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1 SCOPE

This document defines the Mission Requirements applicable to the Hera mission. And it further describes the measurement objectives by different payloads to achieve them.

The primary requirements refer to the demonstration of asteroid deflection by kinetic impact, in conjunction with NASA's DART mission. As a by-product, asteroid science will be achieved by the Hera mission. Scientific requirements will only be pursued if they do not increase the need of resources significantly, and, in practice, most scientific goals are reached with the measurements needed for deflection. Therefore, scientific requirements are not explicitly specified.

Finally, requirements for technology demonstration opportunities are specified. These technologies could be needed to enable new future deep-space mission concepts, however they should not be mission drivers for Hera.

2 REFERENCES

2.1 Reference Documents

All documents listed below are provided as references for information relevant to the definition of the mission requirements and payload measurement objectives.

[AD3] Didymos Reference Model (DRM)

2.2 Acronyms

AFC	Asteroid Framing Camera(s)
AIDA	Asteroid Impact & Deflection Assessment
APE	Absolute Pointing Error
DART	Double Asteroid Redirection Test
DRM	Didymos Reference Model
DV	Data Volume
FOV	Field Of View
GNC	Guidance Navigation & Control
Lidar	Light detection and ranging
PALT	Planetary ALTimeter
PID	Payload Interface Document
RSE	Radio Science Experiment
S/C	Spacecraft
TBC	To Be Confirmed
TI	Thermal inertia
TIU	Thermal inertia unit
TT&C	Telemetry, telecommand & command
YORP	Yarkovsky–O'Keefe–Radzievskii–Paddack effect

2.3 Definition of Terms

The target of Hera is the binary asteroid 65803 Didymos (1996 GT) [AD3]. In the following, we will call the primary (central body) of the binary system 'Didymos' and the smaller component/satellite 'Didymoon'.

3 INTRODUCTION

3.1 Mission Overview

The international Asteroid Impact & Deflection Assessment (AIDA) cooperation is the first demonstration of asteroid deflection. It consists of a kinetic impactor, NASA's Double Asteroid Redirection Test (DART) and of ESA's Hera inspector spacecraft that will rendezvous the target asteroid, the binary 65803 Didymos, in 2026, nominally 4 years after the DART impact.

An overview of the mission is given in Fig. 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 early characterisation phase of Didymos will start from a moderate distance of ~30 km to determine the shape and the gravity field. The detailed characterisation phase will be conducted from about 10 km distance. During this phase the CubeSats will also be released. Very close flybys of Didymoon are envisioned towards end of mission as part of the technology demonstration based on the so-called onboard landmark navigation.

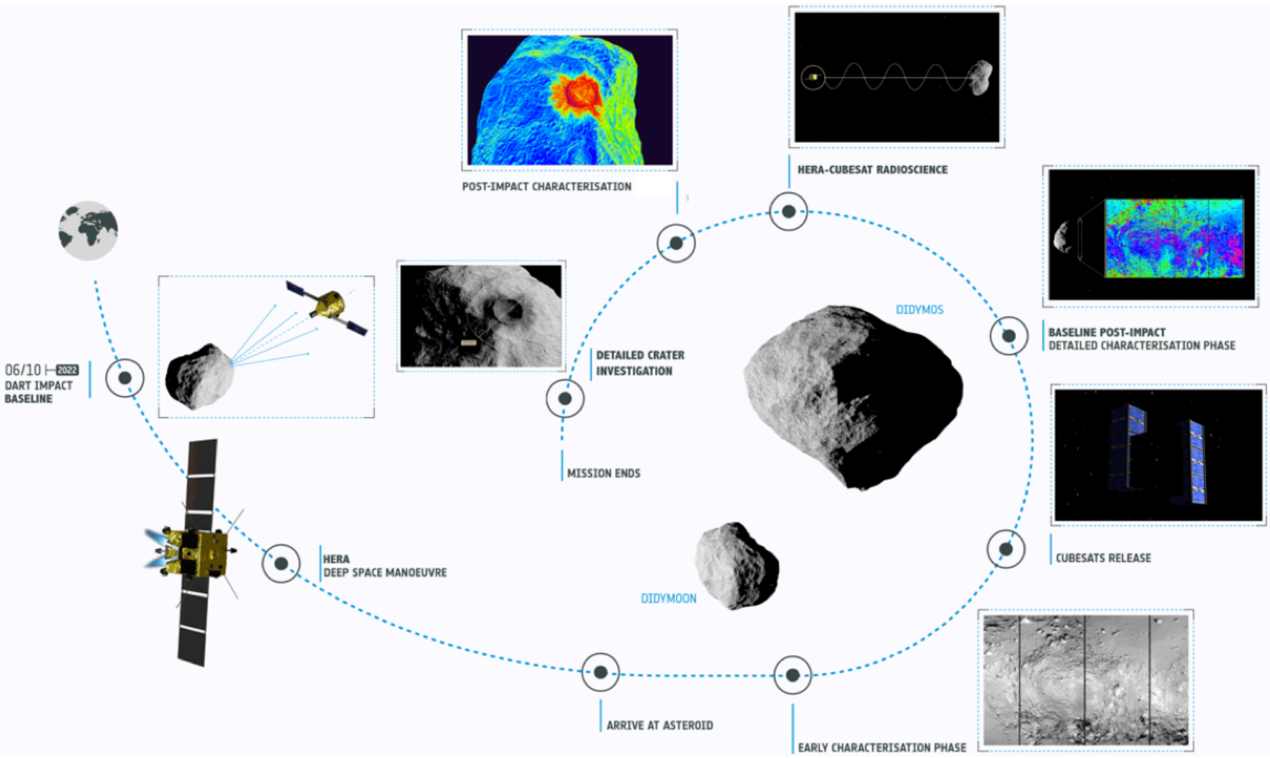

Figure 1 AIDA mission overview

The end-of-mission currently foresees two options: the possibility e to land Hera in the polar region of Didymos, alternatively the spacecraft may be handed over to an industrial consortium to test spacecraft or payload elements. The cubesat is expected to end its mission by landing on Didymoon.

