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HERA MISSION REQUIREMENTS DOCUMENT

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APPROVAL

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CHANGE LOG

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CHANGE RECORD

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Reason for change	Date	Pages	Paragraph(s)
	19/05/2021		-
Clarify that there is no ISL between the two cubesats		11	Section 3.2.2
Explanations on usage of global coverage and spatial resolution		12	Section 4
Change 1% accuracy in mass of Dimorphos from opportunity requirement to goal requirement			Tables 1 and 2

DISTRIBUTION

Name/Organisational Unit

1. SCOPE

This document defines the Mission Requirements applicable to the Hera mission. It further describes the measurement objectives by the different payload instruments in order to achieve them.

Hera is a planetary defence mission in ESA's Space Safety and Security program. Its primary mission goal is to characterize an asteroid in the 100-200 m size range, the range most relevant for planetary defence. For smaller objects, no deflection effort would be made, while larger objects have lower impact frequency with Earth. The target of Hera is the binary asteroid Didymos. The smaller component of the Didymos system, Dimorphos, will be impacted by NASA's Double Asteroid Redirection Test (DART) spacecraft four years before Hera's arrival. Both missions are mutually independent, however their value is increased when combined together. To take advantage of the added value of the combination of DART and Hera, the scientific communities involved in the two missions cooperate in the Asteroid Impact Deflection Assessment (AIDA) collaboration.

For Hera, we distinguish between core mission requirements and opportunity requirements. Core requirements are those determining asteroid properties that are critical for planetary defence. Opportunity requirements are those who either measure properties that are of some relevance for asteroid deflection missions, but their value is mostly scientific, or more accurate measurements of parameters that correspond to core requirements, but may require trajectories or additional measurements that are beyond the consolidated mission baseline.

Both core and opportunity requirements shall be treated as mandatory requirements in terms of system design, verification and validation. Partial compliance to opportunity requirements will be accepted on a case-by-case basis if the following is demonstrated:

- The fulfilment of the requirement leads to the need of change in the current baselined technologies

- The impact at system level leads to mission feasibility issues in terms of cost, schedule or performance
- The fulfilment of the requirement would jeopardize the 2024 launch opportunity

Within both categories (core and opportunity), we identify which measurements can be done independent of a successful DART impact, and which measurements require the DART impact and therefore take advantage of the synergy of the two missions. 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.

Being Hera a planetary defence mission, there are no pure scientific requirements. However, the measurements needed to cover asteroid science goals are mostly included in the measurements foreseen to fulfil the planetary defence objectives. Therefore, asteroid science will be achieved by the Hera mission as a by-product.

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.

[RD1] Didymos Reference Model (DRM), ESA-TECSP-AD-017258, V5.5, 03/03/2021

2.2. Acronyms

AFC	Asteroid Framing Camera(s)
AIDA	Asteroid Impact & Deflection Assessment
APE	Absolute Pointing Error
ASPECT	Asteroid SPECTral Imager
DART	Double Asteroid Redirection Test
DRM	Didymos Reference Model
DV	Data Volume
FOV	Field Of View
GNC	Guidance Navigation & Control
ISL	Inter Satellite Link
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
TIRI	Thermal InfraRed Imager
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 a 100m-class diameter asteroid, the secondary of binary asteroid 65803 Didymos (1996 GT) [RD1]. In the following, the name Didymos we will be used for both the binary system and for the primary. The name of the secondary is Dimorphos.

3. INTRODUCTION

3.1. Mission Overview

Two upcoming missions will provide the first demonstration and validation of asteroid deflection. First, NASA’s Double Asteroid Redirection Test (DART) will impact Dimorphos, the moon of asteroid Didymos. Then, ESA’s Hera inspector spacecraft will rendezvous the target asteroid. The scientific communities of the two missions cooperate in the AIDA collaboration through three common working groups.

An overview of the Hera mission is given in Figure 1. DART will be launched in 2021 or early 2022 and impact Dimorphos in September or October 2022. Hera will be launched in October 2024 and arrive at Didymos in January 2027. The early characterisation phase of Didymos will start from distances between 20 and 30 km to determine the shape and the gravity field. The detailed characterisation phase will be conducted from about 10-20 km distance. During this phase the CubeSats will be released. Very close flybys of Dimorphos are envisioned in the Close Observation Phase and Experimental Phase towards the end of the mission.

