

Independent Overview of Proximity Operations Considerations for the Asteroid Retrieval Mission Concept



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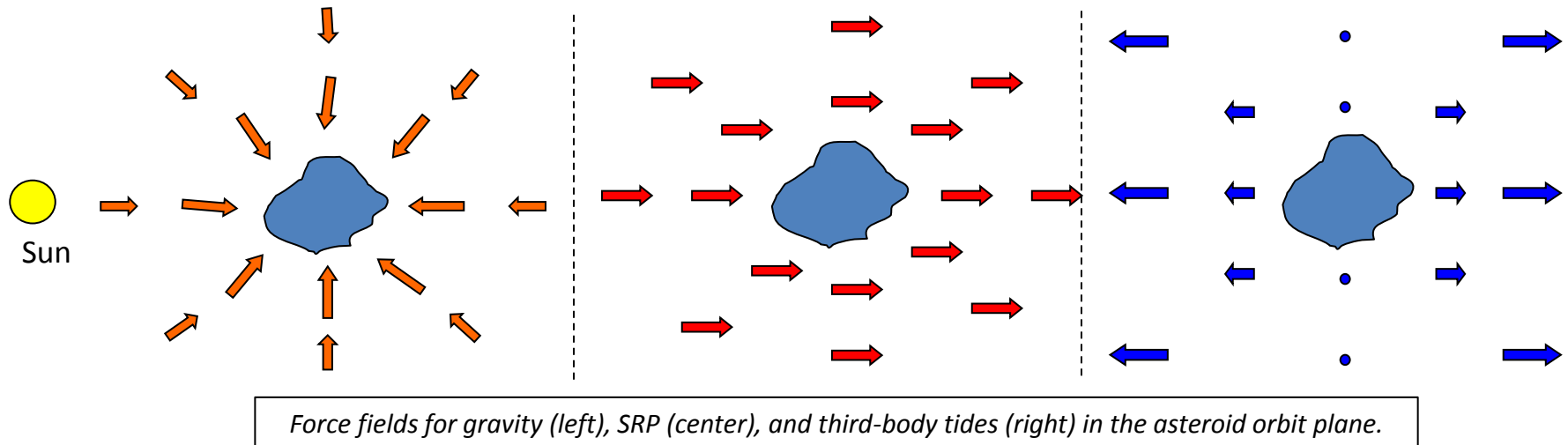
Navigation and Mission Design Section

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****Contents of this presentation have been prepared independently from any ARM concept activity and in no way reflect the plans or analysis done in support of the ARM activity.****

- Dynamics

- Complex; several accelerations may have significant effect on the spacecraft (S/C)
 - Gravity
 - Solar Radiation Pressure (SRP)
 - Third-body gravity (Sun or planet)
 - S/C small forces and maneuvers
- Uncertain; *a priori* knowledge of target gravity and spin is poor.
 - Knowledge is improved via bootstrapping throughout the encounter

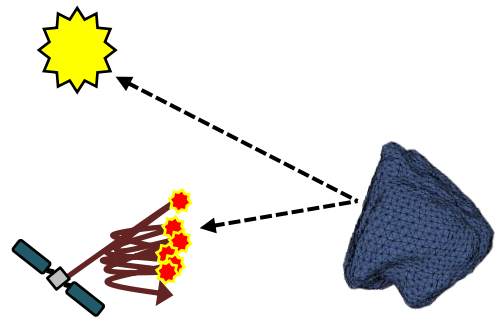


- Spacecraft response time

- S/C must recognize and respond to undesirable situations sufficiently quickly
 - More precision, closer range, and less knowledge require faster response
- Uncertainty necessitates that the mission design and operations plan are tightly coupled

- The broad range of primitive body mission parameters (mass, orbit, etc.) and the diversity of mission requirements allow for many different, mission-specific approaches to Prox-Ops!

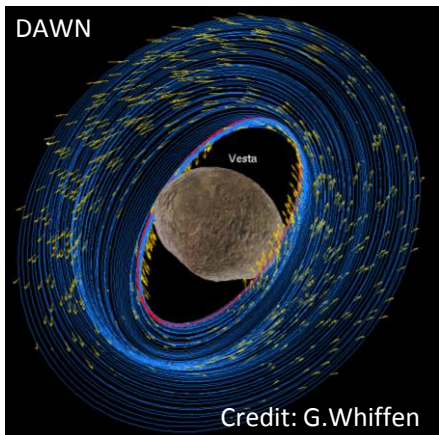
With autonomous GNC, high-speed flybys can get closer, better pictures