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.

3.2 Payloads Overview

The Hera spacecraft will carry two identical Asteroid Framing Cameras (AFC) as part of the spacecraft guidance and navigation system. 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 (TIR), a Lidar (Planetary ALTimeter, PALT), and two6U CubeSats. One of the cubesats (Asteroid Platform Explorer), will carry the ASPECT visual and near-IR imaging spectrometer, a Secondary Ion Mass Analyzer (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 spacecraft TT&C hardware.

4 HERA MISSION REQUIREMENTS

4.1 Asteroid Deflection Requirements

The mission requirements that allow evaluating the outcome of the asteroid deflection experiment are the primary ones of the Hera mission. They are defined within this section and, for convenience, summarized in Table **1**.

1. **Determination of the mass of Didymoon**

The principle of the deflection by kinetic impact is to change the orbit of the asteroid by transferring the momentum of the impactor. The momentum transfer is enhanced due to the momentum of the impact ejecta (Figure 2).

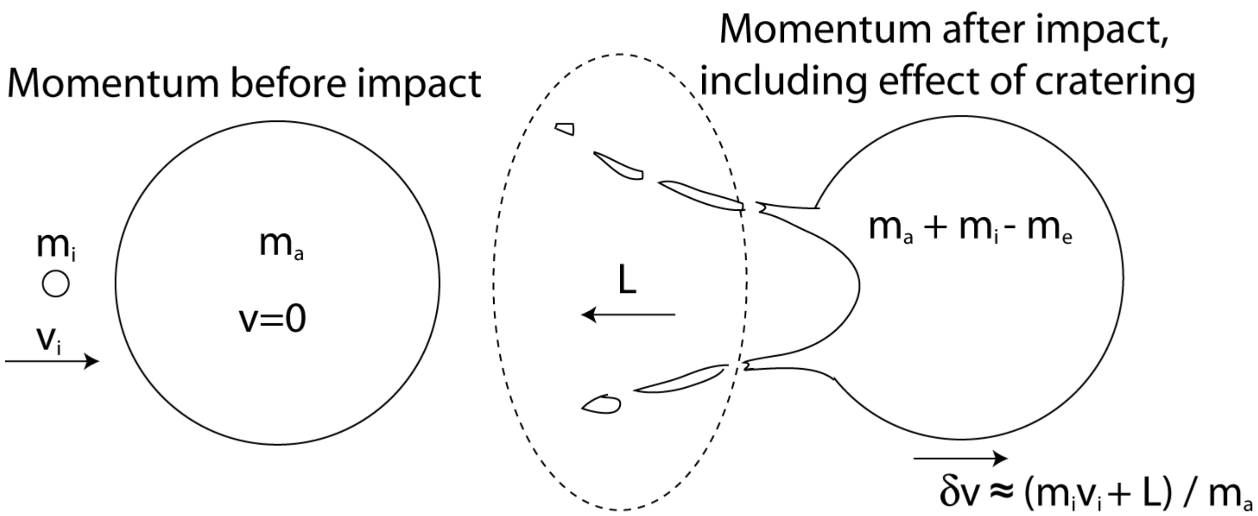

Figure 2: In a kinetic impact, the momentum transferred from the impactor to the asteroid is enhanced through the momentum of the impact ejecta.

With m_i and v_i being the mass and velocity of the kinetic impactor, m_a the mass of the asteroid, δv the velocity change of the asteroid due to the impact, and L the component of the momentum of the ejecta opposite to the impact direction, conservation of momentum can be expressed as:

$$m_i\, v_i + L = m_a\, \delta v$$

The momentum transfer enhancement through the impact ejecta is commonly expressed through the quantity β:

$$m_a\, \delta v = \beta\, m_i\, v_i$$

If the momentum transfer enhancement is exclusively caused by the ejecta, then

$$\beta = m_a\, \delta v/(\, m_i\, v_i) = 1 + L/(\, m_i\, v_i).$$

In practice, other effects like a torque exerted on the target due to the impact being off-center may contribute to β.

According to the most recent model calculations, β may vary between slightly above 1 and 5. The larger variation is due to dependence of the amount of ejecta on the properties of the target asteroid and due to uncertainties in impact physics.

Measuring β is important not only to determine the momentum enhancement as such, but also to improve our understanding of the impact process. As the mass and velocity of the impactor are known, and the δv of the asteroid due to the impact will be measured by ground-based observations and DART imaging from the change of the orbital period of Didymoon, the only missing quantity is the mass of Didymoon.

The first asteroid deflection requirement for the Hera mission is to measure the mass of Didymoon. The required accuracy is 10 %, being considered sufficient to interpret the impact (goal 1%).

2. Shape and volume of the DART impact crater

The AIDA mission is unique in that Hera can observe a crater for which the impactor properties are accurately known. This allows testing and improving impact models, and therefore predictions of the outcome of future kinetic impacts.

The DART impact is expected to create a crater of 6-17 m diameter. About 50-100 resolution elements are required to use the information about shape and volume of the crater to distinguish between different models of crater formation, corresponding to a required image resolution of 10 cm.

