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# Ejecta evolutions and fates from the AIDA impact on the secondary of the binary asteroid Didymos: a NEOShield-2 project contribution

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## Abstract

The Asteroid Impact & Delfection Assessment mission is a project composed of two components: the European (ESA) Asteroid Impact Mission (AIM) and the USA (NASA) Double Asteroid Redirection Test (DART) mission. The objectives of AIDA are: (1) to perform a test of asteroid deflection using DART, and (2) with AIM, to investigate the binary near-Earth asteroid Didymos, in particular its secondary and target of DART, called hereafter Didymoon, and to observe the impact outcome of DART using both the main spacecraft and a Cubesat [1]. In order to determine the safest position for the AIM spacecraft to observe the DART impact and to better understand the evolutions and fate of ejecta produced by such an impact, we have developed a model that computes the evolutions of ejecta in the Didymos system, including the gravitational perturbations of the system, the solar radiation pressure, and the solar tides [2]. We have then performed a study showing how the ejecta evolutions and fate depend on the launching speed and location on Didymoon.

## 1. Introduction

One of the purposes of the Asteroid Impact & Deflection Assessment (AIDA) space project is to understand the post-dynamics of the ejecta cloud produced by a hypervelocity impact on the secondary of the binary near-Earth asteroid (65803) Didymos. In a preliminary work also supported by the NEOShield-2 project funded by the European Commission (H2020 program), a two-stage method to track the motion of arbitrary individual ejected particles was developed and applied to a full-scale simulation of the ejecta cloud in the Didymos system [2]. In a second work, using this method, we have then performed systematic simulations over a wide parameter space, and the results reveal several global features of the ejecta fate distribution. In particular, a grid search of launching sites of ejecta was defined over the globe of Didymoon, and considering a wide range of possible ejection speeds, we determined the dependency of ejecta fate on launching sites and speeds. This range allows us to track all the complex cases that include different types of dynamical fates, such as a collision with one of the binary components or the escape from the region of influence of the system.

## 2. Results

25 groups of simulations in total were performed to sweep the parameter space and to analyse the dependencies of the ejecta fate on ($\lambda$, $\phi$) and $v_l$, where $\lambda$ and $\phi$ denote the longitude and latitude of the launching site, respectively, and $v_l$ is the ejecta launching speed, which is supposed to follow the purely normal direction of the launching site. We then performed simulations of two-month long evolutions of the tracer particles. This time is supposed to be long enough for the interest of AIDA, and to enable a complete observation, i.e. most tracer particles may have either impacted a binary component, escaped the system or entered a period of relatively stable motion within the simulated time. We first consider a large size of ejecta, in order to neglect the solar radiation pressure and first check the role of purely gravitational perturbations.

Our results reveal the detailed proportions of the ejecta that are either orbiting, escaping or re-accreting on the primary/secondary before the final simulation time, as a function of the ejection speed and launching site, which allows us to explore the global characteristics of the ejecta dynamical fates (Fig. 1; [3]). Two major mechanisms are found to be working broadly during the post-ejection evolution of the ejecta cloud: 1) ejecta on mean-motion resonance orbits with Didymoon produce long-term quasi-periodic re-accretion peaks over at least a couple of weeks after the projectile impact, 2) ejecta on non-resonant orbits produce a rapid re-accretion peak that is not recurrent; this is because ejecta on such orbits that do not experience a collision during their first encounter with a binary component leave the system. The slingshot effect occurs in both mechanisms, which is a source of chaotic motion as ejecta with similar initial conditions can then have very different fates. Moreover, a vacuum of ejecta is noticed to emerge around the mid-latitude zone of the celestial sphere in a period posterior to the impact.

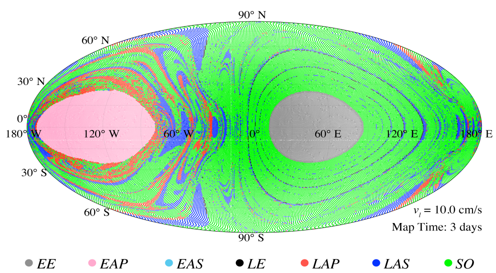


Figure 1: Dynamical fate of ejecta from Didymoon's surface. The solar radiation pressure is neglected. The example map shows the distribution of the 7 types of dynamical fates pictured against the launching sites of the sampled particles, each for a unique ejection speed of 10.0 cm/s. The primary of Didymos is in the direction of the left of the image. The different colors correspond to the 7 different fates: Early Escape (EE), Early Accretion on the Primary (EAP) or Secondary (EAS), Late Escape (LE), Late Accretion on the Primary (LAP) or Secondary (LAS), Surviving Orbit (SO).

We then performed full-scale simulations of the ejecta cloud released from 6 hypothetical impact sites and assuming two types of material of the subsurface, combining a power-law size distribution and a scaling-law crater ejection model. Results of these simulations, as well as the role of the solar radiation pressure, the re-impact speeds of the ejecta that fall back on the primary or secondary and other results of this extensive investigation will be shown at the conference. Our model can be applied to other binary or individual asteroids and impact scenarios.

## Acknowledgments

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# The Asteroid Impact Mission – Deflection Demonstration (AIM-D$^2$)

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## Abstract

The Asteroid Impact Mission (AIM) is ESA's contribution to the international Asteroid Impact Deflection Assessment (AIDA) cooperation, targeting the demonstration of deflection of a hazardous near-earth asteroid. AIM will also be the first in-depth investigation of a binary asteroid and make measurements that are relevant for the preparation of asteroid resource utilisation. AIM is foreseen to rendezvous with the binary near-Earth asteroid (65803) Didymos and to observe the system before, during, and after the impact of NASA's Double Asteroid Redirection Test (DART) spacecraft. Here we describe the observations to be done by the simplified version Asteroid Impact Mission – Deflection Demonstration (AIM-D$^2$) and show that most of the original AIM objectives can still be achieved.