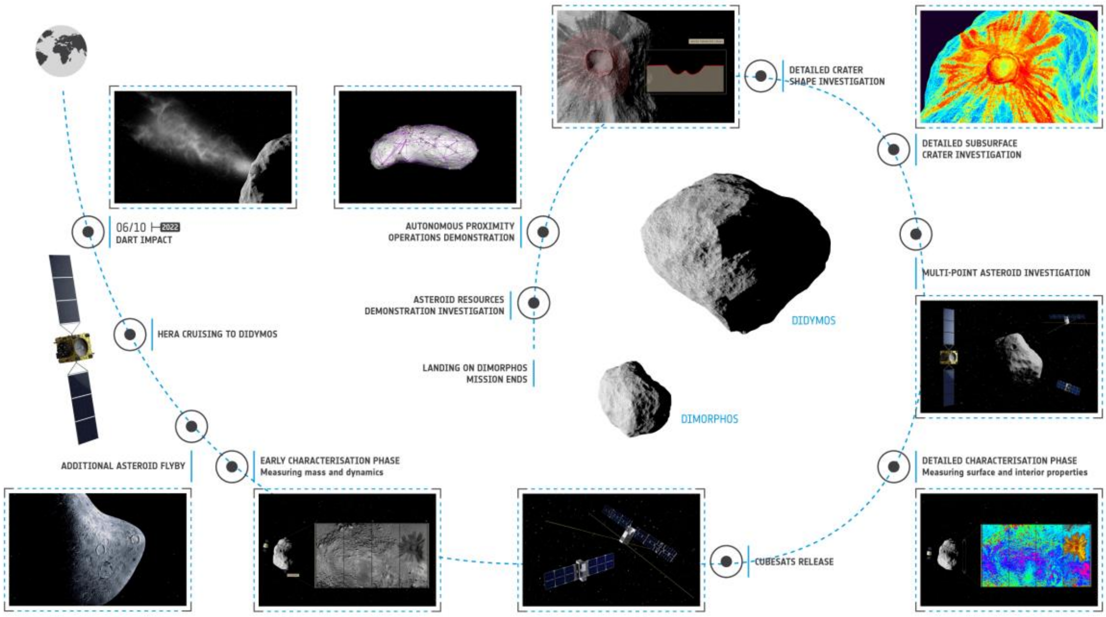

Figure 1 Hera mission overview

During very close flybys of Dimorphos (pericentre distance < 2km), it is foreseen to use both onboard cameras in parallel, one for Guidance, Navigation, and Control (GNC), the other for science images. Should this not be possible (e.g. failure of one of the cameras), GNC would have priority over science imaging.

The end-of-mission currently foresees an attempt to land the Hera spacecraft in the polar region of Didymos. The CubeSats will try landing on Dimorphos at the end of their 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 characterize an asteroid of the size range most important for deflection. DART and Hera together will allow to quantify the deflection and to enable the application of the results to other asteroids, therefore fully validating the technique. This is critical information, a mandatory step, to be able to effectively deflect a hazardous asteroid should it be needed in the future.

3.2. Payload Overview

3.2.1. Core payload

The Hera spacecraft will carry two identical Asteroid Framing Cameras (AFC) as part of the spacecraft guidance, navigation and control (GNC) system. This 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. In addition, a Radio Science Experiment (RSE) will be performed using the spacecraft TT&C equipment.

3.2.2. Opportunity payload

The additional baseline payloads are:

- A Thermal Imager (TIRI)
- A ranging Lidar (Planetary ALTimeter, PALT)
- A visible spectral imager (Hyperscout-H)
- two free-flying 6U CubeSats

The first cubesat, Juventas, will be equipped with a monostatic radar as well as accelerometers and a gravimeter. The second cubesat, Milani, will carry the ASPECT visual and near-IR imaging spectrometer and a thermogravimeter. The gravity field determination as part of the RSE will be complemented by using the Inter-Satellite Link (ISL) between Hera and Juventas and between Hera and Milani.

4. HERA MISSION REQUIREMENTS

In this section we define the mission requirements. Section 4.1 discusses the core requirements, and section 4.2 the opportunity requirements. Section 4.3 lists the technology demonstrations Hera will perform.

In the following requirements, global coverage on Didymos or Dimorphos excludes permanently shadowed surface areas, as well as an area facing towards the other asteroid, which could be observed from in between the two asteroids only. The size of those areas depends on object shape and can be determined only after arrival at the asteroids.

When not stated otherwise, spatial resolution refers to the pixel scale of the imager used (normally AFC), e.g. a resolution requirement of 1m means the image scale on an AFC image shall be 1m/pixel or better.

4.1. Core Requirements for Planetary Deflection

In this section the core requirements are defined for Hera. The goal of the mission is to perform the characterisation of a 100m-class body as representative of the most hazardous class of asteroids. The target is Dimorphos, providing the unique opportunity to take advantage of the DART impact.

The following list of core requirements starts with those that can be achieved without a successful DART impact, followed by those that demonstrate the value of the AIDA cooperation by taking advantage of the DART impact having happened ~4 years before Hera arrival.

The core requirements are described in this section and summarized in Table 1.

1. Determination of the mass of Dimorphos

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).

