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ArgoMoon and LICIACube: Italian first missions operated in Deep Space

S. Pirrotta[a]*, G. Impresario[a], E. Bruno[b], F. Cavallo[b], M. Ceresoli[e], B. Cotugno[b], I. Gai[c,d], L. Gomez Casajus [c,d], E. Gramigna [c], M. Lavagna[e], M. Lombardo [c], P. Tortora[c], M. Zannoni[c,d], G. Zanotti[e]

[a] *Italian Space Agency, via del Politecnico snc, 00133 Rome, Italy,* simone.pirrotta@asi.it
[b] *Argotec srl, Via Cervino 52, 10155 Turin, Italy,*
[c] *Università di Bologna, DIN – Aerospace Division, Forlì (FC), Italy*
[d] *Nautilus srl, Viale Giuseppe Fanin, 48, 40127 Bologna, Italy*
[e] *Politecnico di Milano – Aerospace Science and Technology Department, via La Masa 34, 20156 Milano, Italy.*
editor-in-chief@iaamail.org
* Corresponding Author

Abstract

Small satellites are nowadays extremely powerful, flexible and sustainable platforms that can be used to complement the missions usually assigned to larger spacecrafts. Modularity, standardization, intensive use of state-of-the art COTS technologies consent to prepare cheaper missions in shorter timeframes, thus allowing a more frequent access to space environment, including Cislunar and Interplanetary. The Italian Space Agency – ASI promotes, funds and coordinates the national initiatives also in this promising sector, both for national missions and within international cooperation. The first products of this effort are ArgoMoon and LICIACube, both 6U cubesats manufactured and tested for ASI by the Italian company Argotec, which operated as first Italian spacecrafts beyond the Low Earth Orbit. The Light Italian Cubesat for Imaging of Asteroids - LICIACube participated in the NASA Double Asteroid Redirection Test - DART mission, the first active Planetary Defense mission; on September 26th 2022, few minutes after DART's impact on asteroid Dimorphos, LICIACube captured unique images of the impact effects, primarily the plume of ejecta, and the not visible side of the secondary asteroid. ArgoMoon has been injected in cislunar orbit on November 16th 2022 by the NASA Space Launch System - SLS at its maiden flight in the occasion of the "Artemis-1 mission", testing relevant technologies for small satellite in this environment. For both missions, the Mission Control Centre set up in Italy used NASA Deep Space Network - DSN antennas as terminal elements for the communication with the cubesats. The operations have been conducted by a national team lead by Argotec, coordinated by the Agency and the investigation leaders. For both missions, the desired imaging required an accurate target tracking, autonomously managed by the on-board software designed by Argotec, and also guidance along the predicted nominal trajectory, that for LICIACube has been designed, together with the corrective manoeuvres, by Polytechnic of Milan. Navigation based on radiometric observables has been accomplished independently by specialized teams of the University of Bologna and JPL and then compared and adopted. This paper provides a description of the missions' preparation and preliminary outcomes of the missions' operations, with a focus on the main common and specific challenges and the first assessment of the executed activities.

Keywords: cubesat, Deep Space, Operations, Navigation

1. Introduction and missions' description

The current season of Space Exploration of the Solar System benefits of the contribution of small spacecraft to scientific investigation and technology demonstration, usually focusing the mission design towards specific goals, thus mitigating the effect due to the limited on-board resources but at the same time keeping a high level of capabilities and performances. Moreover, the new interest in the access to the Moon orbit and surface generated the growth of launch opportunities also for small satellites as rideshare during the delivery of modules, landers and other elements of large program like NASA's Artemis, Commercial Lunar Payload Services, Lunar Gateway. ASI is currently working to develop a new generation of Italian cubesats, for example through the dedicated national program named "Alcor" started in 2021, but was also working in the past to provide the technical and scientific community with deep space access opportunities to the first small satellites involved in international initiatives beyond the Earth orbits. LICIACube and ArgoMoon are the Italian pathfinder missions that experienced the early operations in such extreme conditions and paved the way to the next generation of interplanetary cubesats under preparation.

1.1 LICIACube in support of NASA DART mission

Near-Earth Asteroids (NEAs) are celestial bodies with a large variety of natures and orbits that are subject to an increasing and intensive monitoring and study, due to their scientific and strategic interest (in fact, they are nowadays considered as potential sources of critical resources), but also because of the risk of their potential impact on the planet Earth and subsequent catastrophic effects. To mitigate this risk, the discipline of Planetary Defense raised with the aim to identify and catalogue near-Earth objects such as comets and asteroids and potentially hazardous objects that could impact Earth and, at same time, to prepare for a potential impact event and also to try to prevent it by active initiatives. In this frame, NASA appointed the Applied Physics Laboratory APL of the Johns Hopkins University in Baltimore to prepare the Double Asteroid Redirection Test - DART mission, based on a spacecraft of about 660 kg used as a kinetic impactor set to deliberately crash on Dimorphos, the moonlet of the Didymos binary system (65803), with the aim to modify its revolution period around the primary body and so validating this as an orbital deflection and active planetary defence technique [1].

The small satellite "LICIACube – the Light Italian Cubesat for Imaging of Asteroids", developed under the Italian Space Agency - ASI management and coordination, has been included in the DART mission, with the main objectives to fly by the asteroid system right after the impact and collect unique pictures of the post-impact scene, in support of the DART mission goals but also to perform dedicated unique scientific investigations [2].
In detail, the objectives of LICIACube mission are:

- To testify DART's impact on Dimorphos;
- To obtain multiple (at least 3) images of the ejecta plume taken over a span of time and phase angle, that, with reasonable expectations concerning the ejecta mass and particle size distribution, can potentially:
  - allow measurement of the motion of the slow (< 5 m/s) ejecta. This requirement is intended as the possibility to acquire images at spatial scale better than 5 m/pixel, with the possibility to distinguish the movements of the slowest particles of the plume by the sequence of images.
  - allow estimation of the structure of the plume, measuring the evolution of the dust distribution;
- To obtain multiple (at least 3) images of the DART impact site with a sufficient resolution to allow measurements of the size and morphology of the crater. These images are expected sufficiently late after the impact that the plume can be reasonably expected to have cleared;
- To obtain multiple (at least 3) images of Dimorphos showing the non-impacted hemisphere, hence increasing the accuracy of the shape and volume determination.