The DART impact may cause fractures or other surface features on Didymoon, in the most extreme case even an antipodal crater. As a goal, those features should be searched for with the same resolution as the impact crater itself, corresponding to a global resolution of 10 cm.

3. Density of Didymoon

The target density (or more accurately, the ratio between target density and impactor density) is a parameter needed in the interpretation and scaling of the impact. Furthermore, knowledge of the density is needed to estimate target porosity.

The density is required to an accuracy of better than 20 %.

As the mass is determined to an accuracy of 10 % or better, the density requirement corresponds to a volume measurement to at least 17 % accuracy. This is equivalent to determining the shape of Didymoon to about 6 % or a few meters.

4. Porosity of Didymoon

Porosity is an important parameter for the impact process. For highly porous bodies, much of the energy of the impactor may be transformed into compression of the target, and little ejecta are produced, resulting in a low β. Furthermore, due to the target compression, the ejecta volume may be different from the volume of the crater.

Determination of porosity requires density and some measure of composition (to derive the density of the asteroidal material without porosity). Composition will be derived in two ways: Firstly, by determination of the taxonomic type of the asteroid to determine its meteoritic counterpart. Full spectral classification requires a spectrum from 0.45 µm to 2.45 µm with a spectral resolution of 0.05 µm. There are no stringent requirements on spatial resolution. Secondly, unweathered material is expected to be found in the interior of the DART crater. A spectrum of the crater interior may allow direct identification of the meteoritic counterpart of Didymoon. The spectral requirements are the same as for the classification of the full asteroid. Approximately 10 resolution elements within the crater will be required to clearly identify regions of unweathered material. At a crater diameter of 5 m, this corresponds to a resolution of 50 cm.

5. Size distribution of surface and excavated material

The size distribution of the material at the impact site is another observable that strongly affects the impact process and β. Sizes down to the order of a factor of a few smaller than the size of the impactor are relevant. A resolution of 50 cm (scale 25 cm/pixel) is considered sufficient. A goal requirement is a resolution of 10 cm. This can be provided through close imaging and/or radar and the bistatic radio science experiment.

If the dominant particle size is below cm-scale, this will be inferred from the thermal properties of the surface (the thermal inertia of a powdery surface is much lower than that of a rocky surface).

It is possible that the size distribution at the specific location of the impact crater may be different from the overall one. This cannot be spotted by Hera. However, this would be identified by the DART impactor itself when taking images of the surface before impacting.

6. Asteroid dynamics

The effect of the impact is a change of the dynamical state of the target asteroid, which is imprinted in the system and will not change within a few years from DART's impact.

Knowing the final state and some dynamical parameters pre-impact (spin rate of primary, orbital period, approximate semi-major axis and eccentricity) as well as the impactor and crater properties, the impact will be modelled and the missing parameters (target strength and porosity, some pre-impact dynamical parameters) will be determined or estimated. This process requires Hera to measure the post-impact dynamical state of Didymos accurately. The change in the orbital period will be determined through Earth-based observations. However, Hera will directly measure all orbital and rotational parameters which, together with crater observations, will allow to re-enact the impact in models and refine the calculation of β. The semimajor axis shall be determined to an accuracy of 5 m, and the eccentricity to an accuracy of 0.001. Required accuracies are 0.1 percent in the spin rate, 1 deg. in the spin pole and orbit pole orientation. The spin pole orientation of Didymos is needed for the mass determination.

7. Surface strength

The tensile strength of the target material is an important property for the outcome of an impact. The CubeSat is going to land or bounce on the surface of Didymoon at the end of its mission. The penetration depth on landing provides the order of magnitude of strength, and the coefficient of restitution, equivalent to the kinetic energy of the CubeSat transferred into the surface, further constrains surface properties.
The strength measurement will allow to confirm if the impact on a very low gravity body is indeed strength-dominated (it would be dominated by gravity for nearly zero strength only), and to distinguish between a hard or soft surface. Layering near the surface (layers of different strength) may also be detected.

8. Interior structure of Didymoon

For the interpretation of the impact and scaling to other asteroids it is important to get information about the interior structure of Didymoon. For an asteroid of its size, it is a priori not clear if it is a rubble pile (reaccumulated from impact ejecta or particles ejected by the YORP effect), a fractured fragment or an intact fragment. The requirement is to measure the homogeneity of Didymoon down to a scale of a few meters, relevant for the impact interpretation, and up to a scale of a few tens of meters, relevant for a potentially larger impact needed for the deflection of a hazardous asteroid.

9. Transport of impact ejecta from Didymoon to Didymos

Part of the impact ejecta on Didymoon may impact Didymos. This effect may contribute to the velocity change of Didymoon and is therefore important for the interpretation of the impact.
The ejecta transport cannot be measured directly, however, subsurface material from Didymoon is not affected by space weather and will be brighter and bluer than the weathered surface material of Didymos. A colour and spectral map of Didymos is required to measure the variation of the grade of weathering over Didymos. High accuracy (2 % in colours or 1 %

/ 100 nm in spectral slope) is expected to be required, as the surface fraction covered by the ejecta may be small. Additional information about ejecta transport may be derived from a change in the spin rate of Didymos. It may be measured by ground-based observers and Hera.

