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HERA autonomous Guidance, Navigation and Control experiments: enabling better asteroid science & future missions

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Abstract

HERA is a mission of opportunity to validate kinetic impact as planetary defense technique in collaboration with NASA's DART mission. As a by-product, asteroid science will be achieved using the needed for deflection. In addition, HERA will demonstrate several Guidance, Navigation and Control (GNC) technologies. These GNC experiments permits the achievement of some deflection and science goals of HERA mission and enable the use of the GNC technologies in future space missions. The design of the GNC experiments considers the balance between mission safety, flight operations, payload characteristics, and spacecraft and schedule constraints.

1. Introduction

HERA is a mission of opportunity to validate kinetic impact as planetary defence technique in collaboration with NASA. In addition, HERA will test Guidance, Navigation and Control (GNC) technologies for future space missions and deep-space cubesats. HERA provides the optimal balance between risk and innovation to test novel technologies for future low-cost planetary mission architectures. In particular, high on-board autonomy permits longer science operations, more accurate instrument pointing and flying closer to the surface of the asteroid.

HERA is ESA's contribution to the Asteroid Impact & Deflection Assessment (AIDA) mission, which will be the first test of the kinetic impactor technique for asteroid deflection. NASA's DART will collide with the moon of a binary asteroid (Didymos), while HERA will study the effect of such impact and characterize for the first time a binary asteroid [2]. HERA will rendezvous with binary 65803 Didymos, in 2026, nominally 4 years after the DART impact.

An overview of the mission is presented in Figure 1. DART will be launched in 2021 and impact Didymos B (hereafter Didymoon) in October 2022. Hera will be launched in 2023 (backup 2024) and arrive at Didymos in 2026. The proximity operations at Didymos will start from a moderate distance of ~30 km. This proximity operations phase is where the GNC experiments takes place to support the scientific objectives of the mission.

The DART mission will demonstrate that the technology to deflect an asteroid by kinetic impact is available, in particular the terminal guidance system. Hera will allow to quantify the deflection and to enable the application of the results to other asteroids. Both missions together provide critical information, as a mandatory step, to be able to effectively deflect a hazardous asteroid should it be needed in the future.

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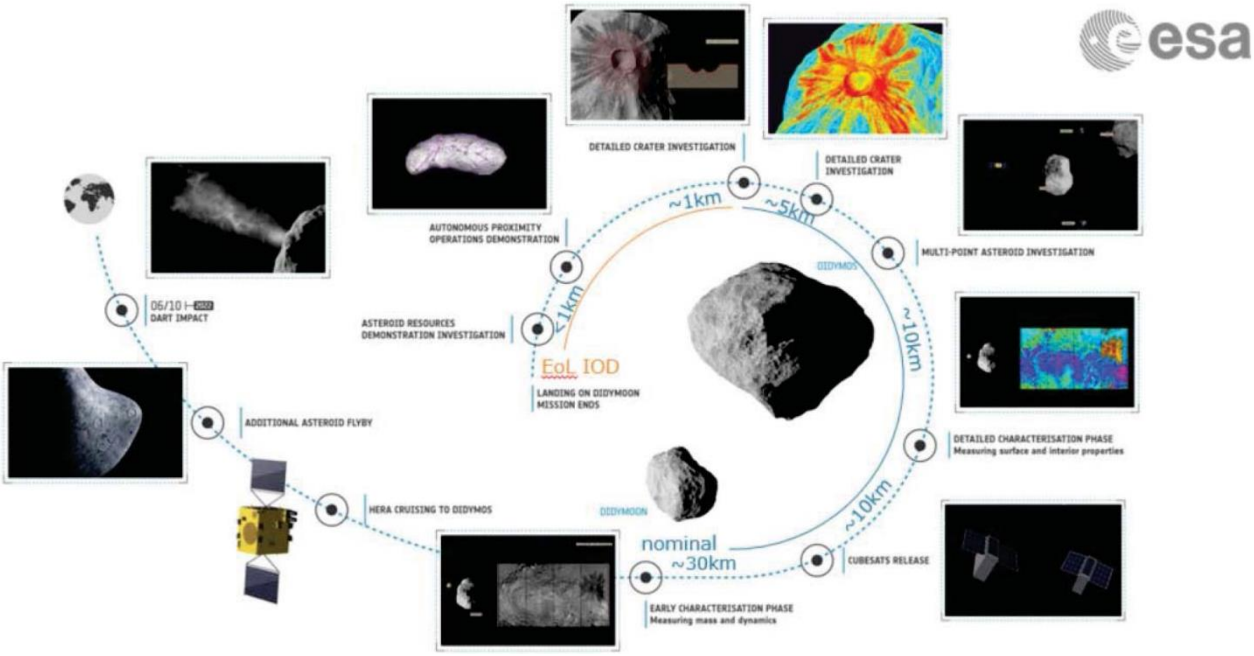

Figure 1: HERA mission overview

The Hera spacecraft will carry two identical Asteroid Framing Cameras (AFC) [2]. The payload will also feature ‘dual-use’ as science and technology payload that can gather data and provide navigation or positioning information, increase operations flexibility or enhance the mission performance in other ways.