The LICIACube spacecraft has been designed in order to guarantee the objectives to be achieved, in respect of the mission constraints; the performances of the 6U platform have been optimized to allow the desired manoeuvring and attitude control capabilities during the extremely fast flyby of the scene to be imaged. In fact, it was expected for the smallsat to follow DART after the release at a quite similar velocity, so passing at the distance of few tenths of kilometres from the asteroids, with a relative velocity of more than 6 km/s. Propulsion and ADCS subsystem have been selected accordingly among COTS units on the market, while a dedicated On-Board Computer & Data Handling - OBC&DH unit has been developed and qualified with the desired functions and performances. In terms of payload, LICIACube is equipped with two imaging cameras:

- LEIA - LICIACube Explorer Imaging for Asteroid, the primary payload, is a catadioptric camera composed of two reflective elements and three refractive elements with a FoV of 2.93 x 2.93 deg, IFoV 25 µrad/px. The optic is designed to work in focus between 25 km and infinity and the detector is a CMOS sensor (CMV4000) with 2048 x 2048 pixel. It is a monochromatic sensor and it is able to operate in the NIR and visible spectral range between the 400 nm and 900 nm;
- LUKE - LICIACube Unit Key Explorer a wide-angle camera, the secondary payload, is the COTS Gecko imager from SCS space, a catoptric camera composed by four refractive element and two reflective elements. The detector is an RGB CMOS sensor (CMV2000) with 2048 x 1088 pixel with a Bayer pattern filter and the lenses with a focal length (70.55 mm) are designed to work in focus between 400 m to infinity. The FoV is 9.15 x 4.8 deg and IFoV 78 µrad/px with a spatial scale about 4 m/px at 51 km. The detector is interfaced with the NanoCU, the data elaboration unit of the camera, through a flexible PCB, to minimize any mechanical stress. A SPI interface is used to connect the NanoCU to the OBC&DH and for payload commanding and telemetry. Moreover, the hardware is capable of directly integrating the image data to the combined mass storage.

Both cameras were intended to capture pictures during the scientific phase of the flyby, while LEIA's pictures were also used on board by the Autonomous Navigation System – ANS to control in real-time the satellite attitude and to maintain the pointing towards the targets for the whole duration of the observation.

For the download of scientific images and telemetries, the Ground Segment of the mission includes the NASA Deep Space Network antennas for the direct link to the cubesat. The DSN terminals were then connected to the ASI Mission Control Centre located in Italy at Argotec premises (Figure 1). Moreover, the archiving and processing data have been managed at the ASI Space Science Data Centre, where the Science operation Centre was established [3].

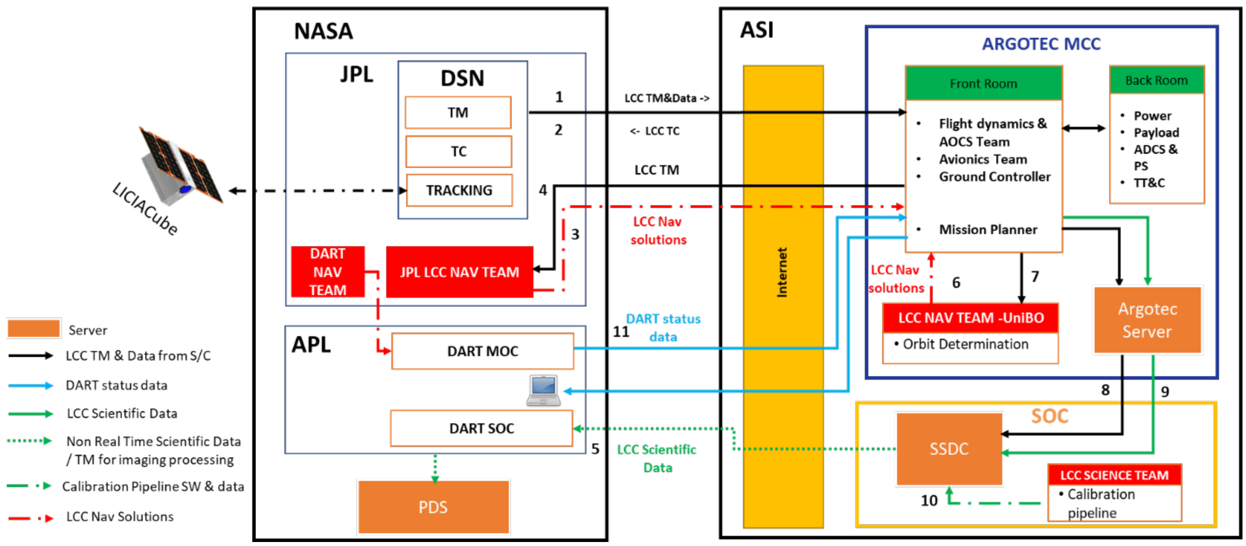

Figure 1 – LICIACube Ground Segment Architecture

The design, manufacturing, testing and operations of the space and ground segment elements have been performed by the Italian firm Argotec under ASI management, while a wide scientific team supported the investigation preparation with impact modelling simulation and data analysis and interpretation, under the coordination of the National Institute of Astrophysics INAF. The engineering teams of Polytechnic of Milan and University of Bologna were in charge of trajectory design and optimization and the orbit determination and navigation, respectively.

LICIACube flight segment, meaning the 6U cubesat and its dispenser and the External Battery Changer for the power supply during the cruise phase, has been integrated and tested during the last months of 2020 and the first of 2021. The system has been accepted by ASI and then delivered to APL in august 2021; on 8th September 2021 the system has been integrated on the DART spacecraft (Figure 2).

