Hera Trajectory Design: from Launch to Arrival at the Didymos Binary Asteroid

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***Abstract* – Hera is ESA's planetary defence mission part of the Asteroid Impact and Deflection Assessment (AIDA) international collaboration. It is set for launch in October 2024 on an expendable Falcon 9 rocket, injecting the spacecraft into an Earth-escape trajectory with an asymptotic departure velocity of 5.6 km/s. The main mission objectives are the characterization of the Didymos binary asteroid system and to study the aftermath of NASA's DART impact. This paper discusses the trajectory design for the Hera mission from launch to arrival at the Didymos system. It describes the Earth-Didymos transfer opportunities in the period of interest for the mission, the resulting baseline (Oct 2024) and backup (Oct-Nov 2026) launch periods, the trajectory optimization concept, the mission constraint setup, and the obtained trajectory solutions. Furthermore, it describes the modifications to the delta-v-optimal trajectory that enable observations of Deimos from close distances during the Mars swingby, as well as the design of the rendezvous phase.**

I. INTRODUCTION

Hera is ESA's planetary defence mission part of the Asteroid Impact and Deflection Assessment (AIDA) international collaboration [1], [2]. Its main objective is the comprehensive characterization of the Didymos binary asteroid system, including detailed measurements of Dimorphos, the secondary asteroid of the system, and the aftermath of NASA's DART impact [3]. This would make Hera the first-ever spacecraft to rendezvous with a binary asteroid and would provide an accurate measurement of the momentum transfer efficiency resulting from DART's impact. A successful completion of the Hera mission would provide very valuable information for potential asteroid deflection missions in the future, as well as increase our understanding of asteroid geophysics and the evolution of our solar system.

The study of the near-Earth Didymos system (illustrated in Fig. 1), is not only crucial for its planetary defence objectives but also very relevant from a scientific perspective, as it will provide the first comprehensive characterization of the binary asteroid including, for the first time, its internal properties. Additionally, the primary asteroid, Didymos, is already interesting on its own, as its fast rotation rate places it close to the limit of structural stability (asteroid spin-barrier), and Dimorphos, the secondary asteroid, would become one of the smallest objects in the solar system ever studied in full detail.

To accomplish its mission objectives, Hera spacecraft carries on-board the following instruments (Fig. 2): two fully redundant Asteroid Framing Cameras (AFCs) used also for optical navigation; a spectral imager (Hyperscout-H); a laser altimeter (PALT); and a thermal infrared imager (TIRI). Additionally, the mothership carries two 6-unit CubeSats (Milani and Juventas), with their own instruments, which are to be released during the Proximity Operations (PO) phase once the early characterisation of the asteroid system is completed. Finally, the measurements from the X-band deep-space transponder and the Hera-CubeSat inter-satellite link transceivers will be used for radio science experiments.

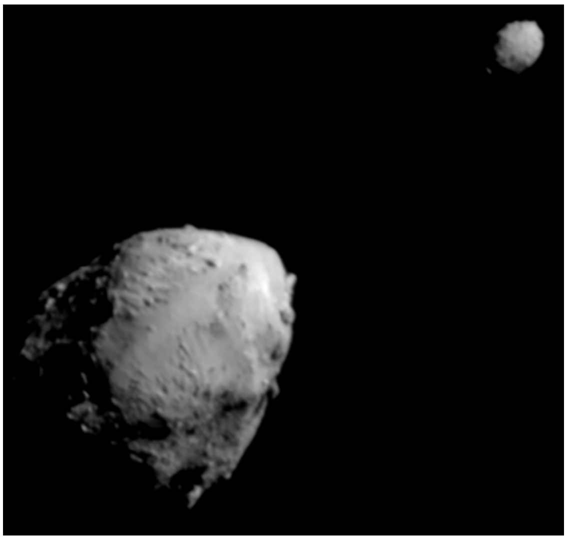

Fig. 1. Didymos (bottom left) and Dimorphos (top right) imaged by DART 2.5 minutes before impacting Dimorphos. Credit: NASA/Johns Hopkins APL

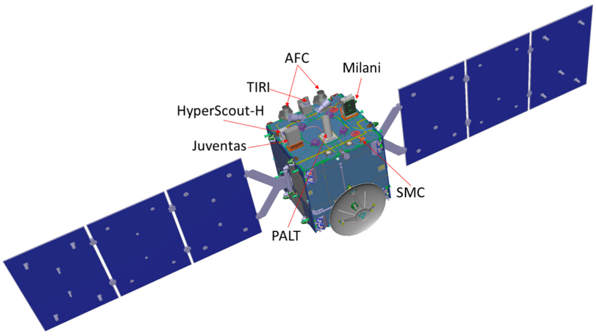

Fig. 2. Overview of Hera spacecraft [2]

II. MISSION OVERVIEW

Hera is set for launch in October 2024 on an expendable Falcon 9 rocket, injecting the spacecraft into an Earth-escape trajectory with an asymptotic departure velocity of 5.6 km/s. After the Launch and Early Operations Phase (LEOP) and a period for commissioning of the spacecraft platform, the first deep space manoeuvre (DSM-1) targets the Mars swingby (MSB), at minimum altitudes in the range of 4,500-10,000 km. The gravity assist manoeuvre by Mars results in significant delta-v savings for the mission and, incidentally, becomes an opportunity for calibration observations of the planet and its moons with the on-board scientific instruments before arriving to the Didymos system. Almost one year later, the second deep space manoeuvre (DSM-2) is executed to acquire the required velocity to intercept the trajectory of the binary asteroid in late 2026.

