National Aeronautics and Space Administration

Asteroid Redirect Robotic Mission Concept GN&C Overview

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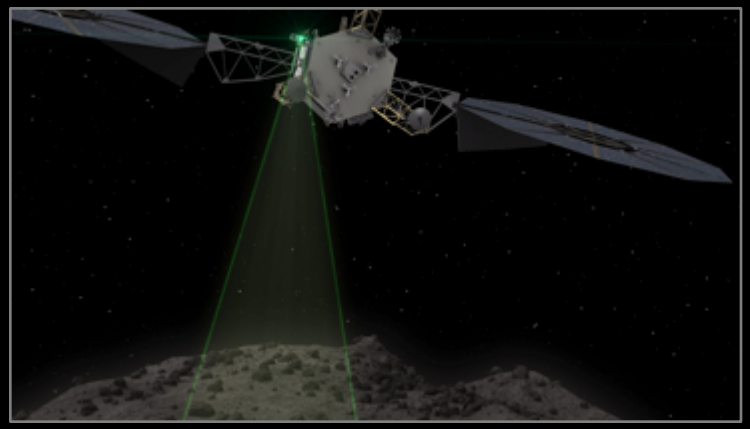
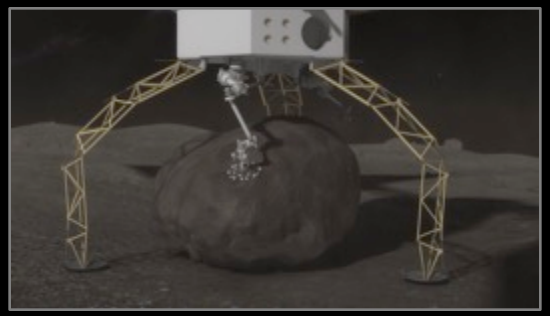
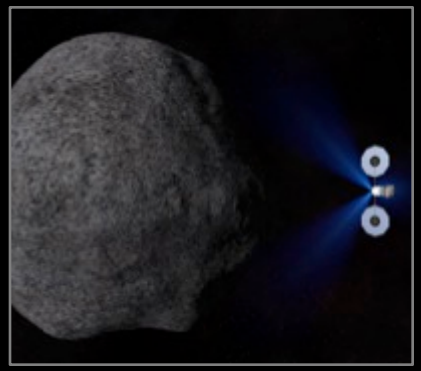
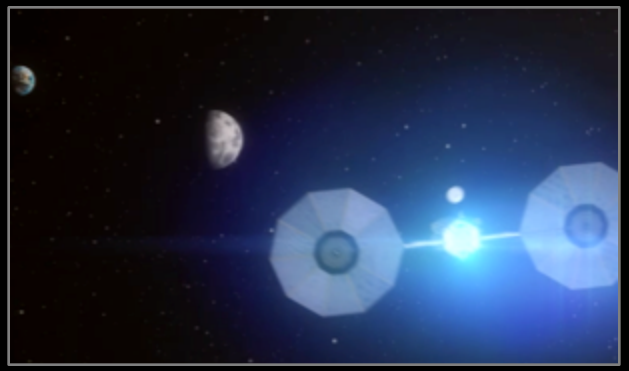
Section 344 Seminar
July 28, 2016





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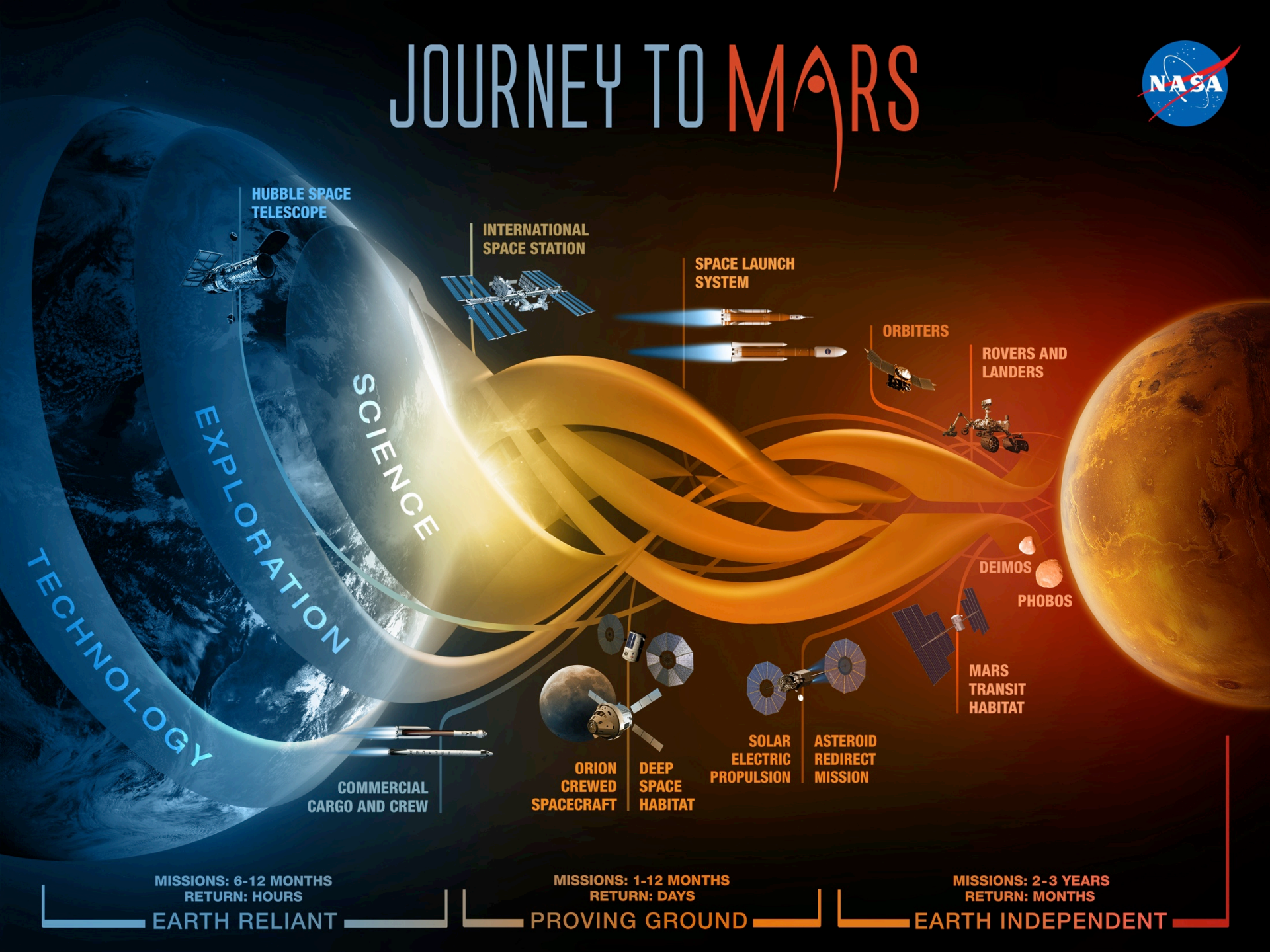
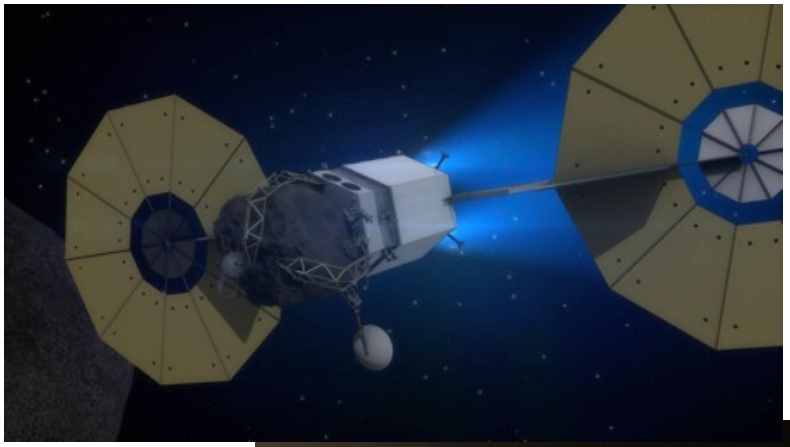
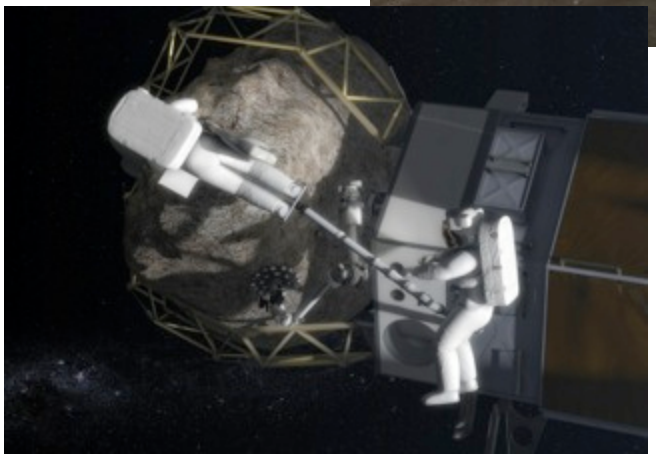
JOURNEY TO MARS