Figure 2 – LICIACube integrated on DART spacecraft

1.2 ArgoMoon on board of Artemis1

In order to increase the scientific and technological return of the Artemis I mission, NASA has directed the SLS Program to accommodate Secondary Payloads on board of the Space Launch System - SLS, to be deployed together with the Orion capsule; among them, ArgoMoon cubesat has been selected as European contribution [4]. The spacecraft is a 6U platform designed by Argotec under the management and coordination of the Italian Space Agency - ASI, accommodated on SLS to be released in orbit with the objectives of:

- Capturing pictures to document the status of the SLS Interim Cryogenic propulsion Stage – ICPS, the upper stage designed to propel Orion capsule to the Moon, after the deployment of the Orion capsule and of the other secondary payloads released by SLS,
- Capturing pictures of the Earth and the Moon,
- Validating guidance and autonomous targeting technology, and
- Verifying a new technology for power distribution, satellite data acquisition and processing suitable for nanosatellite volume.

ArgoMoon design is based on the Hawk platform, designed by Argotec following an "all in-house" concept. Some of the main features of this platform are the focus on rad-hard subsystem components, a high level of autonomy capability supported by artificial intelligence, and the scalability towards larger bus sizes.

Early after deployment, ArgoMoon has been designed to perform SLS tracking and proximity flight, making use of a complex image recognition algorithm based on artificial intelligence, that analyses the pictures continuously captured by two optical cameras that are the main payloads of the spacecraft. The same set of pictures are part of the mission's results, since they could be used to support the NASA and payload communities in providing information regarding the status of their deployment and the condition of the ICPS as it completes the final phase of its mission. After the early phase of operations in the proximity of ICPS, the mission design foresees a second phase devoted to Earth and Moon imaging and to technological validation [5].

The Mission Control Centre has been prepared to be connected to the Deep Space Network - DSN antennas, while the mission Flight Control Team - FCT guides the orbital operations with in-house developed software. Orbit Determination and Navigation were performed by the same University of Bologna team involved in the LICIACube mission.

ArgoMoon has been prepared for the launch and integrated in the SLS Orion Stage Adapter (Figure 3) on August 19th 2021.

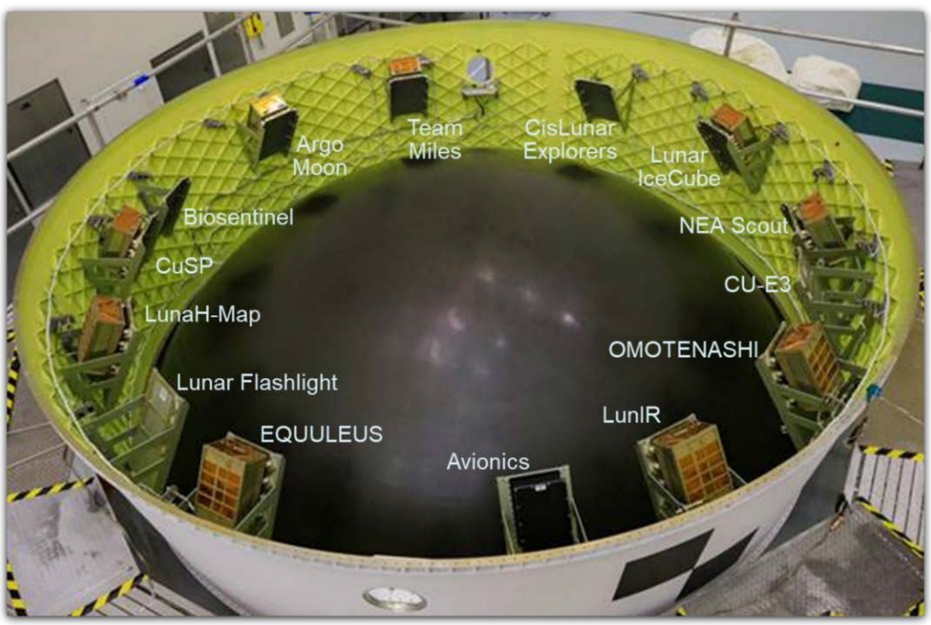

Figure 3 – Artemis 1 Secondary Payloads installed on SLS Orion Stage Adapter
Credits: NASA – Kennedy Space Centre

2. Common challenges and approach to solutions

Both LICIACube and ArgoMoon mission profiles posed similar technological and operational challenges, due to the need of guiding the satellites along extremely precise interplanetary and cislunar trajectories, to be implemented in an optimized but very tight timeline and making use of the limited resources on board of small spacecraft.

For both cases, the trajectory design has been led by a set of requirements associated to the best observation conditions but also considering additional constraints, imposed with the aim to guarantee a safe flight and manoeuvring with very low probability of impact with the materials ejected from the asteroid's surface after DART's impact in the case of LICIACube [6], and the SLS ICPS in the case of ArgoMoon.

To achieve these goals, trajectory design must be supported by an accurate Orbit Determination. The OD process used to estimate the trajectory of these two deep-space cubesats is mainly based on radiometric observables. These observables, namely ranging and Doppler, are acquired deep space stations (for these missions mainly the NASA Deep Space Network, with occasional support by ESA ESTRACK) using the onboard X/X coherent IRIS transponder. In addition, astrometric observations, acquired through the on-board cameras, may be used to support the orbit determination. However, due to the low data rate available and the performances of the cameras, both LICIACube and ArgoMoon OD tasks relie on radiometric observables only. Nonetheless, any optical observable can be used for the a-posteriori orbit reconstruction [7].

A significant source of uncertainty is also due to the thrusters: in fact, in case of poor characterization of the thrusters' real performances in flight, it is quite difficult to provide realistic values for the related accuracy. Also, for this case the low number of manoeuvres does not allow for an accurate in-flight calibration.

