Multi-spacecraft Navigation for the HERA Mission

Inês Passos de Almeida
inespassosalmeida@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal
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Abstract

The HERA mission is ESA’s contribution for an asteroid deflection test. The mission comprises one mothercraft and two CubeSats which will orbit the binary asteroid system 65803 Didymos. Navigation around asteroids is challenging due to their extremely low gravity and different strategies must be assessed from the early stages of the mission. A multi-spacecraft navigation strategy is implemented, combining the measurements of HERA mothercraft and Juventas CubeSat together with Inter-Satellite measurements in a SRIF ground filter. So far, interplanetary missions’ navigation strategies are independent for each spacecraft and so, the available mission analysis tools are designed for the simulation of one spacecraft at a time. This work is focused in the update of one of these tools to allow the simulation of two or more spacecraft simultaneously. A comparison between an independent and a multi-spacecraft navigation strategy for the HERA mission is made in order to assess which approach allows for a more accurate state estimation and dynamical parameters estimation.

Keywords: HERA, Interplanetary Mission Analysis, Navigation, Formation Flying

1. Introduction

The AIDA mission is a collaboration between ESA and NASA with the objective of testing an asteroid deflection strategy. A kinetic impactor and its effect on the target’s trajectory will be evaluated. The target is the binary asteroid system Didymos, composed of a main body, Didymain, and a secondary, Didymoon. NASA’s DART Mission will impact a spacecraft on the smallest body of the system, Didymoon. HERA will be ESA’s contribution for the project and it will follow up the impact with a detailed survey. The HERA mission will comprise a mothercraft and two CubeSats, Juventas and Milani, to provide extra data on the binary system. At the time of writing, Milani was still not approved for funding and so this work focused on the navigation of HERA and Juventas only.

Navigation in this environment has been proved challenging and multiple solutions are being studied to accomplish the mission requirements. The objective of this work is to develop an alternative navigation solution, to improve the current one of HERA mothercraft and Juventas CubeSat, by combining the measurements from the sensors of both spacecraft and inter-satellite measurements for the simultaneous estimation of the spacecraft’s states.

The current strategy of navigation for HERA and Juventas is to consider the spacecraft as independent. Each spacecraft uses its own measurements to compute its state. HERA’s current navigation approach includes optical centroiding measurements and radiometry, filtered on a batch-sequential Square Root Information Filter (SRIF) by the Flight Dynamics System (FDS) and optical centroiding measurements filtered on a UKF onboard.

Juventas’ navigation strategy also uses centroiding techniques, with a higher autonomy level than HERA. Absolute range measurements are not possible, however, since the spacecraft does not communicate directly with the ground segment, using HERA as relay for data transmission with Earth. An altimeter and Inter-Satellite Link (ISL) measurements are also used for navigation purposes.

The accuracy obtained in simulation with Juventas’ current navigation strategy is sufficient to achieve the mission requirements but has still a considerable margin for improvement, according to the studies in the Juventas Mission Analysis Report (MAR) and Juventas GNC Analysis Report.

Previous work in the literature proposes the use of multi-spacecraft missions to improve the overall system performance [1, 2].

In the proximity of an asteroid, data fusion of the measurements gathered by four spacecraft can improve the navigation performance [1]. Also, the addition of inter-spacecraft measurements was shown to further improve the results. In this study,

1Courtesy of GMV
each spacecraft computed its own state and so no multi-satellite filter was used.

A navigation approach around a binary system was proposed using a main spacecraft and two CubeSats [2], considering simultaneous state estimation on board of the main spacecraft. Issues on the tracking of the CubeSats were mentioned, due to lack of visibility. The measurements considered in the study, however, were only the camera of the main spacecraft and inter-spacecraft measurements.

Considering all different approaches for navigation around small bodies and spacecraft formations, the one proposed is to consider the spacecraft as part of a centralized formation: the state of each spacecraft and the unknown parameters will be estimated in one single filter, which receives as input all the measurements from both vehicles and Inter-satellite measurements. The estimation process will occur on-ground, using a SRIF filter.

2. Background

After launch, the HERA mission can be divided in two phases: interplanetary transfer and proximity operations. The proximity operations phase is divided in smaller phases, with different durations, orbits and objectives.

The Detailed Characterisation Phase (DCP) is the first phase after payload deployment (which includes the CubeSats deployment) and so it was the chosen phase for the navigation analysis.