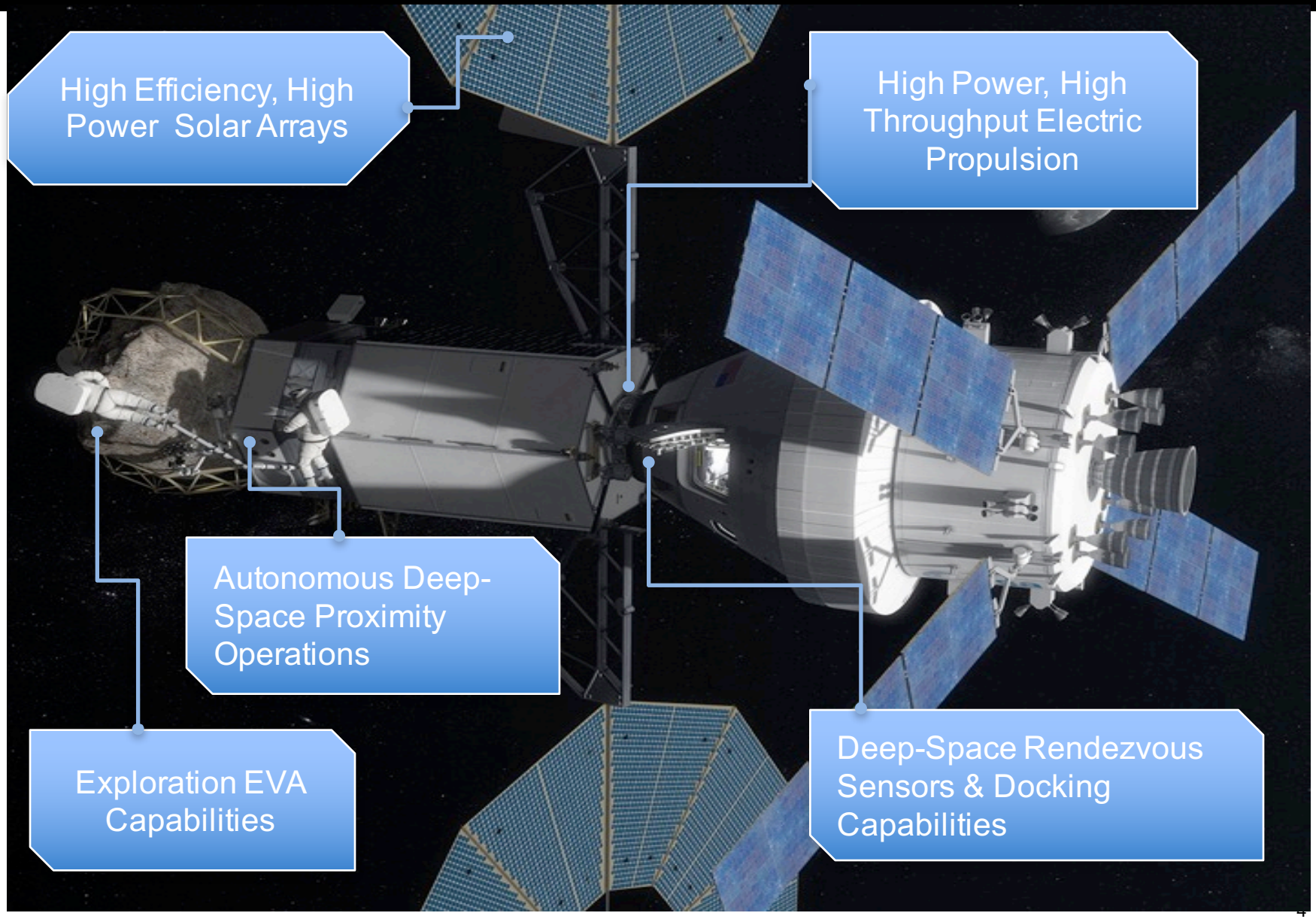
ARM Concept Key Contributions to the Proving Ground

- 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





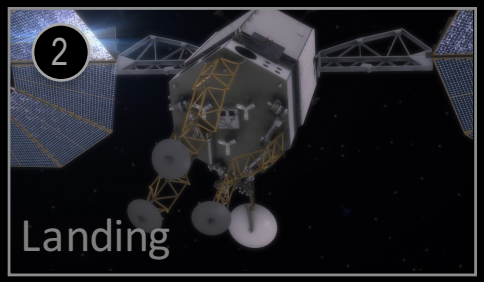
Key Technology Highlights

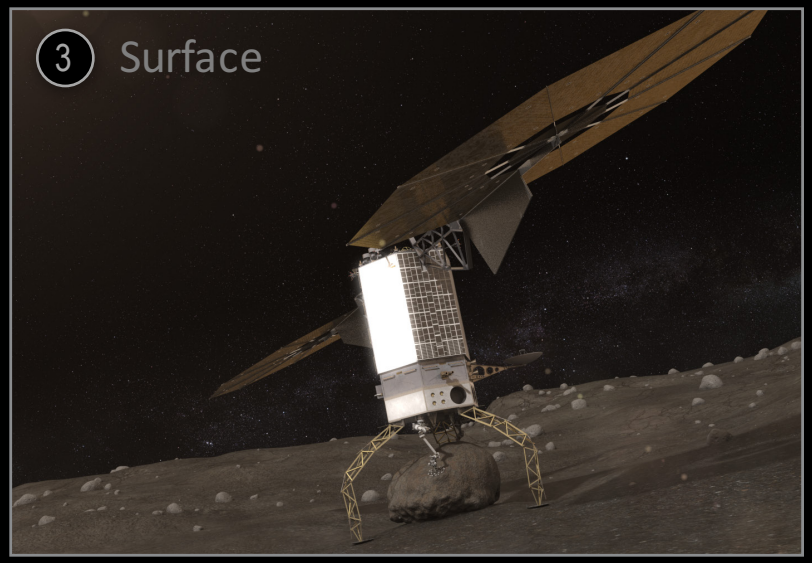


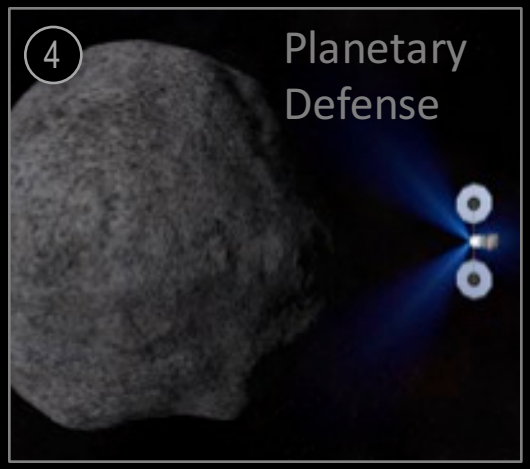
Asteroid Redirect Mission Concept Objectives

