CM</th><th>CK</th><th>CR</th><th>CI</th><th>CM</th><th>CK</th><th>CR</th><th>CI</th><th>CM</th><th>CK</th><th>CR</th></tr>
<tr><td>1 m +0.5 m</td><td colspan="4">Robust</td><td colspan="4" rowspan="2">Robust</td><td colspan="4" rowspan="3">Robust</td><td colspan="4" rowspan="3">Robust</td></tr>
<tr><td>2 m +/- 0.5 m</td><td colspan="4">Some</td></tr>
<tr><td>3 m +/- 0.5 m</td><td colspan="4" rowspan="2">No Capability<br>Force Limited</td><td colspan="4">Some</td></tr>
<tr><td>4 m +/- 0.5 m</td><td colspan="4">No Capability</td><td>M</td><td>M</td><td>N*</td><td>N*</td><td>R</td><td>S*</td><td>N*</td><td>N*</td></tr>
<tr><td>5 m +/- 0.5 m</td><td colspan="16" rowspan="2">No Capability*<br>Mass Limited</td></tr>
<tr><td>6 m - 0.5 m</td></tr>
</table>

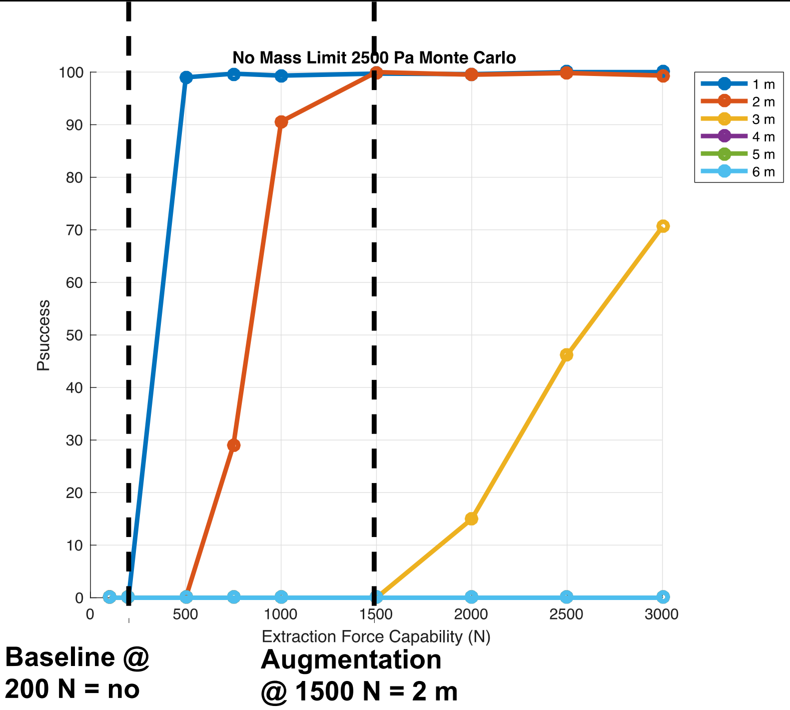
**Key Assumptions**

99% number of boulder estimates derived from radar data and SFD
Maximum return mass of 20 t
Cohesion range 25-250 Pa
Depth-of-Bury range 5%-75%
Size estimation accuracy 2 cm length/width 3 cm height for DOB < 25%
95% estimate of P(success) required for selection
Able to determine spectral type and select boulder after arrival at asteroid

- Robust capability, P(s) > 95%
- Some capability, P(s) ~50-95%
- Marginal capability, P(s) ~10-50%
- No capability, P(s) < 10%
- * Limited by return mass

# Sensitivity Analyses to Establish Robustness




An extraction force level of 1500 N provides 4 m nominal and 2 m off-nominal capability

# Results of Performance Analysis and Trades

Mission Performance analyses created a common language to discuss the expected size of boulder the mission could return given a capability level of the capture system

Stakeholders agreed to update requirements to reflect capability of 3-4 m boulder

