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

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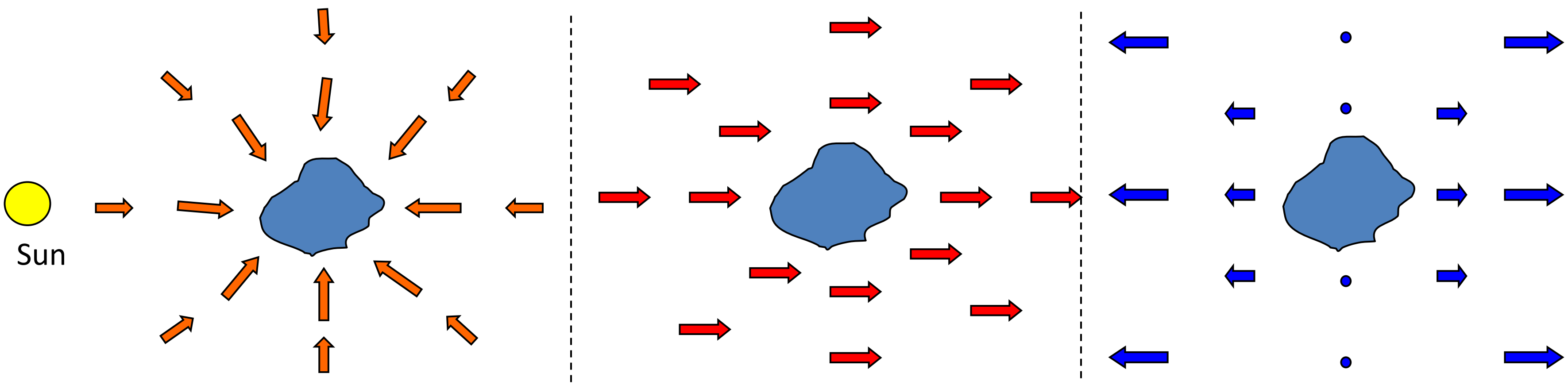
Contents of this presentation have been prepared independently from any ARM concept activity and in no way reflect the plans or analysis done in support of the ARM activity.

Image Credit: NASA

Driving Considerations for ProxOps

- 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



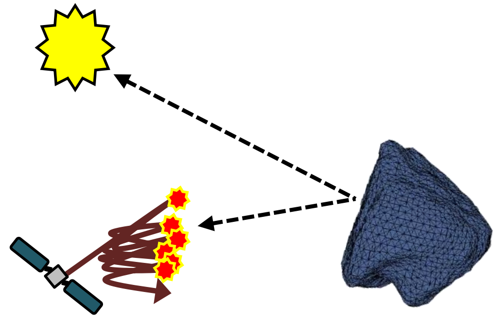
Force fields for gravity (left), SRP (center), and third-body tides (right) in the asteroid orbit plane.

- 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

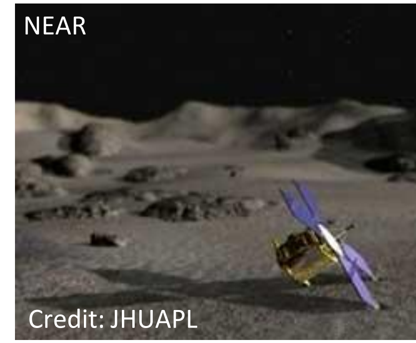
Many Approaches

- 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!

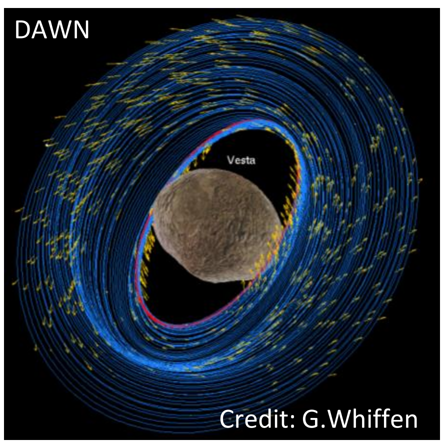
With autonomous GNC, high-speed flybys can get closer, better pictures