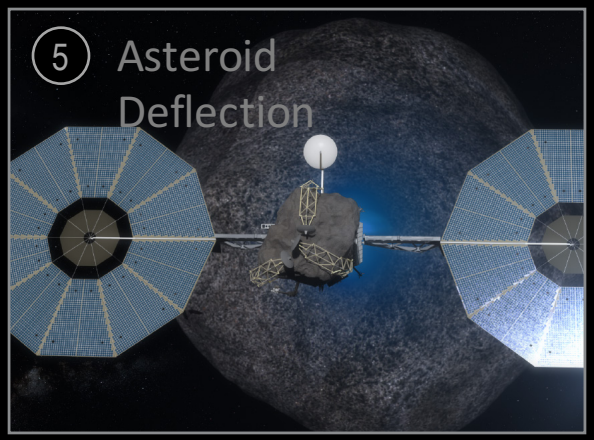
1. **Conduct a human exploration mission involving in-space interaction with an asteroid boulder in the mid-2020's, providing systems and operational experience required for human exploration of Mars.**
2. **Demonstrate an advanced solar electric propulsion system, enabling future deep-space human and robotic exploration with applicability to the nation's public and private sector space needs.**
3. **Enhance detection, tracking and characterization of Near Earth Asteroids, enabling an overall strategy to defend our home planet.**
4. **Demonstrate basic planetary defense techniques that will inform impact threat mitigation strategies to defend our home planet.**
5. **Pursue a target of opportunity that benefits scientific and partnership interests, expanding our knowledge of small celestial bodies and enabling the mining of asteroid resources for commercial and exploration needs.**

Asteroid Redirect Mission Concept Highlights

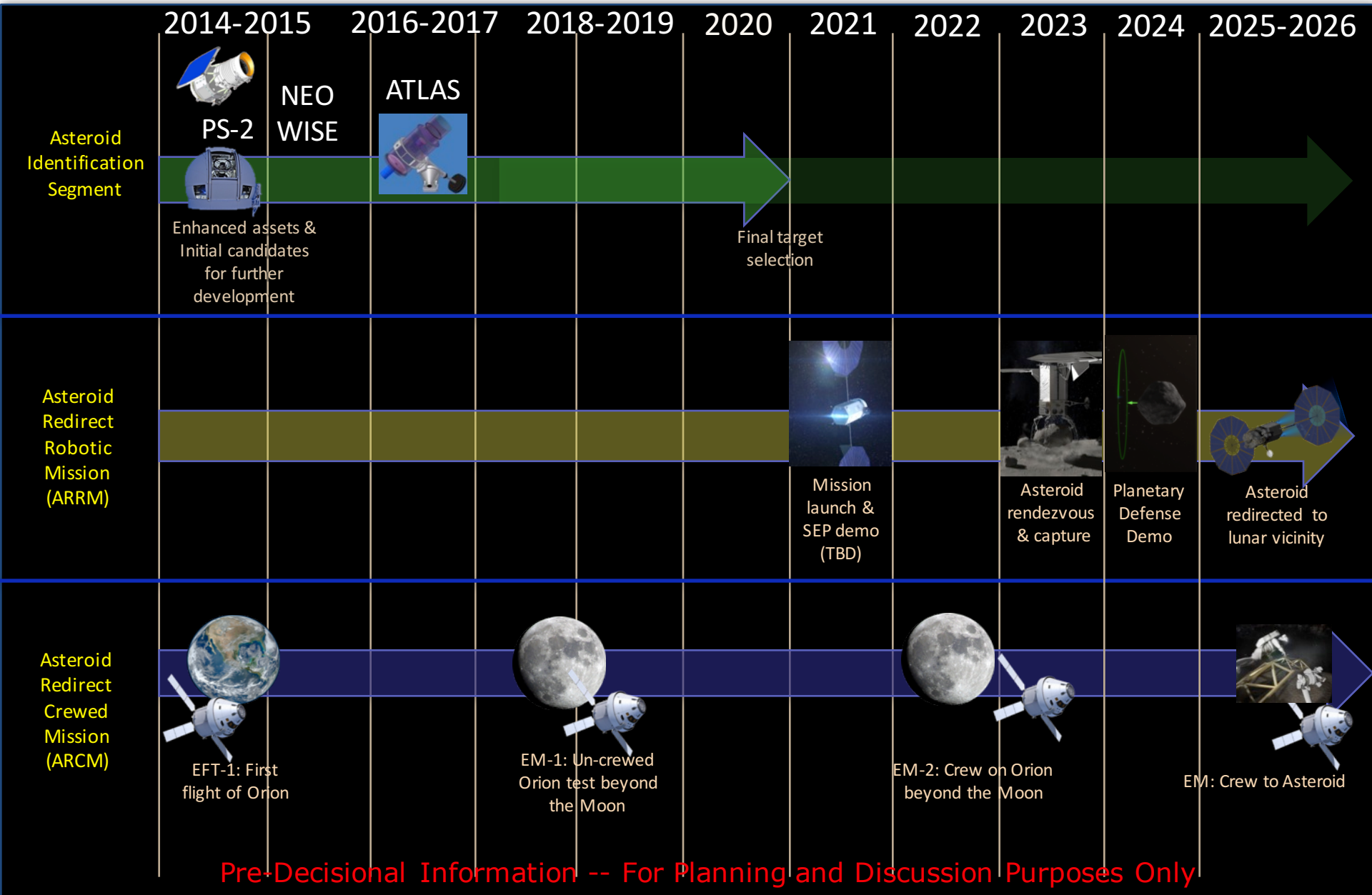








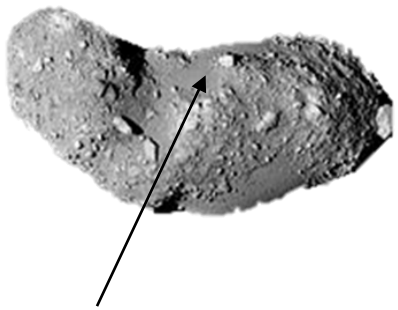
Asteroid Redirect Mission Concept Timeline



Pre-Decisional Information -- For Planning and Discussion Purposes Only

Current Candidate Parent Asteroids

ITOKAWA



Muses C – Hayabusa landing

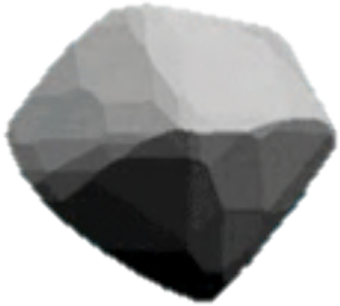
BENNU

Radar – OSIRIS-REx target

2008 EV5

Radar – boulders and extremely pronounced bulge at equator suggests movement of loose material

1999 JU3



Expected valid target - Hayabusa 2 target

Asteroids not to scale

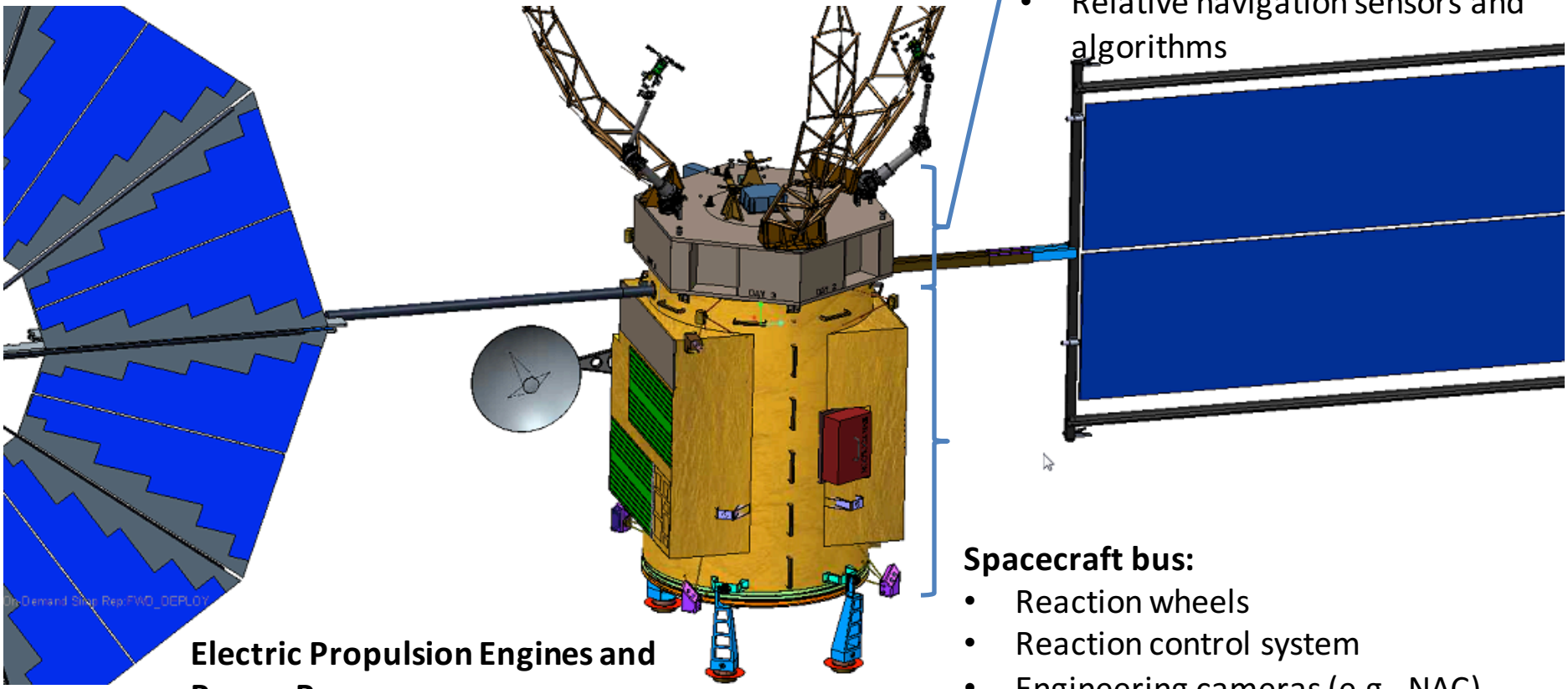
Comparison of current candidate parent asteroids