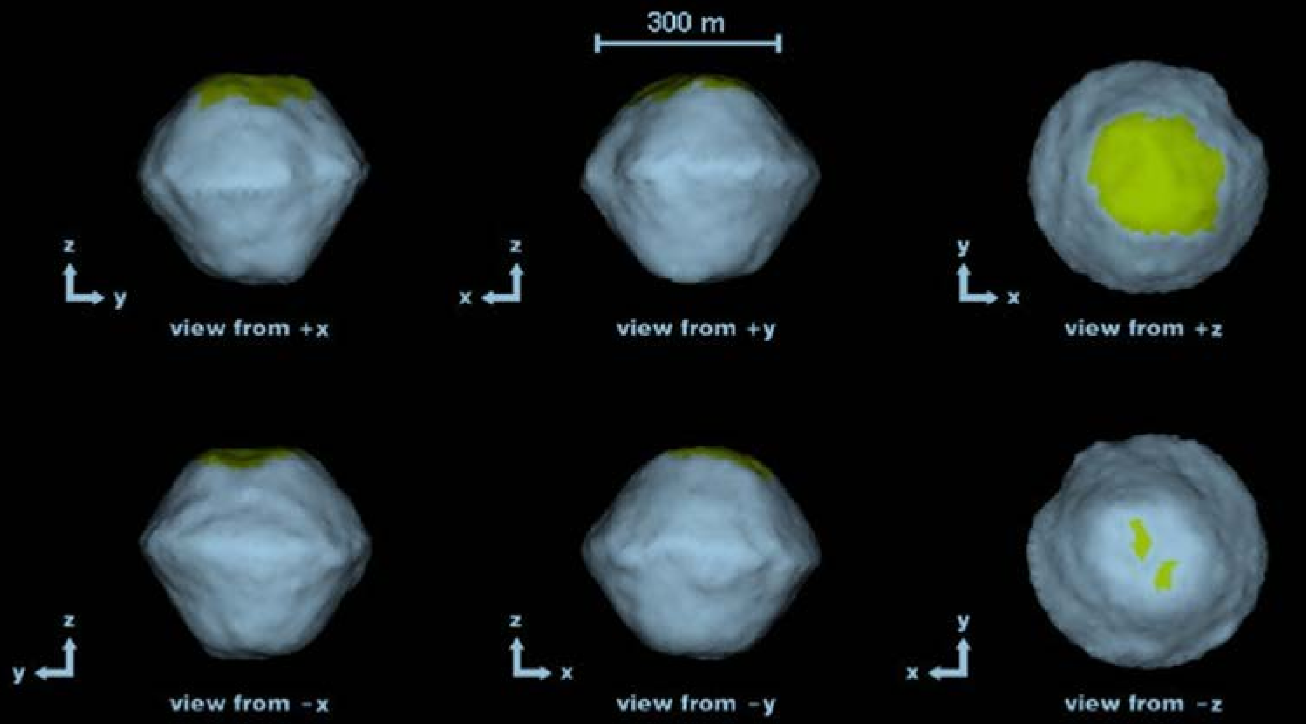
Capture Module team in turn augmented Capture Module design with additional robot arm and load bypass cables in order to robustly meet 1500 N extraction force requirement

Updates to requirements and design retired major implementation risk, and put the team on a credible path towards PDR