The NAV team periodically performed an Orbit Determination analysis and delivered the trajectory reconstruction considering the whole data set until a specific time called Data Cut-Off - DCO. The OD reconstruction is used to compute the necessary trajectory correction manoeuvres using a trajectory differential correction. A suitable amount of time, not less than 48 hours, was allotted between each DCO and the manoeuvre execution, to allow not only for the manoeuvre computation, but also the implementation and testing of the commands

2.1 LICIACube mission scenario and design

LICIACube operations have been designed to start just after the release from the DART spacecraft and to guide the approaching phase of the following 15 days, before being injected into the final trajectory and to execute the scientific acquisition during the impacted asteroid's fly-by. The cubesat reduced the distance from the target until the minimum distance at the Close Approach $d_{C/A}$ and acquired several images of the target impact and non-impact sides, as well as of the plume of materials ejected from the surface just after the DART impact.

The asteroid proximity operation and image acquisition have been scheduled on the basis of the trajectory design and orbit determination constraints. For the trajectory design, the maximum allowable distances at the Close Approach $d_{C/A}$, depending on the expected spatial resolution of the scientific images capable to guarantee the scientific objectives combined with the payload optical features, was set as:

$d_{C/A} < 200$ km for low-speed particles imaging;
$d_{C/A} < 40$ km for crater imaging;
$d_{C/A} < 80$ km for Dimorphos non-impact side imaging;

The minimum threshold for the parameter $d_{C/A}$ has been obtained minimizing the risk of collision with the fastest particles of the plume and respecting the performances of the service module, in particular of the attitude control system ADCS that had to allow an appropriate angular rate to maintain the pointing towards the target keeping the asteroids as much as possible in the centre of the cameras' Field of View, for the whole duration of the fly-by.

Together with spatial parameters, the trajectories have been designed considering the timing of the different phases. In fact, the closest approach should occur with the plume already well developed and visible for the LICIACube cameras, so to be able to reconstruct the evolution of the ejecta dynamics. Hence, the delay time t_{delay}, meaning the epoch of C/A occurrence with respect to the DART impact, was considered as one of the key parameters for the optimization process. The upper limit value of $t_{delay_max} = 200$s has been then derived from the set of mission constraints.

The sequence of the events after the release and satellite commissioning included a first braking manoeuvre (Orbital Manoeuvre 1 – OM1) defined through a deterministic component plus a statistical one, to be determined during the Operations, followed by a set of two corrective manoeuvres (OM2 and OM3) introduced to clean-up the effect of perturbations, mismodelling and execution errors on the final flyby location and time, with magnitude and direction dependent on the deviation of the real cubesat's trajectory with respect to the nominal one. Therefore, OM2 and OM3 are purely statistical manoeuvres. The driving idea were to perform a correction as late as possible, to minimize the effect of deviations after the manoeuvres, while some delay time between correction manoeuvre and flyby was required to be able to cope with contingencies. Furthermore, an excessive delay in the corrective manoeuvre leads to a high ΔV exacerbating the effects of manoeuvre errors on the final flyby uncertainties. A trade-off has then been found by placing two sequential corrective manoeuvres, at T-10d5h and T-1d5h respectively.

To perform a fly-by of a body with relatively large ephemeris uncertainty, during the approach phase optical navigation (OPNAV) plays a crucial role in reducing the uncertainty in the LICIACube relative position. Nevertheless, to maintain a conservative approach, the navigation requirements had to be satisfied using only the classical radiometric observables. Optical measurements were considered just to enhance the a-posteriori orbit reconstruction, given the small gravitational acceleration induced by the Didymos binary system. The dynamical model used in the simulation includes the gravitational acceleration induced by the Solar System planets, the Moon, and the Didymos asteroid. All the manoeuvres have been modelled as impulsive at this first stage of the mission. Moreover, a preliminary analysis had been carried out based on a rough trajectory, in order to assess the perturbations' order of magnitude. The results highlighted that Solar Radiation Pressure (SRP) were higher than any other perturbation by at least one order of magnitude, thus it was the only non-gravitational force considered.

Four different phases were planned:

- During the pre-launch phase several simulations were performed to support Mission Analysis and Platform Design, such as link budget definition, tracking schedule and manoeuvre execution plan. The expected performances of trajectory reconstruction and prediction are assessed through numerical simulations and a realistic model for observables generation [8]. The simulated data considers a conservative level of noise based on available SNR of the platforms at the allocated band;
- During operations, a quasi-real-time OD of LICIACube with respect to Didymos should have been performed. This also would have involved the propagation of the estimated trajectory, along with associated uncertainty, and the assessment of possible Orbit Trim Manoeuvres (OTM);
- During DART post-impact phase, with LICIACube leaving the Didymos system, OD should have been limited to the heliocentric trajectory reconstruction, to ensure the DSN pointing capability to the spacecraft and allow data downlink;
- Activities after mission include a complete a-posteriori OD of LICIACube. Although this is not a primary task, it would be useful to combine all the data available, possibly including also the optical observables collected during the science phase, to determine some scientific parameters of interest of Didymos, such as the Didymos/Dimorphos mass ratio, and the Dimorphos orbit parameters around Didymos.

Once in the proximity of the DART terminal phase and impact on Dimorphos, LICIACube mission was planned to enter in the scientific observations phase. This event was set to happen with a dynamical envelope so quick that at that distance (of roughly 11E06km) from Earth the two-way light travel time made a real-time control of spacecraft states not efficient or even possible. Therefore, a level of on-board autonomy was needed for the main scientific phase. With the satellite following the final approach trajectory, it was the Autonomous Navigation System (ANS) in charge of managing the attitude control to guarantee the pointing towards the targets, and imaging by means of the LEIA and LUKE cameras. The ANS has been designed to make use of the just-captured on board LEIA images and to process them at high speed, allowing the on-board software to identify and keep the different targets in the cameras' FoV; the software was intensively tested and trained with synthetic images during the mission preparation.

The different imaging subphases relative to DART's impact epoch (T0) are depicted in Figure 4:

- the red bar is the time interval dedicated to witness the DART impact;
- the yellow bar identifies the time interval focused on the expanding plume observation;
- the blue bar is the time period dedicated to the surface High resolution imaging of the Didymos system;
- the green bar is the observation phase dedicated to the non-impacted hemisphere;
- the violet bar is the observation time dedicated to the Plume observation at high phase angle.