	Itokawa	Bennu	2008 EV_5	1999 JU_3
Size	535 x 294 x 209 m	492 x 508 x 546 m	420 x 410 x 390 m	870 m diameter
V_∞	5.68 km/s	6.36 km/s	4.41 km/s	5.08 km/s
Aphelion	1.70 AU	1.36 AU	1.04 AU	1.42 AU
Spin Period	12.13 hr	4.297 hr	3.725 hr	7.627 hr
Type	S	B (C-grp volatile rich)	C (volatile rich)	C (volatile rich)
Precursor	Hayabusa (2005)	OSIRIS-REx (9/2016 launch, 8/2018 arrival)	None currently planned (boulders implied from 2008 radar imaging)	Hayabusa 2 (launched 12/4/2014, 7/2018 arrival)

NASA continues to look for additional targets in accessible orbits.

Reference ARRM Target

Reference Asteroid Return Vehicle - GNC



Capture Module:

- Robotics for landing and capture
- Relative navigation sensors and algorithms

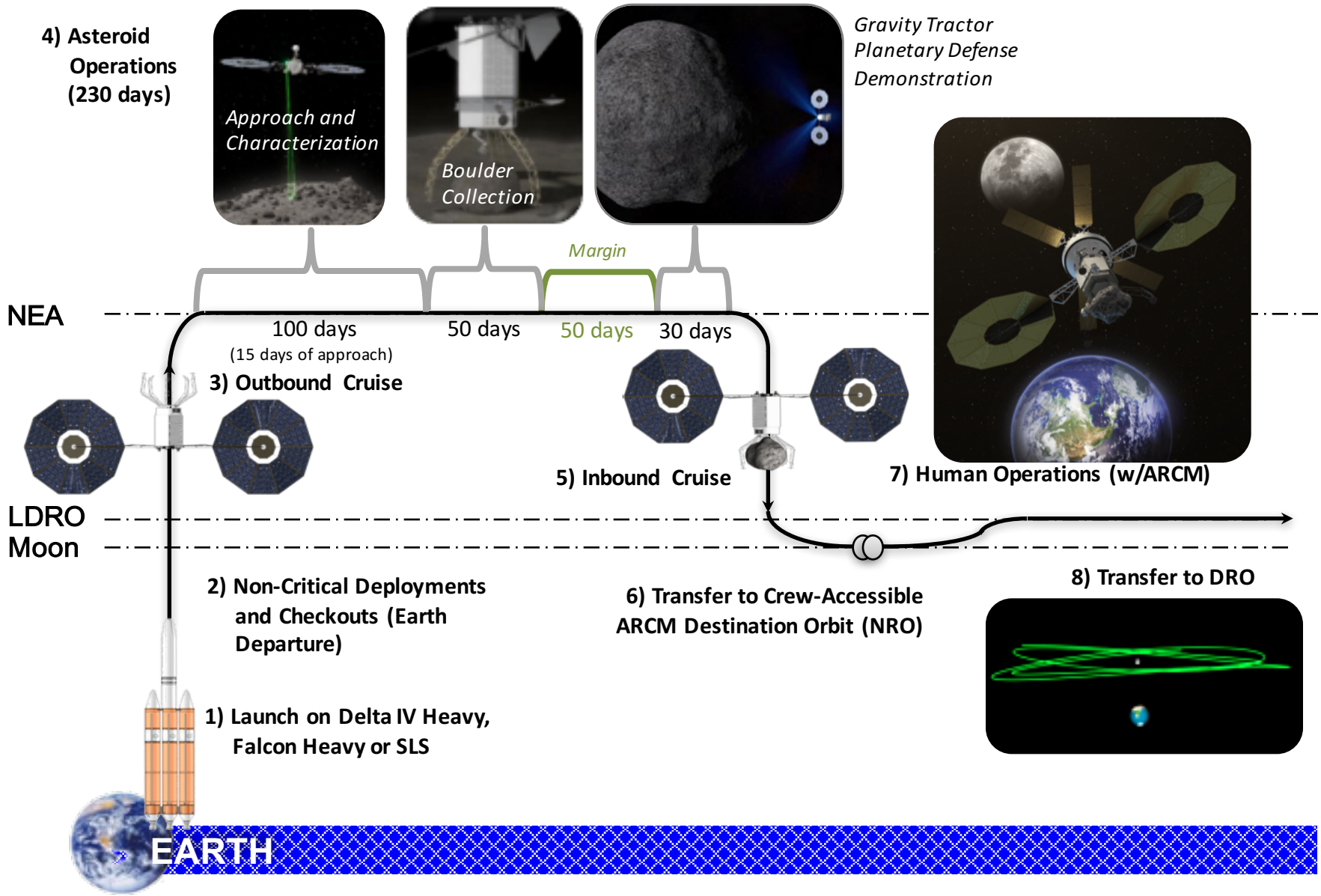
Spacecraft bus:

- Reaction wheels
- Reaction control system
- Engineering cameras (e.g., NAC)
- Inertial attitude sensors (e.g., star trackers, IMU, sun sensors)
- Additional sensors and payloads