The DCP trajectory was designed to accomplish the following requirements, as from HERA’s Proximity Operations Guidelines:

- The limb of Didymain must be contained in the camera’s FOV, in order to use a Centroiding Image Processing (IP) algorithm;
- Due to high dynamical uncertainties, the velocity of the SC must be larger than the system’s escape velocity. During DCP, a velocity margin of 40% is applied;
- Hyperbolic arcs must have a duration of 3 and 4 days, interchangeably to complete 7-day cycles due to operations scheduling;
- Ground station visibility should be possible using the ESTRACK-DSA stations: New Norcia, Cebreros and Malargüe;
- To ensure proper conditions for target observation, the angle between the +Z panel and the Sun around the boresight must be higher than 20°. The SC must be capable of acquiring at least 30 visible images of Didymoon with a resolution equal or better than 40 cm.

Accounting for these requirements, HERA’s DCP trajectory, used for the navigation analysis, is represented in Figure 1.

![Figure 1: HERA’s Trajectory during the DCP, as from the HERA MAR. The SC trajectory is represented by the blue lines. Green dots (Man.) correspond to manoeuvres. The trajectory initial point is X₀ and the arc that follows is the transition between the Early Characterisation Phase (ECP) and DCP. The rotation axis is referent to Didymain and the red line is Didymoon’s path during DCP.](image1)

During DCP Juventas will orbit Didymain in a Self-Stabilized Terminator Orbit (SSTO). This orbit was chosen because it is inherently stable and favorable for the purposes of radio science for gravity field measurements. The orbit stability minimizes the required delta-v for station keeping and reduces operation costs [3]. Current baseline is an orbit at 3300 m from Didymain (Figure 2).

![Figure 2: Juventas’ Trajectory during DCP, as from the Juventas MAR. The SC trajectory is represented by the blue lines. The red line is Didymoon’s trajectory.](image2)
from the antenna choice, operations must be carefully designed. Each day is segmented in two operations: data acquisition and data transmission. In a single operational day, one set of each is programmed in 16 hours for data acquisition and 8 hours for transmission. Data cut-off is produced two days before a manoeuvre and measurements posterior to the data cut-off are not used in the consequent manoeuvre computation. It should be noted that, during the data acquisition periods, the camera captures one image per hour. Radiometric measurements, instead, are performed during the transmission periods, when the spacecraft is pointing towards Earth. Range measurements are performed every hour and doppler measurements are performed every 15 minutes.

Juventas does not have the need to point to Earth for communications, since it uses HERA as a relay and has visibility at all times. Therefore, Juventas’ timeline can be defined by the sensor measuring frequency and the manoeuvres schedule. Juventas’ camera will capture only one image every 12 hours, due to the link budget that does not allow for the downlink of more. Altimeter and ISL measurements will be performed every hour. Manoeuvres are planned at 4 days and 7 days after DCP beginning.

Juventas will be placed in the 3300 m SSTO in 09/04/2027 16:00:00. However, HERA’s DCP phase is scheduled from 20/04/2027 16:00:00. Therefore, the performed navigation analysis considered the period from 20/04/2027 16:00:00 to 29/04/2027 16:00:00.

HERA mission’s main objective is to validate an asteroid deflection technology. In order to do so, after DART’s impact, it is necessary to characterize thoroughly the asteroid system. The knowledge obtained from Earth of Didymos dynamics is superficial but key as the starting point for initial navigation and parameter estimation. The rigorous study of Didymos environment throughout the mission is essential for the progress of this deflection technology and it is only possible with a suitable navigation strategy and estimation technique. During the multi-spacecraft navigation analysis, some dynamical parameters will be included in the SRIF state: Ephemerides, Gravitational Parameter and Center of Mass of both Didymain and Didymoon will be estimated during DCP.

3. Methodology
The navigation problem can be divided in three parts: reference trajectory definition, orbit determination and path control.3

Before any navigation analysis, a reference trajectory is generated using the best knowledge existent on the dynamics around the target body.

Orbit determination means keeping track of where the spacecraft has been, where it is and where it will be. The spacecraft is always drifting from the planned path, due to disturbances that cannot be taken into account in the reference trajectory, because of their randomness and unpredictability. Also, once the spacecraft is launched, it can no longer be directly observed: to determine its position at any given epoch, various forms of tracking data must be processed. This data is mathematically tied to the evolution of the spacecraft orbit and so it allows for the estimation of the spacecraft location.