The additional baseline payloads are a Thermal Imager (TIRA), a Lidar (Planetary ALTimeter, PALT), and two 6U CubeSats. One of the CubeSats (Asteroid Platform EXplorer) will carry the ASPECT visual and near-IR imaging spectrometer, a Secondary Ion Mass Analyser (SIMA), and a magnetometer. The second CubeSat, (Juventas), will be equipped with a monostatic radar as well as a gravimeter and accelerometers. In addition, the Radio Science Experiment (RSE) and the BiStatic Radio Science Experiment (BSRE) will be performed with the spacecraft TT&C hardware.

2. Proximity Operations Phases

The approach phase will start in September 2026 and last about one month, based on a strategy similar to Rosetta. Once in situ, the proximity operations are divided in several phases where different scientific and GNC objectives will be achieved.

Early Characterization Phase (ECP)
This phase takes place at a distance beyond the gravitational sphere of influence (typically around 30 km) and only as soon as optical remote sensing instruments will be operable with the objective of conducting a physical and dynamical characterization of Didymos (notably: size and shape by imaging, and dynamical characterization - including orbital and rotation periods- by imaging).

Detailed Characterization Phase 1 (DCP1)
It involves closer proximity operations at a minimum distance of ~10 km from the system barycentre, enabling the accurate characterisation of Didymoon’s mass (by determining the ¨wobble¨ period of Didymain around the system barycentre) and density in the combination with size measurements, medium-resolution imaging and the operation of the Planetary Altimeter (PALT). Different viewing angles will be used as in the DCP1 to access different latitudes and longitudes from different local times by means of (intrinsically safe) hyperbolic arc flyby trajectories.

Payload Deployment Phase (PDP)
During this phase, the CubeSat(s) are released and commissioned until they reach full operational capabilities.

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Detailed Characterisation Phase 2 (DCP2)
Equivalent to DCP1 but involves also operations of the CubeSat(s).

Detailed Characterisation Phase 3 (DCP3)
HERA will progressively approach Didymoon to characterize in detail DART´s impact crater. The minimum distance to the barycentre will go well below 10 km (the minimum distance shall enable operations of all payloads). Higher resolution images of the crater will be taken with close flyby trajectories down to 2 km distance from the surface of Didymoon. This phase also involves higher-risk autonomy demonstration experiment close to the surface.

End of life Phase (ELP)
Following the nominal mission of the spacecraft, it will disposed by landing on the surface of "Didymain". Alternatively, the spacecraft operations will be funded by, or handed over to, private operators interested in gaining experience and operating payload in support to resources utilisation objectives.

3. GNC Constraints and Objectives

One of the fundamental tasks of the GNC analysis is to design the proximity trajectories that fulfils the scientific requirements, the ground operations constraints and can be flown by the HERA GNC. Based on ESA's expertise in ROSETTA, it was agreed that during proximity operations HERA will fly trajectories with pericentre velocity larger than the escape velocity (aka parabolic velocity), with a safety margin C defined in the equation below.

$$v_{peri} = (1+C)\sqrt{\frac{2\mu}{r_{peri}}} \quad , \quad C > 0 \tag{1}$$

The safety margin C is selected to ensure that there will be no collision during the arc in presence of relevant uncertainties in the gravity field and the dispersion in the delta-V execution error. The minimum safety margin initially selected for HERA proximity operations is C = 0.4

In the analyses of possible trajectories, the trajectories shall have a duration compatible with operation team shifts (4-3 day pattern). Therefore, at most two manoeuvres can be executed every 3 or 4 days, for a total of 4 delta-V manoeuvres per week. This will avoid having very fast ground turn-around times that would require very demanding ground operations.

Furthermore, to avoid large relative delta-V execution error, the minimum delta-V for the nominal proximity operations is 5 cm/s. This would prevent that the systematic delta-V execution error will become the dominant source of error.

A final constraint on the design of the baseline trajectories comes from the use of vision-based navigation, either on-ground or on-board. The nominal proximity operations shall take place in the dayside of "Didymain" in order to ensure valid images for optical navigation.

The above constraints comes from the necessity to achieve the primary scientific mission objectives while keeping the complexity of the mission in a level that ensures feasibility of fast development. However, in order to achieve the secondary HERA mission objectives, HERA shall fly at very low altitudes to acquire high-resolution images of the impact crater on Didymoon.

In order to achieve the above mentioned mission objectives and fulfil the constraints, the HERA GNC includes some new technologies that would be useful in future missions. First, the HERA GNC will provide improved attitude pointing capabilities using vision based navigation. There are two different image processing techniques used in the autonomous navigation chain depending on the distance to the asteroid. During the 'far range', that is when the asteroid fits completely in the AFC image, the image processing will compute the Line-Of-Sight (LOS) that will be used by the navigation filter to refine the on-board knowledge ([3]). This technology can be applied with minor modifications in the far rendezvous phase of in-orbit servicing missions ([4]), active debris removal, or Mars Sample Return, or during high-velocity fly-by of asteroids (like ROSETTA fly-bys of Steins or Lutetia) or in kinetic impact missions.

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In the ‘close range’, the image processing will track unknown features on the surface and the navigation filter will process them to avoid knowledge degradation. The same terrain-relative navigation can be applied in the terminal phases of landing missions on the Moon or Phobos, or during the terminal phases of capture or docking with cooperative or uncooperative satellites.