## 1. Introduction

The Asteroid Impact Mission (AIM) is a small mission of opportunity whose objectives are to investigate a binary asteroid, to observe the outcome of a kinetic impactor test and thus, to provide extremely valuable information for mitigation, mining and science purposes [1]. It is part of the Asteroid Impact & Deflection Assessment (AIDA) mission, in which the second component is the NASA Double Asteroid Redirection Test (DART) mission, which aims to send an artificial projectile to perform an asteroid deflection test and to observe the outcome from ground-based observatories [2] as well as from AIM. AIDA will thus be the first test ever to use a kinetic impactor to detect an asteroid. The AIM/AIDA target is the binary Near-Earth Asteroid (NEA) (65803) Didymos (1996 GT), in particular the secondary component and target of the DART mission, called hereafter Didymoon. The original AIM design and objectives were studied during a Phase A/B1 that took place from March 2015 to August 2016 at ESA, however the mission did not receive full funding at ESA's ministerial conference in Dec. 2016. Here we discuss a simplified version of the mission, called AIM-D2 for AIM-Deflection Demonstration, which keeps the main mission objectives and is capable of providing crucial data for the interpretation of the DART impact. This modified mission concept provides the opportunity to reduce risk and cost by simplifying the spacecraft design and operational concept.

## 2. AIM-D$^2$ firsts

The mission will provide for the first time data from a new world, i.e., a binary asteroid and the smallest asteroid ever visited. In effect, the secondary is only 163 ± 18 meters in diameter. In addition, AIM-D2 will also carry, deploy and communicate with an interplanetary Cubesat, for the first time, which will also perform in-situ spectral observations. The satellite and its Cubesat will also observe for the first time a kinetic impactor deflection test and improve drastically our understanding of the impact process at asteroid scale, which will serve for the extrapolation to other cases, with many important implications on Solar System science.

## 3. AIM-D$^2$ payload

The AIM-D$^2$ mission profile and spacecraft are similar to those of the original AIM mission [1]. Spacecraft interfaces could be simplified and the mass reduced by down-selecting the payload to the most essential items:

- AIM-D$^2$ Framing camera. This is a flight spare of the DAWN framing cameras [3] and will be used for science imaging and Guidance, Navigation, and Control. The image scale is ~1m/pixel from a distance of 10 km.

- Asteroid SPECTral imaging (ASPECT) cubesat. This is a 3 U cubesat that will carry a Fabry-Perot spectrometer, working as a spectral imager from 0.5 µm to 1.6 µm and as a point spectrometer from 1.6 µm to 2.5 µm.

- Radio Science Experiment (RSE). Radio science makes use of existing hardware on the spacecraft to measure the gravity field of Didymos

## 4. AIM-D$^2$ relevance for mitigation of an asteroid impact

Although the probability of an asteroid impact on Earth during the coming years is low, the potential consequences to our society could be very severe. Small bodies are continually colliding with Earth, however, the vast majority of these objects are very small (below 10 m in size) and pose no threat to human activity. Larger impacts (1 km or more) occur far less often but, when they do occur, they can lead to a major natural catastrophe. Fortunately more than 90% of the asteroid population with diameter of 1 km or larger is known and poses no risk. On the intermediate size (100-500 m range), damage can still be of regional scale (a country or a continent) and we only know a small fraction of these objects while their impact frequency becomes high enough (centuries to millenia, i.e., within the duration of a civilization) that we must study how to protect ourselves from the threat they pose. Indeed, the impact of an asteroid is the only natural disaster we may be able to accurately predict and prevent. For this we need to (1) improve our knowledge of the geophysical properties of bodies in this size range, (2) test our ability to detect such a small asteroid, (3) complete the inventory of this population.

AIDA will allow us to address (1) and (2) for the first time. In terms of detection techniques, we will never know whether we are ready if no test is performed. AIM-D$^2$ images will thus tell us for the first time what a 163 m asteroid looks like (Didymoon) as well as what a 780 m body looks like (Didymos), with important information regarding the geophysical and surface properties of both bodies and therefore of a binary system. Moreover, DART will hit the smallest component, whose size is the most relevant one for mitigation purposes. With its geophysical characterization by AIM-D$^2$, AIDA will provide the first documented detection experiment. Such an experiment at actual asteroid scale is the only direct way to check our ability to use kinetic impactor techniques to detect a body of this size, and to validate/refine our numerical impact models that can then be used with higher confidence at such scales.

## 5. Science Return

The Science return of AIM-D$^2$ includes:

- First images of a binary asteroid in orbit.

- First images and in-situ compositional analysis of the smallest asteroid ever visited.

- Constraints for binary formation models.

- Understanding of physical/compositional properties and geophysical processes in low gravity, with implications for our understanding of small-body surface properties and their evolution.

- First documented impact experiment at asteroid scale, orders of magnitude beyond the scale accessible in laboratory.

- Validation of numerical simulations of hyper-velocity impacts that are used in planetary science (planet and satellite formation, impact cratering and surface ages, asteroid belt evolution).

- Constraints for collisional evolution models of small-body populations and planetary formation.

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# Using passive seismology to study the sub-surface and internal structure of Didymoon

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## Abstract

As there is evidence to suggest that asteroids are seismically active, passive rather than active seismology could be performed thus simplifying the mission design. Here we discuss the possibility of performing a passive seismic experiment on Didymoon; the secondary component of asteroid (65803) Didymos and the target of the joint ESA-NASA mission AIDA [1,2].

