ARM Reference Mission AR&D Concept of Operations

The purpose of the **Rendezvous Phase** is to first search and acquire the asteroid with the Narrow Angle Camera (NAC), then to determine the position of the spacecraft relative to the asteroid based on multiple NAC images of the asteroid relative to the celestial background and, finally, to compute and execute a series of Solar Electric Propulsion (SEP) burn-arcs to bring the spacecraft to the proximity of the asteroid, here defined to be at 1 km range, to start the next phase.

The Rendezvous Phase starts when the spacecraft is within a 50,000km range of the asteroid. At this point, the spacecraft approaches the asteroid from the illuminated side with a very small Solar Phase angle (<20degrees) to maximize the asteroid illumination. Typically the asteroid position uncertainty is mostly downtrack and, therefore, approximately perpendicular to the spacecraft approach trajectory. A reasonable upper bound for the asteroid downtrack ephemeris uncertainty is about 10,000km, which is equivalent to an angular uncertainty of 1/5 radians, or 11.4 degrees.

The NAC FOV size is a compromise between the resolution of the camera and the difficult in searching and finding the asteroid. For example, a camera FOV of 1.4 degrees would require about 8 non-overlapping exposures to cover the uncertainty region of 11.4 degrees stated above. Assuming a 1000x1000 pixel detector, this FOV corresponds to a pixel resolution of 24micro-radians, which is more than adequate to reduce the spacecraft asteroid-relative position uncertainty and start the SEP burn-arcs to rendezvous with the asteroid.

The aperture of the NAC has to be sized to require reasonable low exposure times (10’s of seconds) at the largest distances the asteroid is to be acquired (i.e. 50,000km), given asteroids with diameters of less than 10 meters and albedos of as low as 3%. The baseline NAC has an aperture of 6cm.

The NAC is mounted on a 2axis gimbal to facilitate the search of the asteroid at the start of the Rendezvous Phase, to robustly recover from a fault event where knowledge of the asteroid direction is lost, and to continue to image the asteroid during SEP thrusting.

During the Rendezvous Phase, all the image processing, navigation, and SEP maneuver computation is done on the ground. The SEP burn-arcs are executed autonomous on-board by the Attitude Control System (ACS). The duration of this phase is of less than 4 weeks with margin for periods of no SEP thrusting.

The next phase, **Asteroid Characterization**, starts when the spacecraft is acquired by the 3D LIDAR at a range of 1km. As its name implies, the purpose of this phase is to “orbit” the asteroid at a safe distance, and at different ranges and illumination angles to allow the full characterization of the asteroid: shape, rotational dynamics, and mass properties.

The LIDAR is mounted rigidly on the spacecraft with its boresight parallel to the Capture Bag symmetry axis (Z-axis). To acquire the asteroid with the LIDAR for the first time, the spacecraft is commanded to point the LIDAR boresight along the best estimate of the asteroid direction, which requires slewing the spacecraft accordingly.

The LIDAR FOV size needs to be as large as possible to accommodate the largest uncertainty in the location of the asteroid. At a 1km range, a LIDAR with a 10degree FOV results in a search area per frame of 173 meters, which is more than adequate to compensate for the uncertainty in the asteroid position estimated from Ground Optical Navigation using the NAC, and to recover from loss-of-knowledge faults. The angular resolution must be such that in one frame the asteroid is imaged by multiple range measurements. Assuming asteroid diameters between 3 to 10 meters, a 0.5meter angular resolution is also adequate. At a 1km range a 0.5m angular resolution is equivalent to 0.5milliradians. Assuming that the asteroid is within the 10x10degree FOV centered at the boresight of the LIDAR, the LIDAR must be able to find the asteroid within 15 seconds.

After the asteroid is acquired by the LIDAR, the LIDAR continuously tracks the Center-Of-Figure (COF) of the asteroid at a 1Hz rate and an accuracy of less than 1 meter in all dimensions, while the spacecraft ACS autonomously turns the spacecraft to keep the LIDAR boresight pointed in the direction of the asteroid COF. The attitude control deadbands are kept large enough to allow for asteroid COF to Center-Of-Mass (COM) discrepancies.

During the Asteroid Characterization phase the position of the spacecraft is controlled autonomously in an asteroid-centered inertial frame by a series of waypoints. Waypoint Guidance prescribes a series of trajectories (arcs and “orbits”) that the spacecraft must follow around the asteroid in order to characterize it. Those trajectories are then followed by a deadband position controller, which commands a set of RCS thrusters that allow 6 degree-of-freedom decoupled control (i.e. attitude and translation).