During very low-altitude fly-bys, autonomous on-board guidance and control is needed to obtain high-resolution imaging of the impact crater. Using the on-board navigation solution, the autonomous guidance and control can perform small modifications in the pre-defined manoeuvre sequence to ensure small deviation of the flown trajectory with respect to the nominal trajectory relative to Didymoon, which ensures implicitly the safety of the spacecraft. This autonomous guidance and control can increase the pointing accuracy for missions performing fly-bys

There are additional technology demonstrations that aim to increase the autonomy periods. These demonstrations are related to the GNC Failure, Detection, Isolation and Recovery (FDIR) algorithms. The main objective is to avoid that equipment unavailability or temporary degradation of the on-board GNC performance trigger a SAFE mode. For that purpose the GNC FDIR use sensor data fusion to avoid alarms escalation. In that sense, all the available payloads are used in the monitoring or in the navigation loop, depending on the distance to the asteroid and on the proximity operations phase.

The use of the thermal infrared camera can provide navigation measurements after the pericentre of the hyperbola at 2 km from Didymain (about 1 km from the surface of Didymoon). In that arc, HERA will be flying in the dark side of the asteroid and the optical navigation cannot provide measurements. The thermal infrared images can improve the LOS accuracy because they are not affected by the Sun phase angle, as shown in Figure 2. The use of the laser rangefinder improves significantly the on-board navigation accuracy, in particular after the repointing manoeuvre from Didymain to Didymoon before the pericentre. The combination of optical image processing and ranging or the use of thermal imager are fundamental technologies for future applications like capture of uncooperative satellite, or docking with large space structures. In both cases, the proper illumination conditions for vision based navigation cannot be ensured and there will be significant changes of scale in the imaged object (from full object to only small portion). Therefore, ensuring smooth transition of image processing algorithms and even imaging sensor is fundamental even in the presence of large shadows or very high Sun phase angle.

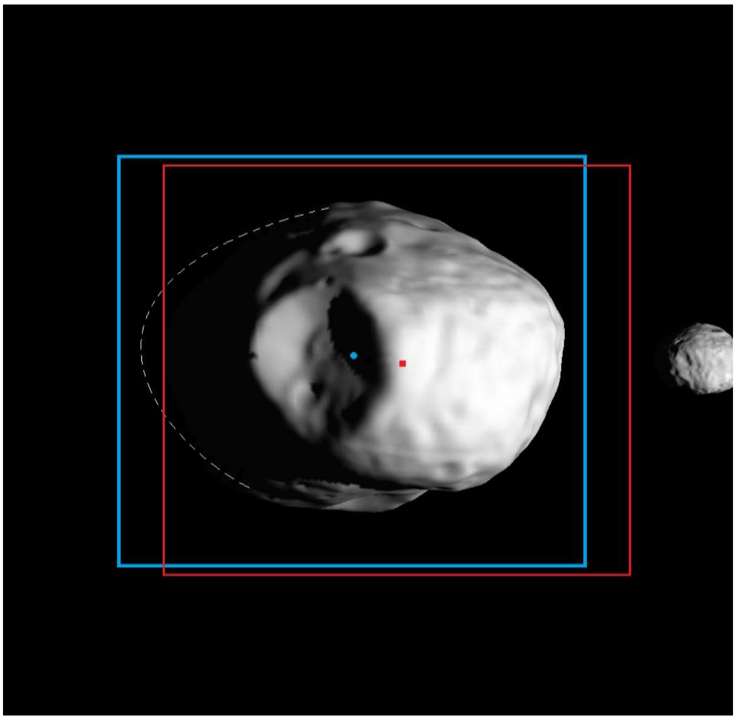

Figure 2: Illustration of Line-Of-Sight accuracy from thermal infrared and visual images

An additional GNC FDIR algorithm is the on-board real-time estimation of collision risk. This monitoring will be used to autonomously trigger a collision avoidance manoeuvre before enter SAFE mode. This is a critical functionally required in the proximity operations of future in-orbit servicing missions. In the terminal phase of these

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missions, before entering SAFE mode, a collision avoidance manoeuvre is needed. When the rangefinder is not in the loop (either outside operational range or not validated yet), the collision risk is based on a corridor of the navigation solution and its covariance. When the range finder is in the loop, range and range rate corridors with direct measurements are added (and possible replace the equivalent checks using navigation filter products).

Finally, the HERA GNC shall support the Cubesats safe and reliable deployment. This is as a by-product of the proximity operations analysis. The dispersion introduced by the pointing accuracy of HERA and the cubesat deployment mechanism are equivalent to the delta-V dispersion error. HERA shall also support the relayed operations of the Cubesats. The images of the AFC will help the orbit determination of the Cubesats. After the deployment of the Cubesats, HERA can track the cubesats during the commissioning phase.

More details on the baseline algorithms, equipment and validation status of the HERA GNC and FDIR can be found in [5].

4. Proximity Operations Trajectory Design

The trajectories during the different phases of the proximity operations shall be computed and analysed in order to verify the fulfilment of the HERA scientific requirements, to compute the data volume generated during the proximity operations, and to contribute to the definition of the payload interfaces and specifications. These trajectories shall fulfil all the constraints presented in the previous section.

For DCP1, the minimum pericenter radius has been preliminary selected at 10 km. These manoeuvres are safe in presence of 10% delta-V execution error or 10% error in the estimation of the asteroid gravity parameter. This pericenter radius ensures that Didymain fits entirely in the AFC image even with dispersion on the pericenter altitude.