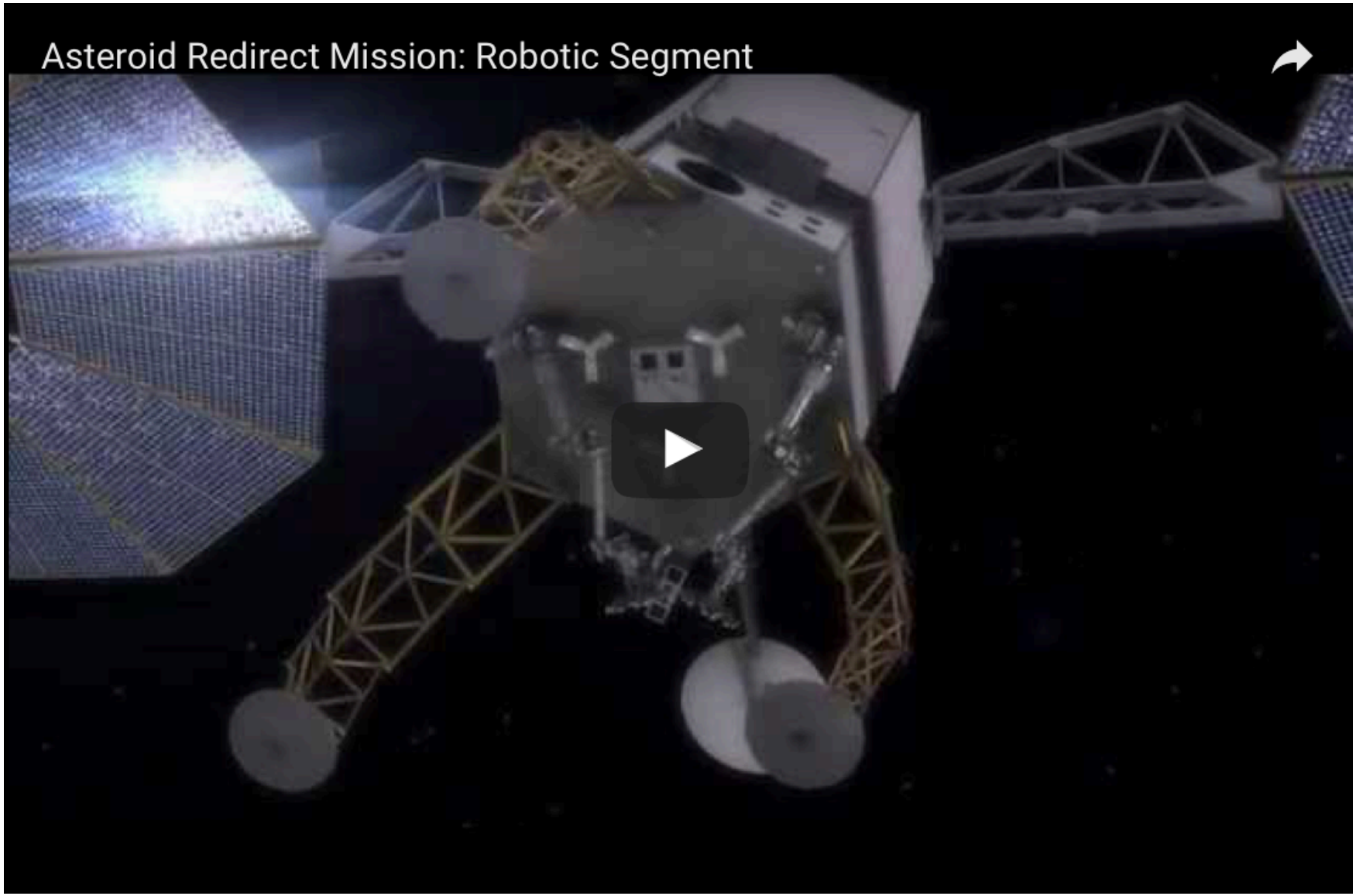
Electric Propulsion Engines and Power Processors

- 4 2-axis gimbaled thrusters
- High-power Solar Arrays (10s of kilo-watts):

ARRM Mission Concept Overview



Robotic Segment Animation



Outbound Cruise - GNC

- **Most of the mission takes place in the cruise state**
  - Controlling attitude and momentum while thrusting on 2+ more electric propulsion strings
  - CG and thruster location potentially vary with gimbal angle
  - Odd thruster configurations and other factors may cause us to fly in nonstandard orientations relative to the thrust vector
  - All guidance and navigation are inertial and generated on the ground
  - Attitude is dictated by navigation, thermal, and power constraints

- **During cruise we'll start looking for the asteroid using Optical Navigation techniques**
  - This is the transition to the approach phase
  - Eventually we navigate using measurements of the asteroid taken on-board the spacecraft
  - Transition to chemical propulsion at the end of cruise

Characterization - GNC

- **Goal: map the surface of the asteroid sufficiently to descend at a later date**
  - Need high-resolution maps with global coverage
  - Begin the site selection process
  - Map generation is based on stereophotoclinometry technique
    - Many lighting conditions and variations in geometry are required
    - GNC must be responsive to the navigation trajectories

- **During characterization we begin controlling the spacecraft relative to the asteroid-fixed frame**
  - Translational maneuvers are still planned in the inertial frame
  - Attitude is relative to the asteroid frame
  - Requires more agility than in cruise
    - NOTE: agility is a relative term
    - Given the size of the spacecraft, nothing happens fast!

Capture Sub-Phase - GNC

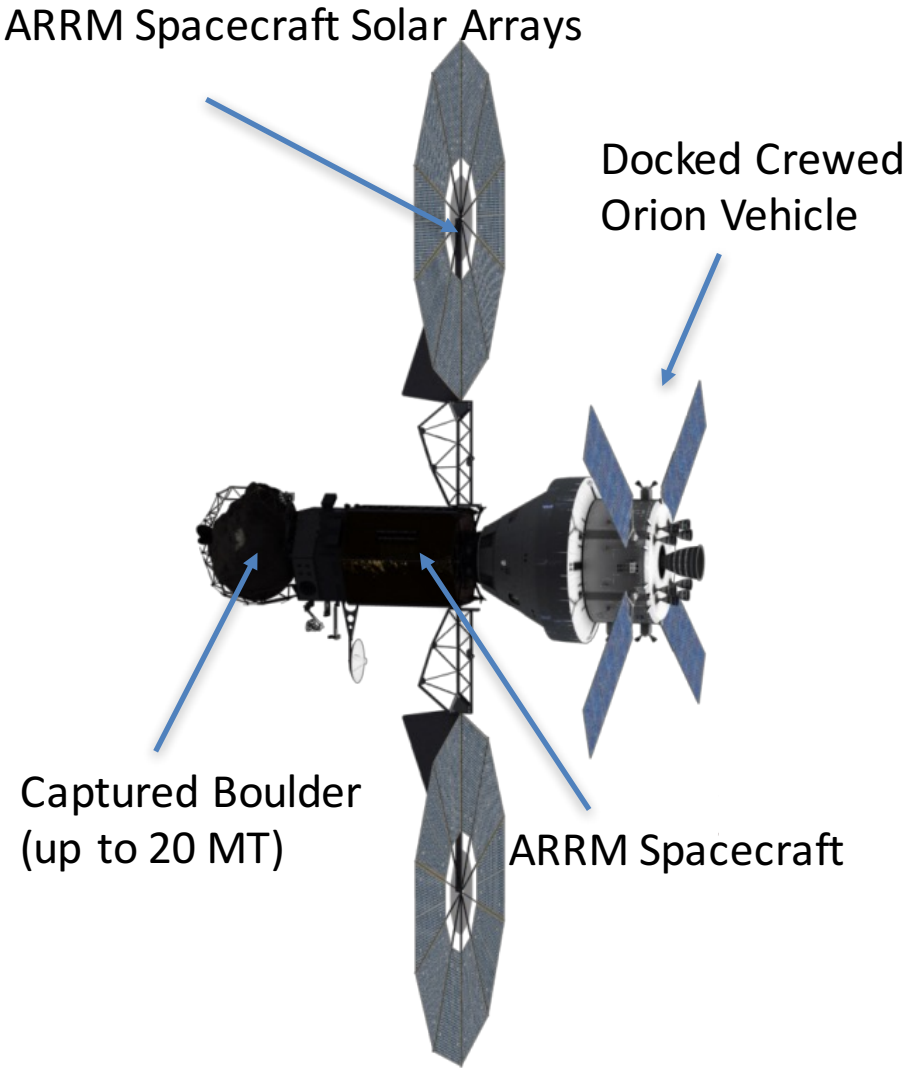
- **Descending to the asteroid surface:**
  - On-board relative navigation system providing asteroid-relative state estimates
  - Guidance and control are still under investigation, but will most likely take the form of way-point maneuvering with 6-DOF control

- **On the surface:**
  - GN&C is mostly idle

- **Ascending away from the surface:**
  - GN&C needs to handle the uncertainty introduced by the captured boulder
    - Need stability guarantees

The primary objective is to safely control the spacecraft in proximity to the natural body and land at the pre-selected ground asteroid location

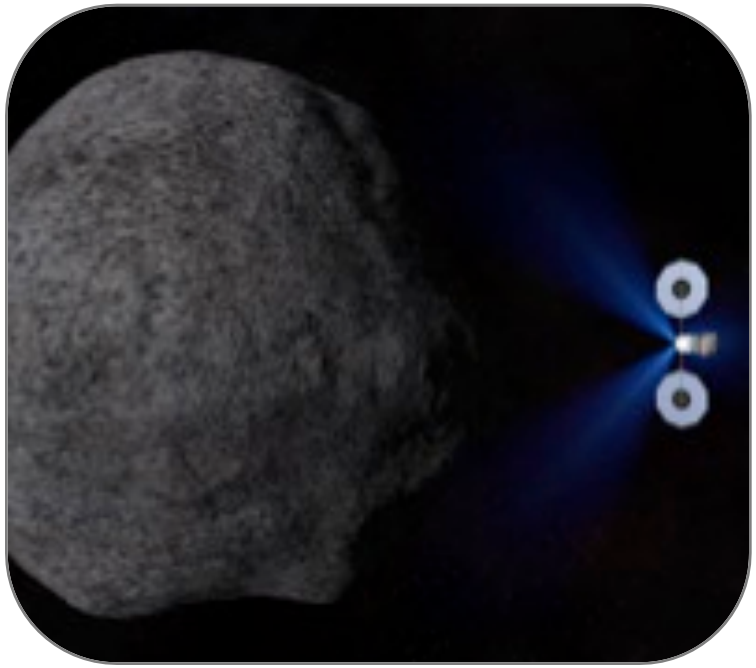
Human Operations



- **The ARRM spacecraft performs the following actions prior to crew activity:**
  - Rendezvous and docking with Orion (ARRM is passive, Orion is active)
- **ARRM spacecraft must be capable of:**
  - Controlling the integrated Orion-ARRM stack for multiple several hour extravehicular activities
  - Control cannot be achieved with thrusters due to human safety
  - Momentum and attitude control must be robust to all internal and external forces and torques (e.g., kick loads and solar pressure, respectively)