Once there is a good estimate for the current location of the spacecraft, there is the need to evaluate how far the spacecraft has drifted from the reference trajectory. At this point, a manoeuvre can be designed/re-designed to correct the spacecraft path. A set of commands to accomplish the correction are then computed and uplinked to the spacecraft, which in turn performs the manoeuvre. After the manoeuvre has been performed, the cycle repeats.

The core of this process is orbit determination and, particularly, the navigation filter. The spacecraft location determination starts when the filter receives new measurements, from one specific epoch. The algorithm propagates the previous estimated state to the current epoch (a priori state) and computes the expected measurements at that epoch, if the spacecraft state was this a priori state. These “expected measurements” are called observables and the difference between them and the actual measurements is called the residual. Consequently, the residual represents the degree to which the spacecraft has drifted from the expected a priori state. The algorithm then adjusts its estimation of the spacecraft location in a way to minimise the magnitude of the residual values. The spacecraft state which minimises the residual is considered to be the new “best estimate” of the spacecraft location.

In the proposed navigation strategy, two spacecraft states will be estimated simultaneously. This means that the location of both HERA and Juventas, together with their measurements, are correlated for the estimation update of any of the spacecraft.

The HERA mission is a survey mission and one of its objectives is “To determine the momentum transfer by the hyper-velocity impact of DART and the resulting effects on Didymoon’s surface” [4]. To achieve this objective, the dynamical parameters of the Didymos system have to be characterised. In this context, the navigation problem needs to

3https://solarsystem.nasa.gov/basics/chapter13-1/navigation, last accessed on 2020-10-07
estimate not only the spacecraft’s states (position and velocity) but also some dynamical parameters. These parameters are included in the overall state that is used as the navigation filter input. They are correlated with the spacecraft’s locations and measurements. The minimisation of the residual is therefore affected by the estimation of these dynamical parameters, which is improved in the same fashion as the spacecraft’s state estimation.

In this process, none of the taken measurements quantifies directly the spacecraft location. However, the measurements are all mathematically tied in one way or another to the spacecraft’s motion and, by exploiting these mathematical relationships, it is possible to get an estimate of where the spacecraft is, at any given time. To simulate this, sophisticated computer software must be used.

The navigation analyses carried out in this work use as a base the software environment FCS-ATOMIC, provided by GMV, which was modified to match the needs of this work.

4. Results
The objective of this work is to develop an alternative navigation solution by combining the measurements from the sensors of both spacecraft and inter-satellite measurements for the simultaneous estimation of the spacecraft’s state. This navigation solution was simulated and analysed. The navigation analysis of any scenario can be defined as the answering to several questions:

1. What defines the success of a navigation strategy?
The achieved navigation performance must fulfil the mission requirements that are defined to ensure the platform’s safety while ensuring the required performance to achieve low level objectives, such as the scientific performances.

2. What particular parameters represent this success?
The previous success definition can be translated into explicit parameters. Ensuring the platform’s safety implies maintaining the SRIF filter convergence. The filter performance can be assessed by the error between the state knowledge and the real state and by its covariance. HERA is a survey mission, which means that the estimation of Didymos’ dynamical parameters is the main scientific purpose. Therefore, in this case, a successful navigation strategy is also one that allows for the dynamical parameters best estimation. The performance on the dynamical parameters estimation can be assessed by the covariance of each parameter’s knowledge. The estimated parameters are: Ephemerides, Gravitational Parameter and Centre of Mass, all for both Didymain and Didymoon.

3. How is the parameters’ performance in the case of independent navigation?
This will be answered further on, where the results of an independent navigation strategy are shown.

4. How is the parameters’ performance if each spacecraft’s state and the estimated parameters are integrated in one single ground filter?
This will be answered further on, where the results of an integrated navigation strategy are shown.

5. Are there improvements from the independent to the integrated navigation strategy?
This will be answered in the end of this section, where the results of both navigation approaches will be compared and discussed.

In order to assess the navigation performance of both HERA and Juventas when an independent strategy is applied, two simulations were run: HERA independent simulation and Juventas independent simulation.

4.1. HERA independent simulation
Figure 3 shows the trajectory followed by HERA mothercraft, alongside with its nominal trajectory. The longer arc corresponds to the transition between ECP and DCP and two manoeuvres can be noticed at the edges, where the trajectory changes abruptly. The origin of the 3D plot corresponds to Didymain’s centre.