The initial considered trajectories are presented in Figure 3 (including the secondary asteroid). The X-axis points towards the Sun at the beginning of the DCP1. The red stars indicate the pericenter of each hyperbola (note that the 1-day arcs do not fly through the pericenter, the manoeuvre is performed before reaching it). The ’Northern’ trajectories and the Equatorial arc are flown counter clockwise seen from the Sun. The ‘Southern’ trajectories are flown clockwise. The day of the week for manoeuvre execution are indicated.

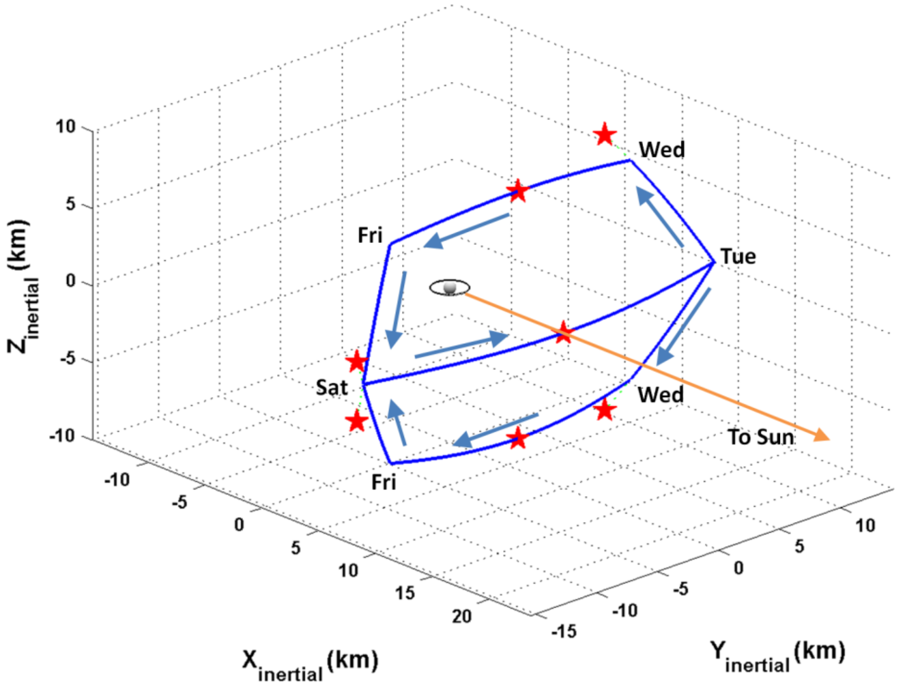

Figure 3. Initial DCP#1 trajectory (blue arrows indicate flying direction)

Figures 4 and 5 show the distance to Didymoon and the Sun phase angle (Sun-asteroid-SC angle). In these figures, the hyperbolas flying through its pericenter has the zero time at pericenter passage (correspond to arc numbers #1 (3-day),

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#2 (2-day), #4 (3-day), #6 (2-day), #8 (3-day)). Note that hyperbolas number #1, #4 and #8 are the same arc (the 3-day arc) but flown at different times. The connecting hyperbolas of 1-day duration do not pass through the pericenter and the time starts at the beginning of the arc (correspond to arc number #3, #5, #7, #9).