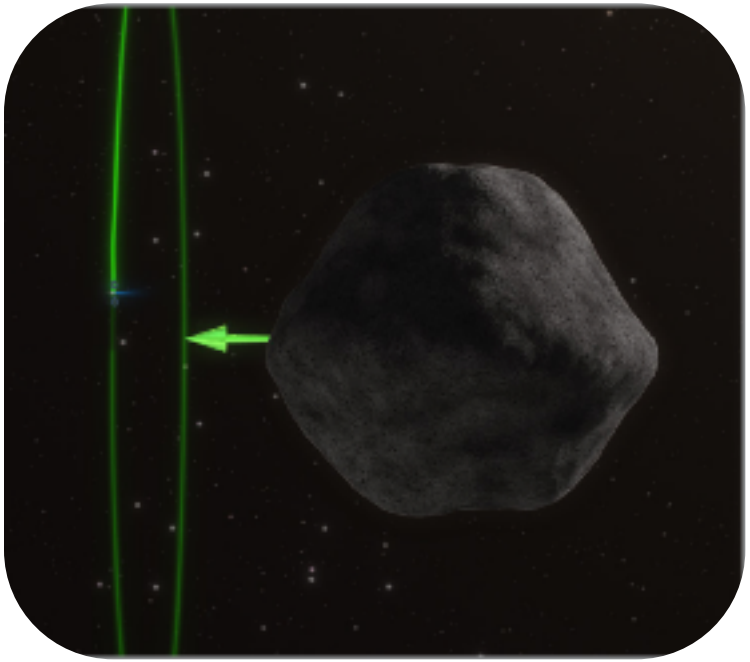
Planetary Defense Techniques

In-Line Stationary Gravity Tractor



Ref: Lu, E. T. & Love, S. G., "Gravitational Tractor for Towing Asteroids", Nature, Nature Publishing Group, 2005, 438, 177-178

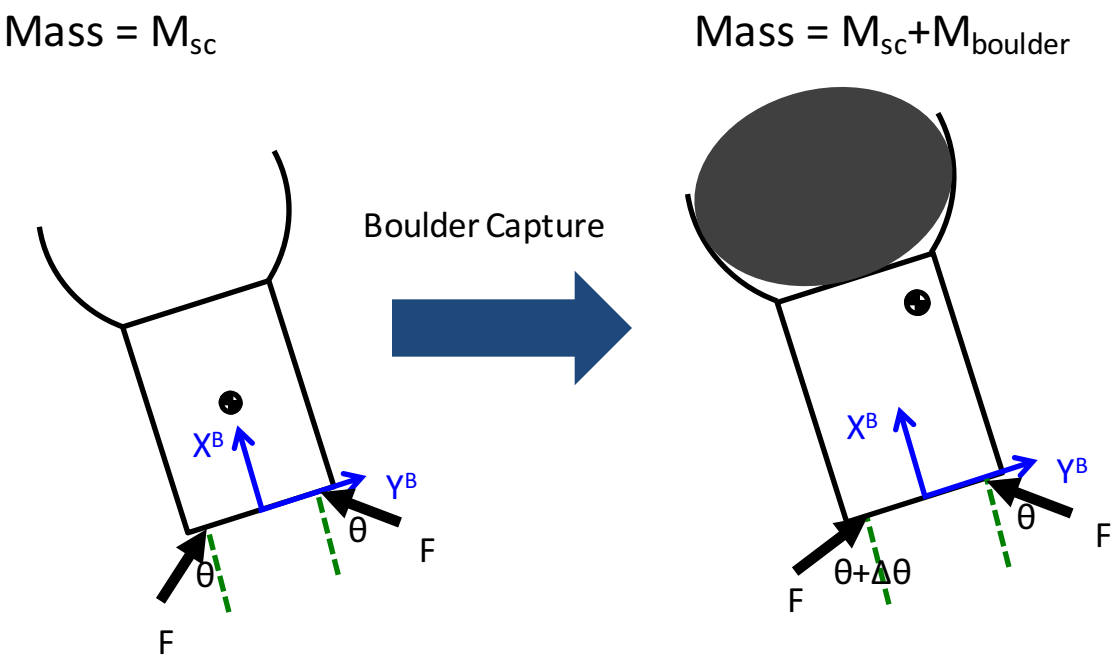
Halo-orbit Gravity Tractor



Ref: McInnes, C. R., "Near Earth Object Orbit Modification Using Gravitational Coupling", Journal of guidance, control, and dynamics, 2007, 30, 870-873

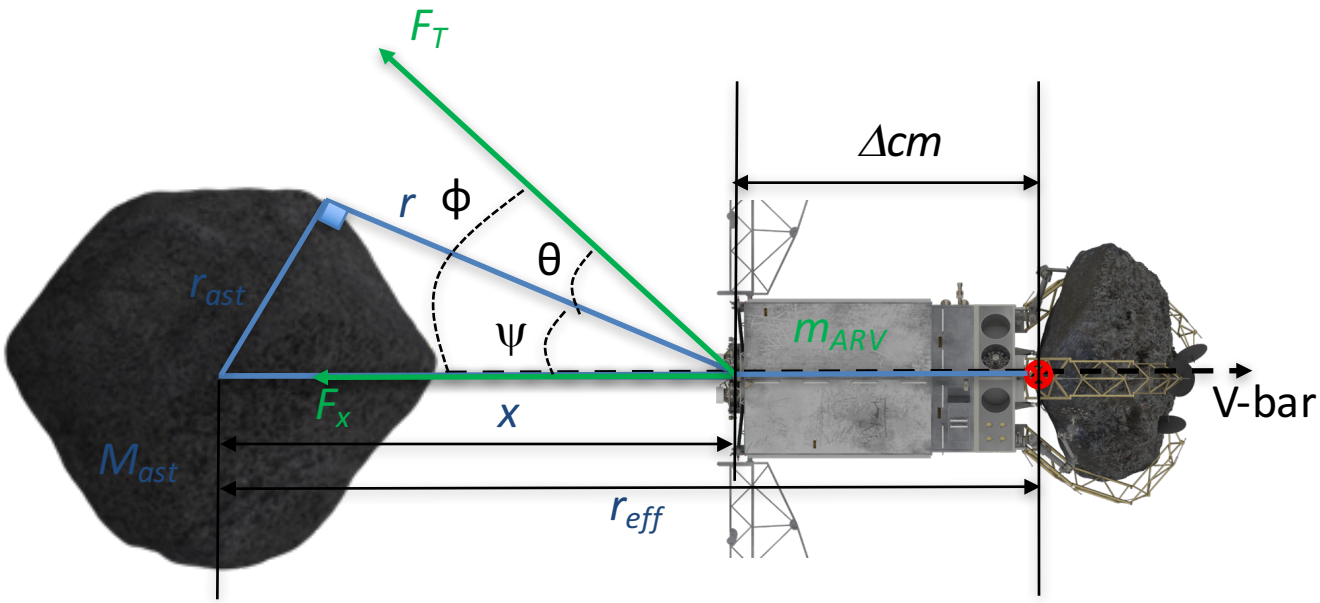
Enhanced Gravity Tractor

- **Gravity tractors make use of the mutual gravitational attraction to "Tug" the asteroid into a new orbit**
- **Fundamentally, gravity is proportional to the mass of each body**
  - The "enhancement" is to acquire mass from the asteroid and secure it to the spacecraft to increase the gravitational force per unit distance
  - Boulder capture is already needed for ARRM