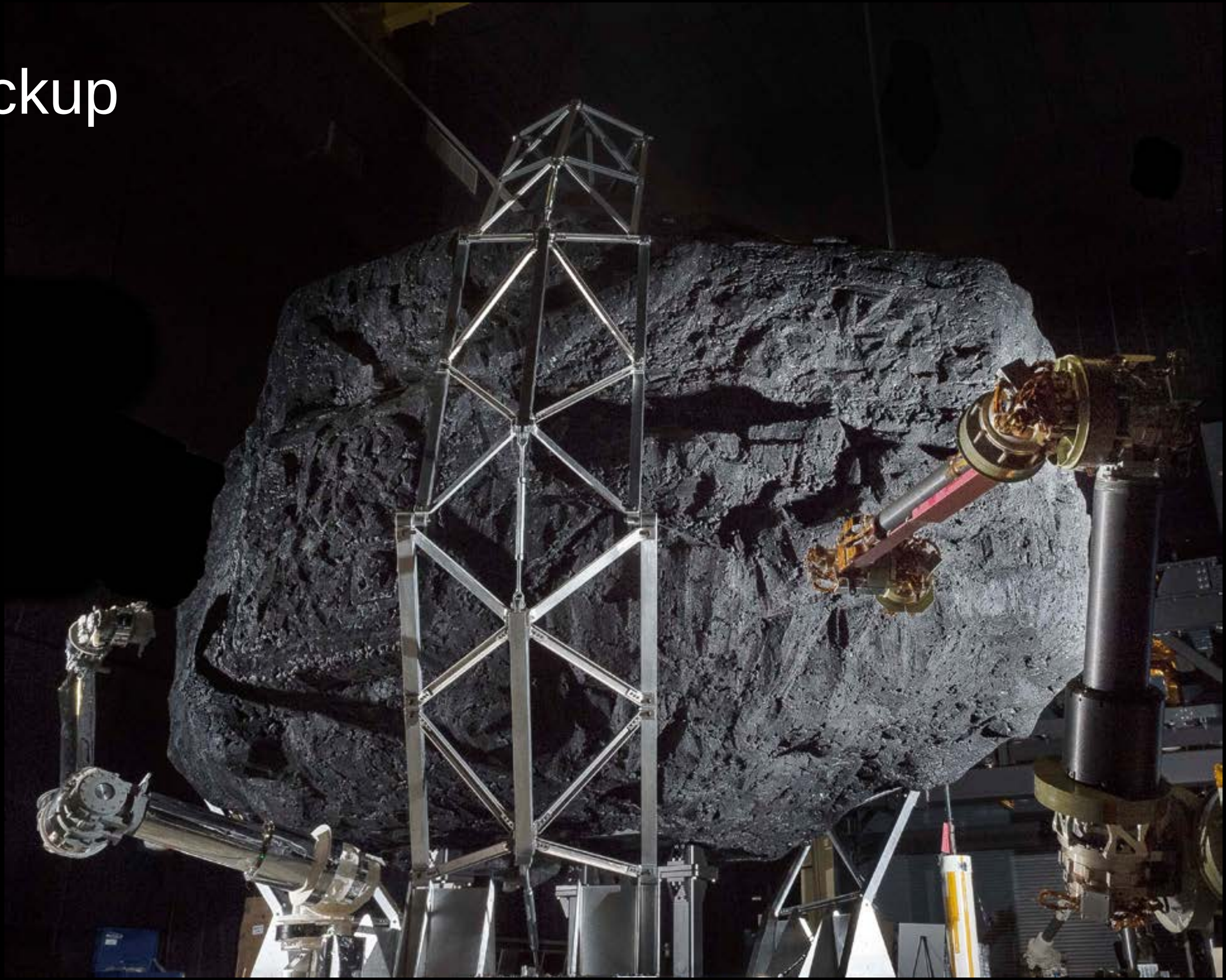
NASA

# Supplementary Material

# ARRM Reference Target 2008 EV5



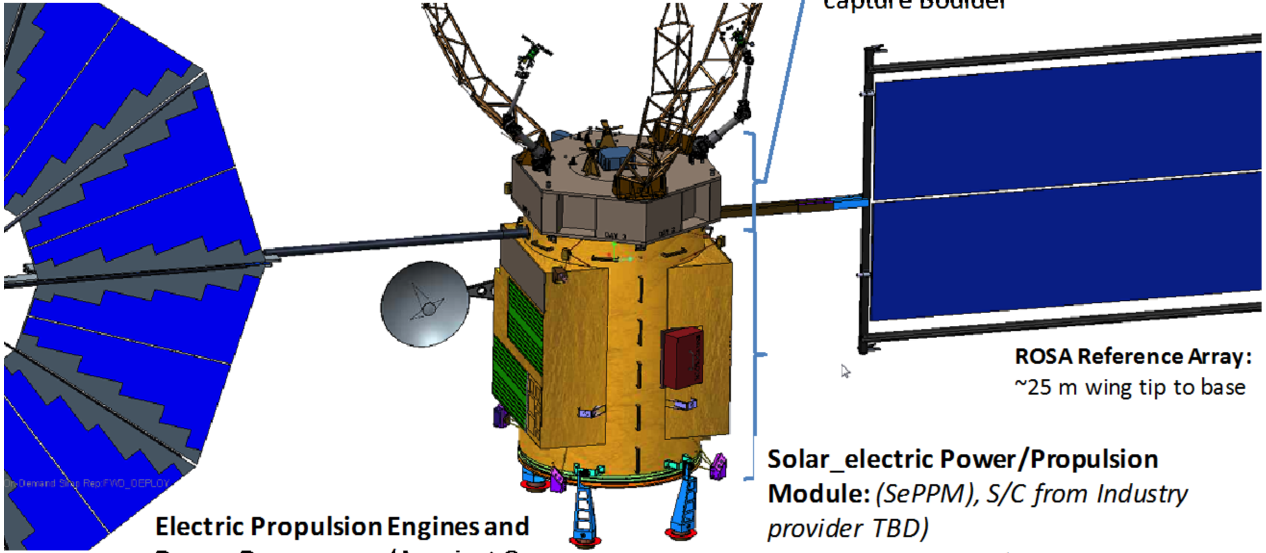
# Capture Module Mockup



# Reference ARV

**MegaFlex Reference Array:**
~20 m wing tip to base