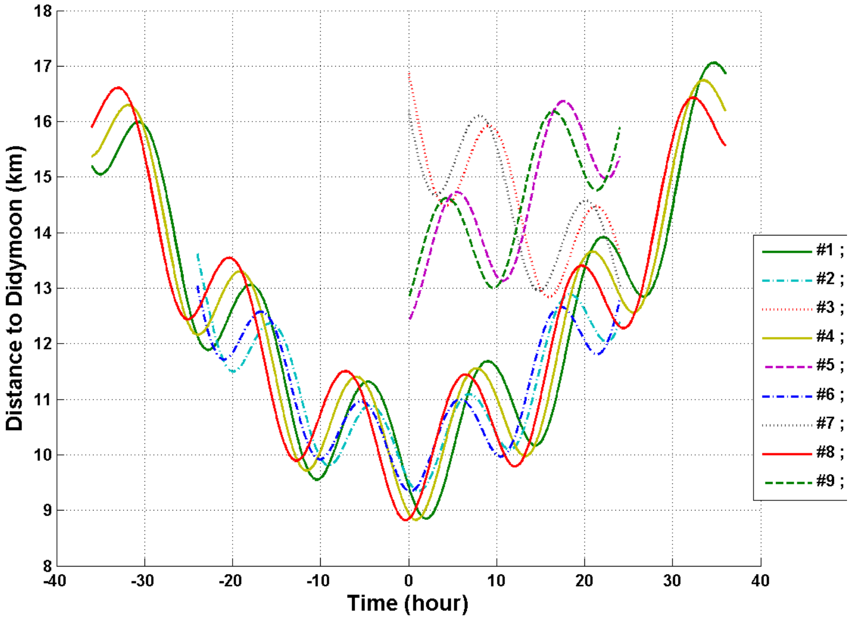

Figure 4. Distance to centre-of-mass (COM) of Didymoon for each hyperbola

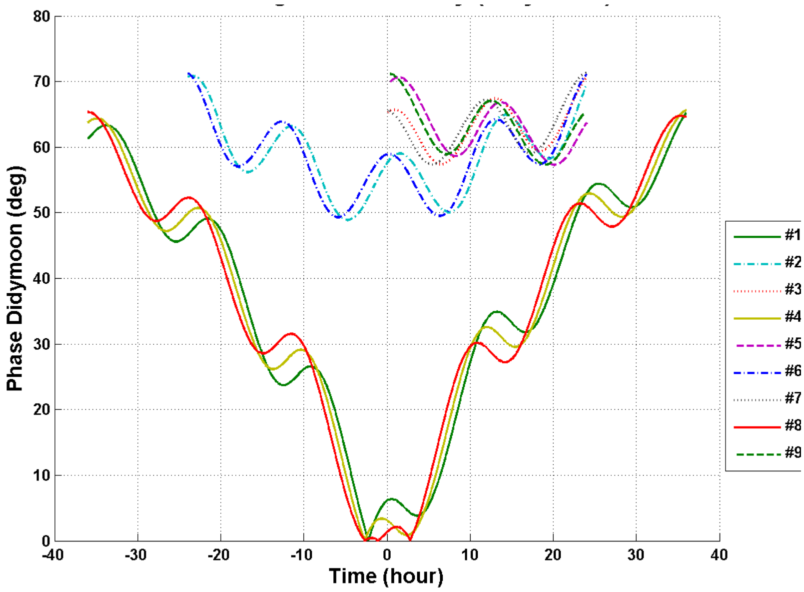

Figure 5. Sun phase angle of Didymoon for each hyperbola (assumes Sun is fixed at X-axis)

The main drawback of these trajectories is that there are two delta-V performed in open loop, that is without feedback from ground orbit determination. Other trajectories requiring only one delta-V every ground loop have being investigated, so called Z-shaped trajectories. These trajectories include then a 3-day arc and a 4-day arc. The trajectories are shown in Figure 6. Note that the trajectories can be rotated around the Sun line (the X axis) to obtain different coverage and illumination conditions of the surface of Didymain and Didymoon. For the trajectory presented above, the distance to Didymoon and the Sun phase angle are plotted in Figure 7 and 8. The combinations of short arcs and long are depicted in Figure 9 and 10. Note that these combinations give flexibility to the mission operators to adapt to the actual HERA spacecraft performances and the needs from the science team.