## 1. Introduction

Understanding the internal structure of an asteroid has important implications for interpreting its evolutionary history, for understanding its continuing geological evolution, and also for asteroid deflection and in-situ space resource utilisation. Given the strong evidence that asteroids are seismically active, an in-situ passive seismic experiment could provide information about the asteroid surface and interior properties. Didymos is characterised as an S-type object [3]. Following [4] we assume that Didymain (the primary) and Didymoon (the secondary) both have a bulk density of 2146 kg/m$^3$ [5]. The mean diameter of Didymain is 775 m, and the mean distance between the center of the primary and the centre of the secondary is 1180 m. Didymoon has a mean diameter of 163 m and a likely retrograde orbit around Didymain with a rotation period of 11.9 h and an eccentricity of, at most, 0.03 [5].

## 2. Didymoon seismicitiy

Although meteoroid impacts are rare on an asteroid as small as Didymoon, thermal cracks and tidal stresses are expected to produce seismic signals. Based on our detailed tidal stress calculations, it is very likely that quakes occur on and in Didymoon due to failure from tidal stress if Didymoon has an eccentric orbit. In both the homogeneous and the layered internal structure models that we have considered, failure is found to be reached first at the poles, and to occur close to the asteroid's surface (Fig. 1).

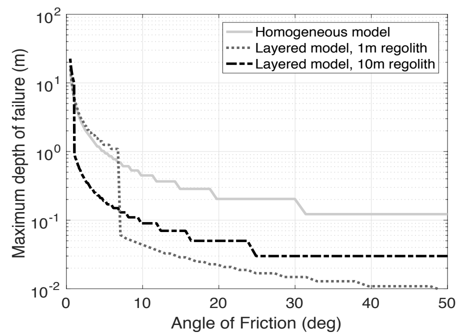


*Figure 1. Maximum depth of failure due to tidal stresses versus the angle of friction. Results are shown for the homogeneous model (light grey solid line), the layered model with a 1 m regolith (darker grey dotted line), and the layered model with a 10 m regolith (black dashed line). The regular discontinuities are due to the quantification of the body into sub-layers of equal size. The spatial resolution varies between the models, however, the depth of failure for large angles of friction always occurs between the upper two sub-layers in our models. See [6] for details.*

## 3. Seismic wave propagation in Didymoon

Our simulations of seismic wave propagation in a homogeneous Didymoon show that the seismic moment of even small meteoroid impacts can generate clearly observable body and surface waves that can travel several times around the tiny asteroid due to the low seismic attenuation. When a regolith layer is included, the seismic energy can become trapped in the regolith layer due to the strong impedance contrast at the regolith-core boundary. With macro-porosity (voids) included, the wavefield becomes more complex and the onsets of seismic waves become less clear due to increased scattering.

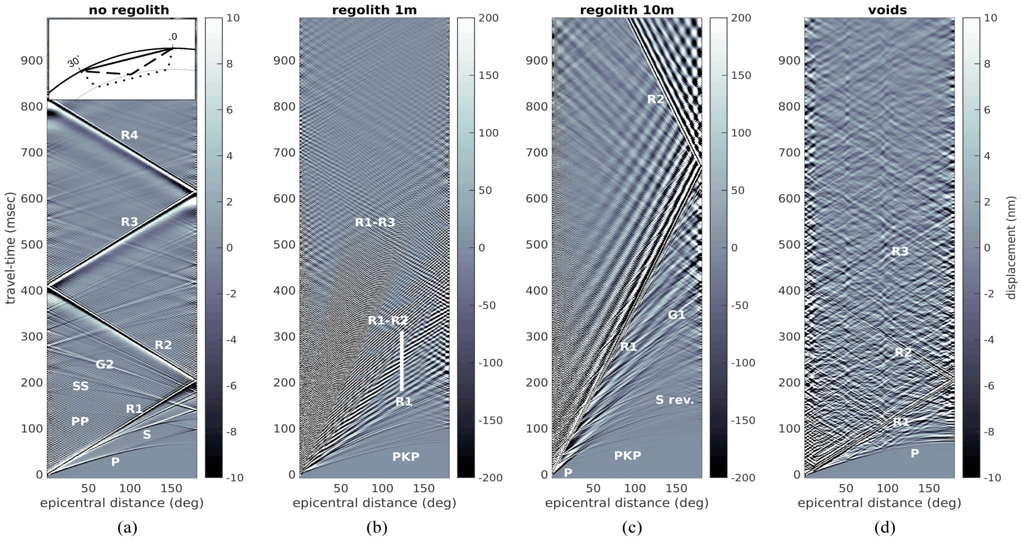


*Figure 2. Didymoon seismic wavefields - The vertical seismic wavefield for models with regolith thicknesses of a) 0, b) 1 and c) 10 m as well as d) an asteroid containing voids of 5 m average diameter. Marked phases include the body waves P and S, their multiples PP and SS, the core phase PKP, as well as the surface waves. See [6] for details.*

Nonetheless, the most prominent waves remain those traveling along the surface of the asteroid and those focusing in the antipodal point of the seismic source (Fig. 2).

# 4. Determining the internal structure of Didymoon

Both the direct waves and signals in transmission, and the diffuse wave field can be exploited to study the sub-surface and internal structure of the asteroid using in-situ seismic instrumentation. Our simulations show the strong effect interior structure such as layering or random heterogeneities of length-scales between centimeters and meters have on the seismic amplitudes as well as the frequencies, and on the types of seismic phases that can be observed. If the first arrival is strong enough to be detected, it gives the average P wave velocity of the interior. The arrivals with the strongest amplitude, however, characterise the S wave properties of the uppermost layer. In the case where the asteroid can be simplified as an asteroid-core covered with a regolith layer, these measurements will allow the computation of seismic velocities as well as regolith thickness. Strong resonance frequencies or long coda will indicate either trapped waves or strong heterogeneity.