Figure 3: HERA Trajectory, real world and nominal. The longer arc is the transition between ECP and DCP and two manoeuvres are represented by the edges in each line. Independent navigation, Baseline results.
Figures 4 and 5 represent the error between real and estimated states. From the perspective of performance evaluation, it is important that the performance falls inside $3\sigma$, although not critical. The convergence of the SRIF can be verified by the fact that the error is kept inside the $1\sigma$ limit during most of the simulation. In Figure 5, an increase in the sigma and error values is noticeable at 3 days and 7 days, which are the epochs of the manoeuvres. The navigation $1\sigma$ is kept around 40 m in position and around 0.2 mm s$^{-1}$ in velocity.

Table 1 represents Didymain’s ephemerides estimation initial sigma, in cartesian coordinates. The final $1\sigma$ values of Didymain’s ephemerides errors are displayed in Table 2. Comparing initial and final $1\sigma$ values, it is noticeable that the estimation improves for some coordinates but it gets worse for others. Since the initial errors for DCP are defined as the final estimation of ECP, one possible reason for the worsening of part of the estimation might be related to an optimistic set of results from ECP. Also, in the particular trajectory of DCP, it is possible that a more precise estimation of Didymain’s ephemerides is not achievable.

Table 3 represents Didymoon’s ephemerides estimation initial sigma, in orbital coordinates [SMA, ECC, INC, RAAN, OMG, MEAN0], which correspond to [Semi-major Axis, Eccentricity, Inclination, Right Ascension of the Ascending Node, Argument of Perigee, Mean Anomaly at reference epoch and Reference Epoch in MJD2000]. The final $1\sigma$ values of Didymoon’s ephemerides errors are displayed in Table 4. During DCP simulation, the estimation improves for every coordinate.

<table>
<thead>
<tr>
<th>Table 1: Didymain’s ephemerides errors, $1\sigma$ initial values</th>
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<tbody>
<tr>
<td>$x$ [m]</td>
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<td>$y$ [m]</td>
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<td>$z$ [m]</td>
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<th>Table 2: Didymain’s ephemerides errors, $1\sigma$ final values</th>
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<tr>
<td>$x$ [m]</td>
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<td>$y$ [m]</td>
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<td>$z$ [m]</td>
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<tr>
<th>Table 3: Didymoon’s ephemerides errors, $1\sigma$ initial values</th>
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<tr>
<td>SMA [m]</td>
</tr>
<tr>
<td>ECC</td>
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<td>INC [°]</td>
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<tr>
<th>Table 4: Didymoon’s ephemerides errors, $1\sigma$ final values</th>
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<tr>
<td>SMA [m]</td>
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<tr>
<td>ECC</td>
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<td>INC [°]</td>
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Didymain and Didymoon’s gravitational parameters ($\mu$) estimation started with sigma values of 5% for Didymain’s gravitational parameter and 0.4% for Didymoon’s. The error and sigma values are estimated as a percentage of the “real” value of the estimated parameter. The final $1\sigma$ values are
0.1566% for Didymain’s gravitational parameter and 0.3722% for Didymoon’s. It is noticeable that Didymain’s gravitational parameter estimation improves considerably. Didymoon’s gravitational parameter estimation, however, has no considerable improvement.

Table 5 represents Didymain and Didymoon’s centre of mass estimation initial sigma. The final estimation 1σ values are displayed in Table 6.

Table 5: Didymain and Didymoon’s centre of mass, 1σ initial values

<table>
<thead>
<tr>
<th>Didymain</th>
<th>Didymoon</th>
</tr>
</thead>
<tbody>
<tr>
<td>x [m]</td>
<td>0.5</td>
</tr>
<tr>
<td>y [m]</td>
<td>0.5</td>
</tr>
<tr>
<td>z [m]</td>
<td>5</td>
</tr>
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Table 6: Didymain and Didymoon’s centre of mass, 1σ final values

<table>
<thead>
<tr>
<th>Didymain</th>
<th>Didymoon</th>
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<tbody>
<tr>
<td>x [m]</td>
<td>0.4731</td>
</tr>
<tr>
<td>y [m]</td>
<td>0.4740</td>
</tr>
<tr>
<td>z [m]</td>
<td>3.2720</td>
</tr>
</tbody>
</table>

4.2. Juventas independent simulation

Figure 6 shows the trajectory followed by Juventas CubeSat, alongside with its nominal trajectory. The origin of the 3D plot corresponds to Didymain’s centre.