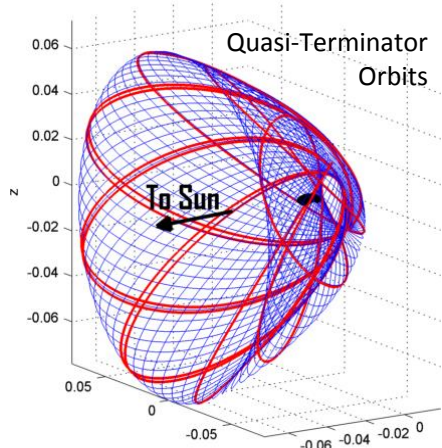
“Hovering” or other station-keeping strategies are appropriate when SRP dominates (e.g., Hayabusa)



Landing open-loop is possible if touchdown requirements are loose.



Orbiting can be done when gravity dominates, but higher-order gravity terms are important

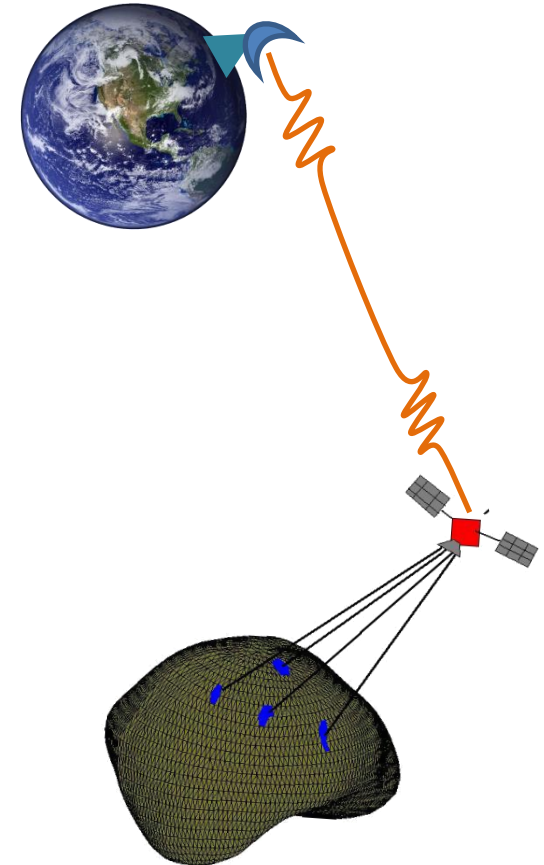


A balance between gravity and SRP can allow for novel orbital approaches



Precise operations close to the surface require autonomous GNC

- Measurement types (in descending TRL order)
 - DSN 2-way Doppler / Range
 - Excellent for measuring line-of-sight velocity and range
 - Optical Landmark Tracking
 - Important for measuring position relative to the body
 - Scanning/Flash Lidar
 - Single measurement positioning supports autonomous activities; also velocity frame-to-frame
 - Earth-to-S/C 1-way Doppler (*a la* Deep Space Atomic Clock)
 - Could provide precise velocity information for on-board orbit determination
- In-situ measurements (OpNav and/or Lidar) are ***required*** for primitive body close-proximity operations!
 - Needed for approach (to refine body ephemeris)
 - Needed up-close (small accelerations don't always provide enough velocity change to use Doppler)
- With sufficient Doppler and OpNav measurements, typical epoch state estimates should be accurate to ~1 pixel in position (~1 m or less) and ~0.1 mm/s in velocity.

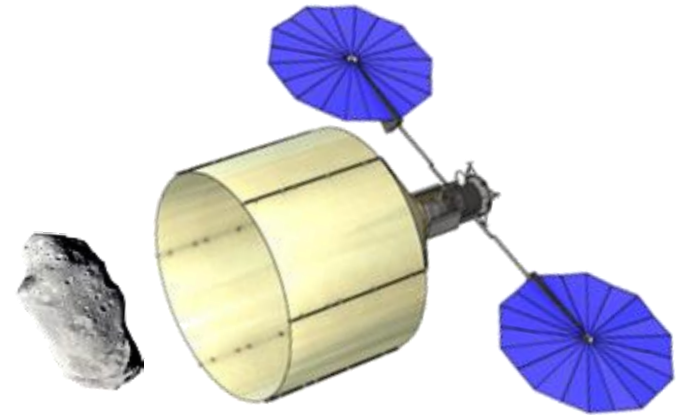


Proximity operations utilize both Earth-based and in-situ measurements

- Target Asteroid Characteristics
 - Shape: Unknown, ~5-10 m longest diameter
 - 100-400 metric tons
 - $GM = 7-27 \times 10^{-15} \text{ km}^3/\text{s}^2$
 - $3.7 \times 10^{-7} \text{ g}$ surface acceleration!
 - Spin State: Unknown