The strategy for images shooting sequence and the subphases durations have been optimized considering the platform and payload performances and software functions.

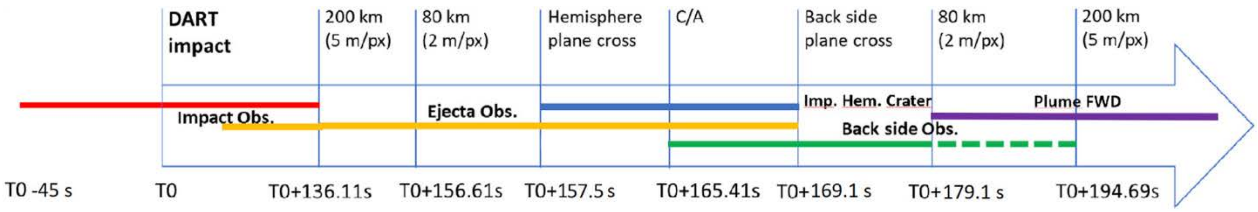

Figure 4 - LICIACube scientific observation phases timeline

The Flight Dynamics (FD) team for LICIACube mission was composed by four main actors, whose cooperation has been fundamental for the successful outcome of the mission.

- Mission Control (MCC) represented by Argotec. MCC was in charge of monitoring and operating the whole spacecraft, receiving the housekeeping telemetry. For the interest of the FD particular attention was put to the AOCS subsystem and the Propulsion unit telemetries. In the process of generating the manoeuvres, MCC has been responsible for translating the requested Δv magnitude and direction into actual telecommands to the spacecraft;
- Navigation (NAV) represented by two teams of University of Bologna and NASA's Jet Propulsion Laboratory. The NAV teams were responsible of performing the Orbit Determination (OD) tasks, thus analysing the tracking data received from the DSN stations. Together with the orbital state, the OD process was able to retrieve also other useful parameters associated to the spacecraft and to reconstruct the manoeuvres performed by the spacecraft. Moreover, shortly before manoeuvre execution, the OD process was used also to re-correct the predicted Δv parameters, to adapt them to the actual flying condition, with the aim of targeting the target point on the B-plane at fly-by;
- Mission Design (MD) represented by the Polytechnic of Milan team. The MD team, was responsible for the generation of the reference trajectories and manoeuvres exploiting the most up-to-date conditions at release from DART. Moreover, during the manoeuvre definition schedule, MD was responsible for performing the conversion of the impulsive corrected manoeuvre to finite burn ones, adjusting also Δv direction, in order to compensate for spurious effects caused by the activation of attitude control thrusters during the manoeuvres;
- Coordination team, represented by the Italian Space Agency (ASI). ASI had the role of coordinating the different entities involved in the FD processes, performing also the critical task of choosing the navigation solution and approving the associated manoeuvre strategy.

The pipeline of the manoeuvre generation is depicted in the following Figure 5. The involvement of the different teams and their specific interfaces exploited during each orbital maneuver generation step are detailed in the following paragraphs.

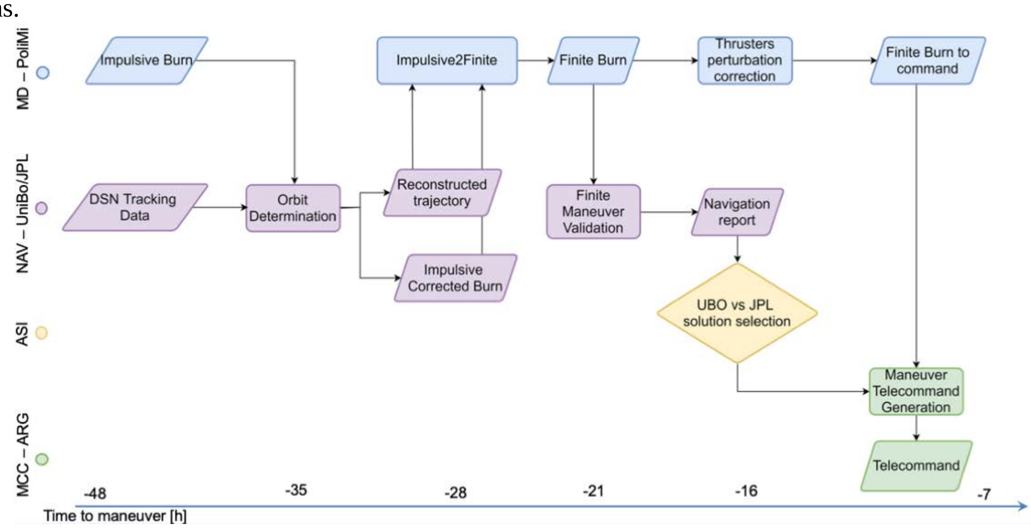

Figure 5 - Manoeuvres generation pipeline

2.2 ArgoMoon mission scenario

The Artemis 1 mission timeline started with the launch of the SLS vehicle from Launch Pad 39B. Shortly before lift-off, all four RS-25 engines on the Core Stage are ignited followed by both SRBs. At approximately two and a half minutes into the flight, both SRBs drop away while the Core Stage continues on for about another six minutes of powered flight. Once Core Stage Main Engine Cut Off – MECO is complete, the remaining spacecraft made up of the ICPS, Orion Stage Adapter, and the Multi-Purpose Crew Vehicle separates from the Core Stage at the Launch Vehicle Stage Adapter and continues to coast until the spacecraft reaches apogee. At this point, the ICPS performs its first burn in order to raise the perigee of the orbit. The spacecraft is expected to then coast in this orbit until it is ready for the Trans Lunar Insertion (TLI) burn. About ten minutes after TLI, the MPCV separates at the OSA and then continues on its course to the Moon using its own propulsion system. The ICPS with the OSA still attached continues to coast for another 30 minutes before it reorients itself for its disposal burn. Following the disposal burn, the ICPS shuts down. Its last act is to send a discrete signal to the SLS Payload Deployment System (SPDS) to activate the SPDS Sequencer and start the countdown to the deployment of the secondary payloads.