Juventas does not estimate any dynamical parameter if independently navigated. Therefore, to assess the navigation filter performance in this scenario, only the estimates of Juventas’ position and velocity are available.

Figures 7 and 8 represent the error between real and estimated states. The convergence of the SRIF can be verified by the fact that the error is kept inside the 1σ limit during most of the simulation and is kept inside the 3σ limit during all the simulation. However, a significant oscillation is verified and, although the error can be considered low for both position and velocity, the estimation does not show a sign of improvement with the course of the simulation. The navigation 1σ is kept around 70 m in position and around 3 mm s⁻¹ in velocity.

4.3. Integrated Navigation Performance

The integrated navigation strategy can be evaluated by running a simulation of both spacecraft simultaneously. The inputs are the same as for the independent runs. Figures 9 and 10 show the trajectory followed by each spacecraft, alongside with their nominal trajectories.

Figures 11 and 12 represent the error between real and estimated states of HERA. The good performance of the SRIF is verified by the fact that the error is kept inside the 1σ limit during all of the simulation. In Figure 12 an increase in the sigma and error values is noticeable at 3 days and 7 days, which correspond to manoeuvre epochs. The navigation 1σ is kept around 9 m in position and 0.05 mm s⁻¹ in velocity.

Figures 13 and 14 represent the error between
real and estimated states of Juventas. The good performance of the SRIF is verified by the fact that the error is kept inside the 1σ limit during most of the simulation. Contrary to what was observed in Figure 7 and Figure 8, the error and sigma are now more stable and an improvement in the estimation is noticeable throughout the simulation. The navigation 1σ is kept around 8 m in position and 0.3 mm s⁻¹ in velocity.

Didymos estimated dynamical parameters have the same initial 1σ values as the HERA independent run, and so Didymain's ephemerides initial sigma is represented in Table 1, Didymoon's ephemerides in Table 3 and Didymain and Didym-
Figure 12: Filter’s performance on HERA’s state estimation: velocity error and $1\sigma$. The error is kept below $1\sigma$ during all of the trajectory. Integrated navigation, Multi-spacecraft results.

Figure 13: Filter’s performance on Juventas’ state estimation: position error and $1\sigma$. The error is kept below $1\sigma$ during most of the trajectory. Integrated navigation, Multi-spacecraft results.

Figure 14: Filter’s performance on Juventas’ state estimation: velocity error and $1\sigma$. The error is kept below $1\sigma$ during most of the trajectory. Integrated navigation, Multi-spacecraft results.

The final $1\sigma$ values of the centre of mass estimation improves for some coordinates but it gets worse for others, as was observed in HERA’s independent simulation. The possible justification for this is the same as in the independent case: optimistic set of results from ECP or a more precise estimation of Didymain’s ephemerides is not possible.

Table 7: Didymain’s ephemerides, $1\sigma$ final values

<table>
<thead>
<tr>
<th>$x$ [m]</th>
<th>$v_x$ [m s$^{-1}$]</th>
<th>$1\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3.535 \times 10^4$</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>$3.681 \times 10^4$</td>
<td>0.024</td>
<td></td>
</tr>
<tr>
<td>$7.849 \times 10^4$</td>
<td>0.050</td>
<td></td>
</tr>
</tbody>
</table>

The final $1\sigma$ values of Didymoon’s ephemerides are displayed in Table 8. Comparing initial and final sigma values, it is noticeable that during DCP simulation, the estimation improves for every coordinate.

Table 8: Didymoon’s ephemerides, $1\sigma$ final values

<table>
<thead>
<tr>
<th>$SMA$ [m]</th>
<th>$RAAN$ [°]</th>
<th>$ECC$</th>
<th>$OMG$ [°]</th>
<th>$MEAN$ [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.218</td>
<td>0.0027</td>
<td>0.0010</td>
<td>0.0072</td>
<td>0.0072</td>
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</tbody>
</table>

The final $1\sigma$ values of the gravitational parameter estimation are $0.0395\%$ for Didymain’s and $0.3735\%$ for Didymoon’s. Comparing initial and final sigma values, it is noticeable that Didymoon’s gravitational parameter estimation improves considerably. Didymoon’s gravitational parameter estimation, however, has no considerable improvement, as noticed in HERA independent simulation.