# 5. Conclusions

Although the science return will be enhanced by having multiple seismic stations, one single seismic station can already vastly improve our knowledge about the seismic environment and sub-surface structure of an asteroid. In addition to performing the first surface-based geophysical investigation of an asteroid, a seismic experiment on Didymoon could lead to very unexpected and exciting scientific discoveries.

# Acknowledgements

We gratefully acknowledge financial support from the French space agency (CNES), the European space agency (ESA), and the French national research agency (ANR).

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# Momentum Enhancement from Hypervelocity Crater Ejecta: Implications for the AIDA Target

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## Abstract

Porosities of asteroids range from 0 to >50%, with most >20%. Meteorites, which sample asteroids, have a similar range. Since porous targets react differently to hypervelocity cratering than non-porous targets, it is critical to measure the response of asteroid samples to impacts. We impacted 13 meteorite targets by 1/16" Al-spheres shot at 4.34 to 5.89 km/s at the NASA Ames Vertical Gun Range. Using high-speed video images we measured the recoil speed of each target and determined the momentum multiplication factor ($\beta$), the ratio between the recoil momentum of the target and the momentum of the impactor. For the meteorites $\beta$ decreased with increasing porosity, with $\beta$ = 3.37 for NWA 4502 (mean porosity 2.1%), 2.70 for NWA 869 (mean porosity 6.4%), and 1.49 for Saratov (porosity 15.6%), consistent with hydrocode modeling, but the highly porous pumice gave a higher value of ~2.2. These $\beta$ values are larger than results from hydrocode modeling for 5 km/s impacts into porous rock targets. Although little is known about the Asteroid Impact and Deflection Assessment (AIDA) target, the ~160 m moon of asteroid Didymos, the model porosity of Didymos itself is ~40%. If the Didymos moon has similar properties, our $\beta$ values for Saratov and terrestrial pumice likely provide the best starting point for modeling behavior of the target of the AIDA mission.

## 1. Introduction

The physical properties of meteorites are quite different from those of compact terrestrial rocks, whose properties are frequently used in modeling the behavior of the asteroids that are the parent bodies of the meteorites. For example, hypervelocity impact experiments by Flynn and Durda [1] demonstrated that it requires more than twice as much impactor kinetic energy per unit target mass to produce the equivalent disruption of an ordinary chondrite meteorite as it does for a terrestrial basalt target.

### 1.1 Momentum enhancement by ejecta

The momentum change of an asteroid in response to an impact cratering event has two components: 1) the direct transfer of momentum by the impacting projectile, and, 2) the recoil of the asteroid in response to the crater ejecta, which is directed in the half-plane away from the surface of the asteroid. The total momentum gain of the target is characterized by the momentum multiplication factor, $\beta$, which is the ratio of the change in momentum of the target to the pree-impact momentum of the impactor. If the only contribution to the momentum gain is the direct transfer by capture of the projectile, then $\beta$ is equal to 1. Any momentum transfer due to the crater ejecta increases the $\beta$ value, where $\beta$ - 1 is the increase in momentum due to the ejecta.

### 1.2 Importance of $\beta$ for kinetic deflection

Kinetic impactor deflection of an asteroid on a collision course with Earth was described in a 2007 NASA Report to United States Congress as "the most mature approach and could be used in some deflection/mitigation scenarios, especially for NEOs that consist of a single small, solid body." However, the value of $\beta$ is the major uncertainty associated with the use of kinetic impact to deflect hazardous asteroids, especially for porous target asteroids.

Hydrocode modeling indicates the momentum added by the crater ejecta can exceed that from direct momentum transfer by a factor of ten or more for hypervelocity impacts into non-porous rock targets, but there is a significant decrease in $\beta$ with increasing porosity or decreasing impactor speed. Modeling by Jutzi and Michel, in support of the proposed Asteroid Impact and Deflection Assessment (AIDA) mission, indicates both porosity and strength can have a large effect on $\beta$, with $\beta < 2$ for impactor speeds $\leqslant$15 km/s into moderately porous targets [2].

### 1.3 The AIDA target

The AIDA target is the 160 m diameter satellite orbiting asteroid Didymos. The mass and shape of the Didymos, indicate a bulk density of ~2.15 $g/cm^3$ and its reflection spectrum suggests Didymos is an S-type asteroid, the type sampled by ordinary chondrite meteorites. Using the mean grain density for ordinary chondrite meteorites, varying from 3.52 $g/cm^3$ for LL ordinary chondrites to 3.71$g/cm^3$ for H ordinary chondrites, we infer a model porosity for Didymos ranging from 39% to 42%. Very little is known about the composition or physical properties of the secondary, which is the AIDA target, but if the secondary is a fragment of Didymos, it likely has a similar composition and porosity.

## 2. Samples and Procedure

We conducted hypervelocity cratering experiments of 13 samples of three different chondritic meteorites spanning porosities from 2% to 16%, and 2 high porosity terrestrial pumice samples.

### 2.1 Samples

We conducted 5 cratering impacts of the minimally weathered (W1) and minimally shocked (S2) dry CV3 carbonaceous chondrite Northwest Africa (NWA) 4502, two samples of which had porosities of 1.2 and 3.0% with a mean porosity of 2.1%**.** NWA 4502 is an unusual CV3 carbonaceous chondrite in that it is at the lower end of the porosity range for this type of meteorite. We conducted 7 cratering impacts of the minimally weathered (W1) and moderately shocked (S3) Northwest Africa (NWA) 869 L3-6 ordinary chondrite, which had porosities ranging from 2.7% to 10.2% with a mean porosity of 6.4%. The porosity of NWA 869 is within the typical range for ordinary chondrites. We conducted one cratering impact of the L4 ordinary chondrite Saratov, a fall with minimal weathering and minimal shock (S2), with porosities of two similar samples of 15.2 and 16.1% and a mean porosity of 15.6%, making it one of the most porous ordinary chondrite meteorites. To further extend the range, we impacted two terrestrial pumice targets with ~70% porosity.