- ARM Spacecraft Concept
 - ~8 metric tons (at the asteroid)
 - Propulsion: 40-kW SEP system
 - Provides up to $2 \times 10^{-7} \text{ km/s}^2$ acceleration
 - Shape:
 - Two 5-m radius circular solar arrays
 - ~10-m x 8-m radius deployable cylindrical capture mechanism
 - ~8 x 3.5 x 3.5 m rectangular bus
 - Various configurations have significant effect on dynamics (through SRP)
 - Wide range of possibilities, but doesn't change conclusions much

- Close-proximity phase trajectory plan:
 - Several options under consideration

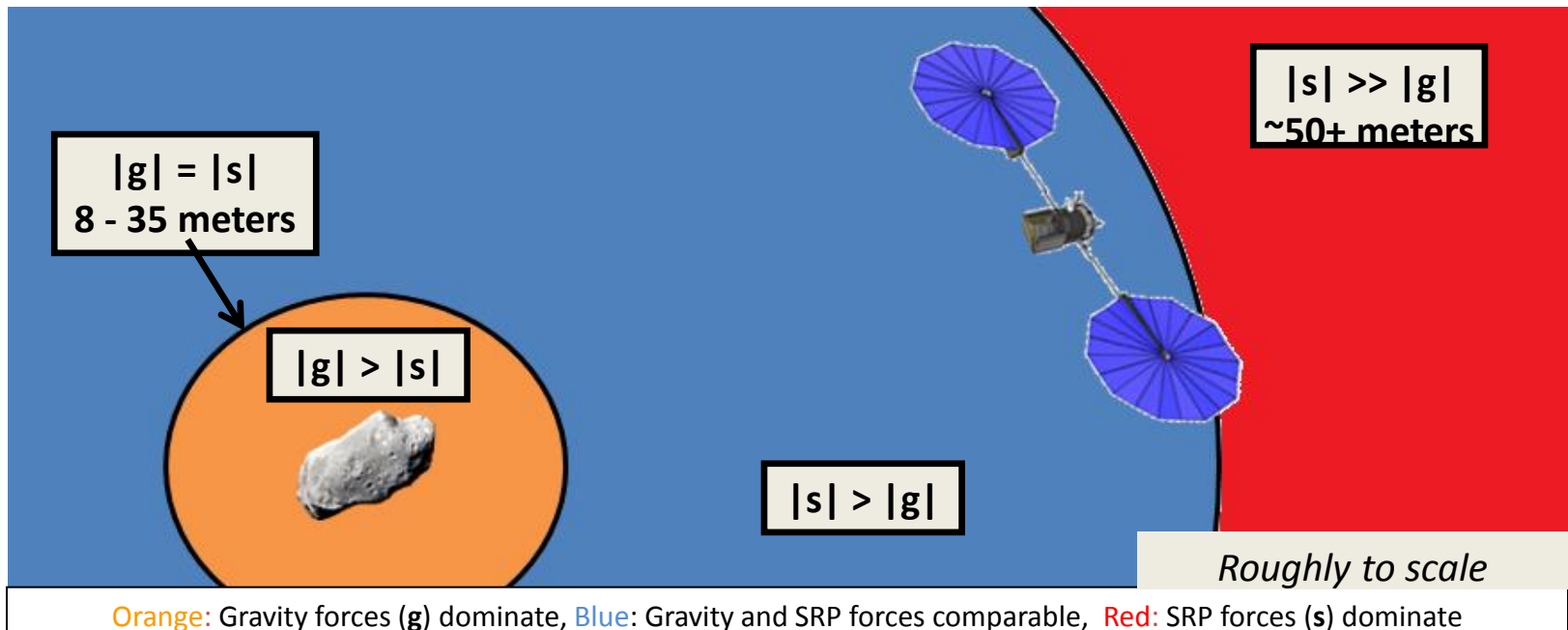


Conceptual ARM Spacecraft and target asteroid. Roughly to scale.