Didymos rendezvous phase (RDV) lasts two months and consists of: eight braking manoeuvres that progressively reduce the relative velocity with respect to Didymos as the distance continuously shrinks; and three transition manoeuvres that bring the spacecraft to the initial point of the Proximity Operations phase, at 30-km distance from the primary asteroid. During the braking phase, the spacecraft propulsion must produce about 300 m/s of total delta-v, which is split in burns of progressively smaller size, in order to mitigate the consequences of a contingency in which one of the manoeuvres was not successfully executed. It is during this phase that the binary asteroid can be detected with the on-board optical cameras, enabling optical relative navigation, which is required to navigate the spacecraft to close distances. The trajectory design provides for optical relative observations from slightly changing directions, so that the full relative state can be determined with sufficient accuracy for navigation feasibility.

Once arrived at Didymos system, the PO start with the early characterization of the binary asteroid, then three weeks are reserved for the CubeSat deployment and initial operations, and afterwards Hera would continue with the detailed characterization of the system, and execution of observations from short distances by performing close and very-close flybys of Dimorphos. The baseline duration for the Proximity Operations phase is about six months. The focus of this paper is the interplanetary transfer and the rendezvous phase. More details on the proximity operations and the optical navigation analyses can be found in [4].

III. HERA INTERPLANETARY TRANSFERS

The main characteristics of Didymos' orbit around the Sun are listed in Table 1 (based on the asteroid ephemeris from [5]). Its orbital plane has a relatively low inclination with respect to the ecliptic. The perihelion is not too far from Earth's orbit, while the aphelion is well beyond Mars's orbit. This effectively implies that the simplest and most efficient transfers for a rendezvous mission must start with departure from Earth around its closest point to Didymos' orbit, which corresponds to October and early-November each year, which is furtherly reduced to one opportunity every two years to have a sufficiently close orbital phase with the asteroid.

The distance from Didymos to Earth and Sun is shown in Fig. 3 for the period from 2020 to 2032. The closest approach (CA) to Earth occurred on October 4th, 2022, at a distance of about 0.071 au. DART's impact on Dimorphos took place just a few days earlier, on September 26th, as the privileged short distance from Earth was very favourable for the ground-based observations of the event. The orbital period of Didymos close to two Earth's orbital revolutions implies that there are occurrences of local minima of the Earth-distance every two years from the 2022, with increasing offset in the orbit phase, and thus increasing minimum distance.

Table 1. Characteristics of Didymos' heliocentric orbit

Perihelion distance	1.013	au
Aphelion distance	2.272	au
Inclination, ecliptic	3.414	deg
Orbital period	2.105	years
Perihelion velocity	34.798	km/s

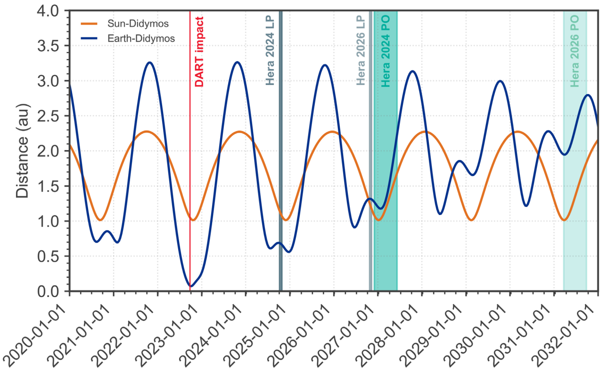

Fig. 3. Distance from Didymos to Earth and Sun, with highlighted dates of: DART impact, Hera launch periods (LP) and proximity operations (PO)

Two launch periods (LP) are considered for Hera mission: the baseline launch opportunity in 2024, spanning from October 7th to 27th, and a backup opportunity in 2026, from October 24th to November 10th. Hera's heliocentric trajectories are shown, in ecliptic projection, in Fig. 4 and Fig. 5, for the Launch Period Open (LPO) of the 2024 and 2026 options, respectively. In both LPs, the Earth is located close to the point of minimum distance to Didymos orbit track, while Didymos is around its perihelion. However, since Didymos was almost in perfect phase with Earth in 2022 encounter, then in 2024 the Earth will be 0.105 years ahead of Didymos in crossing the point of minimum distance between the orbits, and in 2026 it will be 0.21 years ahead. This offset effectively implies that Hera shall reach a heliocentric orbit with longer period, thus, further aphelion, than Didymos, so that the proper orbit phasing can be achieved at the rendezvous, one orbital revolution (2024), or two (2026), later. This is clearly unfavourable from an overall fuel-efficiency perspective (combining the launcher and spacecraft consumption) as it requires first to overshoot, injecting the spacecraft into a wider orbit, and later this excess velocity must be cancelled out, effectively paying twice the penalty. In this respect the transfer opportunities after 2022 are inferior to the ones before.