Asteroid Deflection Requirements					
Req.	**Quantity**	**Required accuracy**	***Goal***	**Contributing instruments**	***DV Req.***
D1	Mass of Didymoon	10 %	1 %	AFC PALT RSE Cubesat landing APEX/ASPECT JUVENTAS/ accelerometer and gravimeter	*2936 Mbit [in DCP1 (,DCP3?)]*
D2	Shape of the DART impact crater	10 cm resolution	5 cm	AFC APEX/ASPECT	*440 Mbit [during close flyby DCP3 and/or extended mission]*
D3	Density of Didymoon	20 % Corresponds to 17 % in volume and 6 % in linear scale	1 %	AFC PALT APEX/ASPECT	*910 Mbit[1)] [in DCP1 as early as possible as shape model will be needed for later mission activities. Also in ECP to get shape of both objects.]*

D4	Porosity of Didymoon	Through Density and composition information. Requires spectra 0.45 – 0.9 µm with 0.05 µm resolution. Study of crater interior requires 0.5 m spatial resolution Porosity of sub-surface layer and interior derived from radar and BSRE	Spectra 0.45 – 2.45 µm with 0.05 µm resolution for full spectral characterization. Additional information through thermal IR spectroscopy (10 µm feature)	AFC APEX/ASPECT APEX/SIMA TIR BSRE JUVENTAS/ radar	*9450 Mbit[2)] Ideally in parallel with D2 and D3]*
D5	Size distribution of surface and excavated material		Coverage of a 100 m x 100 m area Global coverage at 10 cm resolution	AFC TIR BSRE APEX/ASPECT JUVENTAS/ radar	*440 Mbit[3)] [During close flyby DCP3]*
D6	Dynamical properties of the Didymos system	Semimajor axis: 5 m Eccentricity: 0.001 Spin rate of Didymoon: 1 % Spin pole orientations of Didymos and Didymoon: 1 deg. Orbit pole: 1 deg.	1 m - 0.1 % 0.1 degree 0.1 degree	AFC APEX/ASPECT	*1761 Mbits [DCP1/2 at intermediate distances]*
D7	Strength of near-surface material from cubesat landing/bouncing	N/A	N/A	Cubesats	
D8	Interior structure of Didymoon	Rubble pile vs. monolithic structure	N/A	JUVENTAS/radar APEX/magnetometer	

D9	Material transport (*Weathering on Didymos*)	Colours to 2 % or Spectral slope to 1 % / 100 nm Absorption line depth to 2 % of continuum Spatial resolution 1 m	Colours to 1 % and spectral slope to 0.5 %/ 100 nm	*AFC* *TIR* *APEX/ASPECT*	*6370 Mbit[5)] [DCP1 at minimum distances]*

Table 1 **Asteroid Deflection Requirements. See text for further explanation, section 5 provides more details on how the corresponding measurements may be performed**

4.2 Technology Demonstration

The following mission requirements are supplementary to those of the asteroid deflection experiment and contribute to demonstrate some technologies needed to enable new future deep-space mission concepts. They are defined within this section and, for convenience, summarized in **Error! Reference source not found.**.

1. **Deep-space cubesat operations**

1.1. Inter-satellite link network with ranging capabilities

In order to overcome computation capability limitations as well as complexity of fully independent GNC visual based navigation systems on-board cubesats, establishing a network of space elements connected by inter-satellite link systems providing ranging capabilities could enhance the navigation system by providing relative positioning.

This experiment shall demonstrate the capability of using ranging information from the inter-satellite link systems to enhance cubesat autonomous position determination.

1.2.Spacecraft-relayed cubesat operations in deep space

In order to overcome direct Earth communication capability limitations of cubesats in deep-space, establishing a relay network through a mother-ship spacecraft would be a simple and efficient mean to reduce resources needs to operate cubesats in deep-space.

A solution to this problem is to relay all communications between ground and the cubesat through a mother-ship spacecraft with full communication capability with ground. This can be done using inter-satellite link systems.

This experiment shall demonstrate the capability of using inter-satellite link systems to transfer housekeeping, telecommands and payload data between the Hera spacecraft and the cubesat.

2. Navigation

2.1. Autonomous visual based navigation for semi-autonomous attitude guidance

The proper pointing of the instruments depends on the knowledge of the spacecraft position relative to the target object. If the distance is larger than 8.5 km, the entire primary asteroid will fit in the image of the camera and Line-Of-Sight (LOS) based navigation can be performed. Position knowledge errors can produce a wrong pointing and Didymos and/or the Didymoon will not be in the FOV of the AFC. ROSETTA experienced the problem of losing the comet from the camera images due to the increase of the error of ground-predicted trajectory.

This experiment shall demonstrate autonomous Line-Of-Sight (LOS) based relative navigation in the vicinity of the asteroid. The navigation based on AFC images shall provide the complete state of the spacecraft centre of mass relative to the central body with an accuracy better than the ground orbit prediction.

The experiment shall also demonstrate an autonomous attitude guidance that ensures the target asteroid remains within the camera FoV, effectively improving the pointing accuracy compared to the ground-defined attitude profile, while ensuring that spacecraft constraints are not violated.

2.2. Autonomous visual based navigation for low altitude fly-bys

During low altitude fly-bys, i.e. when the asteroid is larger than the FOV, the LOS-based approach cannot be used.

This experiment shall demonstrate autonomous optical navigation under these conditions (considering the shortest distance that allows limb imaging), effectively enabling safe low altitude fly-bys of Didymoon.

In addition, the experiment shall demonstrate the capability to change the navigation reference frame, from Didymos-centred to Didymoon-centred, and acquire and maintain Didymoon in the FOV. This change is critical to demonstrate the capability of repointing the AFC and rest of payloads from Didymain to Dydimoon, in order to ensure acquisition of high resolution images of Didymoon.

The use of altimetry information cannot be assumed during this experiment as the distance to the asteroid might be above the operational range of the PALT.