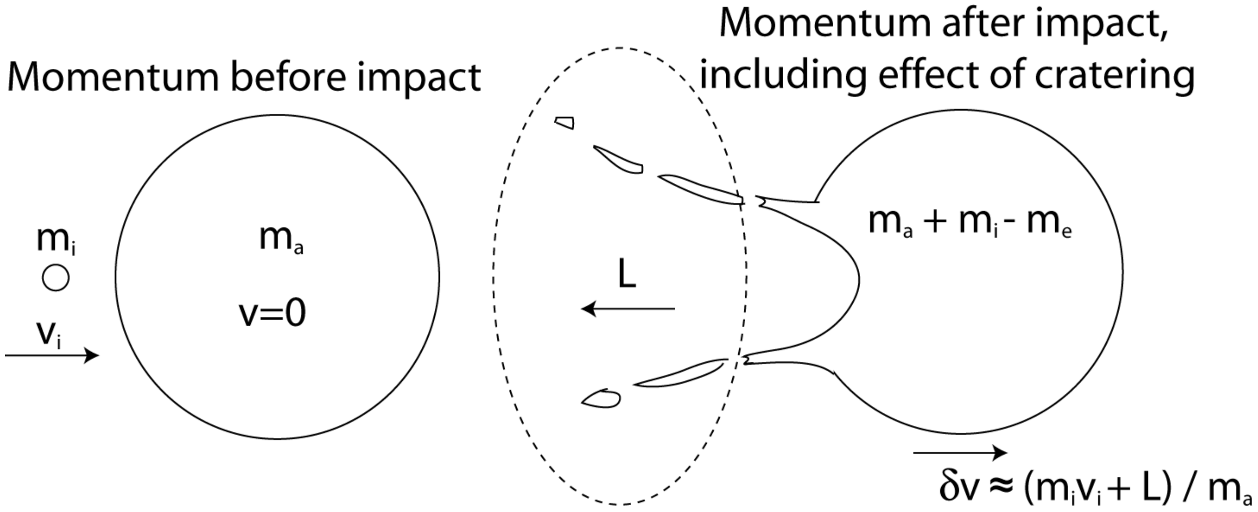

Figure 2: In a kinetic impact, the momentum transferred from the impactor to the asteroid is enhanced through the momentum of the impact ejecta.

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 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 Dimorphos, the only missing quantity is the mass of Dimorphos.

In case there is no successful DART impact, the mass of Dimorphos will still be measured, however the detailed objective will be different. Firstly, the capability to measure the mass of the small moon in a close binary system at a mass contrast $M_{Primary}/M_{Secondary}$ ~100 will be demonstrated, providing a valuable tool for future planetary defence or science missions. Secondly, the mass will allow to determine density, providing information if the interior structure of small, 100m-sized asteroids compared to larger objects of the same taxonomic type.

The first asteroid deflection requirement for the Hera mission is to measure the mass of Dimorphos with a relative error of at most 10 %, being considered sufficient to interpret the impact. The goal is an accuracy of 1 %, allowing a detailed comparison in density and internal structure between Didymos and Dimorphos.

2. Global properties of Dimorphos (size, global shape, volume, density, porosity)

To understand the properties of a small asteroid, first its global properties are required. The shape, combined with density and porosity may provide information about its formation and structure (e.g. rubble pile vs. monolith). Models of binary formation predict that Dimorphos was part of Didymos before the binary pair was created and is therefore the same taxonomic type (S-type). The assumption can be tested by measuring the colour or the spectrum of Dimorphos. As the composition of S-type asteroids is well known, measurement of the density will allow to estimate the porosity.

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). As Didymos is an S-type asteroid, with ordinary chondrites as the likely meteoritic analogue, the non-porous density may be estimated, and, when combined with the asteroid bulk density of Dimorphos measured by Hera, porosity can be estimated.

Porosity inside of surface rocks and boulders, if it exists, is estimated from their thermal inertia, derived by diurnal temperature profile, since heat conduction in rocks and boulders decreases with more internal pores or cracks.

Measurement with relative error of the density of 20%, the mass of 10 %, the linear dimensions of 6 % (global shape) and the volume of 17 % is considered adequate for the global characterisation of Dimorphos.

3. Size distribution of surface 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. Taking the DART impactor as a measure, a resolution of 50 cm is considered sufficient. An opportunity requirement is a resolution of 10 cm, ensuring the direct measurement of decimetre-sized boulders.. This can be provided through close imaging and/or radar and the bistatic radio science experiment. Those requirements based on DART will (over)fulfil the resolution requirements in cases where a larger impactor than DART is needed, i.e. they improve our capability of predicting the outcome of a kinetic impact even if DART is not impacting.

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).

In the case of a successful DART impact, one would ideally want to know the size distribution at the impact location before impact, as this may possibly 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.

4. 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 within 5 m, and the eccentricity to within 0.001. Accuracies of within 0.1 percent in the spin rate, and 1 deg. in the spin pole and orbit pole orientation are required.

Without DART impact, the high accuracy determination of dynamical parameters will provide information about the interior structure of Dimorphos (in case of non-principle axis rotation) and improve our understanding of the dynamics of a binary system of two small asteroids. The spin pole orientation of Didymos is needed for the mass determination.

For long term orbital and rotational changes called Yarkovsky and YORP effects, Hera will directly map the surface temperature to construct precise thermophysical models of Didymos and Dimorphos.