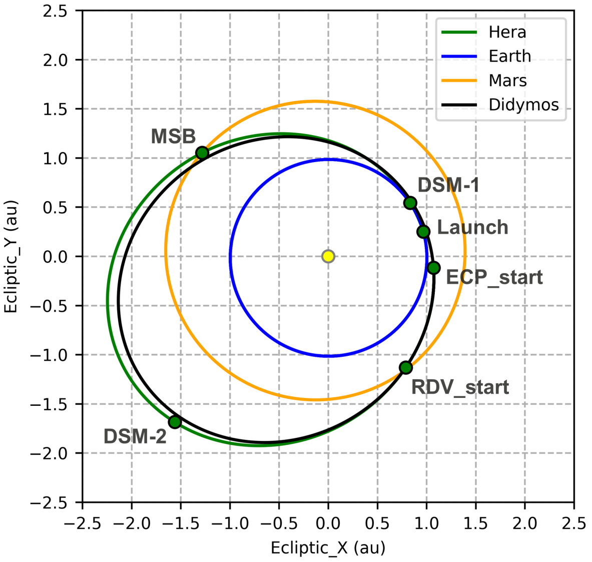

Fig. 4. Hera trajectory plot, ecliptic projection, for launch at the beginning of the 2024 LP (baseline)

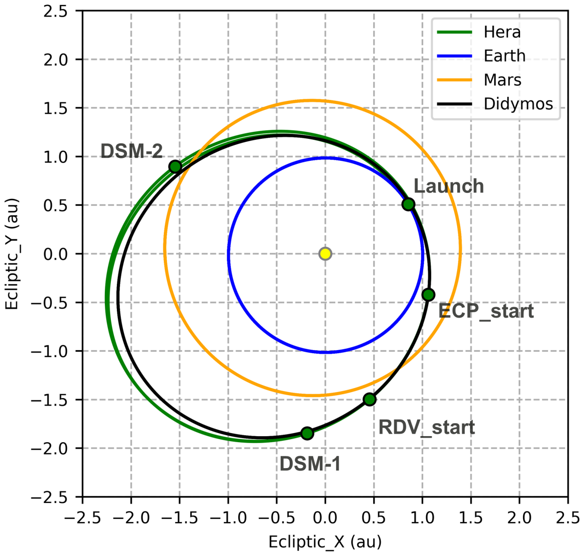

Fig. 5. Hera trajectory plot, ecliptic projection, for launch at the beginning of the 2026 LP (backup)

Fortunately, for the 2024 transfer, Mars happens to be at the right location such that a planetary swingby can be performed, bringing significant delta-v savings to the mission. For the backup 2026 transfer, this option is not available and, therefore, it becomes much more expensive in delta-v both on the spacecraft side and on the launcher side. The required Earth departure V_∞ raises to 6 km/s for most of the launch period (except for the first few launch dates).

Table 2 provides a summary of the 2024 and 2026 transfers for a launch on the middle of the LPs. Note that the information provided in the table corresponds to the interplanetary optimization (modelling the rendezvous as a single impulsive manoeuvre), and in the 2024 case for the trajectory without Deimos flyby (see section V).

The remainder of this paper will focus on the 2024 trajectory, providing more details on the trajectory optimization setup, as well as on the trajectory results obtained for the 2024 launch period.

Table 2. Summary of 2024 and 2026 transfers for a launch on the central date of the LP, modelling the rendezvous as a single impulsive manoeuvre

Launch opportunity	2024	2026
Central launch date	Oct. 17th	Nov. 1st
Departure V_∞ (km/s)	5.6	6.0
Dep. declination (deg)	34.0	39.1
DSM-1 date	2024/11/18	2028/07/07
DSM-1 delta-v (m/s)	28	258
Mars swingby date	2025/03/14	-
MSB altitude (km)	7015	-
MSB V_∞ (km/s)	8.847	-
DSM-2 date	2026/02/02	2029/06/28
DSM-2 delta-v (m/s)	365	464
Impulsive RDV date	2026/10/12	2031/01/08
Imp. RDV delta-v (m/s)	301	490
Imp. RDV Δv SAA (deg)	129	117
Total duration (days)	729	1529
Total delta-v (m/s)	694	1048

IV. TRAJECTORY OPTIMIZATION SETUP

Trajectory optimizations, navigation analyses, and other mission analysis tasks for Hera mission are performed using a set of tools developed in-house (ESA/ESOC's Mission Analysis Section) on top of the following software packages:

- GODOT: ESA/ESOC's Flight Dynamics astrodynamics infrastructure software for operations and mission analysis [6].
- Pagmo/pygmo: ESA's scientific library for massively parallel optimization [7].
- WORHP: mathematical library for numerically solving continuous large-scale nonlinear optimisation problems [8].
- Pyoptgra: python interface to OPTGRA, an optimization algorithm specifically designed for near-linear constrained problems, which commonly occur in trajectory optimization [9].

The process for Hera trajectory optimization from launch to arrival to Didymos system is, for mission analysis purposes, split in two optimization steps that are executed sequentially: (1) the so-called interplanetary optimization, spanning from launch to arrival at Didymos system but modelling the rendezvous as a single impulsive manoeuvre; and (2) the rendezvous optimization, taking the initial spacecraft state vector at the beginning of the rendezvous from the result of the first step and splitting the arrival delta-v in multiple manoeuvres, for mission robustness and navigation feasibility. This split has multiple advantages for mission analysis as the optimization problem is reduced to two simpler steps. Interplanetary trajectory trade-offs and launch period computations, including the definition of the launcher injection targets, can all be performed with the simpler interplanetary optimization setup, with high confidence that the global optimization combining both stages would lead to very small differences. Additionally, the more demanding rendezvous optimization only needs to be performed for a subset of cases, the most relevant ones, effectively saving precious time. Nevertheless, for actual operations, the global optimization is performed, which typically results in a delta-v saving of about 2 m/s for the 2024 launch period.