2.3. Autonomous Guidance, Navigation and Control for very low altitude fly-bys

In order to perform fly-bys at very low altitudes with proper orientation of the payload, the relative distance to the surface must be accurately estimated at all times. The decrease of the pericenter altitude of the hyperbola is done stepwise in order to ensure the safety of the spacecraft, considering the trajectory perturbations, in particular stochastic errors in the delta-V manoeuvres. This sequence of autonomous delta-V manoeuvres relies on improved (or at least not worsened) knowledge of the spacecraft trajectory relative to both Didymain and Dydimoon.

In order to achieve the required accuracy and reliability of the GNC system, the use of the altimeter measurements in the navigation filter needs to be considered.

This experiment shall demonstrate autonomous computation and execution of trajectory manoeuvres corrections for very low altitude flybys (few hundred meters) relative to Didymoon, effectively reducing the deviation between the target and the flown trajectory based on on-board measurable events (e.g. distance to target, time to closest distance, etc.).

This experiment would allow acquiring high-resolution images e.g. of the crater produced by DART, but would also demonstrate the capabilities required for accurate deployment of passive landers (i.e. without propulsion system).

2.4. Sensor data-fusion for robust navigation

The capability to fly orbits behind the terminator ('night' side of the asteroid) or to track Didymoon during periods of eclipse, requires the use of thermal infrared imagers due to the impossibility to image the asteroid in visual light. Additionally, during the approach phase when the distance to the asteroid is estimated based on the angular size of the asteroid in the cameras FOV, brightness alone in visual light (due to albedo) does not correspond to actual asteroid size, while in infrared light it does.

This experiment shall demonstrate the benefits of autonomous navigation based on fusion of information from visual and thermal infrared imaging.

Note that the simultaneous processing of all the images is not feasible in some cases (e.g. during 'night' or eclipse passes only thermal infrared images can provide relevant information, while during low altitude fly-bys TIR images can provide higher accuracy than AFC images). The transition between these situations are, in particular, important to demonstrate the robustness of the filter to sensor switching.

2.5. Sensor data-fusion for collision detection and avoidance

The capability to assess continuously the current distance to the asteroid and the minimum distance during the trajectory is important to detect any risk of collision in case of unforeseen errors. But this is also relevant for other missions like rendezvous and capture.

This experiment shall demonstrate the capability to assess the collision risk of the trajectory being flown by means of a set of sensors and navigation algorithm independent from the nominal GNC chain.

The experiment shall consider **different** image processing techniques and navigation algorithms from those used in the nominal GNC chain to estimate the collision risk.

In case of high collision risk, the autonomous system shall trigger an autonomous collision avoidance manoeuvre that increase the minimum distance to the asteroid above a certain threshold.

Technology Demonstration Requirements			
Id	**Experiment**	**Objective**	**Relevant Unit(s) or Payload(s)**
T1.1	Inter-satellite link network with ranging capabilities	Relative distance accuracy <10 m (TBC). Goal is to reach 1 m.	Cubesat ISL
T1.2	Spacecraft-relayed cubesat operations in deep space	To transfer housekeeping, telecommands and payload data required to operate the cubesat.	Cubesat ISL
T2.1	Autonomous visual based navigation for semi-autonomous attitude guidance	Position knowledge error (any axis) lower than 100 m relative to the centre-of-mass of Didymos with 95% probability 90% confidence level. Contribution of attitude guidance to APE lower than 0.5 deg (95% probability, 90% confidence level). NOTE: This includes the autonomous navigation error.	AFC

T2.2	Autonomous visual based navigation for low altitude fly-bys (TBC)	Relative distance to COM knowledge error lower than 10% of real distance to the target asteroid COM (Didymain or Didymoon) with **95% probability**, 90% confidence level. Contribution of attitude guidance to APE lower than 0.5 deg (95% probability, 90% confidence level).	AFC PALT
T2.3	Autonomous visual based navigation for trajectory guidance	Relative distance to COM knowledge error (any axis) lower than 10% real distance to the target asteroid COM (Didymain or Didymoon) with **99.7% probability**, 90% confidence level. Altitude error at closest distance lower than 10% of nominal altitude with 99.7% probability, 90% confidence level. Attitude Pointing Error relative to the surface point of interest lower than 1 deg (95% probability, 90% confidence level).	AFC PALT
T2.4	Sensor data-fusion for robust navigation	At least the same as the equivalent vision-based navigation solution.	AFC
T2.5	Sensor data-fusion for collision detection and avoidance	Distance knowledge error lower than 10% of real distance to the target asteroid with 99.7% probability, 90% confidence level. Position knowledge error across-LOS lower than 100 m to the target asteroid with 99.7% probability, 90% confidence level. Altitude error at closest distance lower than 10% of nominal altitude with 99.7% probability, 90% confidence level.	AFC PALT

Table 2: Summary of the Technology Demonstration Requirements.

5 HERA PAYLOAD MEASUREMENT OBJECTIVES

In this section, the contribution of each of the baseline payload instruments to fulfilling the requirements defined in the previous section is described.

5.1 Asteroid Framing Cameras (AFC)

The Asteroid Framing Cameras (AFC) are two identical cameras with a two-dimensional detector. Spectral information is gained using multiple filters. AFC will be used both for GNC and to perform scientific measurements. While it will be mostly used with the clear filter for navigation, in its scientific role it will be imaging the target asteroid system from multiple positions and from various distances during the course of the Hera asteroid observation phases. The purpose of the measurements is to provide information on the binary asteroid dynamics and (especially for the smaller "Didymoon", DART's target), its physical characteristics.