The following requirements are applicable only in case of a successful DART impact:

5. Shape and volume of the DART impact crater

The DART impact crater provides the unique opportunity to Hera to 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. As an absolute minimum, basic information of the crater structure can be obtained with about 10 linear resolution elements, corresponding to a resolution of 50 cm (core requirement).

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

6. Size distribution of excavated material

The material from the fresh DART impact crater will be unweathered and is therefore expected to be brighter and bluer than the overall surface material on Dimorphos. It can be identified by its albedo, colour, or spectrum. The requirements on spatial resolution are the same as for the size distribution of surface material (D3).

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Core Asteroid Investigation Requirements						
Req.	**Quantity**	**Requirement (relative or absolute error if not stated otherwise)**	***Goal***	**Prime instrument**	**Contributing instruments**	***DV Req. (see Sect. 5)***
D1	Mass of Dimorphos	10 %	1 %	AFC RSE	PALT Hyperscout-H ISL Cubesat landing ASPECT JUVENTAS/ accelerometer and gravimeter	*2936 Mbit*
D2	Global properties	Volume 17 % Linear scale 6 % Density 20 %	1 % in all parameters	AFC	PALT RSE Hyperscout-H ISL Cubesat landing ASPECT JUVENTAS/ accelerometer and radar TIRI	*911 Mbit*
D3	Size distribution of surface material	Coverage of a 100 m x 100 m area at 50 cm resolution	Global coverage At 50 cm resolution	*AFC*	TIRI BSRE ASPECT Hyperscout-H JUVENTAS/ radar	*440 Mbit3)*

D4	Dynamical properties of the Didymos system	Semimajor axis: 5 m Eccentricity: 0.001 Spin rate of Dimorphos: 0.1 % Spin pole orientations of Didymos and Dimorphos: 1 deg. Orbit pole: 1 deg.	1 m on semimajor axis, 0.1 degree On spin and orbit pole orientation	AFC RSE	Hyperscout-H ASPECT ISL (on HERA, Juventas and 2nd cubesat) PALT CubeSat landed operations (JUVENTAS/gravimeter and star tracker and/or sun sensor) TIRI	*1761 Mbits*
D5	Shape of the DART impact crater	50 cm resolution	-	AFC	Hyperscout-H ASPECT	*440 Mbit*
D6	Size distribution of excavated material	Coverage of a 100 m x 100 m area at 50 cm resolution	Global coverage 100m x 100m area at 50 cm resolution	AFC	TIRI Hyperscout-H BSRE ASPECT JUVENTAS/ radar	440 Mbit3)

Table 1 Core Asteroid Investigation Requirements.

4.2. Opportunity Requirements for Planetary Defence

7. Surface Strength

The impact strength as a relevant quantity for crater size vs. impactor size, mass, and velocity is determined through models and scaling laws from the known impactor properties and the Hera measurements of the crater. The strength derived this way is interesting to compare with actual strength measures of the asteroidal material. In particular, the impact strength is expected to be directly related to the tensile strength.

The Cubesats are going to land or bounce on the surface of Dimorphos at the end of their 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 Cubesats transferred into the surface, further constrains surface properties. The strength measurement will allow to distinguish between a hard or soft surface. Layering near the surface (layers of different strength) may also be detected.

8. Interior Structure of Dimorphos

For an asteroid at the size of Dimorphos, 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 Dimorphos on a scale of a few meters to a few tens of meters, relevant for a potential impact needed for the deflection of a hazardous asteroid.

The strength or solidity of rocks and boulders, the main constituents of asteroids, can be estimated from the thermal inertia, derived from diurnal temperature profiles of Didymos and Dimorphos.

9. Composition of Dimorphos

The porosity measurement (D2) determines porosity based on density and its S-type classification, providing the uncompressed density. Colour images will be taken to confirm the possible S-type classification.

An independent estimate of the taxonomic type by Hera would provide final proof of the correctness of that procedure. It 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 Dimorphos. 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.

The following requirement is applicable only in case of a successful DART impact:

10. Transport of impact ejecta from Dimorphos to Didymos

Part of the impact ejecta on Dimorphos may impact Didymos. This effect may contribute to the velocity change of Dimorphos and is therefore be considered as a secondary effect in the interpretation of the impact.

The ejecta transport cannot be measured directly, however, subsurface material from Dimorphos is not affected by space weather and will be brighter and bluer than the weathered surface material of Didymos. A colour or 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. If the surface grain size is changed with the ejecta, the ejecta sediments will be detected as the changes of surface temperature. 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.