ArgoMoon has to be deployed from the ICPS at Bus Stop 1 and just after, automatic deployment of the solar panels is expected. The spacecraft then follows the release path for at least 15 seconds while booting up the system, except for the propulsion subsystem for safety reasons. The ADCS is powered-on immediately when the satellite is released, in order to determine its attitude relative to ICPS and to point the payloads towards it. At 10 minutes since release, the PS is ready to fire, first with cold-gas RCS thrusters only, then with the main LMP thruster. Two relative dynamic maneuvers are planned approach ICPS between 100 m and 1 km. Operational constraints defined by NASA require the satellite to fly further than 100 m from ICPS at all times and within a 35-degree cone around its symmetry axis to avoid capturing detailed images of ITAR equipment. Two main Proximity Maneuvers (PM) are also planned to be executed with the aim to maintain a close and safe distance from ICPS during the first hours after release. At T+10 minutes, ArgoMoon cancels its deployment velocity with respect to ICPS approximately (1.14 ± 0.07 m/s) via a braking maneuver using only its 4 cold-gas RCS thruster. Between T+20 minutes and T+30 minutes, the main thruster, equipped with LMP-103S/LT propellant, are used for a shorter burn to approach ICPS again. A third maneuver (PM-3) might be included to ensure ArgoMoon stays out of the Keep-Out Zone (KOZ).

After proximity operations and ICPS imaging, ArgoMoon mission profile includes a series of Orbital Trim Maneuvers (OTMs) to target a specific flyby of the Moon, aimed at closing its trajectory into a geocentric profile and remain within Earth’s Sphere of Influence (SOI). The first flyby sets ArgoMoon on the nominal trajectory: after 5.5 months and up to 4 intermediate lunar fly-by at higher altitudes, one last flyby below 10,000 km results in an escape orbit from Earth and onto a heliocentric trajectory for the mission disposal. Depending on the required ΔV for a specific launch window, 2 or 3 OTMs were planned to be performed by the main engine while in communication with the MOC, allowing for gathering tracking data before and after each burn and increase the accuracy of the orbit reconstruction and estimate. A nominal ΔV of 8 m/s is expected, which can increase up to a factor of 2 for larger release uncertainties. During the months following the first lunar flyby, ArgoMoon’s orbit was expected to change significantly due to solar radiation pressure and the gravitational attraction of the Moon (Figure 6).

ArgoMoon’s Mission Control Center (AGM-MCC) monitors and controls the ArgoMoon satellite after deployment and during mission operations. All the commands to the ArgoMoon and on-board instruments are generated at the Mission Control Center and telemetry and ancillary data such as Housekeeping, science and ranging data are received at the MCC for further processing and analysing. The Mission Control Center is responsible for the in-orbit operations of the space segment. These tasks are carried out by a dedicated ArgoMoon Flight Control Team (FCT). The FCT is functionally divided into Front room and Back room engineering support.

Table 1 – ArgoMoon mission timeline

	Mission Phase	Entry Event	Exit Event	Duration
	Launch	Launch sequence	Deployment	≈ 3 hours (Bus Stop-1)
LEOP	**Release**	Deployment	OBC-ADCS Boot-Up	10 s
LEOP	**Satellite Boot**	OBC-ADCS Boot-Up	Detumbling and attitude reconstruction	60 s
Mission Operations	**Proximity ICPS In-Orbit Operations**	Detumbling and attitude reconstruction	ICPS locked	75 s
		ICPS locked	Start PM-1	455 s
		Start PM-1	End PM-1	65 s
		End PM-1	Start PM-2	9 min
		Start PM-2	End PM-2	24 s
		End PM-2	Bus Stop 2	2.5 hours
	Pre flyby Operations	Start OTM-1	End OTM-1	518 s
		End OTM-1	Start OTM-2	15 min
		Start OTM-2	End OTM-2	524 s
		End OTM-2	First Moon flyby	4.5 days
	Geocentric Operations	First Moon flyby	Last Moon flyby	≈ 5.5 months
	DISPOSAL	Last Moon flyby	Last COMM with MCC	≈ 15 days

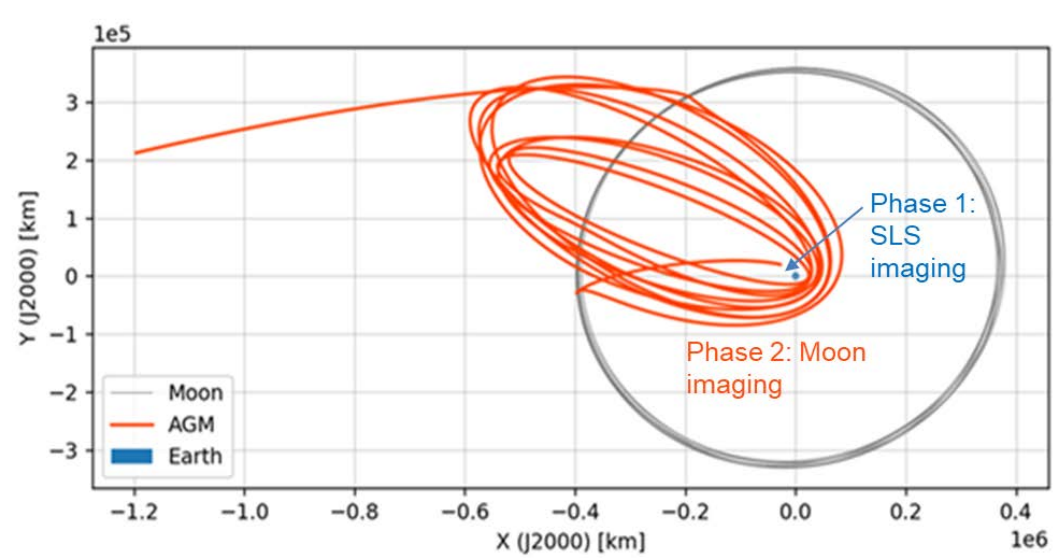

Figure 6 - ArgoMoon nominal trajectory

3. LICIACube operations: preliminary assessment

3.1 *Sequence of events*

DART has been launched from the Vandenberg Space Force Base, California, leaving the pad onboard a Falcon-9 launcher at 06:21:02 UTC on November 24th 2021, carrying the LICIACube spacecraft inside a dedicated dispenser. The two spacecrafts travelled together for a long stretch of DART's interplanetary cruise towards the target, until 23:14 UTC on September 11th 2022, when LICIACube was released from DART and started operating autonomously, just before the NASA probe initiated the final targeting and approaching phase to impact on Dimorphos's surface planned to happen 15 days later.

