Precise orbit determination of the LICIACube deep space CubeSat

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Abstract – LICIACube was the first Italian CubeSat ever flown in deep space. It represented the contribution of the Italian Space Agency to the Asteroid Impact and Deflection Assessment international collaboration, in the framework of the NASA Double Asteroid Redirection Test (DART) mission. Thanks to its small size, LICIACube took advantage of the DART cruise to the Didymos asteroid system, stowed on a piggyback dispenser, until its arrival to the vicinity of the asteroid system. LICIACube was released on September, 11th 2022, 15 days before the planned DART impact on the asteroid secondary, Dimorphos. Its primary aim was to provide close observations of the short-term effects of the intentional DART crash on the surface of an asteroid. After its release, in order to achieve the optimal observation point to document the impact, LICIACube was independently navigated by two different teams, the Radio Science and Planetary Exploration Lab of the University of Bologna, and the NASA Jet Propulsion Laboratory. Thanks to the acquired data, LICIACube was able to document the DART impact by light magnitude peak, the shape and evolution of the ejecta cone, and an overview of the Dimorphos hidden side, providing key information for the characterization of the kinetic impactor technique for asteroid deflection.

The operative navigation of the LICIACube probe relied on the classical range and range-rate observables, acquired using the two-way X/X communication link between the antennas of the Deep Space Network and LICIACube, enabled by the IRIS coherent transponder. Unfortunately, during the nominal operations, the narrow-angle camera LEIA (LICIACube Explorer Imaging for Asteroid) experienced an issue with its lenses causing defocused images. Therefore, dedicated optical navigation pictures were not available during the operations due to a rescheduling of the activities, and therefore the Orbit Determination (OD) only exploited radiometric observables. In this work the operative dataset is completed with the implementation of optical observables, retrieved from the scientific images acquired by the wide-angle camera LUKE (LICIACube Unit Key Explorer) in proximity of the flyby. Such a limited set of pictures cannot completely upset the operative results, rather they increase the precision and the robustness of the existing OD solution to aid the scientific analyses.

I. INTRODUCTION

LICIACube [1] was a 6U CubeSat that took part to the NASA's DART mission in the framework of the Asteroid Impact and Deflection Assessment (AIDA) international collaboration with ESA for planetary protection. DART aimed at assessing the feasibility of asteroid deflection technique through a kinetic impact on Dimorphos, the moonlet of the Didymos binary asteroid, to modify its trajectory relative to the primary. In this context, its companion CubeSat, LICIACube, was fundamental to acquiring in situ images of the impact and its short-term effects, in particular the developed ejecta cone and the shape of the non-impacted hemisphere. Other images of the impact are available from both ground and space observers (Hubble, JWST, ground-based telescopes), but LICIACube pictures offer a closer insight of the scene. The collected images revealed fundamentals to support the modeling of the ejecta cone and improve the evaluation of the impact kinetic energy [2,3,4,5].

The 11-month trip of the CubeSat to the Didymos system was demanded to the DART probe, which carried LICIACube inside a piggyback dispenser until its release in the proximity of the asteroids.

II. SPACECRAFT

LICIACube was the first European CubeSat ever flown in deep space, the second worldwide after the JPL's MARCOs in 2018 [6]. LICIACube was funded by the Italian Space Agency and entirely designed and manufactured in Italy by the space company Argotec with the scientific coordination of the National Institute of Astrophysics (INAF). The Italian team includes the Polytechnic of Milan in charge of the mission analysis, the University of Bologna (UBO) for the Orbit Determination (OD) and Navigation (NAV).

The spacecraft consisted of a 6U CubeSat with extensible solar panels and weighted about 13kg. It was equipped with a VaCCO cold gas propulsion system powered with R-236fa inert gas, consisting of a main nozzle for the maneuvers and 4 slanted secondary nozzles for attitude stabilization. The tank was separated from the nozzle by the presence of a plenum and the firing valves.

The spacecraft was equipped with a JPL's IRIS radio capable of supporting TMTC and coherent X-band Doppler and ranging compliant to the deep space standard currently supported by the NASA Deep Space Network (DSN) and ESA ESTRACK. The signal was received and transmitted through the four patched antennas mounted on two opposite sides of the probe.