Opportunity Asteroid Investigation Requirements						
Req.	**Quantity**	**Required accuracy**	***Goal***	**Prime instrument**	**Contributing instruments**	***DV Req.***
D3_o	Size distribution of surface material	100m x 100m area at 10 cm resolution	Global coverage	*AFC*	TIRI BSRE ASPECT Hyperscout-H JUVENTAS/ radar	*440 Mbit[3)]*
D7	Strength of near-surface material from cubesat	N/A	N/A	Cubesats	JUVENTAS/ accelerometers	

	landing/bouncing					
D8	Interior structure of Dimorphos	Rubble pile vs. monolithic structure	N/A	JUVENTAS/ radar ISL (on HERA, Juventas and 2nd cubesat)	RSE TIRI	
D9	Composition of Dimorphos	Requires spectra 0.45 – 0.9 µm with 0.05 µm resolution. Study of crater interior requires 0.5 m spatial resolution	Spectra 0.45 – 2.45 µm with 0.05 µm resolution for full spectral characterization. Additional information through thermal IR spectroscopy (10 µm feature)	ASPECT Hyperscout-H JUVENTAS/ radar	 TIRI VISTA	9450 Mbit2)
D5_0	Shape of the DART impact crater	10 cm resolution	5 cm resolution	AFC	Hyperscout-H ASPECT	*440 Mbit*
D6_0	*Size distribution of excavated material*	*Coverage of a 100 m x 100 m area at 10 cm resolution*	*Global coverage*	*AFC*	*TIRI* *Hyperscout-H* *BSRE* *ASPECT* *JUVENTAS/ radar*	440 Mbit3)
D10	*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*	*ASPECT* *Hyperscout-H*	*TIRI*	*6370 Mbit5)*

Table 2 Opportunity Asteroid Investigation Requirements.

4.3. Technology Demonstration Opportunities

The following mission requirements are supplementary to those of the asteroid deflection and contribute to demonstrate some technologies enabling new future deep-space mission concepts. They are intended as “opportunities” and their success shall not be required to achieve the mission core objectives.

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 the resources needed to operate cubesats in deep-space.

With this relay network all communications between ground and the cubesat will go 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 in deep space 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. Position knowledge errors can produce a wrong pointing and Didymos and/or the Dimorphos 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.

If the distance is larger than ~8.5 km, the entire primary asteroid will fit in the image of the camera and autonomous vision-based navigation can be performed without detailed knowledge of the shape or surface properties of Didymos.

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 estimate the position and velocity of the spacecraft 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, when Didymos is larger than the FOV (below ~8.5 km), different on-board image processing and navigation strategy are needed. This experiment shall demonstrate autonomous optical navigation under these conditions, effectively enabling safe low altitude fly-bys of Dimorphos.

In addition, the experiment shall demonstrate the capability to change the navigation target, either Didymos or Dimorphos, and acquire and maintain Dimorphos in the FOV at the closest distance. This change is critical to demonstrate the capability of pointing the AFC and rest of payloads to Dimorphos and acquire high resolution images.

The use of altimetry information cannot be assumed during this experiment to show robustness.

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

In order to perform safe fly-bys at very low altitudes with proper orientation of the payload, trajectory manoeuvres need to be performed without any ground feedback.

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 errors in the manoeuvres execution. This sequence of autonomous trajectory manoeuvres relies on improved knowledge of the spacecraft trajectory relative to both Didymain and Didymoon.

In order to achieve the required accuracy and reliability of the GNC system, the relative distance to the surface must be accurately estimated at all times. Thus, the use of the altimeter measurements in the navigation filter can be considered in addition to AFC image processing measurements.

This experiment shall demonstrate autonomous computation and execution of trajectory correction manoeuvres (TCM) for very low altitude flybys (down to 1 km) relative to Dimorphos, effectively reducing the deviation between the reference and the actually flown trajectory.

This experiment would allow acquiring high-resolution images of the crater produced by DART.

2.4. Sensor data-fusion for robust autonomous navigation

The capability to fly orbits behind the terminator (‘night’ side of the asteroid) or to track Dimorphos during periods of eclipse, requires the use of thermal infrared imagers due to the impossibility to image the asteroid in visual light.

This experiment shall demonstrate the benefits of autonomous navigation based on fusion of information from visual and thermal infrared imaging, complemented by slant range information from PALT when available

During very low altitude flybys, Hera will fly to the night side of Didymos shortly after the pericenter. During that part of the trajectory, only thermal infrared images can provide relevant navigation information.

2.5. Independent autonomous collision detection and avoidance

The capability to assess continuously the current distance to the asteroid and the minimum distance during the trajectory with algorithms completely independent from the nominal navigation chain is important to monitor the GNC subsystem and to detect any risk of collision in case of unforeseen errors. This capability is also relevant for other missions like rendezvous and capture of uncooperative satellites.

This experiment shall demonstrate the capability to assess the collision risk of the trajectory being flown by means of algorithms **different and independent** from the nominal on-board navigation chain. For robustness, an algorithm using only AFC images shall be considered.