**Capture Module:** (GSFC provided)
Robotics to support landing and capture Boulder

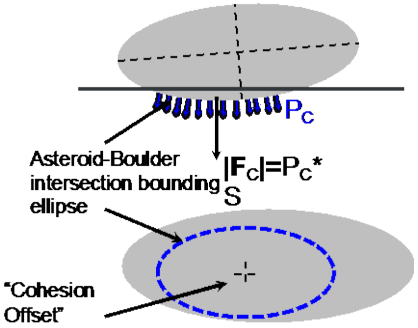


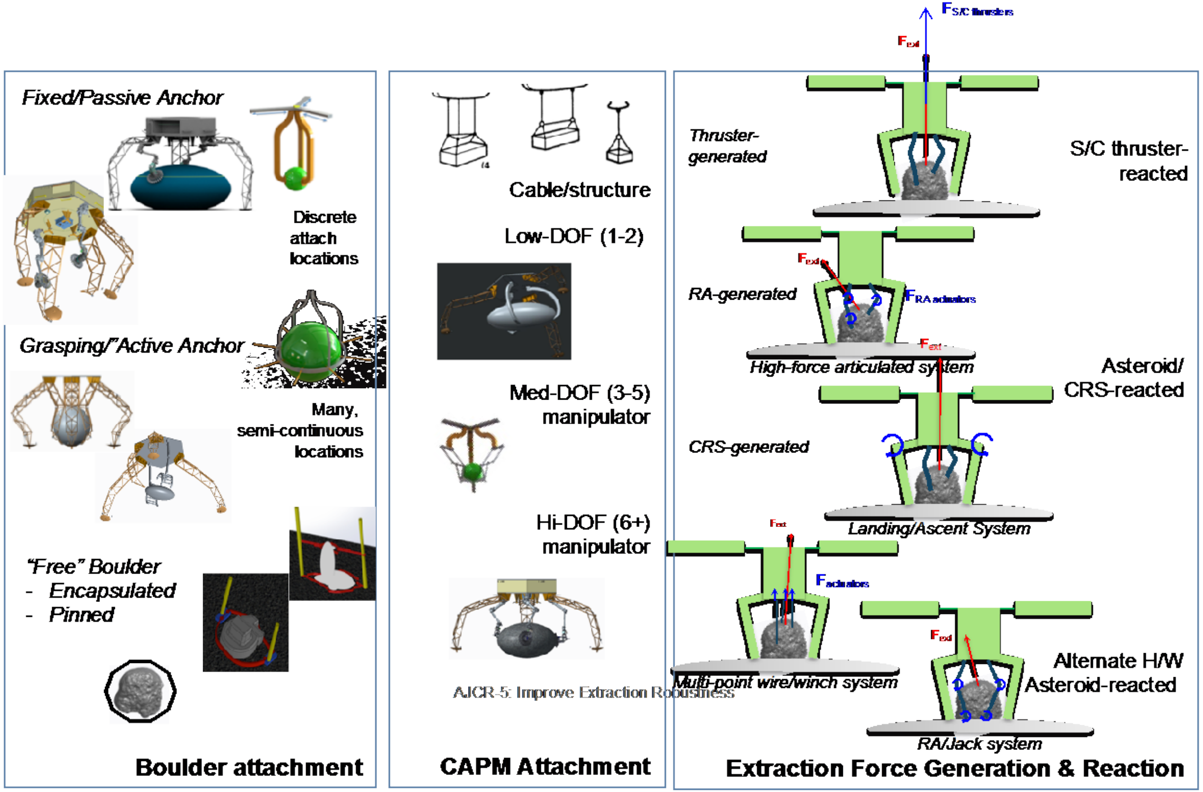
**ROSA Reference Array:**
~25 m wing tip to base