The measurements required by the AFC to meet the deflection requirements are:

D1: The resolution of the images shall be such that surface landmarks can be identified in order to determine Didymoon's mass with an accuracy of at least 10%. This will be done by measuring the motion of Didymos around the common centre of mass of Didymos and Didymoon. The amplitude of this motion is of the order of 10 m, it therefore needs to be determined to an accuracy of 1 m. According to simulations this can be done in the following way:

- Taking 200 images over a 10 day orbit arc with a resolution of 1 m (corresponding to a distance of 10 km)
- Determination of the inertial position of 100 landmarks in those images with an accuracy of at least 1 arcmin (this is in fact a requirement on the spacecraft attitude reconstruction).
- Determination of the spin pole orientation of Didymos to 1 deg.
- Determination of the orbit pole of the orbit of Didymoon around Didymos to 5 deg.
- A distance determination from Hera to one of the landmarks is required to an accuracy of 1 percent. This can be either done by reconstruction of the spacecraft position, or utilizing PALT.

Data volume: 200 images correspond to 2.936 Gbits, assuming full frame 14 bit images and no compression. To be done in DCP1, can be tried in ECP already.

D2: The shape of the DART impact crater shall be imaged with a pixel scale of 10 cm/pixel, corresponding to an optical resolution of 20 cm (Nyquist sampling). As a result, a three-dimensional reconstruction to an accuracy of 50 cm shall be obtained. To meet the requirement, flybys over Didymoon are needed that reach the following geometry:

- Coverage of the full crater from at least three different viewing geometries with stereo angles (angle between the spacecraft at two viewing positions as seen from the surface) between 15 deg. and 40 deg.
- Both incidence and emission angles shall be between 10 deg. and 65 deg.
- Phase angle shall be > 10 deg.
- Solar incidence angle between observations of the same stereo pair shall not exceed 10 deg.

Assuming a distance of 1 km, approximately 10 images are needed per geometry, for a total of 30 images. Assuming uncompressed full frames, the corresponding data volume is 440 Mbits. To be done during close flybys in DCP3 or extended mission.

D3: For the purpose of volume estimation to 17 % accuracy, a closed shape model shall be obtained with an accuracy of 2 m in height and less than 5 m in spatial resolution with respect to the centre of mass. Data from AFC may be combined with those of other instruments. The geometrical requirements for the shape model are as follows:

- Coverage of the full illuminated surface from at least three different viewing geometries with stereo angles (angle between the spacecraft at two viewing positions as seen from the surface) between 15 deg. and 40 deg.
- Both incidence and emission angles shall be between 10 deg. and 65 deg.
- Phase angle shall be > 10 deg.
- Solar incidence angle between observations of the same stereo pair shall not exceed 10 deg.

To get full geometrical coverage, it is assumed that Didymoon shall be imaged every 30 deg. in longitude, from five equatorial and mid-latitudes, and from both poles. This is a total of 62 images, corresponding to 910 Mbits. As Didymoon does not fill the field of view, it is assumed that doing this once will provide enough images of the surface from difference viewing geometries.

It is recommended to perform this observation first during ECP when both Didymos and Didymoon are in the field of view, as then it provides a shape model of both objects.

D4: Imaging of the surface of Didymoon in all filters at a resolution of 0.5m/pixel. Imaging of the crater at a resolution of 10 cm/pixel in all filters. While the full spectral measurement will be done by APEX/ASPECT, the accuracy of the results in the visible will be improved through cross- calibration with AFC, as the latter can be calibrated more accurately than ASPECT.

For complete geometry, the measurements are those of D2 and D3, but in 7 colour filters. Without compression, this corresponds to 9450 Mbits. Consider to do those observations simultaneously with D2 and D3.

D5: Imaging a 50 m radius area around the crater with a resolution of 25 cm/pixel, corresponding to a distance of 2.5 km is a minimum requirement. Goal is global imaging at a resolution of 10 cm/pixel (1 km distance from Didymoon) Intermediate phase angles (40 – 80 deg.) are ideal as they allow identifying small objects through their shadows. Data from AFC may be combined with those of other instruments.

Data volume corresponds to D2. There is some overlap, although somewhat different geometry may be desirable. For the moment we assume same data volume as D2 without overlap. This is rather conservative.

D6: There are several requirements on the determination of dynamical parameters:

- Semimajor axis of the orbit to 5 m accuracy: The accuracy of imaging from a distance of e.g. 10 km would be 1m. However, there may be some uncertainty of the position of the centre of mass of the secondary. On the other hand, the common centre of mass will be accurately determined by the mass measurement (D1). Therefore the semimajor axis of the orbit shall be determined to an accuracy of 5 m.
- Eccentricity: With the image resolution of 0.1 % of the distance between the asteroids, eccentricity shall be determined to an accuracy of 0.001. As it is the variation of the distance that determines eccentricity, it is not strongly affected by the uncertainty in the centre of mass of the primary. However, the shape model of Didymoon may be critical here, as the accuracy of the shape model is expected to be of the same order (~1 m) as the linear accuracy required for the determination of eccentricity.
- Spin period of Didymoon to 1 % accuracy: The most accurate way of measuring the spin period may be to measure its deviation (if any) from its well known orbital period, by determining the change in the longitude that faces Didymos. Librations shall be determined through observations of landmarks on Didymoon close to the point facing Didymos. Those observations are required over ~10 (TBC) orbital periods.
- Spin pole directions of Didymos and Didymoon to 1 deg accuracy: Those can be derived from the motion of landmarks when the spacecraft position is known. In practice, they can be considered a by-product of shape model generation.
- Determination of the orbit pole of Didymoon to 1 deg accuracy: Regular imaging of both objects for a full orbit of Didymoon with known spacecraft position. This may be supplemented with measurement of eclipse timing.
- To find evidence for non-regular rotation of Didymoon, like spin precession, it should be continuously monitored, with at least three images per orbit, separated by at least two hours.