In case of high collision risk, the autonomous FDIR 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	Absolute Pointing Error of the AFC boresight w.r.t. the COM of the target asteroid during proximity operations at distances equal or higher than 8.5 km shall be lower than 0.5 deg with 99.73% probability at 90% confidence level (mixed interpretation).NOTE: this APE will ensure AFC imaging the entire Didymain at 8.5 km distance..	*AFC*
T2.2	Autonomous visual based navigation for low altitude fly-bys	Absolute Pointing Error of the AFC boresight w.r.t. the COM of the Dimorphos during proximity operations at a distance between 8.5 km and 3.5 km to the target shall be better than 0.82 deg with 99.73% probability at 90% confidence level (mixed interpretation). NOTE: this APE will ensure AFC imaging the entire Dimorphos at 3.5 km distance (assuming a semimajor axis perpendicular to AFC boresight and elongation of 1.3)..	*AFC* *PALT (TBC)*
T2.3	Autonomous Guidance, Navigation and Control for very low altitude fly-bys	Position error lower than 10% of the real distance to the target with 99.73% probability at 90% confidence level (mixed interpretation).. Absolute Pointing Error of the AFC boresight w.r.t. the target feature during proximity operations at a distance between 3.5km and 1 km to the target feature shall be lower than 1.32 deg with 99.73% probability at 90% confidence level (mixed interpretation). NOTE: the position error is measured between the desired trajectory and the real trajectory.	*AFC* *PALT (TBC)*
T2.4	Sensor data-fusion for robust autonomous navigation	Better than the equivalent vision-based navigation solution.	*AFC* *TIRI (TBC)* *PALT (TBC)*

T2.5	*Independent autonomous collision detection and avoidance*	*Knowledge error of the relative distance to the Centre-Of-Mass of the target body (Didymain or Didymoon) lower than 10% of the real distance with 99.73% probability at 90% confidence level (mixed interpretation)..*	*AFC* *PALT (TBC)*

Table 3: 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. AFC will be used both for GNC and to perform scientific measurements. 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 Dimorphos, 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 Dimorphos's mass to within 10%. This will be done by measuring the motion of Didymos around the common centre of mass of Didymos and Dimorphos. 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). As the orbit arcs are 3-4 days long, this is not strictly achievable. Simulations under more realistic conditions are planned.
- 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 Dimorphos 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: For the purpose of volume estimation to within 17 %, 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 Dimorphos 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 Dimorphos 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 Dimorphos are in the field of view, as then it provides a shape model of both objects.

D3 and D6: Imaging a 50 m radius area around the crater with a resolution of 50 cm/pixel, corresponding to a distance of 5 km is a minimum requirement. The opportunity requirement is 10 cm/pixel, corresponding to a distance of 1 km. Goal is global imaging at a resolution of 10 cm/pixel. 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.

Assuming a distance of 1 km, approximately 10 images are needed per viewing position. For a good characterisation, three viewing positions are needed, 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.

D4: There are several requirements on the determination of dynamical parameters:

- Semimajor axis of the orbit within 5 m accuracy: The resolution of images 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 within 5 m. Preliminary simulations show that the semimajor axis requirement can be easily reached. Assuming 30 observations per Dimorphos orbit, randomly distributed, an accuracy to within 10^{-4} or 10 cm is reached within 1 day.
- Eccentricity: With the image resolution of 0.1 % of the distance between the asteroids, eccentricity shall be determined to within 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 Dimorphos may be critical here, as the accuracy of the shape model is expected to be of the same order (error ~1 m) as the linear accuracy required for the determination of eccentricity.

Preliminary simulations show that, for an assumed eccentricity of 0.01, it can be determined within a few days with a relative error below 1 %, or an absolute error below 10^{-4}.

- Spin period of Dimorphos to within 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 Dimorphos close to the point facing Didymos. Those observations are required over ~10 (TBC) orbital periods.
- Spin pole directions of Didymos and Dimorphos to within 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 Dimorphos to within 1 deg accuracy: Regular imaging of both objects for a full orbit of Dimorphos with known spacecraft position. This may be supplemented with measurement of eclipse timing.
- To find evidence for non-regular rotation of Dimorphos, 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 Dimorphos orbit from different positions on each HERA arc (so 4x30 images in ECP, and DCP1). Total of 1761 Mbit.

D5: As an opportunity requirement, 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 Dimorphos 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.

For the core requirement, the accuracy of 50 cm applies to the pixel resolution.

Data volume corresponds to D3/D6. There is some overlap, although somewhat different geometry may be desirable. For the moment we assume same data volume as D3/D6 without overlap. This is rather conservative.

5.2. Thermal InfraRed Imager (TIRI)

A Thermal Infrared Imager in the range 8 – 14 µm will be part of the Hera mission. The instrument is expected to provide spectral information through 6 filters.
The measurements required by TIRI to meet the deflection requirements are:

D3/D6: The minimum requirement is to discriminate between bare rock and rough surfaces. This requires the measurement of the temperature distribution over the surface over a full rotation 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**.**

D2: The minimum requirement is to discriminate each rock and boulder and track their diurnal temperature profiles to estimate thermal inertia of them. The temperature range and the spatial resolution is the same as those for **D3/D6**.

D4: Determine the global thermo-physical properties of the asteroid surface that contribute to the orbit/rotation evolution, in particular Yarkovsky and YORP effects. The measurements are the same as those for **D3/D6** to construct thermophysical model of Didymos and Dimorphos.

.