Hera interplanetary trajectory optimization is relatively simple. It consists of a multiple-shooting optimization problem with initial states, or control points, defined at launch, Mars swingby, and arrival to Didymos. Matching constraints are imposed in the middle of the interplanetary arcs to enforce continuity. Apart from the Earth departure and Didymos arrival boundary conditions, the following constraints are included in the optimization setup for the baseline 2024 transfer:

- DSM-1 performed at least 15 days after launch.
- Mars swingby altitude higher than 300 km.
- Date of virtual arrival to Didymos, i.e. using a single rendezvous manoeuvre, on 2026/10/16.

Additionally, the cases with Deimos flyby (see section V) also have the following trajectory targets:

- Deimos flyby miss distance equal to 300 km.
- Mars-Hera-Deimos angle lower than 4 degrees at the time of Deimos observations.

The rendezvous optimization setup is significantly more complex and will be briefly discussed in section VI.E.

V. TRAJECTORY UPDATE FOR DEIMOS FLYBY

Members of Hera scientific instrument teams sent out a request to Hera Mission Analysis to study a possible modification of the interplanetary trajectory for the baseline LP in 2024 to perform close observations of Deimos during the Mars swingby. In principle, this was possible because the original Hera trajectory was passing very close to Deimos' orbit track, particularly for the launch dates at the beginning of the LP. Therefore, it would be theoretically sufficient to shift the time of the Mars swingby to have the correct phasing with Deimos. These observations were considered interesting for calibration purposes, as well as complementing previous scientific measurements of Deimos, particularly if the anti-Mars hemisphere was observed. The request was endorsed by the Hera project, allocating 40 m/s for this purpose, which corresponds to the delta-v required to shift the Mars swingby time by half a Deimos orbital period for sizing cases of launching on LPO or LPC (Launch Period Close). Due to the fast-changing geometry and the limited S/C agility, it is not possible to point continuously to the target during the Deimos flyby. Instead, it was decided to observe it during a brief period, while the moon remains within the instruments' field of view (FoV).

The implementation of the Deimos flyby turns the optimization process into a more demanding task, as the Mars swing-by phasing must be adjusted for different Deimos orbital revolutions throughout the launch period, and good initial guesses must be provided to the local optimizers being used, otherwise the optimization would not converge. The trajectory targets for the Deimos flyby were set as: (1) 300 km Deimos miss distance, arbitrarily chosen for safety; and (2) Mars-Hera-Deimos angle constrained to be lower than 4 degrees at 1024 km distance from Deimos before the swing-by, corresponding to the assumed time of AFC observations, as it would guarantee to have the whole moon in the FoV for the assumed accuracy of Hera trajectory prediction and the accuracy of Deimos' ephemeris. The small Mars-Hera-Deimos angle has the advantage of minimizing the slew time required from Mars pointing to Deimos pointing and ensures no outage of Mars observations as Deimos would be observed in front of Mars disk.

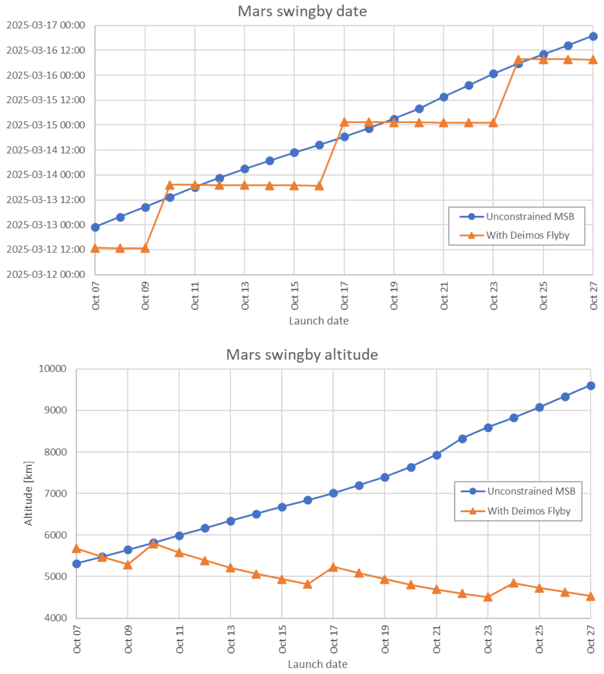

Fig. 6. Mars swingby date and altitude, for each launch date and each option with and without Deimos flyby

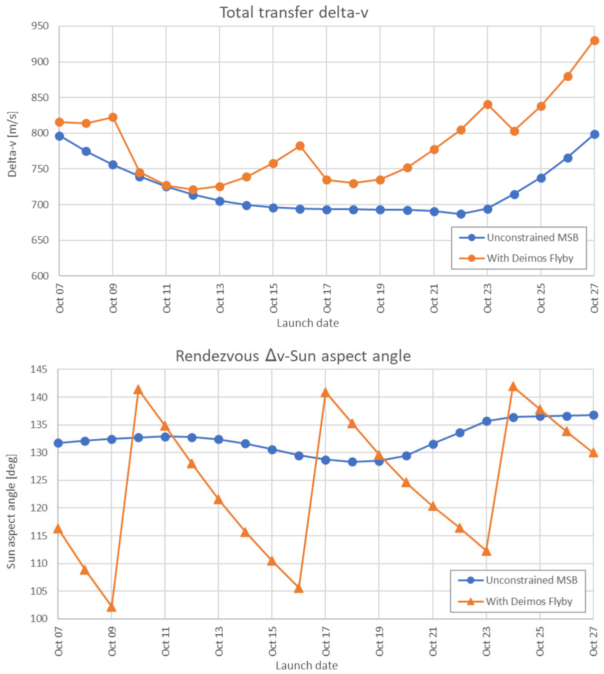

Fig. 7. Total transfer delta-v and RDV delta-V SAA, for each launch date with and without Deimos flyby