The primary payload consisted of two optical cameras: a narrow-angle catadioptric camera called LEIA (LICIACube Explorer Imaging for Asteroid), and a wide-angle RGB camera called LUKE (LICIACube Unit Key Explorer). The parameters of the optical payload are summarized in [1]. For this paper tasks, we will focus on LUKE, a 2048x1088px RGB imager with a FOV=±5.0°.

III. MISSION DESCRIPTION

A. Navigation requirements

The navigation requirements were derived from the high-level scientific requirements, namely the imaging of the ejecta plume generated by the DART impact, the crater, and the non-impacted Dimorphos hemisphere. Navigation requirements were therefore set to be verified at 99-percentile:

- **RQ001** The Closest Approach (C/A) distance from Dimorphos shall be between 40 km and 80 km. The lower boundary was set to avoid ejecta impact risk, the upper to provide a suitable ground resolution of the imagers.
- **RQ002** At the camera locking time (C/A-200s), Dimorphos shall be inside the LEIA Field of View.
- **RQ003** The pointing error between the DSN and the probe shall be lower than the DSN antennas half-power beamwidth, to ensure the link can be established. This results in a maximum pointing error of 0.017 deg [7].
- **RQ004** The Closest Approach to Dimorphos shall occur not later than 200s from the DART impact, to observe the developed ejecta cone.
- **RQ005** The Sun Phase Angle between Dimorphos and LICIACube shall lie between 45 and 70 deg to have the correct illumination.

B. Timeline

The Concept of Operations (ConOps) was designed in advance, together with the LICIACube and DART teams and the DSN scheduler. The trajectory was designed to meet the mission goals but also to ensure the probe's safety and the capability to reconstruct and control its trajectory. The design process took into account two fixed conditions: the release from DART and the B-plane aimpoint. From the release, LICIACube was independently navigated toward Didymos to reach the optimal position for the observation of the impact. Due to the very high speed of DART with respect to Didymos at release (about 6.5 km/s), LICIACube would not have had the thrust capability to enter into orbit around the Didymos system. Hence, a single high-speed flyby was planned to acquire all the images required to achieve the mission goal. Preliminary studies [8] demonstrated the necessity of a precise delay between the DART impact and the LICIACube closest approach to maximize the scientific return, allowing for suitable development of the ejecta cone without allowing particles to be too far. Since increasing the delay directly affected the required distance from Dimorphos, to limit the risk of particle strikes, a trade-off was needed between safety, cone expansion and ground resolution. Finally, the design of the B-plane set the aimpoint at 55 km distance from Dimorphos and 167 s after DART's impact.

The trajectory was consequently designed to be robust against deviations from the baseline due to uncertainties, poor characterization of propagation models, and possible misfiring. This latter was particularly important in light of the MARCOs lessons learned and the tight timeline between the release and the system flyby, leaving little time to debug and recover the propulsion system failure. The nominal ConOps was described in detail in [9]. A set of three Orbital Maneuvers (OMs) were set to control the LICIACube state on the B-plane at the flyby, all of them designed in a closed loop. An additional calibration maneuver (CAL1) was foreseen on day 1 as a firing test for the propulsion system. Among the OMs, the first one (OM1) was provided as a targeting maneuver to address the B-plane aimpoint and cleaning out the trajectory deviation mainly provided by the dispenser release. The remaining OM2 and OM3 were intended as cleanup maneuvers to control any trajectory deviation. Each maneuver has a backup attempt in the following ground pass to increase robustness for the execution of the maneuver.

During this "approach" phase, the ground link was scheduled to guarantee two contacts per day with the DSN, with a duration of about 2 hours each. Range and Doppler measurements were assumed to be available at each pass, except for the first one where only Doppler was acquired to leave the maximum bandwidth for the telemetry download. Opportunity optical navigation images of the Didymos system were supposed to be acquired twice per day, from C/A-12d to C/A-3d. After the flyby, the communication coverage was planned once per day to download the acquired data without any particular maneuver criticality, using the tracking data for trajectory reconstruction purposes.

Maneuvers Data Cut-Offs (DCOs) were set to guarantee about 48 hours to the entire NAV process, which include not only the OD reconstruction and the corrective maneuvers calculation by each navigation team, but also their comparison, implementation, testing, and uplink.