D8: Solidity of Dimorphos (and also Didymos) will be determined by the thermal inertia whether it is a monolithic rock or a loosely bound rubble-pile body. To achieve this purpose, one-rotation global thermal imaging is required. The necessary temperature range is the same as those for **D3/D6**, and the required spatial resolution of 10 m scale.

D9: Comparison of the overall spectrum with that of the crater may allow to distinguish effects of space weathering.

D10: TIRI will contribute to the spectral identification of Didymos by measuring a low resolution spectrum of the 10 µm region. 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 1 mrad (i.e. the diameter of the footprint is 10m at a distance of 10 mk). 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 Dimorphos.

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.

D2: PALT will contribute to the determination of the shape model and therefore volume by measuring the distance between Hera and surface elements on Dimorphos. In addition, PALT will measure the reflectance of Didymos and Dimorphos at the laser wavelength of 1.535 µm.

D4: Whenever Hera is sufficiently close to Didymos for PALT to operate, observations by AFC and RSE shall be complemented by distance measurements with PALT.

The data rate of PALT at maximum observing frequency (10 Hz design goal) is about 3 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. Furthermore, PALT provides to the On board computer, the following time tagged information: distance measurement, housekeeping information, energy of the detected signal (TBC).

5.4. Hyperscout-H

The Hyperscout series are miniaturized spectral imagers. The version for Hera will be equipped with a mosaic filter with TBD spectral elements in the rang 450 nm – 950 nm and a 4k x 2k (TBC) pixels CMOS detector, and a spatial scale of 1.35 m/pixel.

The contributions from Hyperscout-H to the mission requirements are as follows:

D1: Hyperscout-H observations of Didymos may contribute to measuring the mass of Dimorphos through the wobble motion of Didymos. The requirements on those observations are similar to the measurements of the AFC described in section 5.1. However, the resolution of Hyperscout is somewhat lower than that of AFC

D2: Hyperscout-H observations will contribute to shape model determination and volume determination. Although its spatial resolution is inferior to that of the AFC, due to its larger field of view it may provide additional views on Dimorphos while AFC is observing Didymos and the secondary is outside its field of view.

D3/D6: Hyperscout-H may measure the large end of the particle size distribution on Dimorphos. However, the minimum reachable size is larger than for AFC, so the main contribution of Hyperscout-H is further characterization of large blocks through colour information.

D4: Hyperscout-H may contribute to the determination of dynamical parameters from observations of both asteroids. Its larger field of view will allow to observe both asteroids when AFC sees only one of them.

D5: Hyperscout-H will contribute to observations of the crater, although its resolution is inferior to that of AFC.

D9: Hyperscout-H contributes to the spectral classification by measuring the visible spectrum of Dimorphos. In addition, spectra of unweathered material in the DART impact crater will provide information about the meteoritic analogue of Dimorphos. VISTA measurements will provide additional information about the composition of Dimorphos, in particular volatiles and organics.

D10: Hyperscout-H may contribute to the identification of unweathered material on the primary through its spectrum resembling that of unweathered material in the DART impact crater

5.5. Radio Science Experiment (RSE)

D1: Radio Science provides a method of measuring the mass of Dimorphos that complements the determination by imaging.
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.

D2: The porosity of Dimorphos is one of the parameters that is determined when the interior structure of Dimorphos is measured through the higher order gravity field (see **D9**).

D4: Doppler tracking through RSE provides the position and velocity of the spacecraft. Those parameters are required to be able to derive the dynamical properties of Dimorphos from optical observations. The accuracy of those measurements is enhanced when employing the ISL between Hera, Juventas, and Milani

D8: Determination of the higher moments of Dimorphos's gravity field will contribute to the determination of the interior structure. The accuracy of that measurement will be enhanced when the ISL between Hera, Juventas, and Milani is employed.

5.6. BiStatic Radar Experiment

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

D3/D6: To characterize the surface roughness and the texture and composition of the first decimeters of the regolith with BSRE, two measurements configuration could be used:

- The backward configuration (better) with Dimorphos close to the anti-Earth direction by regard to the S/C, and the S/C main antenna tracking Dimorphos. A S/C distance in the range of 10km from Dimorphos 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 Dimorphos surface.

D2: One of the parameters derived from the BSRE is the porosity of the (sub)surface layer. Joint measurement with **D3/D6**.

It is noted that, due to spacecraft constraints, the geometry requested for BSRE may be achievable only few times and for short time periods.

5.7. Juventas Cubesat

After its release from Hera, the Juventas cubesat will move to self-stabilizing terminator orbits around the system, followed by an attempted landing on Dimorphos.

Juventas will carry a monostatic low frequency radar (JuRa), a gravimeter (GRASS) and accelerometers and the InterSatellite Link system (ISL).

Juventas carries three primary science objectives and one secondary science objective based on its payload complement:
SO1: Characterise the gravity field of Dimorphos (D1/D2)
SO2: Characterise the internal structure of Dimorphos (D2/D8)
SO3: Characterise the surface properties of Dimorphos (D3/D5/D7/D9)
SO4 (Secondary): Determine the dynamical properties of Dimorphos (D6)

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

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

D2: Measurements of the Juventas radar will constrain the porosity of Dimorphos.
Observation of the landing of Juventas through its accelerometer measurements will give an indication of porosity. Operations from the surface of Dimorphos after landing with the gravimeter will give an indication of density

See section 5.4 for the contribution of Juventas to **D2** (mass, gravity and porosity) through radio science with the ISL.