The trajectory optimization results are shown in Fig. 6 and Fig. 7, comparing the results with and without Deimos flyby for a few quantities of interest. Deimos flyby solutions were found for all launch dates, although for the last two launch dates the total delta-v was deemed too high, as it exceeds the 40 m/s allocation on top of the previous sizing case. Therefore, the new agreed baseline is having two mission branches: with Deimos Flyby for the first 19 days of the LP, and without for the last 2.

As shown in the plot of Mars swingby date, the cases with unconstrained MSB show a smooth evolution of the time of closest approach, increasing from four to six hours per launch date. On the other hand, the cases with Deimos flyby are grouped in batches of very similar Mars swingby time (differing by a few minutes). From one batch to the next the difference is approximately one Deimos' revolution. The delta-v penalty is higher the longer the shift in swingby time is. For the later launch dates there is an additional delta-v penalty to shrink the gap between Deimos and Hera trajectories, as hinted by the Mars swingby altitude plot.

Implementing the Deimos flyby requires not only to modify DSM-1, which targets the Mars swingby, but also DSM-2 and RDV to correct, a posteriori, the offset in the Mars swingby conditions. This has an important side effect on the RDV delta-v, but also on the RDV Δv-Sun-aspect angle (SAA), a proxy for the Didymos phase angle as seen from Hera during rendezvous which drives how early (or late) can Didymos be detected by the on-board cameras, necessary event to start the optical relative navigation (see section VI.E).

Advancing the Mars swingby is beneficial for both aspects, while postponing it has the opposite effect: increasing significantly the RDV delta-v and the phase angle. To mitigate this, the choice is biased towards advancing rather than postponing the Mars swingby, accepting the corresponding additional delta-v penalty for some of the launch dates. As a consequence, the phase angle during RDV is significantly reduced for most launch dates, and for the few unfavourable ones it is only increased by a maximum of 5 degrees with respect to the worst-case unconstrained trajectory (LPC), which has an acceptable impact on the asteroid detection date.

The minimum Mars swingby altitude is reduced to about 4,500 km from the previous lowest value of about 5,300 km, which is considered acceptable and expected to have a negligible impact on the results of the navigation and planetary protection analyses, A second iteration of these analyses on the new baseline trajectories is the next task to be completed from Hera Mission Analysis side.

Finally, as mentioned above, except for the last two dates of the LP, the total delta-v remains within the 40 m/s allocation on top of the sizing case in the previous baseline. However, the actual delta-v penalty of implementing the Deimos flyby is significantly higher, when looking per launch date at the difference between the Deimos flyby trajectory and the unconstrained one, reaching a maximum penalty of 146 m/s for a launch on October 23rd.

VI. 2024 MISSION BASELINE

A. Overview

The following sections provide more details on the latest baseline trajectories for Hera launch in 2024, with Deimos flyby on the first nineteen launch dates of the LP and without for the last two. Table 3 provides the resulting value ranges obtained for the whole LP, for some quantities of interest.

Table 3. Summary of 2024 mission baseline, with minimum and maximum values for the whole launch period, with rendezvous as a single manoeuvre

	Minimum	Maximum
Launch date	2024/10/07	2024/10/27
Departure V_∞ (km/s)	5.6	5.6
Dep. declination (deg)	34.0	34.0
DSM-1 date	2024/10/23	2024/12/07
DSM-1 delta-v (m/s)	26	164
Mars swingby date	2025/03/12	2025/03/16
MSB altitude (km)	4511	9605
MSB V_∞ (km/s)	8.726	9.009
DSM-2 date	2025/10/04	2026/02/15
DSM-2 delta-v (m/s)	356	457
Impulsive RDV date	2026/10/12	2026/10/12
Imp. RDV delta-v (m/s)	287	355
Imp. RDV Δv SAA (deg)	102	142
Total duration (days)	719	739
Total delta-v (m/s)	721	841

B. Launch and Early Operations

A single launcher flight program is assumed for the whole launch period in 2024, implying that fixed values of departure hyperbolic velocity magnitude (V_∞) and declination are used. The other relevant parameter of the departure hyperbola, the right ascension in Earth-centred inertial frame, can be chosen freely by varying the lift-off time accordingly.

The Launch and Early Operations Phase for ESA deep space missions usually lasts 2-3 days. Fig. 8 shows Hera elevation during LEOP, with a minimum elevation of 10 degrees, for the three ESA deep space stations (New Norcia, Cebreros and Malargüe) as well as Goldstone and Canberra from NASA DSN. The plot is based on the state vector at separation provided by the launcher authority. The time tags correspond to a launch on LPO, but since the LEOP trajectory is effectively frozen in Earth-fixed frame, then the plots are essentially the same for all launch dates, except for a shift in time. Goldstone is the best suited station for the first signal acquisition, achieving visibility shortly after separation. New Norcia could act as backup acquiring the signal a few hours later. Cebreros and New Norcia in combination with Goldstone would enable around the clock link with the spacecraft during the first days of the mission.