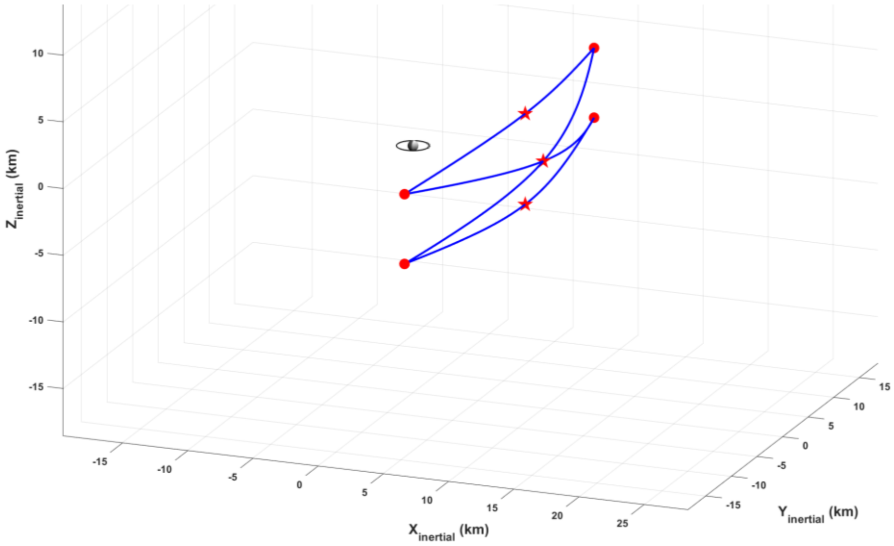

Figure 6. Alternative DCP#1 trajectory

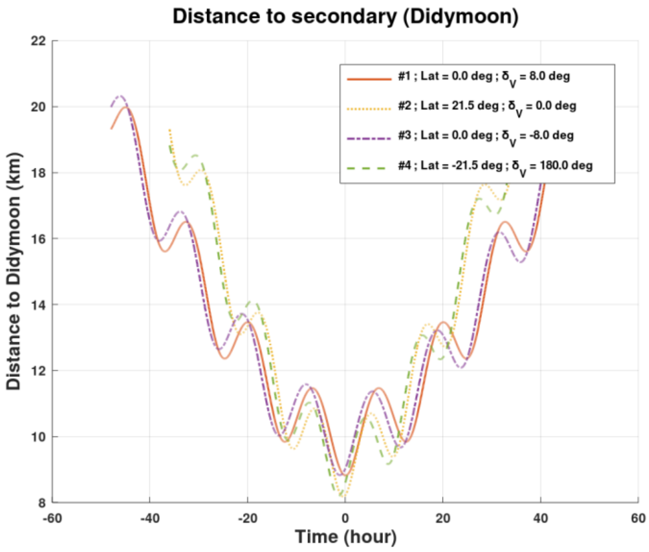

Figure 7. Distance to centre-of-mass (COM) of Didymoon for each hyperbola

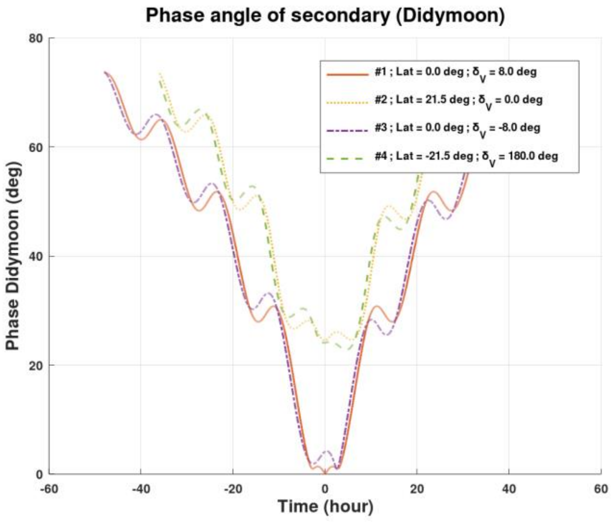

Figure 8. Sun phase angle of Didymoon for each hyperbola (assumes Sun is fixed at X-axis)

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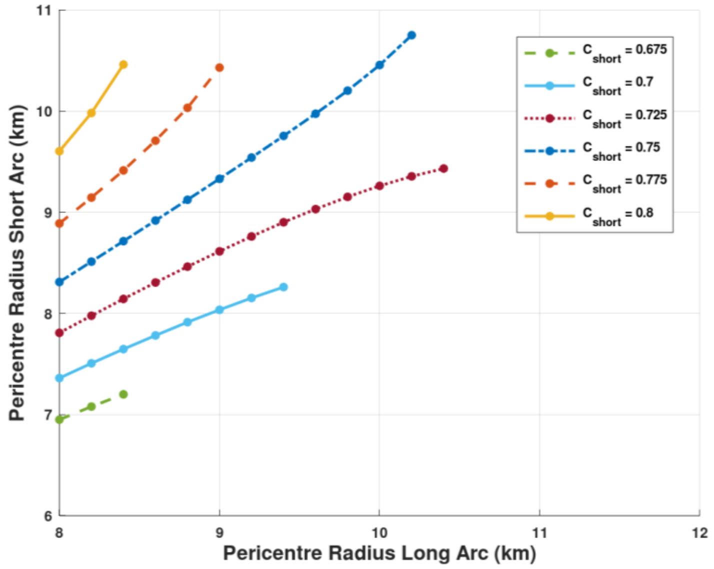

Figure 9. Pericentre radius of long and short hyperbolas for Z-shaped trajectories in DCP1

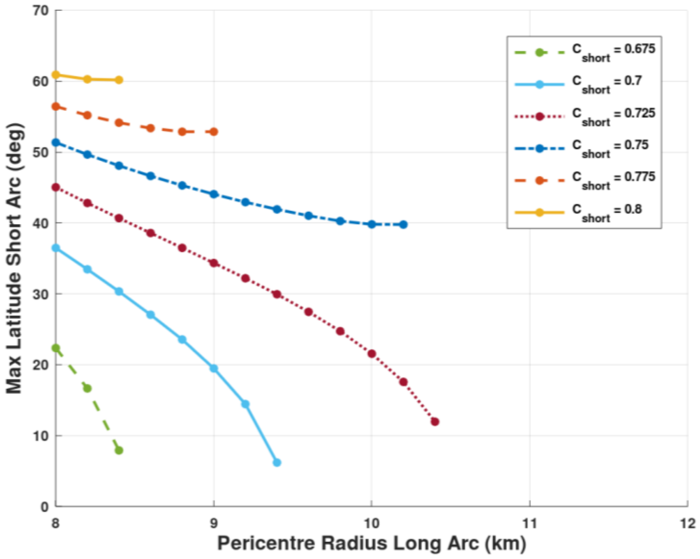

Figure 10. Pericentre radius of long and maximum latitude achieved by short hyperbolas for Z-shaped trajectories

In DCP3, the main objective is to reach low altitude fly-bys to get higher resolution images. The knowledge of the environment and the SC performances (in particular delta-V execution error) should be better than in the previous phases. It is worth noting that below approximately 8 km the asteroid will not fit entirely in the FOV and the navigation based on centre of brightness is no longer applicable.

Keeping the same minimum safety margin C=0.4, patterns of 4-3-4-3 arcs are still feasible. The objective is to have a short 3-day arc with lower pericenter altitude and then a 4-day arc with a higher pericenter forming a Z-shaped trajectory. In this type of trajectories, there are constraints in the different parameters of the hyperbolas. The feasible combinations of pericenter radius for the 3-day and 4-day arcs are depicted in Figure for different safety coefficients of the short arc (for the long arc the coefficient is C=0.4). The maximum latitude above the orbital plane of the secondary is another parameter that can be varied. The feasible combinations are depicted in Figure .