C. Operations

The CubeSat was released on the September 11th, 2022 about 15 days in advance of the DART planned impact. The release of LICIACube was performed nominally as time-tagged. Soon after, the spacecraft entered in safe mode until, after 4 hours, it was commanded back to its operational state. Radiometric data acquired before the complete stabilization of the spacecraft were deemed not reliable, therefore all data before 17:22 of September 12th were discarded. To ensure a correct commissioning of the spacecraft, the project decided to delay of 24 hours the CAL1 and OM1, allowing the collection of sufficient data for a precise reconstruction of the flown trajectory and the targeting to the aimpoint.

CAL1 was successfully executed on mission day 2, providing an important insight into the propulsion system, which has not been tested on the ground due to the lack of a dedicated test campaign. CAL1 has proven the propulsion system to be quite accurate and in line

with the project assumptions. Given two tracking passes after the CAL1, the first Data Cut-Off (DCO) was reached for the OM1 calculation. This represented a critical mission point as it represented the largest maneuvers, with the longest propagation time to the aimpoint. That is, the larger the error in this OM1, the larger would have been the following corrections required. The execution of the OM1 did not face any particular issues, and so was the OM2. At the time of the DCO-OM3, the results showed a complete compliance with the requirements of the free propagated trajectory, therefore the project canceled the OM3.
Table 1 summarizes the main navigation events of the LICIACube mission along with relevant comments and the solution releases.

Table 1. List of the mission events.

Event	**Epoch**	**Notes**
Release	11-SEP-2022 23:15:10 ET	
CAL1	13-SEP-2022 18:01:56 ET	delayed 1 day
DCO1	14-SEP-2022 19:34:19 ET	delayed 1 day, solution UBO001
OM1	16-SEP-2022 17:59:54 ET	delayed 1 day
DCO2	18-SEP-2022 18:45:13 ET	solution UBO002
OM2	20-SEP-2022 17:59:58 ET	
DCO3	23-SEP-2022 20:39:48 ET	solution UBO003
OM3	25-SEP-2022 18:00:00 ET	aborted
DART IMPACT	26-SEP-2022 23:15:32 ET	from DART team
C/A	~167s after DART IMP.	flyby

Fig. 1 shows the tracking schedule, reporting all the received Doppler and range data acquired until the 28th of September, and highlighting the most relevant mission events.
The collection of optical pictures devoted to the navigation was not performed during the operations because the narrow-angle camera, LEIA, faced a misalignment of the lenses, causing defocused images and preventing their application for navigation.

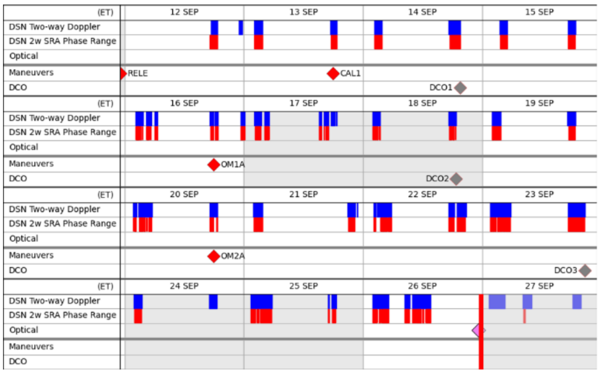

Fig. 1. Mission timeline showing the received passes (Doppler and range) and the maneuvers.

IV. Navigation analysis

The OD analysis was carried out using the software Mission-analysis and Operations Navigation Toolkit Environment (MONTE) [10]. During the operations, the reconstruction and propagation of the trajectory, along with the estimate uncertainties, was necessary to verify the compliance to the requirements and correct the orbit whenever needed. The post-operation reconstruction, which is the focus of this work, has been released to support the scientific investigation, providing the most accurate reconstruction of the state at the time of acquisition of the scientific pictures. To this aim, the images acquired by LUKE during the science phase were also employed. However, in the neighborhood of the C/A, the pointing to Dimorphos required high rotational speed, causing the star tracker to unlock. The attitude during this brief phase (about 5 minutes) was then reconstructed using only the IMU, causing a degradation in the accuracy of the attitude reconstruction. Comparing the real images to simulated ones we found an inconsistency in the position of Didymos and Dimorphos in the picture, incompatible with the estimated trajectory uncertainty. Therefore, we needed to correct the camera pointing along with the orbit reconstruction. If stars were visible in the pictures, the pointing was corrected aligning the stars to their positions from catalogues. Then, the radiometric and star-corrected images were used to evaluate the spacecraft trajectory, while the other images were used to correct the camera pointing. In this way, it was possible to provide a consistent set of trajectory and attitude to feed the scientific analyses.