It is worth noticing that LICIACube was released 5 days earlier than originally planned during the design, due to an unexpected mission necessity on DART side. This led to different challenges:

- ASI had to coordinate the LICIACube Team to compensate a significant timeline deviation at just around 50 days from the originally planned release date, while mission design took two years;
- Since the first communication with the Mission Control Centre (MCC) was not implemented in the hard-coded on-board schedule, telecommands (TC) from MCC were nominally scheduled to be sent to bring the spacecraft in Communication Mode pointing toward the Earth. The on-board ephemeris considered a specific instant for release. Because of the significant shift in the release date, the initial acquisition had to face the additional difficulties resulting from an initially unplanned attitude, and required more time than expected.

Nevertheless, the first LICIACube telemetries were received at 00:04 UTC on September 12th 2022, and proved a good health status of the spacecraft subsystems, marking the first successful deep space ground acquisition from an Italian interplanetary probe.

The commissioning phase of the mission started first with the platform checkout and then with the payload one. The payload commissioning involved the calibration of the two on-board cameras LEIA and LUKE, by the observation of targets having known features (i.e. Didymos, Pleiades, Jupiter, Alcyone, DART and the Earth-Moon system).

This phase has been carried out by means of multiple iterations until the last tracking passes before the impact. In addition to the payload calibration, another crucial element for the mission success was the proper execution of the planned deep space orbital manoeuvres (OMs), as described in the previous paragraph 2.1.

The critical OM1 was performed as planned starting at 17:55:53 UTC on September 16th 2022, for a duration of 490s. Loss of Signal lasted around 14 minutes 50 seconds. As it was the case also for the following OM2 and the desaturation manoeuvres performed before fly-by, the subsequent OD analyses confirmed the nominal performances of the propulsion system, while giving precious information on thrusters' characterization. The spacecraft had finally set course towards its target on the desired trajectory.

The first phase of the LICIACube mission, between the deployment and DART impact, was characterized by a communication strategy that nominally included two tracking passes per day in accordance with the plan previously agreed between DSN and ASI. In occasion of the second-last tracking pass scheduled before the closest approach, the Flight Control Team (FCT) uplinked all the updated parameters required by the autonomous navigation algorithm to compute the trajectory set be followed during the autonomous proximity flight, and fly-by, in such a way to satisfy pointing requirements.

At 23:16 UTC on September 26th 2022, the DART spacecraft impacted Dimorphos and LICIACube was the closest witness of this historical event, from a vantage point just about 1000 km away.

Few hours after the flyby, during the tracking pass beginning at 01:10 UTC on September 27th 2022, the LICIACube MCC was able to establish communication with the spacecraft, obtaining confirmation that LICIACube was healthy after the close approach and then that the spacecraft had successfully recognized the target by shooting more than 600 images, a part of which was scientific while the other for navigation purposes. The first downlinked images reached the MCC at 02:14 UTC on the same day, definitely showing the ejecta plume produced by DART's impact, as well as its irregular shape (Figure 7). Following the flyby, the second phase of the mission started with the nominal operations consisting in the check of the spacecraft health and in the download of all the images stored in the onboard memory. The available data rate of 128 kbps allowed to downlink about 10 images for each tracking pass.