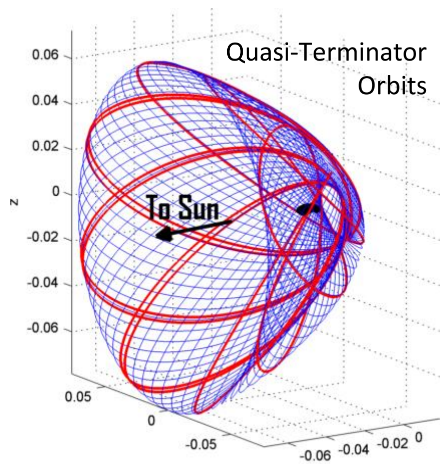
"Hovering" or other station-keeping strategies are appropriate when SRP dominates (e.g., Hayabusa)



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

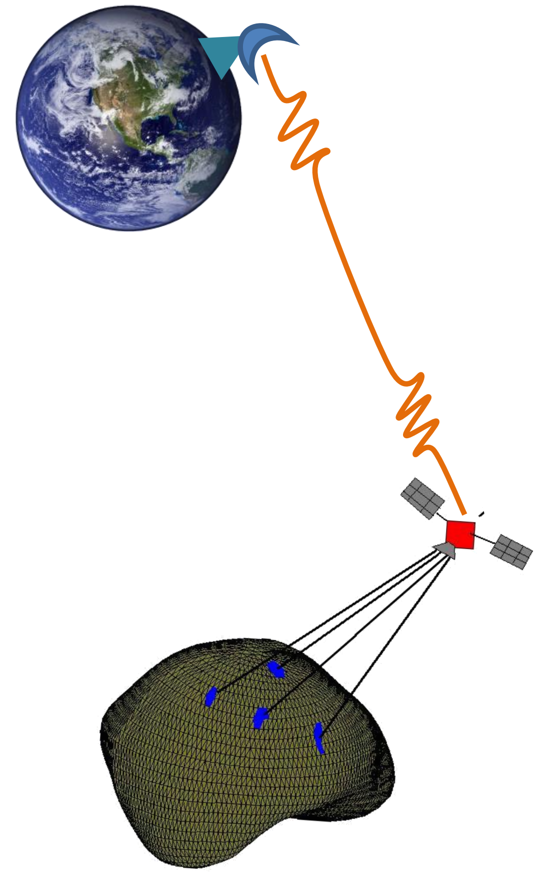
Precise operations close to the surface require autonomous GNC

Orbit Determination at Primitive Bodies

- 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)

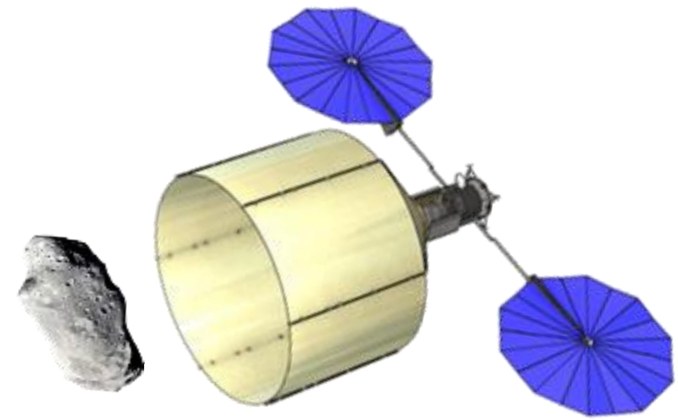
- With sufficient Doppler and OpNav measurements, typical epoch state estimates should be accurate to ~1 pixel in position (~1 m or less) and ~0.1 mm/s in velocity.



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

ARM Mission Parameters

- Target Asteroid Characteristics
  - Shape: Unknown, ~5-10 m longest diameter
  - 100-400 metric tons
    - GM = 7-27 x 10^{-15} km^3/s^2
    - 3.7 x 10^{-7} g surface acceleration!
  - Spin State: Unknown
- ARM Spacecraft Concept
  - ~8 metric tons (at the asteroid)
  - Propulsion: 40-kW SEP system
    - Provides up to 2 x 10^{-7} 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