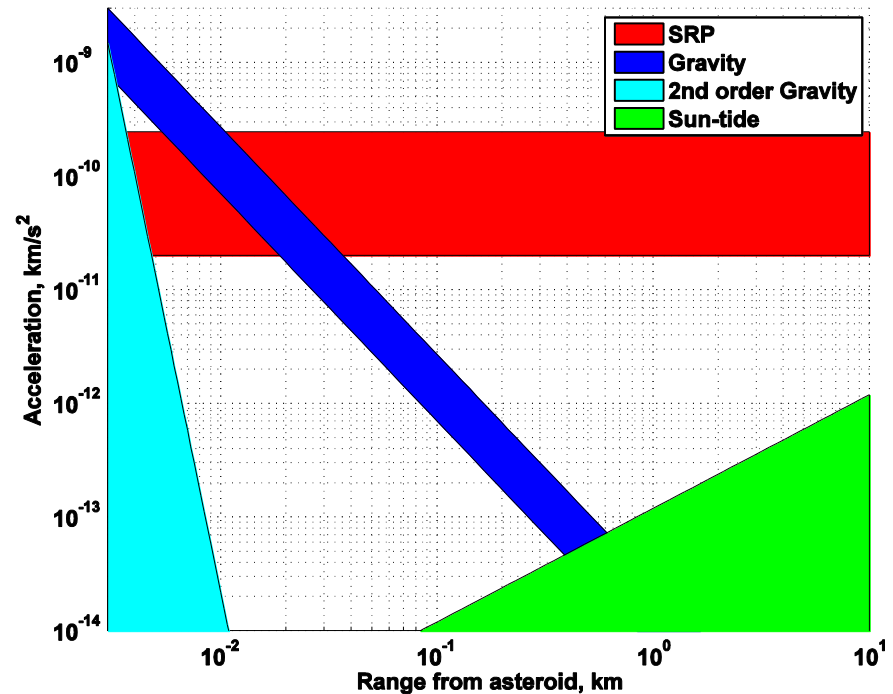
	Panels to Sun	90% Canted Panels
Stowed Catcher	195 m ²	45 m ²
Deployed Catcher	365 m ²	215 m ²

Projected area in different S/C configurations. Important for SRP calculations.

- ARM would be a bizarre situation, even for a primitive body...
 - S/C operating range can be comparable to the size of the spacecraft!!
 - SRP equals gravity at just 8 - 35 meters from the asteroid center of mass!
 - Normal ballistic orbits are probably not feasible since they must be so close.
 - SRP is the primary dynamics driver for most mission phases. These dynamics are relatively easy to deal with.
 - SRP acceleration is effectively constant, akin to dynamics on the Earth's surface
 - SRP can be estimated based on S/C properties and potentially throughout the mission.
 - Uncontrolled trajectories usually escape the vicinity safely without action



- To understand the dynamics timeline, how uncertainties grow, and what can be estimated, look at the absolute magnitude of forces
- For ARM, the dynamics would play out very slowly!
 - May seem fast close to the body...
- If we assume a constant acceleration environment, the position and velocity change from errors in the dynamic model can be estimated.
 - E.g., 10% gravity error at 30 m is $\sim 2 \times 10^{-12}$ km/s² acceleration error, which yields ~ 8 m position error after 1 day
 - May be significant
 - E.g., 10% SRP error at 100 m is $\sim 1 \times 10^{-11}$ km/s² acceleration error, which yields ~ 40 m position error after 1 day
 - Requires care with trajectory design



Acceleration magnitude (km/s ²)	Position change in one day (m)	Velocity change in one day (mm/s)
10^{-10}	370	8.6
10^{-11}	37	0.86
10^{-12}	3.7	0.1
10^{-13}	0.37	0.01