Ref: Mazanek, D. D.; Reeves, D. M.; Hopkins, J. B.; Wade, D. W.; Tantardini, M. & Shen, H., "Enhanced Gravity Tractor Technique for Planetary Defense", IAA Planetary Defense Conference, Frascati, Roma, 2015

Planetary Defense Concept (In-line)



Definitions:

r: range to limb

r_{eff}: cm to cm range

ψ: asteroid viewing half angle

θ: SEP plume half angle

ϕ: SEP gimbal angle

Equations:

$\psi = \mathrm{asin}(r_{ast}/x)$

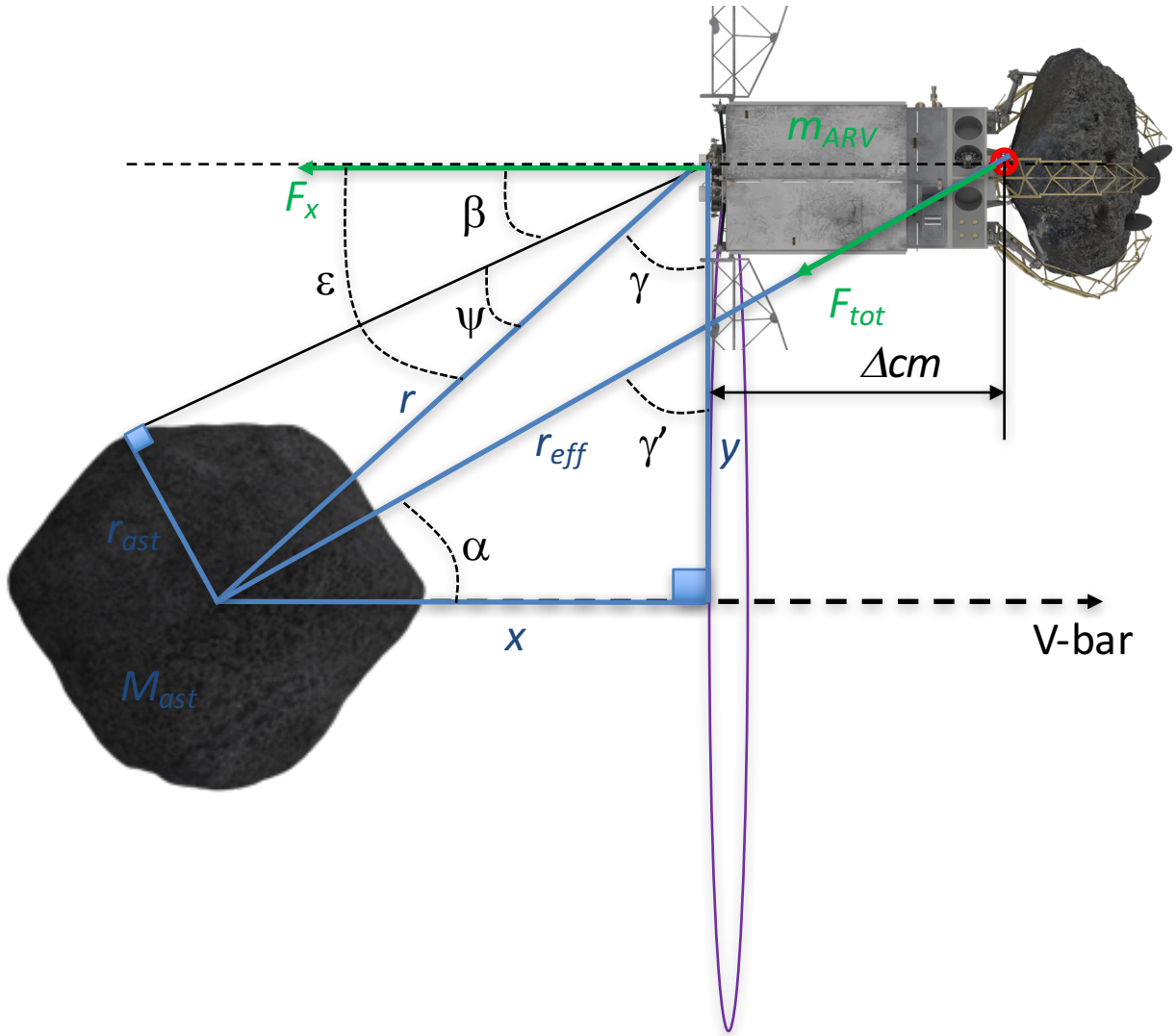
$\phi = \psi + \theta$

$x_{cm} = x + \Delta cm$

$r_{eff} = x_{cm}$

$F_T = GM_{ast}m_{ARV} / [r_{eff}^2 \cos(\phi)]$

Planetary Defense Concept (Halo)



Definitions:

r: range

r_{eff}: cm to cm range

β: limb half angle

ψ: asteroid viewing half angle

Equations:

$\gamma = 90 - \psi - \beta$

$\psi = \text{asin}(r_{ast}/r)$

$\varepsilon = \psi + \beta$

$x = r \sin(\gamma) = r \cos(\varepsilon)$

$y = r \cos(\gamma) = r \sin(\varepsilon)$

$x_{cm} = x + \Delta cm$

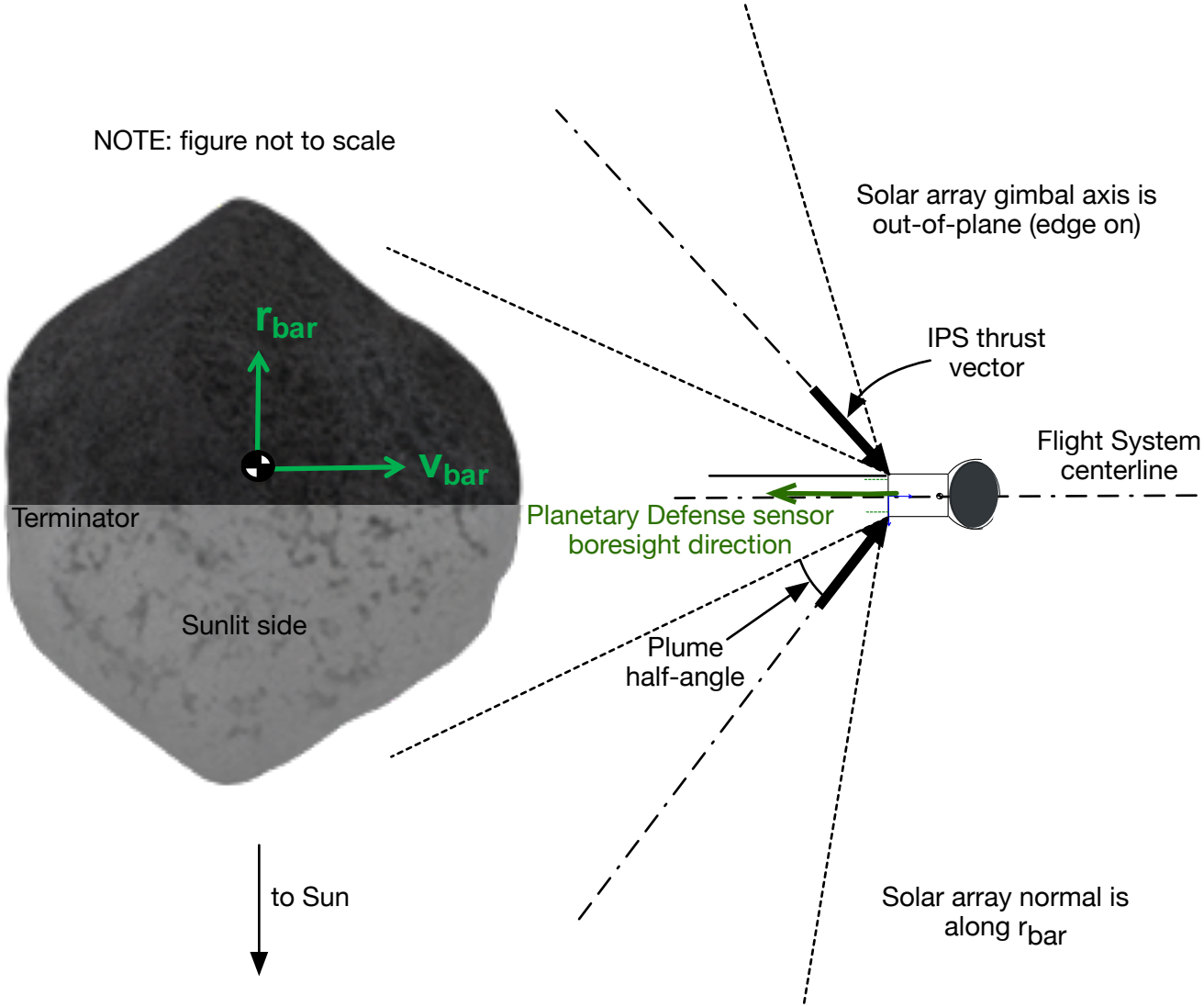
$r_{eff} = \text{sqrt}(x_{cm}^2 + y^2)$

$\gamma' = \text{atan}(x_{cm} / y)$

$\alpha = \text{atan}(y / x_{cm})$

$F_x = GM_{ast}m_{ARV} / [r_{eff}^2 \cos(\alpha)]$

Plume Interaction



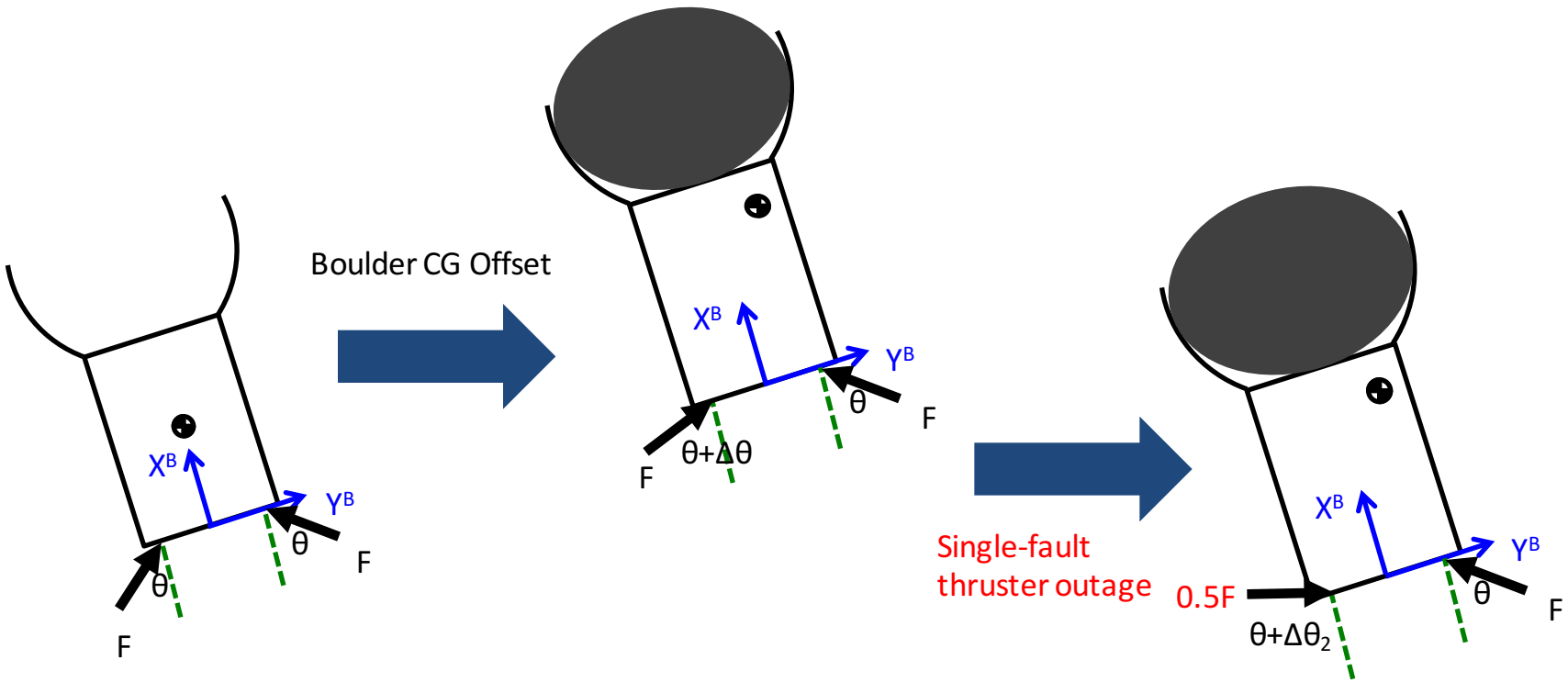
Thruster Challenges

- **Throttleability**
  - EP systems have fundamental limits on how low and high they can throttle in thrust magnitude
    - For example, the plasma physics may limit how low we can throttle
    - Input power and solar array size may limit how high we can throttle

- **Gimbal range-of-motion**
  - We're limited in gimbal range by the gimbal design, but also due to erosion concerns with other spacecraft surfaces

- **Plume divergence**
  - Spreading the plume to the extent that some of the momentum is exchanged with the natural body surface can degrade the performance of the gravity tractor
  - Backsputter of material from the asteroid surface back on the spacecraft can become an issue

Gimbal Challenges

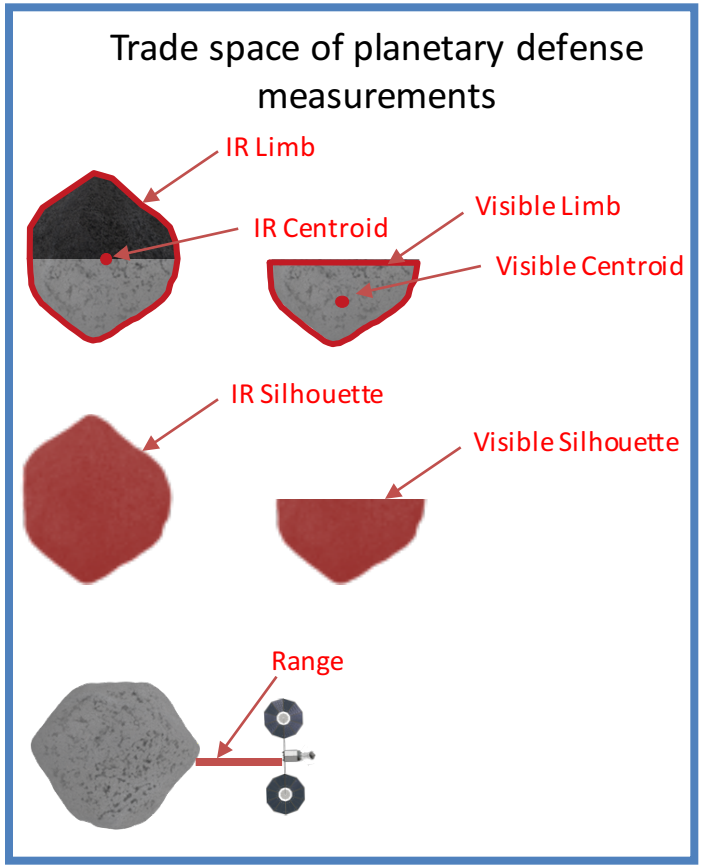


CG offsets and thruster outages can significantly affect the gimbal range. Deeper throttle can alleviate some of the additional stress on the gimbal and erosion concerns with operating at such high gimbals.

Relative Navigation Challenges

- **When can we directly measure our state relative to the asteroid?**
  - Need navigation approach that can handle all conditions we may encounter
    - Varying lighting and eclipse
    - Thermal variations
    - Asteroid spin
    - Assumed guidance

- **We must be robust to sensor outages**
  - Redundant state estimates
    - Ground-estimates



Conclusions

- **ARRM is a proposed mission to demonstrate high-power electric propulsion, and advanced autonomy in the vicinity of an asteroid**
- **The diverse mission phases of ARRM were presented and a small survey of the GN&C challenges were introduced, such as:**
  - Electric propulsion attitude and translational control using more thrusters than any other mission flown
  - Autonomous proximity operations and landing with an accuracy tighter than any other mission flown
  - Demonstrating sustained operation in close proximity with an asteroid for > 30 days to demonstrate the planetary defense technique
  - Designing a spacecraft's GN&C subsystem to handle the docking of another equally massive spacecraft while controlling the integrated stack without propulsion

Crew Segment Animation