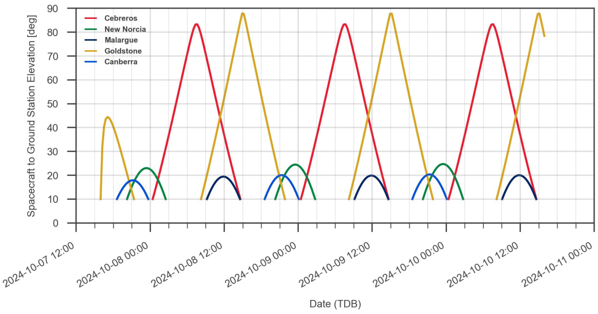

Fig. 8. Ground station elevation plot during LEOP for 2024 LPO case

C. Deep Space Manoeuvres

The first deep space manoeuvre is scheduled not earlier than 15 days after launch to allocate sufficient time for spacecraft commissioning and the conditioning of the propulsion system. It is planned to split each DSM in two burns of 90% and 10% of the total delta-v separated by 14 days. Additionally, purely stochastic correction manoeuvres could be used, in particular after DSM-1 to reduce the dispersion and ensure that the spacecraft in a collision-free trajectory with Mars.

D. Mars Swingby

The gravity assist manoeuvre at Mars allows to save some delta-v on Hera side, despite being at a relatively high altitude and with high hyperbolic asymptotic velocity. As an example, for LPO case, Hera's asymptotic hyperbolic velocity of 8.759 km/s; swingby altitude of 5681 km; which results in a deflection angle of 6.643 degrees; and an effective change on Hera's heliocentric velocity of 1.015 km/s.

The Mars swingby is not a main scientific objective for Hera mission, but it becomes a good opportunity for calibration measurements of the instruments on-board, and potentially scientifically valuable observations of Deimos. Mars observations are very useful for the instrument teams as the planet's disk can fill completely the field of view of each instrument during the approach. For this reason, the Deimos flyby trajectory has been designed as depicted in Fig. 9 for the LPO trajectory.

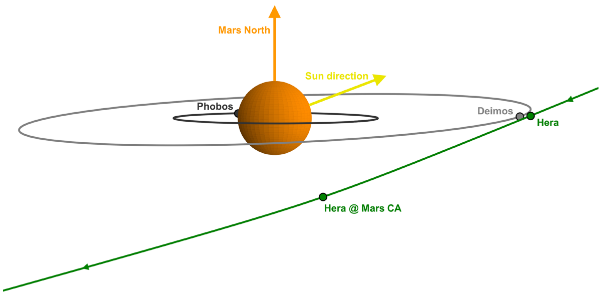

Fig. 9. Mars swingby trajectory plot for LPO case. The points labelled Phobos, Deimos and Hera correspond to their positions at the time of Deimos observation

By enforcing a small Mars-Hera-Deimos angle at the time of the observations it is possible to avoid an outage of Mars observations during the Deimos flyby, because even if the spacecraft performs a small slew from Mars pointing to Deimos pointing, Mars would still be visible in the FoV of the instruments. This geometry implies that Deimos will be observed in front of Mars disk. The resulting trajectory is such that Deimos anti-Mars hemisphere can be observed almost completely at rather low phase angles (about 15-17 deg at the time of observations). After that Hera flies over Deimos' southern high latitude regions, although by then it will have already exited the instruments' FoV.

Another aspect to pay attention to is the possibility of eclipses during the swingby. In our case, Hera approaches Mars from the dayside, at rather low phase angles. This implies that after the closest approach, the spacecraft flies deep towards the nightside, close to the planet's penumbra. Fig. 10 shows the evolution of the eclipse margin starting from closest approach to Mars, where the eclipse margin with respect to the penumbra is defined as the angular separation of minus the angular apparent radii of Mars and Sun as seen from Hera. Having an eclipse margin higher than 2 degrees at all times is considered sufficient in this case, as the expected dispersion due to navigation errors is significantly smaller, by about two orders of magnitude.

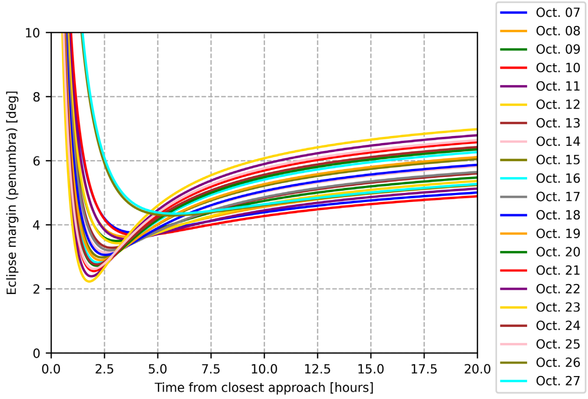

Fig. 10. Hera eclipse margin (penumbra) during the Mars swingby, for all launch dates in 2024 LP

E. Asteroid Rendezvous

As discussed in section IV, the interplanetary optimization setup has the simplification of having a single rendezvous manoeuvre that executes in one burn all the required delta-v. Apart from the challenges for relative navigation that it entails, this option would not be robust against a contingency that could prevent, or interrupt, the execution of the manoeuvre. In that scenario, the spacecraft would pass at high speed beyond the closest approach to the asteroid system, and it would require a long time and a delta-v penalty to come back. To mitigate this risk, a strategy similar to the one applied for Rosetta mission is employed [10]. Hera rendezvous phase and the corresponding navigation analysis was already presented in [11]. In this section we summarise the main ideas and describe the modifications applied as the mission baseline evolved.