### 2.2 Procedure

We hung each meteorite target directly in front of a grid in the sample chamber of the NASA Ames Vertical Gun Range (AVGR). Each meteorite target was impacted by a 1/16" Al sphere shot at a speed ranging from 4.34 to 5.89 km/s. This speed range is comparable to the mean collision speed between asteroids in the main belt and similar to the impactor speed proposed for AIDA. We acquired image sequences using five high-speed video cameras, measured the recoil speed from these images, and determined $\beta$ for each impact.

## 3. Results and Conclusions

Four of the five cratering impacts into NWA 4502 targets produced $\beta$ values in the narrow range from 2.88 to 3.97, with a mean $\beta$ of 3.37 $\pm$ 0.5. One shot produced a remarkably different value of $\beta$ equal to 11.72, likely an impact into hydrous terrestrial weathering material rather than anhydrous meteorite material. All seven of the cratering impacts into NWA 869 targets produced $\beta$ values in the narrow range from 1.82 to 3.81, with a mean $\beta$ of 2.71 $\pm$ 0.6. The single Saratov cratering event produced a $\beta$ value of 1.49, and the two pumice impacts produced a $\beta$ of ~2.2. Our Saratov $\beta$ = 1.49 and pumice $\beta$ = 2.2, bracketing the porosity range expected for the moon of Didymos, are larger than results from hydrocode modeling for impacts into weak rocks, which gave $\beta$ values <1.2 for 10 km/s cratering events over this porosity range [3], and serve as a starting point for modeling the AIDA kinetic impact.

## Acknowledgements

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# The Remote Observing Working Group for the Asteroid Impact and Deflection Assessment (AIDA)

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## Abstract

The Asteroid Impact and Deflection Assessment (AIDA) mission concept is designed to conduct a kinetic impactor demonstration at the asteroid 65803 Didymos, launching in 2020 and impacting in 2022. Ground-based observations are an integral part of AIDA, as the deflection should be easily visible in lightcurve observations. The AIDA Remote Observations Working Group is conducting observations during the pre-impact apparitions and planning for the impact apparition.

## 1. Introduction

The Asteroid Impact & Deflection Assessment (AIDA) is a joint ESA-NASA mission concept currently under study [1,2]. AIDA has two components: the Double Asteroid Redirect Test (DART) is the US component designed to demonstrate a kinetic impactor, while the Asteroid Impact Mission (AIM) spacecraft is on station to do a thorough pre- and post-impact survey of the Didymos system.

Members of the DART and AIM Investigation teams have been organized into several joint and independent working groups, including groups addressing the dynamical and physical properties of the Didymos system, modeling the outcome of the impact and fate of the ejecta, proximity operations for AIM, and Earth-based observations of the Didymos system in preparation for, during, and after the 2022 impact. While there is overlap in subject matter and membership between the groups, we focus here on the activities of the Observing Working Group.

## 2. Purview of Working Group

The Observing Working Group has two overall goals. First, to characterize the Didymos system pre-impact. The interpretability of the impact outcomes are vastly improved as the characterization becomes more detailed. The presence of AIM is of great utility, but data in the pre-launch period provides additional constraints on variations due to "natural" dynamical conditions. Details of the binary orbit, system composition, and pole of the system are primary goals of this period, along with providing other necessary inputs to the other working groups for their efforts. The abstract by Richardson et al. in this volume [3] and a paper by Michel et al. [1] summarize the best current values for the basic properties of the Didymos system, including work by members of this working group.

## 3. The 2015 and 2017 Apparitions

The first work by the group was undertaken during the spring of 2015, before DART entered Phase A. During this period Didymos made an apparition reaching roughly V~20.5 in brightness, and our top priority was constraining which of two very different pole positions for the Didymos system was correct. Several telescopes in the 2-4m aperture range around the world attempted observations. While smaller telescopes were unable to reach the needed S/N on a short enough cadence, a spate of bad weather at stations with larger telescopes limited good data to an observing run by Moskovitz and Thirouin on the 4.3-m Discovery Channel Telescope at Lowell Observatory in April. An observed mutual event allowed the one pole position to be ruled out. Didymos is now thought to be a low-obliquity, retrograde rotator, similar to many other asteroid binary systems and consistent with expectations from a YORP-driven origin for the satellite.

We have also undertaken observing during the 2017 apparition, which occurred in the first half of the year. There were four goals for this apparition: 1) Confirming the preferred retrograde pole position, 2) Gathering data to allow BYORP-driven changes in the mutual orbit to potentially be determined by later observations [4], 3) Establishing whether or not the secondary is in synchronous rotation with the primary, 4) Constraining the inclination of the satellite orbit.

At this writing, observations of Didymos have been successfully made from telescopes in Arizona, Chile, Spain, and South Africa. Data reduction and analysis is underway, and an overview of results from the 2017 apparition will be presented along with an initial assessment of priorities for the 2019 apparition and a look toward the 2022 impact apparition.