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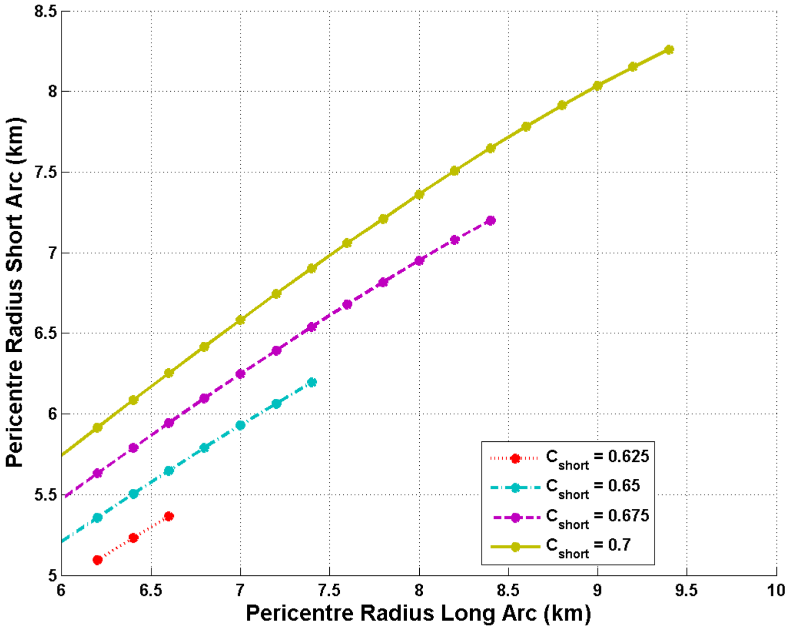

Figure 11. Feasible combinations of pericenter radius for Z-shaped trajectories in DCP3

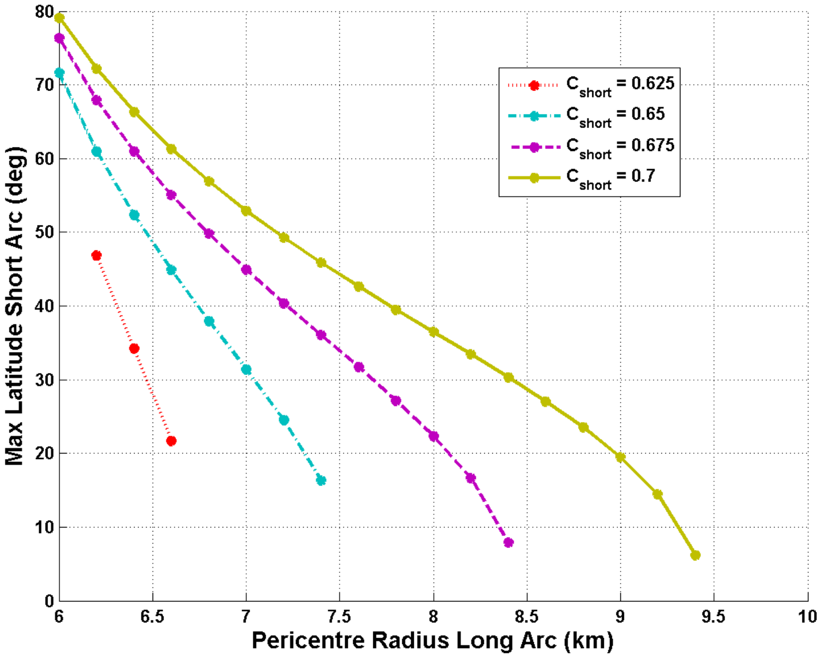

Figure 12. Feasible combinations of maximum latitude and pericenter radius in DCP3

As an example, the arcs for a Z-shaped trajectory with the following parameters are depicted in the following figures.

- pericenter radius of 3-day arc 6.085 km
- pericenter radius of 4-day arc 6.400 km
- maximum latitude of 3-day arc 66.3 deg