The arrival delta-v is split in a sequence of seven progressively smaller braking manoeuvres (BRMs), which steer the spacecraft to a point 500 km away from the target with a low residual relative velocity. Additionally, a test manoeuvre is included at the beginning of the sequence to further increase the robustness of the strategy by testing the propulsion system one week before the first big burn. The braking manoeuvres are scheduled one per week such that there is sufficient time available in between to collect tracking data, perform an orbit determination, and prepare the next manoeuvre. The manoeuvre sizes are designed such that if a manoeuvre is missed, due to any contingency, there is certain time margin to try to recover the spacecraft and command a new manoeuvre attempt before the closest approach to Didymos.

Additionally, the design includes a slight "curvature" of the trajectory, which is achieved by targeting initially higher impact parameter that is progressively reduced in the subsequent manoeuvres. The purpose of this "curvature" is twofold: first to provide a better knowledge on the asteroid-spacecraft relative state in radial direction; and second, to steer the spacecraft towards the Sun side of the Didymos, as the approach to the asteroid starts from very high phase angles, which is unfavourable for initial detection and optical navigation.

A summary of the braking sequence is given in Table 4 for a launch on October 23rd, which corresponds to the worst-case for the RDV delta-v and phase angle. The optimization setup for the BRMs is as follows: each manoeuvre targets the distance to Didymos at the time of the next manoeuvre; from BRM_2 to BRM_6 each manoeuvre targets an impact parameter in the sequence 5000, 5000, 3000, and 1000 km, towards the projection of the Didymos-Sun direction on the B-plane.

Table 4. Summary of braking manoeuvres for the rendezvous worst-case launch date

Manoeuvre	Date	Δv (m/s)	Distance to Didymos (km)	Time margin to CA (days)
BRM_test	2026/10/02	9.1	443,907	14.3
BRM_1	2026/10/09	135.6	232,000	7.7
BRM_2	2026/10/16	112.2	104,000	5.7
BRM_3	2026/10/23	57.2	44,000	5.1
BRM_4	2026/10/30	21.6	19,000	5.1
BRM_5	2026/11/06	13.3	7,000	3.6
BRM_6	2026/11/13	3.8	2,400	3.2
BRM_7	2026/11/18	3.6	500	1.0

Table 5. Summary of transition manoeuvres (TRM)

Manoeuvre	Date	Δv (m/s)	Distance to Didymos (km)
TRM_1	2026/11/21	1.0	240.0
TRM_2	2026/11/25	0.3	120.0
TRM_3	2026/11/28	0.2	60.0

BRM_6 targets a fixed position at the time of BRM_7, at 500 km distance and 40 deg phase angle. From here onwards each manoeuvre targets the corresponding position at the time of the next manoeuvre. Then, three transition manoeuvres (TRMs) bring the spacecraft to the PO initial point, at 30-km distance from Didymos. The trajectory follows a kind of spiral towards Didymos to continuously change the observation direction and thus keep improving the knowledge on the relative state. A summary of the manoeuvres is given in Table 5, where the schedule already follows the 3-4-day pattern used for proximity operations [4].

The evolution of the phase angle and distance to Didymos during the rendezvous phase is shown in Fig. 11, while the final part of the BRM sequence is plotted in Fig. 12. In both cases for the worst-case launch date in terms of RDV delta-v and phase angle. Finally, Fig. 13 shows a projection of the "spiral trajectory" during the transition phase.

VII. CONCLUSIONS

The interplanetary trajectory design for the Hera mission has been presented. The Earth-Didymos transfer opportunities in the time frame of the mission have been discussed, for which the opportunity in 2024 is shown to be much more favourable than the 2026 one, in terms of transfer duration and delta-v. The trajectory optimization setup described in the paper has proved to be very robust and suitable for performing different trajectory analyses and trade-offs in an efficient manner. The modification of the baseline trajectory to accommodate the Deimos flyby will enable interesting measurements from the instrument teams. Finally, a robust approach has been designed for the rendezvous phase, which hopefully will bring Hera to a successful start of proximity operations at the asteroid binary.

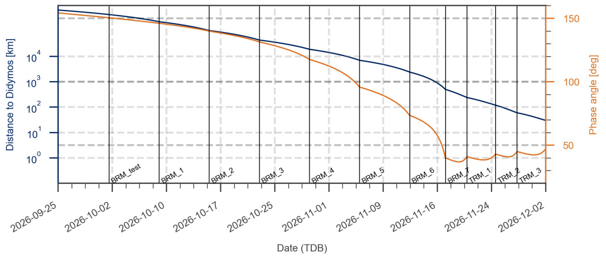

Fig. 11. Distance and phase angle evolution during the rendezvous phase, for the worst-case launch date