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# Asteroid Spectral Imaging Mission (ASPECT) payload for AIM-D$^2$ spacecraft

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## Introduction

Asteroid Spectral Imaging Mission (ASPECT) is a part of the ESA-NASA AIDA (Asteroid Impact & Deflection Assessment) project. In 2016 it underwent preliminary design study and was down selected as the only COPIN payload (CubeSat Opportunity Payload) for European AIDA component AIM-D$^2$ (Asteroid Impact Mission – Deflection Demonstration). ASPECT is a 3U CubeSat with a visible – near infrared (VIS-NIR) spectral imager payload. The payload, avionics, and cold gas propulsion units occupy each 1U space. Its task is to characterize the surface composition of the DART (Double Asteroid Redirection Test) spacecraft impact target – the binary asteroid Didymos.

## ASPECT technical objectives

| ASPECT technical objectives | |
|---|---|
| **AT1** | Demonstration of CubeSat autonomous operations in deep space environment |
| **AT2** | Navigation in the vicinity of a binary asteroid |
| **AT3** | Demonstration of satellite survival during impact |
| **AT4** | Demonstration of joint spacecraft - CubeSat operations |
| **AT5** | Demonstration of spectral imaging of asteroid materials |

# ASPECT scientific objectives

| ASPECT scientific objectives and results | |
|---|---|
| **AS1** | Map the surface composition of the Didymos system |
| **Result** | Composition and homogeneity of the Didymos asteroid, changes as a result of DART impact |
| **Result** | Information on the origin and evolution of the Didymos binary system |
| **AS2** | Photometric observations and modeling of the Didymos system under varying phase angle and distance |
| **Result** | Surface particle size distribution and composition for Didymos II and Didymos I (simultaneous modeling of photometry and spectroscopy) |
| **AS3** | Evaluate space weathering effects on Didymos II by comparing mature and freshly exposed material |
| **Result** | Information on the surface processes on airless bodies due to their exposure to the interplanetary environment |
| **AS4** | Identify local shock effects on Didymos II based on spectral properties of crater interior |
| **Result** | Information on the processes related to impacts on small Solar System bodies |
| **AS5** | Observations of the plume produced by the DART impact |
| **Result** | Evolution and composition of the DART impact plume |
| **AS6** | Map global fallback ejecta on Didymos II and Didymos I |
| **Result** | Detailed global mapping of fallback ejecta on both Didymos I and Didymos II |

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# MASCOT2, a Lander to Characterize the Target of an Asteroid Kinetic Impactor Deflection Test (AIM) Mission

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## Abstract

In the course of the AIDA/AIM mission studies [1,2] a lander, MASCOT2, has been studied to be deployed on the moon of the binary Near-Earth Asteroid system, (65803) Didymos.
The AIDA technology demonstration mission, composed of a kinetic impactor, DART, and an observing spacecraft, AIM, has been designed to deliver vital data to determine the momentum transfer efficiency of the kinetic impact and key physical properties of the target asteroid. This will enable derivation of the impact response of the object as a function of its physical properties, a crucial quantitative point besides the qualitative proof that the asteroid has been deflected at all.
A landed asset on the target asteroid greatly supports analyzing its dynamical state, mass, geophysical properties, surface and subsurface structure. The lander's main instrument is a bistatic, low frequency radar (LFR) [3a,b] to sound the interior structure of the asteroid. It is supported by a camera (MasCAM) [4], a radiometer (MARA)[5], an accelerometer (DACC [9]), and, optionally regarding the science case, also a magnetometer (MasMAG)[6].

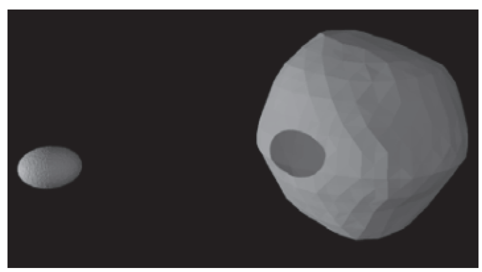

**Figure 1 Sketch of the Didymos binary system. Diameter of primary: (shape from radar) 775m±10%, diameter of secondary (shape assumed) 163m±10%, bulk density 2146 kg/m³, system semimajor axis 1180 m, orbital period and assumed rotation period of secondary 11.92h, rotation period of primary 2.26h.**

## 1. Design

MASCOT2 is a small (~13kg) long-lived lander, based on the design of MASCOT, which is part of the Hayabusa2 mission [7,8].

The lander will be deployed from the mother spacecraft in close vicinity to and soft-land on ”Didymoon”. After several bounces and likely re-location and self-righting by an internal mobility mechanism, it will operate for several months on the asteroid surface and provide detailed information about the asteroid’s interior, its landing site and key physical properties (Mechanical, thermal, structural) of the surface material.

*Deployables*
MASCOT2 will carry deployable LFR antennae (one for descent, one pair for on-surface ops) and a deployable photovoltaic top panel to enhance power generation once it has arrived at the optimal site for LFR operations. The deployment mechanisms have been studied in detail.

## 1.1 Payload

Besides the unit of LFR aboard the lander, a camera will provide high-resolution images of the landing area and of the regolith in particular, and accelerometers will interpret the bouncing dynamics. During the DART impact, MASCOT2 will possibly be able to detect the seismic shock with its accelerometers. Exact timing could give valuable information on the internal structure (from the velocity of p-waves). A radiometer will determine the thermal inertia at the landing site and, with MasCAM, track seasonal changes in the thermo-optical environment. MAG will investigate the interplanetary medium interacting with the binary system while on site on the moonlet as it orbits the primary, and the moonlet’s immediate environment during the descent, landing, and relocation hopping phases.