D3/D6/D9: The Juventas radar will constrain the presence of meter-sized and larger blocks in the surface and subsurface of Dimorphos. In addition, it will measure the dielectric constant, which will constrain their composition.

D4: See Section 5.4 for the contribution of Juventas to **D4** through radio science with the ISL Additionally, surface operations of Juventas through the period of a Dimorphos orbit will contribute to the dynamical properties. The gravimeter will provide variation of local surface gravity and the spacecraft attitude sensors (star tracker / sun sensor) will provide variance of attitude over the orbit.

D7/D9: 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 Dimorphos 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.
See Section 5.4 for the contribution of Juventas to **D8** through radio science with the ISL

5.8. Milani Cubesat

The Milani cubesat will carry the ASPECT visible and near-IR imaging spectrometer, a thermogravimeter (VISTA), and the InterSatellite Link system (ISL). After a far observation phase from about 10-15 km and a close observation phase covering distances of ~2-10 km from the asteroids, Milani will attempt landing on Dimorphos.

Its contribution to the deflection objectives are as follows:

D1: ASPECT observations of Didymos may measure the mass of Dimorphos 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 5 km distance, the resolution is about the same as that of the AFC in the 10 km orbit.

D2: ASPECT observations will contribute to shape model determination and volume determination.

See section 5.4 for the contribution of Milani to D2 (porosity) through radio science with the ISL.

D3/D6: ASPECT will measure the large end of the particle size distribution on Dimorphos (resolution 10 cm/pixel from a distance of 500 m).

D4: ASPECT may contribute to the determination of dynamical parameters from observations of both asteroids.

See Section 5.4 for the contribution of Milani to D4 through radio science with the ISL.

D5: 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.

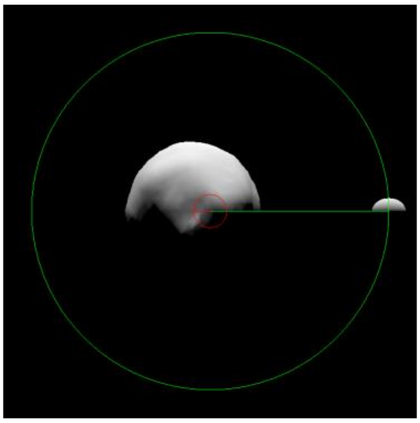
D8: See Section 5.4 for the contribution of Milani to D8 through radio science with the ISL

D9: ASPECT is the main instrument to provide spectral classification by measuring the spectrum of Dimorphos 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 Dimorphos.

D10: 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.

6. ANNEX 1. DETERMINING THE MASS OF DIDYMOS' SECONDARY THROUGH VISUAL IMAGING OF THE PRIMARY'S WOBBLE BY THE HERA SPACECRAFT



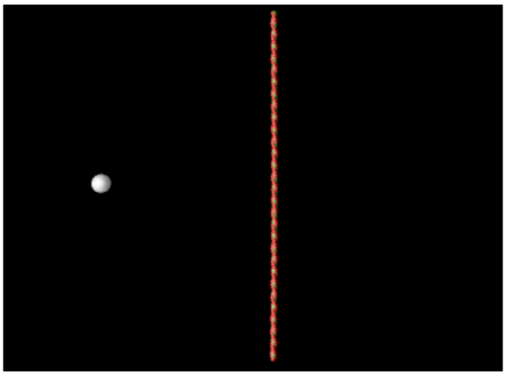
The ratio of the radii equals the inverse ratio of the masses, thus if the mass of the primary and the orbit radius of the secondary are known, the mass of the secondary is determined by the orbit radius of the primary, that is, the "wobble" of the primary.

The estimation of the wobble from landmark imagery is a two-step process. In the first step, from landmark pixel locations in images, the following are simultaneously estimated:

- landmark positions in some body fixed frame,
- asteroid orientations at all image acquisition times, and
- spacecraft positions relative to the asteroid at all image acquisition times.

This is in fact a standard procedure of optical navigation and it has routinely been performed on small body missions.

The spacecraft trajectory is estimated relatively to the primary, thus it actually comprises the wobble, see figure below.



True spacecraft trajectory (green line) and reconstructed trajectory relative to the (wobbling) primary (red dots).

The extraction of the wobble from the reconstructed trajectory is facilitated by the fact that its period (the orbital period of the secondary) is known as well as its direction (opposite to the secondary's direction). Therefore:

1. the trajectory can be smoothened with the wobble period and subtracted that from the original.
2. the result can be projected onto the wobble direction.
3. the mean is taken over all image acquisition times.

Monte Carlo simulations for various scenarios have shown that under reasonably conservative assumptions, the wobble radius can be estimated with an accuracy of about 3.5 %.