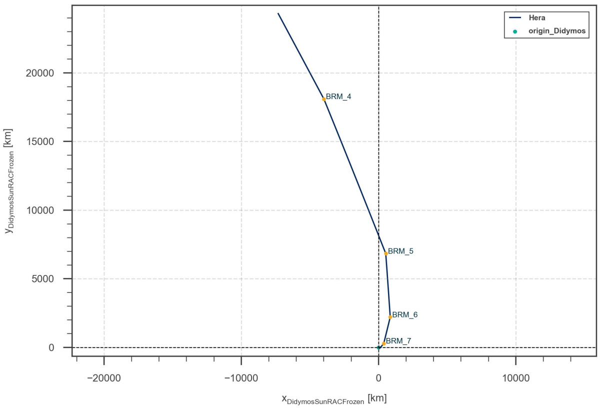

Fig. 12. Final BRM sequence trajectory plot, for the RDV worst-case launch date (Sun direction along +X)

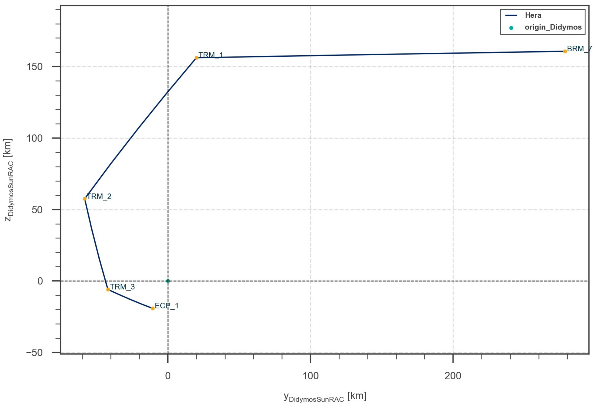

Fig. 13 TRM trajectory plot

VIII. REFERENCES

[1] P. Michel, M. Küppers, H. Sierks. I. Carnelli, A. Cheng. K. Mellab, M. Granvik, A. Kestilä , T. Kohout, K. Muinonen, A. Näsilä, A. Penttila T. Tikka, P. Tortora, V. Ciarletti, A. Hérique, N. Murdoch, E. Asphaug, A. Rivkin, O. Barnouin A. Bagatin, P. Pravec, D. Richardson, S. Schwartz, K. Tsiganis, S. Ulamec, and Ö. Karatekin, "European component of the AIDA mission to a binary asteroid: Characterization and interpretation of the impact of the DART mission," *Advances in Space Research*, vol. 62, no. 8, pp. 2261–2272, Oct. 2018, doi: 10.1016/j.asr.2017.12.020.

[2] P. Michel, M. Küppers, A. Bagatin, B. Carry ,S. Charnoz, J. Leon, A. Fitzsimmons, P. Gordo S. Green, A. Hérique, M. Juzi, Ö. Karatekin, T. Kohout, M. Lazzarin, N. Murdoch, T. Okada E. Palomba, P. Pravec, C. Snodgrass, P. Tortora K. Tsiganis, S. Ulamec, J. Vincent, K. Wünnemann , Y. Zhang, S. Raducan, E. Dotto, N. Chabot, A. Cheng, A. Rivkin, O. Barnouin, C. Ernst A. Stickle, D. Richardson, C. Thomas, M. Arakawa, H. Miyamoto, A. Nakamura, S. Sugita, M. Yoshikawa, P. Abell, E. Asphaug, R. Ballouz, W. Bottke, D.

Lauretta, K. Walsh, P. Martino, and I. Carnelli, “The ESA Hera Mission: Detailed Characterization of the DART Impact Outcome and of the Binary Asteroid (65803) Didymos”*, The Planetary Science Journal*, Volume 3, Number 7, July 2022.

[3] A. F. Cheng, A. Rivkin, P. Michel, J. Atchison, O. Barnouin, L. Benner, N. L. Chabot, C. Ernst, E. G. Fahock, M. Kueppers, P. Pravec, E. Rainey, D. C. Richardson, A. M. Stickle, and C. Thomas, “AIDA DART asteroid deflection test: Planetary defense and science objectives”, *Planetary and Space Science*, Volume 157, 2018, Pages 104-115, ISSN 0032-0633.

[4] I. Acedo and P. Muñoz, “Optical Navigation Analyses for Hera Proximity Operations: Early Characterization Phase and Detailed Characterization Phase”, *29th International Symposium on Space Flight Dynamics (ISSFD)*, Darmstadt, 2024.

[5] https://ssd.jpl.nasa.gov/horizons (JPL Horizons web site).

[6] R. Mackenzie and G. Varga, GODOT, ESA Astrodynamics Infrastructure Software for Operations and Mission Analysis, *9th International Conference on Astrodynamics Tools and Techniques (ICATT)*, Sopot, 2023.

[7] F. Biscani and D. Izzo, “A parallel global multiobjective framework for optimization: pagmo”, *Journal of Open Source Software*, 5(53), 2338, (2020)

[8] Büskens, Christof, and Dennis Wassel. "The ESA NLP Solver WORHP", *Modeling and Optimization in Space Engineering*, (2013): 85-110.

[9] https://github.com/esa/pyoptgra (Pyoptgra GitHub repository).

[10] P. Muñoz, F. Budnik, B. Godard, T. Morley, V. Companys, U. Herfort and C. Casas, “Preparations and Strategy for Navigation during Rosetta Comet Phase”, *23rd International Symposium on Space Flight Dynamics (ISSFD)*, Pasadena, 2012.

[11] I. Acedo and P. Muñoz, “Trajectory Design and Navigation Analysis of Hera’s Rendezvous with the Didymos Asteroid System”, *28th International Symposium on Space Flight Dynamics (ISSFD)*, Beijing, 2022.