  Data volume: 30 images per Didyoon orbit from different each HERA arcs (so 4x30 images in ECP, and DCP1). Total of 1761 Mbit

D9: To detect weathering effects, measure the colour of Didymos in all colour filters to an accuracy of 2 %. The required pixel scale is 1m, corresponding to a resolution of 2m.

Data volume per filter is the same as D3, but this time targeting Didymos. Total of 6370 Mbit. If needed, it can be discussed if we can compromise on spatial resolution by binning 2 x 2 pixels or doing this in ECP.

5.2 Thermal InfraRed Instrument (TIR)

A Thermal Infrared Imager in the range 8 – 14 µm will be part of the Hera mission. Different designs are currently being evaluated, some of them containing several spectral channels. The measurements required by TIR to meet the deflection requirements are:

D4: If it provides spectral information, TIR will contribute to the spectral identification of Didymoon by measuring a low resolution spectrum of the 10 µm region. Comparison of the overall spectrum with that of the crater may allow to distinguish effects of space weathering.

D5: The minimum requirement is to discriminate between bare rock and rough surfaces. This requires the measurement of the temperature distribution over the surface from a single observation geometry for a rough estimate of thermal inertia. To achieve this objective, TIR shall be able to measure temperatures between 200 K and 450 K with an accuracy of 5 K. Goal is to derive the thermal inertia at a spatial resolution of a few metres through observations at a range of local times and phase angles**.**

For data volume considerations, we assume that TIR rides along with AFC on D2, D3, D5, and D9.
D2: 113 Mbits (1024 *768 pixels * 12 bits /pixel * 4 images per flyby * 3 flybys)
D3: 62 images, corresponding to 585 Mbits
D5: 113 Mbits (same as D2)
D9: Same as D3 (585 Mbits), as there are no filters.

D9: The same requirements as for D4 apply. A spatial resolution of 10 m is required to distinguish between different surface regions on Didymos.

5.3 Planetary Altimeter (PALT)

The Planetary ALTimeter (PALT) is a lidar experiment that determines the distance to the asteroids by measuring the time of flight of a laser beam at 1.5 µm wavelength with a footprint of 2.8 mrad. The accuracy of the distance measurement is 0.5 m.
The main science objectives of the laser altimeter PALT are to measure the shape of both objects in the Didymos system. The laser altimeter will also contribute to determining the mass of Didymoon.

The measurements required by PALT to meet the deflection requirements are:

D1: PALT will contribute to the mass determination by determining the distance between Hera and Didymos, allowing to scale the imaging observations and providing additional information about landmark positions. During the mass determination, PALT shall be operated in parallel with AFC and TIR.

D3: At very close distance from Didymos (<2 km), PALT will contribute to the determination of the shape model and therefore volume by measuring the distance between Hera and surface elements on Didymoon.

D6: Whenever Hera is sufficiently close to Didymos for PALT to operate, observations by AFC and TIR shall be complemented by distance measurements with PALT.

The data rate of PARLT at maximum observing frequency (1h0 Hz) is about 1 kbit/sec. It is assumed that PALT will ride along with that data rate, starting in DCP1. The instrument may be tried out during ECP, but the corresponding data volume is negligible, so we count PALT from DCP 1 on.

5.4 Radio Science Experiment (RSE)

Radio Science provides a method of measuring the mass of Didymoon that complements the determination by imaging.

D1: For a mass determination with Radio science, a close flyby with a closest approach distance of less than 2 km is required. The flyby velocity should be not more than twice the escape velocity from the Didymos system. The delta-V imparted by the flyby shall be oriented as close as possible to the Earth/anti-Earth direction.

5.5 BiStatic Radar Experiment

The BiStatic Radar Experiment measures the S/C communication signal scattered by asteroid regolith accessing to access information on the surface roughness and on the texture and composition of the first decimetres of this regolith.

D4: To characterize the surface roughness and the texture and composition of the first decimeters of this regolith with BSRE, two measurements configuration could be used:
- The backward configuration (better) with Didymoon close to the anti-Earth direction by regard to the S/C, and the S/C main antenna tracking Didymoon. A S/C distance in the range of 10km would allow a global characterization of the moonlet. A few dedicated sequences at lower distance (3 km TBC) would allow better characterization of DART impact area.

- The forward scattering (less optimal) with the Didymain masking the direct path from the SC to Earth and the main antenna tracking Didymoon surface.

D5: idem. Joint measurement with D4.

5.6 Asteroid Prospection Explorer (APEX) Cubesat

The Asteroid Prospection Explorer will be released from Hera from a distance of about 10 km. It will first be injected into an orbit at a distance of approximately 4 km from Didymos, and later move into the L4 or L5 Lagrange point within the Didymos system (on the orbit of Didymoon around Didymos). At the end of its mission, APEX is foreseen to land on Didymoon.
APEX will carry the ASPECT visible and near-IR imaging spectrometer, a Secondary Ion Mass Analyzer (SIMA) and a magnetometer (MAG).

Its contribution to the deflection objectives are as follows:

D1: 1) ASPECT observations of Didymos may measure the mass of Didymoon through the wobble motion of Didymos. The requirements on those observations are similar to the measurements of the AFC described in section 5.1. From 4 km distance, the resolution is about a factor of two below that of the AFC in the 10 km orbit. From L4 or L5, it is about a factor of two better.
2) Observation of the landing of APEX will provide constraints on the mass of Didymoon through measurement of the acceleration of APEX through its gravity.