A. Dynamical model

The dynamic of the probe was mainly driven by gravitational accelerations due to the Solar System bodies. After an assessment of the accelerations magnitude, a model was built including the Newtonian point mass acceleration of all the planets of the Solar System, including Pluto, the Moon, and the asteroids; the relativistic perturbation given by the Sun, Jupiter, and the Earth; and the Solar Radiation Pressure (SRP) acceleration based on a simplified probe's shape model.

The gravitational force of Didymos was negligible given the large distance and speed of the spacecraft flyby. The maneuvers were modeled as an instantaneous variations of the probe velocity and a consequent mass variation according to the Tsiolkovsky' rocket equation.
Stochastic accelerations were also implemented as 8 hours time-batched white random noise with an *a priori* standard deviation of 10^{-12} km/s^2, to account for all the unmodelled accelerations.
The trajectories of the asteroid system were assumed from the DART team solutions, namely Didymos Barycenter s205 and Dimorphos s542.

B. *Observable dataset*

The observable dataset consisted of radiometric data and optical data. The radiometric data were the two-way coherent range and Doppler collected by the 34m and 70m DSN antennas, and the ESTRACK 35m antennas. Doppler data were provided every 1sec, but has been compressed to 60s after a quality evaluation and outliers cleaning.
Considering the unavailability of proper optical navigation pictures, we decided to focus on the scientific images taken close to the flyby to establish if any useful information could be extracted. Among the 228 LUKE images, 4 high-exposure images, taken between the 23:15:36 and the 23:16:00 (UTC) of the 26th of September, were found to contains a detectable starfield. These images can be used to constrain the trajectory by setting optical observables with a pointing coming from the stars instead that from the reconstructed attitude. On the other hand, 58 pictures were selected to be used for the pointing correction. These images were collected and the centroid extracted by hand, since the strong illumination of the ejecta plume poses severe restrictions in terms of the detectability of the bodies.
The optical observables have been weighted according to the distance, considering that the centroid finding error in the pixel is larger as the apparent diameter of the bodies increases, as:

$$\sigma = \sqrt{\sigma_0^2 + \left(\sigma_p \cdot d_a\right)^2} \tag{1}$$

where σ_0 is 3.0 px for both bodies, σ_p is 0.08 for Didymos and 0.4 for Dimorphos, and d_a is the apparent body diameter (in pixel). The resulting weighting function for the two asteroids is shown in Fig. 2.
It is also worth noting the limitations of target identification: the plume glare increases the difficulty in the identification of Dimorphos, whereas the partial illumination of the primary introduces a threat in the manual centroid finding of Didymos.

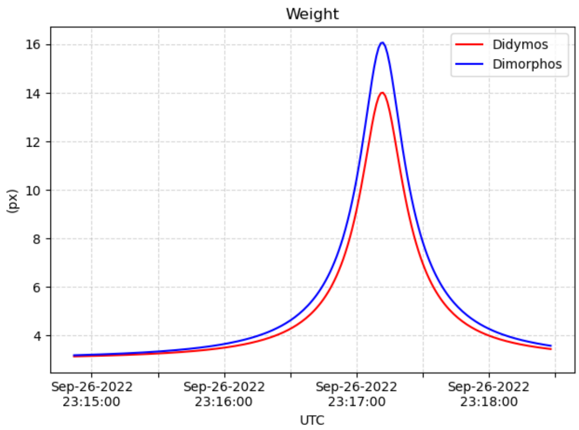

Fig. 2. Weighting functions for Didymos (red) and Dimorphos (blue)

C. *Filter setup*

Model parameters were estimated in MONTE using a weighted least square batch filter. The estimated parameters included the spacecraft state at the release from DART, the orbital maneuvers, the SRP scale factor, the range biases per pass, and the transponder-dependent range delay, fixed for the entire duration of the mission. In addition, 3 pointing errors were estimated for each picture, expressed in the LMN camera frame [11].
Consider parameters included station locations, media corrections, and Earth Orientation Parameters (EOP). In addition, we also set as consider parameters the GM of the asteroids, and the states of Didymos Barycenter and Dimorphos because preliminary simulations demonstrated we were not able to achieve results better than the DART team for these parameters.