**Electric Propulsion Engines and Power Processors:** (Aeroject Corp provided, thru GRC)
Four 13 kW engines using 5 t of Xe propellant

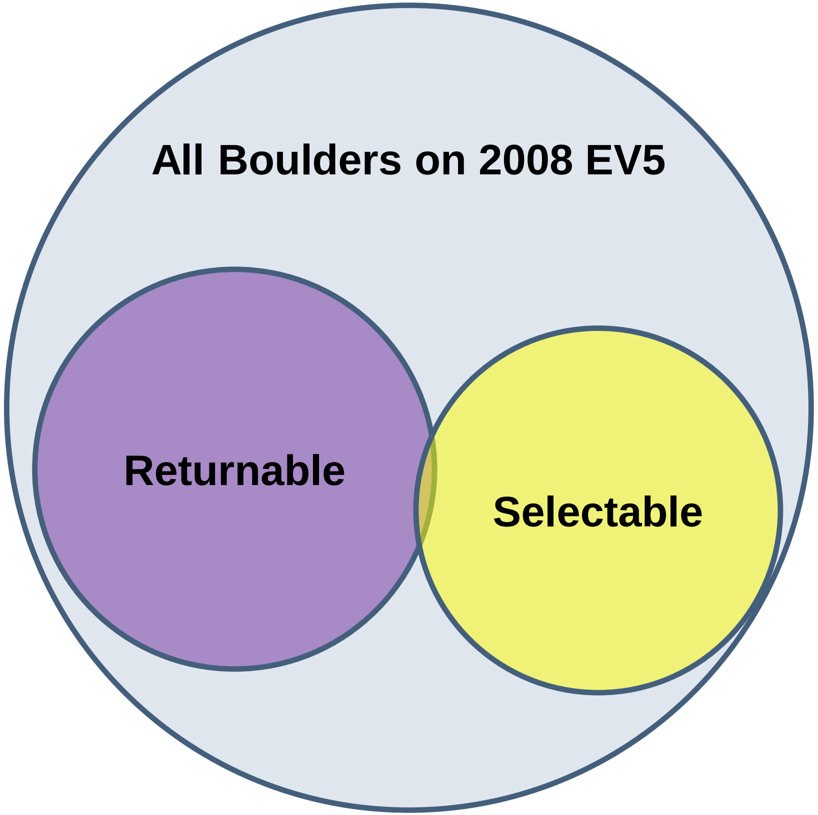
**Solar_electric Power/Propulsion Module:** *(SePPM), S/C from Industry provider TBD)*
Hosts core spacecraft housekeeping functions, GN&C, and Ion Propulsion System

# Augmentation Trade Space



# Example




N = 1000
N(R) = 500
N(S) = 100
N(SR) = 1

Psel = 100/1000 = 10%
Psr = 1/1000 = 0.1 %

P1sel = 1-(1-Psel)^1000
P1sel = 0.999999
P(R|SEL) = 1/100 = 1%
Ps = P1sel*P(R|SEL) = 1%

**Note, this would be wrong:**

Ps = 1-(1-Psr)^1000
Ps = 63.23%