Uncertainty Drives the ARM ProxOps Concept

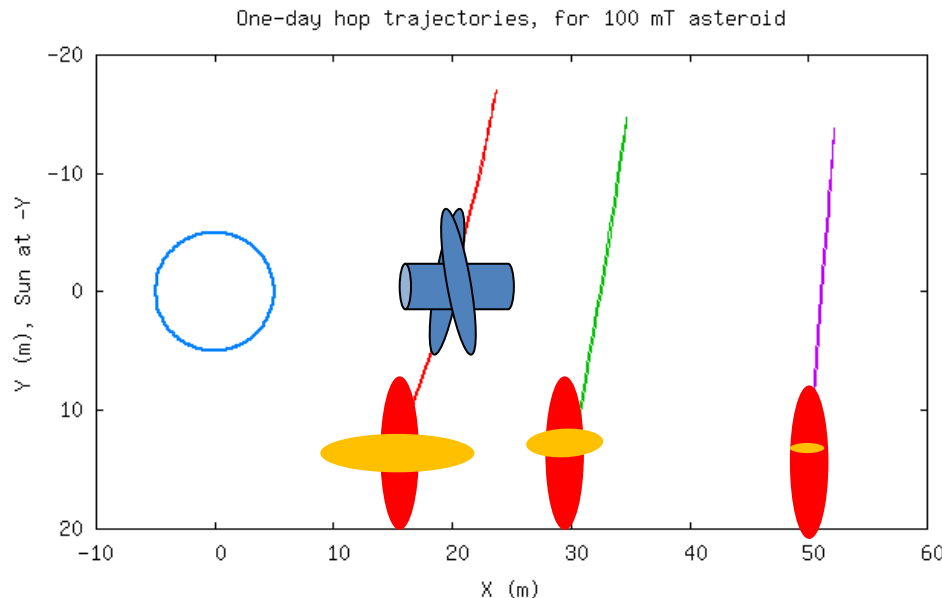


- Propagated gravity, SRP, and maneuver execution errors must fit inside the requirement at the next trajectory correction opportunity

Execution errors	0.1 mm/s	1 mm/s	10 mm/s
Position Error / day	9 m	90 m	900 m

- Closer and closer operations would require tighter control of the S/C flight path
 - E.g., at 100 m, 20 m error may be acceptable; at 25 m, only 2 m error may be acceptable
 - The effect of uncertainty grows with gravity as range decreases
- Two approaches to enable close operations:
 - Minimize errors (through S/C and body characterization campaigns, “boot-strapping”)
 - Allow frequent corrections (through rapid OD and maneuver design turnover)
- For the planned characterization range for the ARM concept (50-100 m), either route (or both) could be a feasible strategy
 - A thorough S/C, thruster, and gravity characterization plan could reduce dynamic uncertainty significantly, increasing the allowable time between maneuvers
 - Fast maneuver turnover can be achieved through an expedited ground process or through on-board autonomous navigation
 - It also may be possible to operate further from the asteroid for characterization.

- Uncertainty would be large initially in both GM and SRP (in the PropOps configuration)
- GM and SRP can be estimated via Doppler (line-of-sight velocity change) and OpNav (accumulated position change) measurements
 - Estimate through closed-loop fuel consumption may work also
- The trajectory and operations design should allow for each error to be isolated as independently as possible.
 - GM and SRP can be decorrelated by estimated SRP at a range where gravity is not important, or using a trajectory geometry where the GM and SRP effects are as orthogonal as possible
 - Trajectory legs should be free of maneuvers for adequate time for acceleration errors to build up without introducing additional uncertainty.
- SRP is best characterized with one or more ballistic trajectory legs of 0.5 day or more at >100 m from the asteroid.
 - SRP uncertainty of a few % should be achievable in select S/C attitudes/configurations.
- GM is best characterized with one or more ballistic trajectory legs of 1 day or more within several 10s of meters
 - 1-5% accuracy should be reasonably achievable, though ultimate performance will depend on trajectory design.
 - Higher order gravity field estimation is not needed (nor reasonably achievable).



*Trajectory notion in consideration for ARM (Sun is "up"). Courtesy of Tim McElrath.
Notional dispersions from dynamic model errors added.*

- Dispersion from SRP error
- Dispersion from GM error



Conclusions



- Solar radiation pressure (SRP) would dominate the dynamics during most ARM phases
 - A station-keeping strategy where thrusters are regularly used to achieve the desired asteroid-spacecraft geometry is more practical than orbiting
- Using a combination of Doppler and in-situ measurement types (OpNav and/or lidar ranging), orbit determination should be accurate to ~ 1 m and a fraction of a mm/s.
- Operations at the planned proximity range (50-100 m) requires a careful balance of OD/maneuver turnover time and execution errors
 - Autonomy can be used to minimize turnover time, which allows for larger maneuver execution errors
 - Good dynamical model estimation can improve predictability
 - At this range just a coarse GM model for the asteroid is sufficient ($\sim 10\%$ 3-sigma)
 - Increasing range to ~ 1 km may make things easier as well
- Asteroid mass should be estimated to better than 5% relatively easily.
 - Higher-order gravity will be difficult, but unnecessary to estimate
- Asteroid shape can be modeled with Lidar and/or camera images to whatever fidelity is required.
- A station-keeping prox-ops strategy that first estimates SRP at a further range (100+ m), then moves closer to refine the mass estimate seems to make sense.
 - Since operations close to the body are more difficult, it would be simplest to do as much as possible at a distance with typical ground navigation.
 - At some point (for capture at least), the spacecraft will move close enough so that autonomy is probably required.