The final $1\sigma$ values of the centre of mass estimation...
4.4. Comparison between independent and integrated navigation

The main objective of this work can be wrapped up in the answer to the question "Are there improvements from the independent to the integrated navigation strategy?". In order to construct a grounded answer, the two navigation strategies were analysed.

The navigation filter performance for HERA and Juventas, run independently, was presented in Figures 4 to 8. The position and navigation estimation for both spacecraft was sufficient to achieve the mission objectives. However, it was evident that Juventas’ state estimation could be further improved, since it presented some oscillations and no improvement throughout the trajectory.

Regarding the dynamical parameters estimated on HERA’s simulation, the independent strategy delivered satisfactory results for every parameter.

Then, the performance for an integrated, multi-spacecraft strategy was described. In the case of HERA, the position estimation error decreased by 77.5%, from an average value of 40m to 9m and the velocity estimation error decreased by 75%, from 0.2mm s$^{-1}$ to 0.05mm s$^{-1}$.

It was in the Juventas’ state estimation, however, that the biggest improvements were verified. The position estimation error decreased by 88.6%, from an average value of 70m to 8m and the velocity estimation error decreased by 90%, from 3mm s$^{-1}$ to 0.3mm s$^{-1}$. Also, not only the errors decreased, as it is clear from Figures 13 and 14 that the integrated strategy has provided a smoothing to the Juventas’ state estimation results.

The state estimation improvements were expected and can be justified by the increase in observability that the multi-spacecraft approach provides, without a disproportionate increase in the state vector dimensions.

When comparing the filter’s performance on dynamical parameters estimation, it is evident that the values do not change considerably between the two navigation approaches. An exception is the estimation of the $z$ coordinate of both Didymain and Didymoon's centre of mass. This can be possibly explained by the addition of Juventas’ altimeter measurements.

Considering all these comparisons, it can be said that a multi-spacecraft navigation strategy improves the position and velocity of both HERA and Juventas, with a stronger impact on Juventas’ state estimation and without considerable changes in the Didymos’ dynamical parameters estimation.

5. Conclusions

HERA mission’s current navigation approach considers an independent navigation for HERA and Juventas. An alternative strategy, here called a “Multi-spacecraft navigation strategy”, was successfully developed.

A pre-existing mission analysis software was further developed and validated in order to allow for a navigation analysis of multiple spacecraft simultaneously. Validation of the software was made possible by comparing the results from the updated version with those of already available scenarios run on a previously validated version of the software.

The updated version of the software enabled the study of a 9-days scenario of the mission’s DCP phase, with a simulation that included measurements acquisition, manoeuvres, both spacecraft’s state estimation and dynamical parameters estimation on a ground SRIF.

By the parallel analysis of the independent and the multi-spacecraft navigation strategies, it was concluded that the second leads to both spacecraft’s state estimation improvements. The dynamical parameters, however, are identically estimated with any of the strategies.

The performed work took in consideration that both HERA and Juventas would be navigated with a ground filter only. A scenario where an on board filter would be used, together with the ground filter, could be analysed in order to confirm if the multi-spacecraft still brings advantages on the spacecraft’s state estimation.

Although offering some advantages concerning HERA and Juventas’ state estimation, a multi-spacecraft navigation strategy introduces a higher risk of failure to the mission. HERA cannot compromise its mission objectives due to a Juventas’ failure. Future work could focus on testing a scenario where Juventas faces either an actuator or sensor failure in order to assess these failures’ impact on HERA’s navigation performance.

The mission analysis software was updated in order to simulate several spacecraft simultaneously and not necessarily only two. Therefore, the multi-spacecraft strategy can be tested for a scenario where HERA is navigated together with Juventas and Milani. Recently, Milani was approved for funding and its inclusion in a navigation strategy is a natural next step.

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**Table 9:** Didymain and Didymoon’s centre of mass, 1σ final values

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<thead>
<tr>
<th></th>
<th>Didymain</th>
<th>Didymoon</th>
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<tbody>
<tr>
<td>$x$ [m]</td>
<td>0.4586</td>
<td>0.4891</td>
</tr>
<tr>
<td>$y$ [m]</td>
<td>0.4581</td>
<td>0.4894</td>
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<tr>
<td>$z$ [m]</td>
<td>1.248</td>
<td>1.575</td>
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References