D2: ASPECT will contribute to observations of the crater. While it will not reach the full required resolution (except maybe in the approach to landing), it will provide stereo information in combination with AFC images.

D3: ASPECT observations will contribute to shape model determination and volume determination.

D4: 1) ASPECT is the main instrument to provide spectral classification by measuring the spectrum of Didymoon from 0.5 to 2.5 μm with a spectral resolution of 50 nm and better. In addition, spectra of unweathered material in the DART impact crater will provide measurements of the meteoritic analogue of Didymoon.
2) ASPECT measurements are supplemented by investigation of the atomic composition of Didymoon by SIMA.

D5: ASPECT will measure the large end of the particle size distribution on Didymoon (resolution 25 cm from a distance of 500 m).

D6: ASPECT may contribute to the determination of dynamical parameters from observations of both asteroids.

D7: For the determination of surface strength, the AFC shall observe the landing or bouncing of the CubeSats, as well as the landing locations after the event. The observations of the event need to be of sufficient resolution to follow the CubeSats. Assuming that the marks on the surface are of a similar size of the CubeSats, they require afterwards to be images with a scale of at least 5 cm/pixel to be resolved.
Ranging capabilities to the Hera spacecraft with 1 m accuracy from 10 km distance will additionally be provided.

D8: The measurement of possible magnetization by MAG will contribute to the determination of the internal structure of Didymoon.

D9: ASPECT will identify unweathered material on the primary through its spectrum approaching that of unweathered material in the DART impact crater.

The cubesats got an assigned data volume of 2 Gbits each, distributed over DCP2, DCP3, and Extended mission. More detailed data volume modelling will be derived from the upcoming operations plan of the cubesats.

5.7 Juventas Cubesat

The Juventas cubesat will be released at a distance of approximately 10 km from Didymos. It will first move to self-stabilizing terminator orbits around the system, followed by close operations and attempted landing on Didymoon.

Juventas will carry a monostatic low frequency radar, a gravimeter and accelerometers.

The contribution of Juventas to the deflection objectives are as follows:

D1: Through its gravimeter and accelerometers, Juventas will directly measure the gravity and therefore estimate the mass of Didymoon.
In addition, observation of the landing of Juventas by the AFC will provide constraints on the mass of Didymoon through measurement of the acceleration of Juventas through its gravity.

D4: Measurements of the Juventas radar will constrain the porosity of Didymoon.

D5: The Juventas radar will constrain the presence of meter-sized and larger blocks in the surface and subsurface of Didymoon.

D7: For the determination of surface strength, the AFC shall observe the landing or bouncing of the CubeSats, as well as the landing locations after the event. The observations of the event need to be of sufficient resolution to follow the CubeSats. Assuming that the marks on the surface are of a similar size of the CubeSats, they require afterwards to be images with a scale of at least 5 cm/pixel to be resolved.
Juventas will carry accelerometers to allow measurement of the dynamics of the landing. Ranging capabilities to the Hera spacecraft with 1 m accuracy from 10 km distance will also be provided.

D8: The Juventas radar will measure the interior structure of Didymoon from a size scale of meters to the global scale. It will allow to distinguish between a monolithic body and a rubble pile, and determine the size of the building blocks of the asteroids in the size range it is sensitive to.

The cubesats got an assigned data volume of 2 Gbits each, distributed over DCP2, DCP3, and Extended mission. More detailed data volume modelling will be derived from the upcoming operations plan of the cubesats.

ANNEX 1. DATA VOLUME SUMMARY

	ECP (Mb/day)	DCP#1 (Mb/day)	DCP#2 (Mb/day)	DCP#3 (Mb/day)	ELP (Mb/day)	Total (Gb)
Duration (day)	*30*	*30*	*30*	*45*	*30*	*165*
AFC	*1 frame/30 min (32 h/day) 14 bit/pixel (no compression)*	*1 frame/h (ROSETTA) No windowing/no compression*	*No windowing/ no compression*	*No windowing/ no compression*	*No windowing/ no compression*	
Navigation	**469.8**	**234.9**	**234.9**	**234.9**	**234.9**	**45.8**
"Hot redundancy" 1 AFC for navigation 1 AFC for science	*D1: 2936 Mb D3: 910 Mb D6: 1761 Mb*	*D1: 2936 Mb D6: 1761 Mb D9: 8631 Mb*	*D4: 9450 Mb*	*D1: 2936 Mb D2: 440 Mb D5: 440 Mb*	*As DCP#3*	
AFC data volume	5607	13328	9450	3816	3816	36.0
Science	**186.9**	**444.3**	**315.0**	**84.8**	**127.2**	**36.0**
TIRI 1024 X 768 pixel 12 bit/pixel No filters	*585.105408*	*585.105408*	*0*	*226.492416*	*226.492416*	1.6
TIRI	**19.5**	**19.5**	**0.0**	**5.0**	**7.5**	**1.6**
PALT	*Out of range (TBC) HK only*	*16 h measurements*	*16 h measurements*	*16 h measurements*	*16 h measurements*	
Range	**0.0**	**7.2**	**7.2**	**7.2**	**7.2**	**1.0**
Cubesat	*HK only*		*16 h comms @ 200 kbit/s is too conservative*	*AFC + TIR + PALT???*		
ISL	**0.0**	**0.0**	**322.2**	**97.0**	**141.9**	**18.3**
TOTAL (per day)	**676.2**	**705.9**	**879.3**	**428.9**	**518.8**	
TOTAL SCIENCE DATA VOLUME						**102.7**