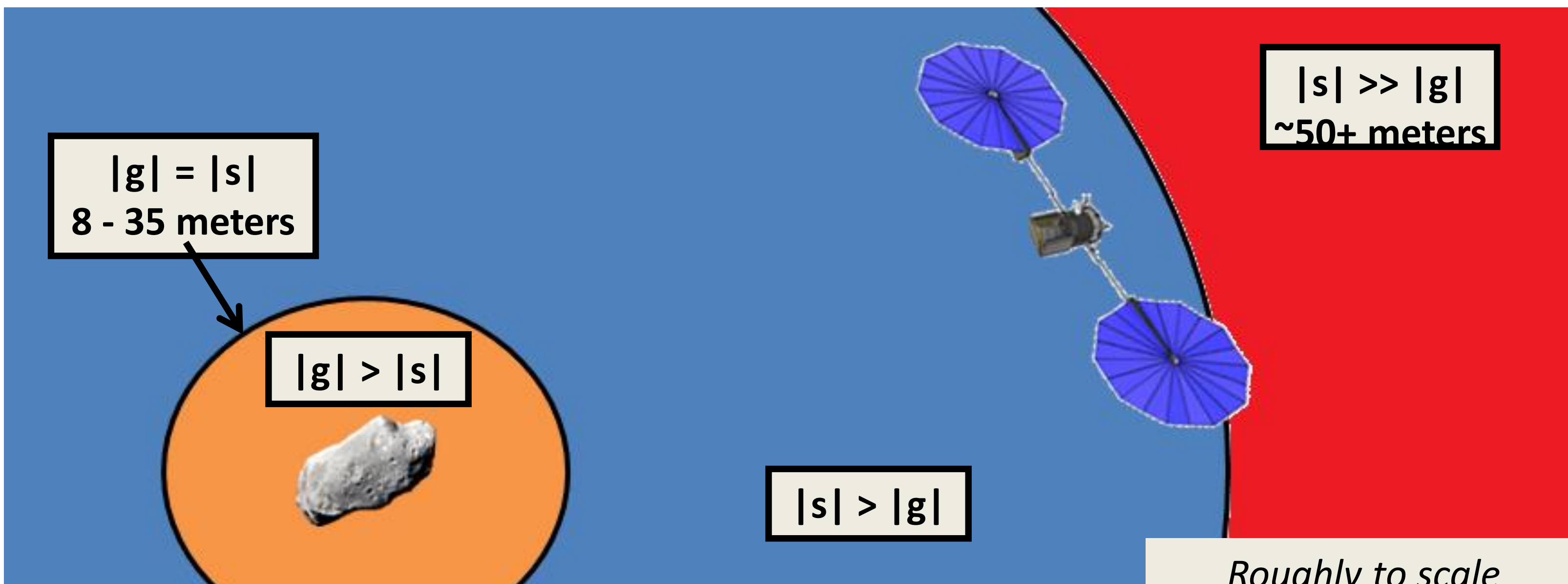
Conceptual ARM Spacecraft and target asteroid. Roughly to scale.

	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 Close-proximity Dynamics

- 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



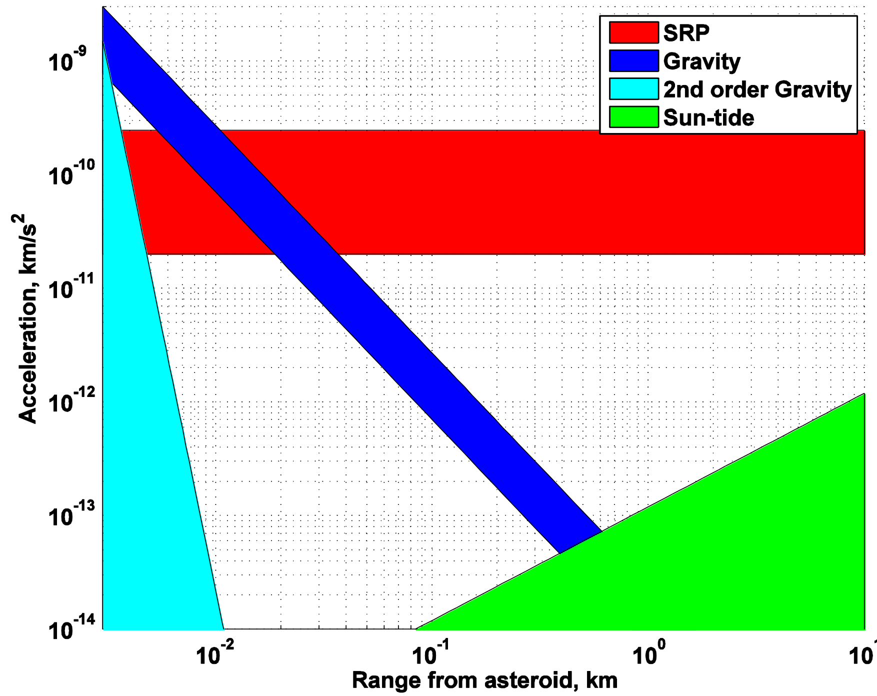
Orange: Gravity forces (**g**) dominate, Blue: Gravity and SRP forces comparable, Red: SRP forces (**s**) dominate