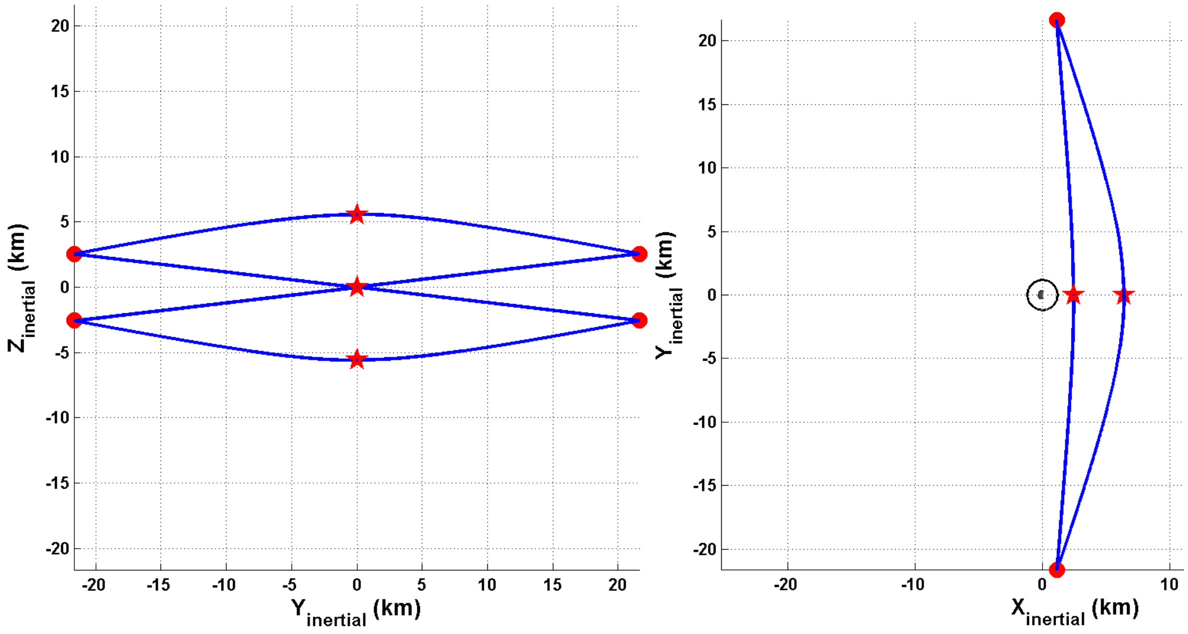

Figure 13. Possible DCP#3 arcs (Sun along X-axis).

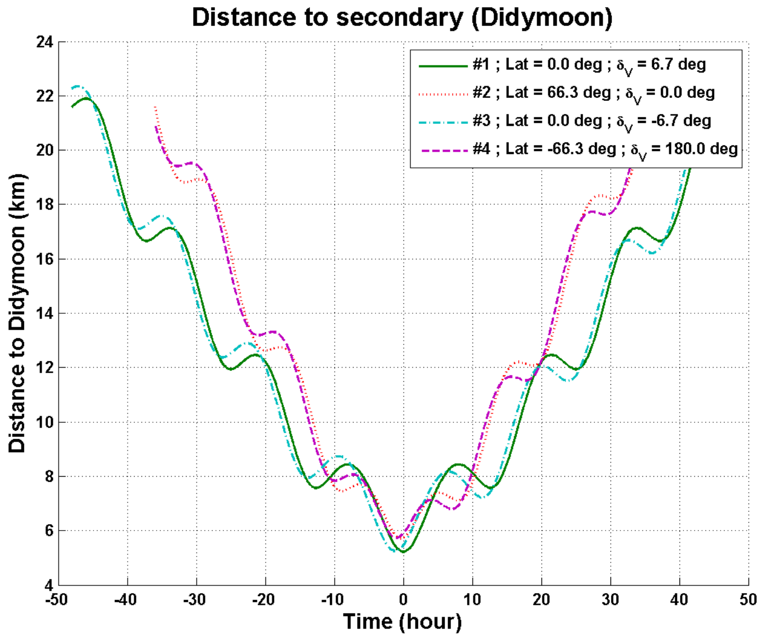

Figure 14: Distance to centre-of-mass (COM) of Didymoon for each hyperbola

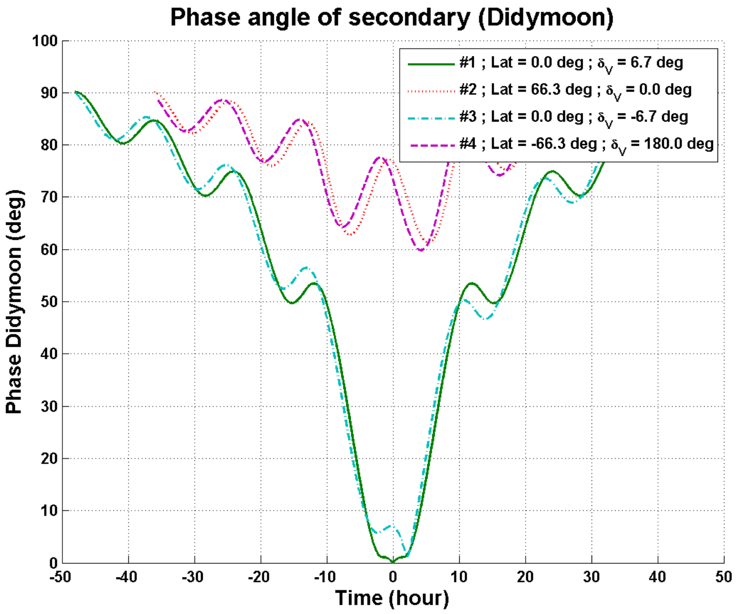

Figure 15: Sun phase angle of Didymoon for each hyperbola (assumes Sun is fixed at X-axis)

3. Conclusions

HERA’s GNC both nominal and novel technology demonstrations will provide new capabilities for future exploration and in-orbit servicing missions. One of the main capabilities is the vision-based navigation combined with semi-autonomous guidance that will significantly improve the attitude pointing accuracy. That capability can be used in target tracking during fly-bys of asteroids or comets, and in the detection and tracking of faint targets in rendezvous missions like Mars Sample Return or Active Debris Removal.

The autonomous guidance and control coupled with the on-board tracking of unknown surface features will enable high-resolution imaging during very low-altitude fly-bys. This capability can enable future high precision landing missions on the Moon or Phobos, or the terminal phases of capture or docking with cooperative or uncooperative satellites.

HERA’s enhanced GNC Failure, Detection, Isolation and Recovery (FDIR) system will significantly increased the autonomy periods, while maintaining the system FDIR as simple as possible. The GNC FDIR will use sensor data fusion to avoid alarms escalation and maintain nominal operations even in case of sensors unavailability. In addition, one of the FDIR functions is the real-time estimation of collision risk that can trigger a collision avoidance manoeuvre. This is a critical functionally required in the terminal phase of future in-orbit servicing or active debris removal missions.

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