The Reference Mission does not require very precise asteroid shape determination because the LIDAR measures directly the position of the asteroid as it enters the Capture-Bag (see next phase explanation). A requirement of 10cm resolution for the asteroid shape model is then levied on the mission. The main instruments used to characterize the asteroid are the NAC and the LIDAR. The NAC, however, starts to lose focus for ranges less than 1km so the range must be kept at that value while imaging the asteroid from multiple sun illumination angles in order to determine its shape through stereophotoclinometry. The LIDAR is also used to determine the asteroid shape and in order to meet the requirement stated above the spacecraft is planned to fly within 200meters of the asteroid for a few days.

If the asteroid is a fast rotator and the LIDAR is a scanning device, the motion has to be compensated in order to achieve the stated shape accuracy. All the image and signal processing required to characterize the asteroid is performed in the ground. The resulting models are then uploaded to the spacecraft for the next phase. On the other hand, the LIDAR image processing that, as part of the Proximity Operations, is required for controlling the attitude and position of the spacecraft relative to the asteroid must be done autonomously on-board either at the sensor or in the spacecraft main computer.

The next phase is the **Approach and Capture Phase**. During this phase the spacecraft attitude is controlled to point the LIDAR boresight to the asteroid estimated COM. Starting at ~100meters and using the same Waypoint Guidance as in the previous phase, the spacecraft is commanded to follow a straight line towards the asteroid COM, at a low approach velocity (~0.1 m/sec).

The reason to choose to navigate with respect to the asteroid COM is that it is an inertial point and, therefore, does not require transverse thruster firings to follow it. In addition, for a moderately fast rotating asteroid, by aligning the Capture Bag axis of symmetry with the asteroid COM the clearances between the bag and the asteroid are distributed evenly for a full period of nutation/spin. In order for this strategy to work, however, the largest distance between the surface of the asteroid and its center of mass (i.e. largest radius) must be smaller (by ~1m) than the radius of the Capture Bag.

The LIDAR, however, after simple image processing, measures the direction to the asteroid “instantaneous” Center-of-Figure (COF), not to the COM. In order to compute the direction to the COM, a Navigation Filter fuses the COF direction computed from the LIDAR measurements with the IMU accelerometer measurements while estimating accelerometer bias and spacecraft position and velocity with respect to the asteroid COM. The Navigation Filter time constant must be long enough to average the time varying error due to the non-colocation of the current asteroid COF and the COM, which has a period consistent with the asteroid spin rate and nutation.

When the spacecraft reaches a distance of 50m to the asteroid, the spacecraft stops autonomously and station-keeps at a fixed position to allow for the Navigation Filter to converge with the latest LIDAR measurements. Then, after the ground gives the go-ahead, the spacecraft starts the sequence to inflate the airbag. Since the LIDAR is mounted in the centerline of the bag, its inflation does not obstruct the LIDAR FOV. Once the ground has inspected through camera images, and other sensors, and the determined the success of the operation, it gives the spacecraft the g-ahead for the capture sequence to start. In this sequence, the spacecraft spins-up to a ground commanded spin-rate in order to match the spacecraft rotation with that of the asteroid. After the spin rate has been achieved, the spacecraft starts to approach the asteroid at ~0.1m/sec in the direction towards the asteroid COM and with the LIDAR boresight pointed in the same direction. Throughout the approach the LIDAR continues to image the asteroid from limb-to-limb while the Navigation Filter continues to estimate the position of the spacecraft relative to the asteroid COM all the way until the capture bag starts to engulf the asteroid.

It is required for the LIDAR to have a very large FOV of 60x60 degrees in order to image the edge of the airbag as the asteroid enters through it. This feature, in addition to the navigation function, allows the LIDAR to be used as a separate Fault Monitor that triggers an abort if the clearances between the bag and the asteroid get below a certain threshold.

The motion of the spacecraft towards the asteroid is stopped autonomously when the instantaneous range gets below ~3meters (the actual threshold value must take into account the variation in the asteroid radius as it rotates and nutates). For this function a ~1meters minimum range operating requirements is levied on the LIDAR.

When the spacecraft velocity relative to the asteroid reaches zero, the autonomous sequence idles the GN&C function (i.e. open loop) and commands the start of the asteroid capture sequence. All the GN&C activities from then on do not require spacecraft asteroid sensing and therefore are out of the scope of this BAA.

Notice that for the Reference Mission there is never a need for on-board/autonomous sensing of the spacecraft 6 DOF pose relative to the asteroid. Bearing to the asteroid Center-of-Brightness (COB) is required during the Rendezvous Phase, and bearing to the COF and range are required during the Characterization and Approach/Capture Phases.