## 1.2 Operational concept

- CAM pictures and MARA measurements at each resting position
- MARA measurement at least during one whole Didymoon day
- Seven LFR measurements to scan the interior of the body
- The MASCOT2 bus will run continuously but also supports duty-cycled operation based on photovoltaic power available at the respective sites.
- Payloads can be used as heat dissipation source for thermal management
- System operation, payload operation and COM is possible during charging of battery
- System operation, payload operation and COM is possible during day or night
- System power consumption is averaged
- Data uplink MASCOT to AIM: 32 kbit/s similar to MASCOT
- Data Margin used: 20%

MASCOT2 will also serve as a technology demonstrator for asteroid landing and extended operations, powered by a solar generator mounted on deployable panels.

**Table 1 – operational phases. The duration of the phases is as follows: Orientation , up to 24h; DCP-2, DCP-3: each 60 moon days; impact, 30 moon days. 1 Moon day is ~11.9h.**

| Phase | LFR | CAM | MARA | DACC |
|---|---|---|---|---|
| SDL | 4 hours | 5 pictures | On | On |
| Orientation | | 14 pictures | On | |
| Relocation | 1 hour | 5 pictures | On | On |
| DCP-2 | 7 scans | 14 pictures | On | |
| Impact | Beacon | | On | |
| DCP-3 | 7 scans | 14 pictures | On | |

# 2. Deployment on Didymoon

Contrary to Keplerian deployment on a single body with a defined escape velocity, the deployment proposed here leads to a dynamical trapping of the lander on the surface despite impact velocities near classical $V_{esc}$ if only very little damping is present. Surface regolith properties cannot be reliably estimated prior to launch. Moreover, the presence of rocks at the surface, that present a hard surface, is likely. Thus, the damping should be considered as the damping of MASCOT2 on a very hard surface (such as concrete). This will give a coefficient of restitution of $\leq 0.6$ from the MASCOT2 structure alone.

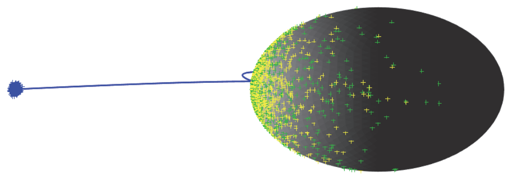

**Figure 2 Typical deployment through L2. COR = 0.60 (constant); Spring delta-v: possible range 3 to 15 cm/s, nominal 5 cm/s, speed accuracy +/-30% at 3sigma, angular accuracy +/-15° at 3sigma. Spacecraft: state vector known, at time of release, to +/-25 m and +/-5 mm/s , both 3sigma. Altitude of release fixed at 200m. Success rate is 100% of trajectory impacted. 99.9% of trajectories are eventually settled (i.e. 1 trajectory out of the 1000 bounced back). Yellow symbols: 1st touchdown. Green symbols: final rest positions**

It was found that robust deployment (meaning at 3sigma success probability) of MASCOT2 on Didymoon is possible even from an altitude of 200m (~150m over L2), provided these conditions are fulfilled, in order of importance:

1) the velocity dispersion (sum of spacecraft velocity dispersion and the one by the separation device) is low enough (order of < 1 cm/s at 3sigma)
2) the combined coefficient of restitution (surface and structural, worst case only structural) is low enough (< about 0.6), and
3) the positional dispersion at the point of release is low enough (order of dozens of m)

Then the resting ellipse dispersion on the surface is also small enough to virtually guarantee sufficient elevation of the Sun such that MASCOT2 can determine its attitude and can relocate (autonomously or commanded) to the desired operational site in about 2 hops.

A sizable libration (geometric libration for orbital eccentricity 0.16) is no hindrance to successful deployment.

## 3. Summary and Conclusions

MASCOT2 as a long-lived, hopping lander for the AIDA/AIM mission will significantly enhance our understanding of the beta factor for kinetic deflectors. This is accomplished by a bistatic radar determination of the interior structure of the target and, from its other experiments, an understanding of the surface mechanical and thermal properties. Detailed design studies have proven the Lander's feasibility; there is also a strong heritage from MASCOT flying on the Hayabusa2 mission (Ho et al., 2016). AIM funding has not been fully confirmed by ESA Member States during the ESA ministerial council meeting in 2016, yet the concept of MASCOT2 stays valid and we support flying MASCOT2 on a full AIM mission even if 2 years later than planned.

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# Post Deflection Impact Risk Analysis of the Double Asteroid Redirection Test (DART)

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## Abstract

Collisions between potentially hazardous near-Earth objects and our planet are among the few natural disasters that can be avoided by human intervention. Kinetic impact based asteroid orbit deflection counts among the most mature impact hazard mitigation concepts, but it is yet to be demonstrated successfully. NASA is currently investigating the DART (Double Asteroid Redirection Test, [1,2]) mission concept that is intended to close this knowledge gap. The DART spacecraft would target the moonlet of binary asteroid (65803) Didymos. This action would help to understand in more detail how a kinetic impact affects the moonlet's orbit in a relatively controlled environment.

Although the main goal of DART is to alter the orbit of the moonlet, the imparted momentum would also slightly affect the heliocentric orbit of the whole binary asteroid system. Due to the fact that the Didymos system has several close approaches with the Earth over the next centuries, small changes in Didymos' orbit are amplified over time. Hence, possible future encounter distances between Didymos and the Earth have to be monitored taking into account uncertainties involved in the deflection process. To this end, we conducted a post deflection impact risk assessment [3] for the most recent DART mission concept scenarios. In this contribution, we present the latest results of the post deflection impact risk assessment confirming that no planetary safety issues would arise in the foreseeable future, were DART to be flown.