Force Magnitudes for ARM

- 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 ~2×10^{-12} km/s^2 acceleration error, which yields ~8 m position error after 1 day
    - May be significant
  - E.g., 10% SRP error at 100 m is ~1×10^{-11} km/s^2 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

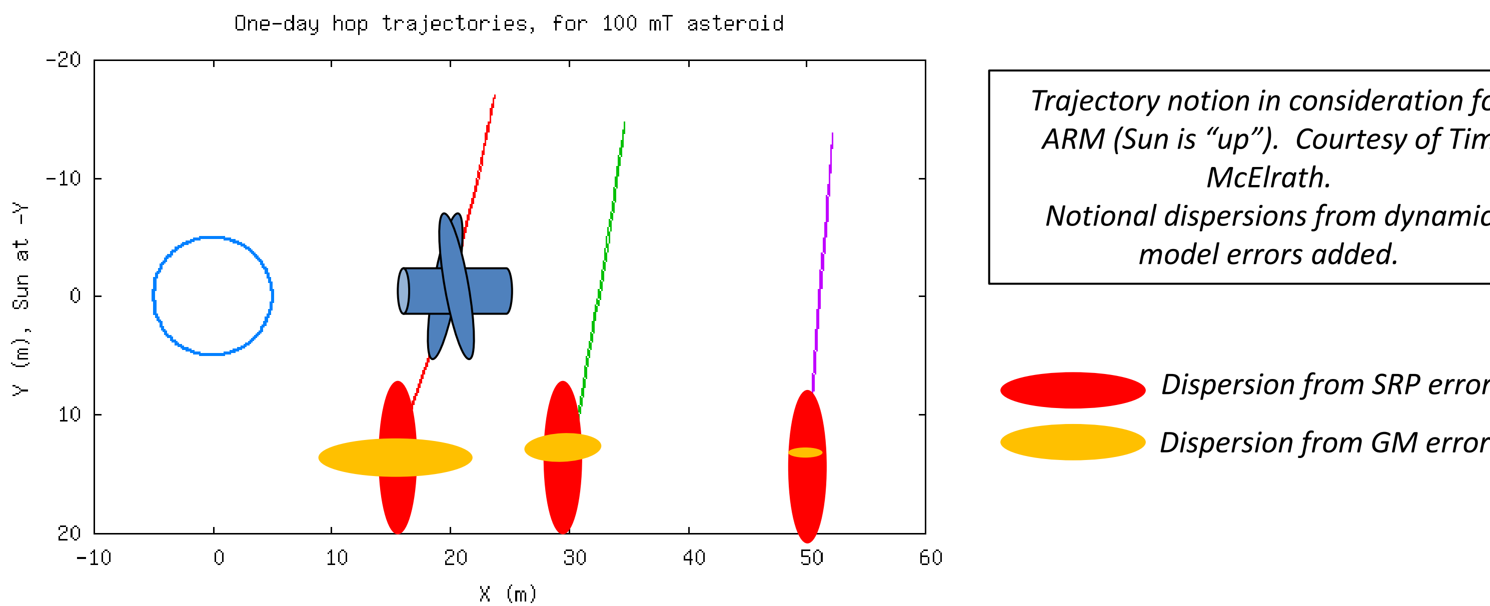
- Closer and closer operations would require tighter control of the S/C flight path
  - E.g., at 100 m, 20 m error may be acceptable; at 25 m, only 2 m error may be acceptable
  - The effect of uncertainty grows with gravity as range decreases

- 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.

Estimating Gravity and SRP

- 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.

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 (~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.