V. RESULTS

The post-operation solution, obtained with the setup explained above and referred to as UBO007, is compatible with the last solution released during operations, UBO006. The difference at the C/A is below 150 m and 0.25 mm/s, in terms of position and velocity along the orbit, and about 25m on the B-plane. The comparison on the B-plane is shown in Fig. 3, where it is clear that the solutions are similar, with a small improvement provided by the additional image information.
The reconstructed distance from Dimorphos center of mass is 57.78±0.31km (1-sigma), slightly larger than the desired distance but still well inside the target area identified by the mission requirements. The reconstructed time of C/A is 26-SEP-2022 23:18:20.88±0.08s ET (1-sigma), 168.15 after DART impact.

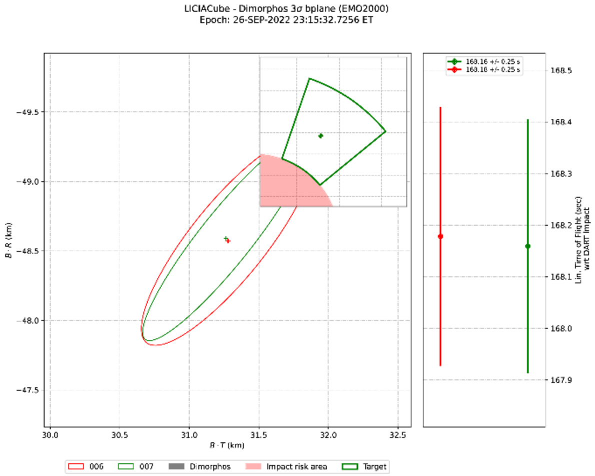

Fig. 3. B-plane comparison between solutions UBO006 and UBO007.

In addition, the estimated picture pointing errors provided important information. Fig. 4 shows the estimating pointing errors per axis in an LMN camera reference frame. In this frame, errors about L are known as clock angle rotations, while M and N provide, respectively, a shift in the vertical and horizontal position of a body in the picture. The pointing error was quite low and steady until the 23:16:30, after which it dramatically increased reaching up to 38 degrees as root sum squared of the components. The largest offsets occurred in axis N which showed great peaks close to a magnitude of 37 degrees.

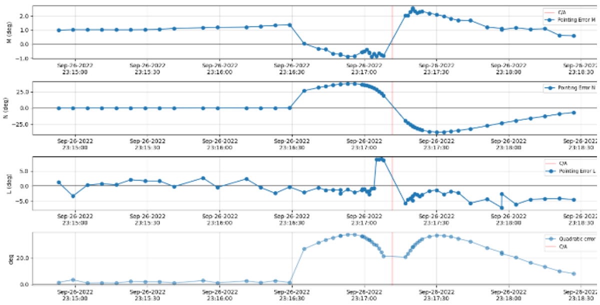
Fig. 4. Picture pointing errors information in the LMN frame. Vertical red lines at C/A epoch.

A. *Validation and discussion*

The proposed approach allowed to compute, in addition to the trajectory, a new attitude file for the timespan covered by the images.

A validation of the computed solution was performed by comparing the real pictures acquired by LUKE and two sets of images simulated using the *shapeViewer* software [12]. In order to assess the improvements of the current reconstruction, synthetic images were generated both for the UBO006, without any pointing correction, and the current UBO007, using the computed attitude file. An example of the comparison is shown in Fig. 5. Noticeably, the modified attitude matched the real scenario much better than the previously available reconstructed pointing, with an error smaller than the weights associated with the image objects.

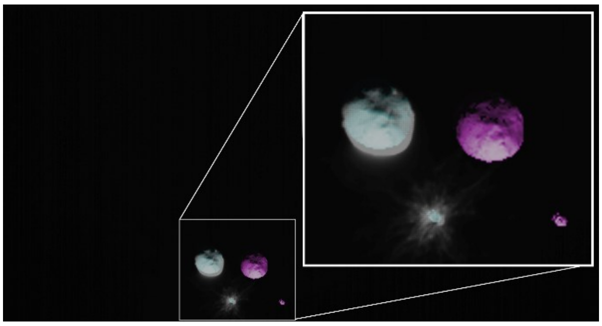
Fig. 5. Example of comparison between the real (white background), simulated previous solution (purple), and simulated current solution (cyan) image obtained for the liciacube_luke_l0_1664234219_00012_01.

Overall, the verification provided by the images demonstrates the importance of attitude correction in matching the real images. This is of particular interest for the scientific exploitation of the pictures rather than for the engineering applications themselves.

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