## Acknowledgements

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# Double Asteroid Redirection Test (DART) element of AIDA mission

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## Abstract

The Asteroid Impact & Deflection Assessment (AIDA) mission will be the first space experiment to demonstrate asteroid impact hazard mitigation by using a kinetic impactor. AIDA is a joint ESA-NASA cooperative project, consisting of the NASA Double Asteroid Redirection Test (DART) kinetic impactor mission [1] and the ESA Asteroid Impact Mission (AIM) which is the asteroid rendezvous spacecraft [2]. The AIDA target is the near-Earth binary asteroid 65803 Didymos. During the Didymos close approach to Earth in October, 2022, the DART spacecraft will impact the Didymos secondary at 6 km/s and deflect its trajectory, changing the orbital period of the moon in the binary system. This change can be measured by Earth-based optical and radar observations.

The primary goals of AIDA are to (1) perform a full-scale demonstration of asteroid deflection by kinetic impact; (2) measure the resulting deflection; and (3) validate and improve models for momentum transfer in high-speed impacts on an asteroid. The combined DART and AIM missions will provide the first measurements of momentum transfer efficiency from a kinetic impact at full scale on an asteroid, where the impact conditions of the projectile are known, and physical properties of the target asteroid are also characterized.

The DART kinetic impactor baseline mission has changed from that given in [1]. DART will launch as a secondary payload to geosynchronous orbit and use the NASA Evolutionary Xenon Thruster (NEXT) ion propulsion system to spiral out from Earth orbit and transfer to Didymos. The Didymos impact will occur on Oct. 7, 2022, a few weeks later than in the baseline design of [1], but the incident momentum is significantly increased from that in [1], leading to a larger target deflection and a larger crater. If the incident momentum is transferred to the target, the binary orbit period is predicted to decrease by over 7 minutes, about 1% of the orbital period of 11.92 hours. Moreover the DART impact may induce librations of the Didymos secondary of several degrees amplitude, depending on its axial ratio. It will furthermore make a ~7 m to ~20 m crater (depending on target properties and other impact conditions) that can be studied by the AIM spacecraft, and it will release a volume of particulate ejecta that may be directly observable from Earth or even resolvable as a coma or an ejecta tail by ground-based telescopes.

AIDA with both DART and AIM will be the first fully documented impact experiment, including characterization of the target's properties and the outcomes of the impact, to test and refine our understanding and models at an actual asteroid scale. AIDA will check whether current extrapolations of material properties such as strength from laboratory scale to asteroid scale are valid. AIDA will validate the kinetic impactor technique to deflect a small body and reduce risks for future asteroid hazard mitigation.

## Acknowledgements

We gratefully acknowledge support from NASA under the DART project.

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# Dynamical and Physical Properties of 65803 Didymos, the AIDA Mission Target

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## Abstract

The near-Earth asteroid (NEA) 65803 Didymos is a binary system and is the target of the proposed Asteroid Impact & Deflection Assessment (AIDA) mission, which combines an orbiter (Asteroid Impact Mission, AIM, or the reduced-scope AIM Deflection Demonstration, AIM-$D^2$) [1, 2] and a kinetic impactor experiment (Double Asteroid Redirection Test, DART) planned to impact the secondary of the Didymos binary system in October, 2022 [3]. The Dynamical and Physical Properties of Didymos Working Group supports the AIDA mission by addressing questions related to understanding the dynamical state of the system and inferring the physical properties of the components.

## 1. Dynamical properties of the Didymos system.

Didymos is an Apollo-class NEA with semimajor axis, eccentricity, and inclination ($a$, $e$, $i$) of (1.64 AU, 0.384, 3.4°). Using a new NEA population model [4], it likely reached its current orbit by exiting the inner main belt near or within the $\nu_6$ resonance between 2.1–2.5 au (> 82% chance). Other possible source regions are the Hungaria asteroids (8%) and the inner/central main belt via the 3:1 mean-motion resonance with Jupiter (7%). Remote observations [5] show Didymos is spectroscopically most consistent with ordinary chondrites, with an affinity for L/LL-type meteorites. Didymos likely originated from a high-albedo family [6]; its geometric albedo, $p_V$ = 0.16 ± 0.04 [7] matches the mean albedo of the prominent Baptistina family in that zone. However, several additional family candidates may also make plausible parents (e.g., Flora, Nysa, Massalia, Lucienne). A model of the short-term binary dynamics suggests possible librations of the secondary with up to ~10-deg amplitude after the DART impact, depending on its axial ratio. Before the impact, an equilibrium orbital and rotational solution is consistent with a libration amplitude of only ~1 deg.

## 2. Main physical features of the Didymos system.

The diameters of the binary components are measured to be about 780 and 140 m [8]. Didymos, the primary of the system, has an estimated 2.1 g/cc bulk density (uncertainty 30%) and a possibly super-critical rotation period of 2.26 h that may imply a cohesive strength of several tens of Pa. At this rate, perturbed regolith material close to the equatorial region may go through take-off/landing cycles and cause loss of fines due to solar radiation pressure. Based on a continuum analysis [9], the internal structure would likely fail before the equatorial region. A discrete analysis [10, 11, 12] shows that a minimum of 2.5 g/cc bulk density is needed for the structure to hold without cohesion. The estimated porosity of the primary is ~35-40% so that the object is likely a gravitational aggregate. Numerical simulations show that such porosity is consistent with a largest component of the asteroid internal structure with a mass smaller than 40% of the whole asteroid mass [13]. The system may be subject to weak thermal radiation forces (BYORP) with a period drift of no greater than 1 s/yr [14]. Materials ejected from the secondary due to the DART impact are likely to reach the primary and may cause the primary to reshape due to landslide or internal deformation, changing the gravity field [15].

## 3. Summary

This contribution is an update of the research conducted by the working group on the Dynamical and Physical Properties of the Didymos binary system in the frame of the AIDA mission.

## Acknowledgements

DCR, AFC, and other members of the DART investigation acknowledge support from NASA under the DART Project.

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