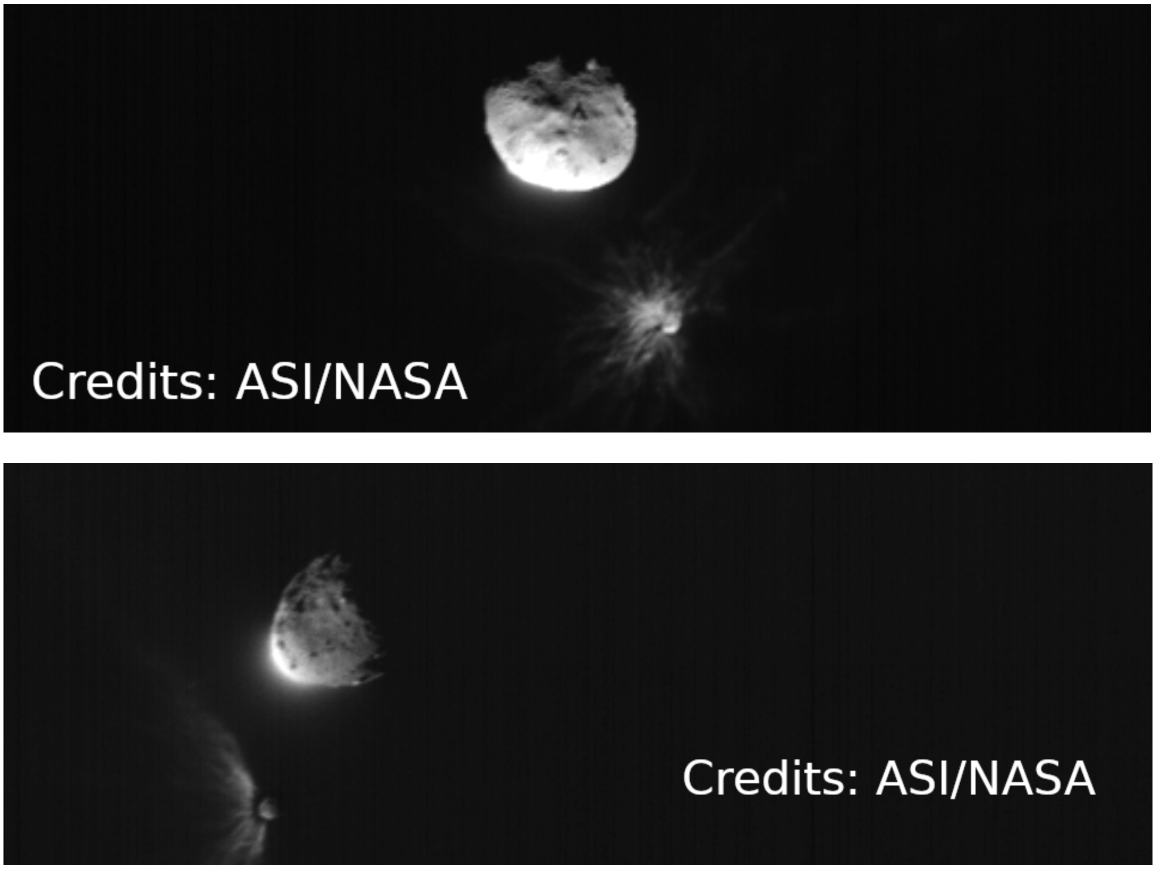

Figure 7 - Didymos and Dimorphos, after DART's impact:
8 seconds before the Closest Approach - 76km away (a), and 7 seconds after the CA – 71 km away (b)

Captured images during the challenging fly-by confirmed the DART success as Planetary Defense initiative and provided scientists with highly valuable data, that allowed a first set of results to be confirmed and are currently under further analysis for scientific investigations. In fact, on October 11th 2022, NASA announced the complete success of the DART mission, confirming that the spacecraft's impact altered Dimorphos' orbit around Didymos by 32 minutes. Moreover, The LICIACube images show that the DART impact on Dimorphos generated a cone of ejected surface material with a large aperture angle (140±4°). This plume has a complex and inhomogeneous structure, characterized by non-radial filaments, dust grains, and single and clustered boulders that allows us to deeply investigate the nature of the ejecta and the structure of Dimorphos.

The mission has maintained its operational status until October 25th 2022, when the communication link with the spacecraft was not established as per schedule. Considering and knowing that many characteristics of the deep space environment (e.g. radiations, micrometeoroids, plasma to cite some) can in principle cause a sudden and undetectable catastrophic failure on a spacecraft subsystem, an ASI-led Task Force has been in any case put in place to perform the Search and Recovery operations. The necessity of the Task Force has been due to the fact that no anomaly in the spacecraft housekeeping parameters had been detected up to the last successful contact, and this made the definition of a strategy very difficult. The naturally finite and discontinuous availability of tracking slots certainly posed a strong boundary to the effort.

The factors driving the effort have been:

- The failure happened at a fraction of the expected spacecraft lifetime;
- There is no evidence of on-board failures on the critical subsystem;
- There is no evidence of telemetry trends that allow a growing failure probability for any subsystem;
- The only evidence of failure had been detected in the communication interface, i.e. radio silence;
- The alive spacecraft is going to enter safe mode soon.

Different strategies for LICIACube recovery have been implemented and actuated with the support of DSN, that implied scanning off-nominal portions of the sky and off- nominal X-band frequencies in Uplink and Downlink.

The search and recovery efforts were not successful and, on December 21st 2022, the Italian Space Agency and Argotec jointly decided on the termination of the mission. The End-Of-Life procedure activation telecommand has been uplinked by LICIACube MOC in the blind at 18:37:06 UTC of December 23rd 2022, with no feedback on reception and execution.

The interplanetary journey of LICIACube spacecraft, up to the uplink of the passivation telecommand, lasted 102 days, 20 hours, 23 minutes, plus the one-way light time to the actual spacecraft position.

LICIACube obtained some historical national and global records performing its mission:

- It is the first deep space mission developed and autonomously managed by an Italian team, the third at global level (after the two MarCO of JPL in the Mars environment);
- It is the smallest human object to intentionally perform the flyby of a minor body of the Solar System, and the first visiting a binary asteroid system

3.2 Discussion

LICIACube's designed trajectory foresaw a Calibration Maneuver (CAL) and a sequence of three possible Orbital Correction Maneuvers (OMi) intended to minimize the effect of off-nominalities and perturbing effects on the B-plane final position dispersions at close approach. Since their magnitude and direction directly depended on the estimated deviation of the real LICIACube's trajectory with respect to the nominal one, a dedicated maneuver generation pipeline was set-up for the operations, lasting 48 hours from the Tracking Data Cut-off (DCO) to the actual maneuver execution. The following sequence of events was repeated before each scheduled OM:

1. Starting from the DCO, each NAV team reconstructed the CubeSat's trajectory using the reference trajectory and the DSN tracking data. An Impulsive Corrected Burn (ICB) was computed to re-target the desired B-plane point and minimize the resulting dispersions at close approach.
2. Once the reconstructed trajectory and the ICB of each NAV solution were delivered to the MCC, the MD team proceeded with the impulsive-to-finite maneuver conversion: using the ICB as an initial guess, the maneuver direction and amplitude were further optimized to account for the finite-duration of the burn, generating a Finite Predicted Maneuver (FMP). Additionally, since significant perturbing effects on the maneuver execution induced by the attitude thrusters were identified during the mission planning, the FMP direction was further rotated into a Finite Commanded Maneuver (FMC), which would be commanded to the spacecraft. Specifically, the FMC was such that when the maneuver was executed, the perturbing effects would turn the FMC in the desired FMP.
3. Each NAV team would then verify the correctness of the FMP associated to its own reconstructed solution, ensuring the convergence of the delivered FMP and the original ICB with respect to the B-plane target point.
4. After a new set of tracking data was acquired, a meeting involving all the Flight Dynamics Team was held to discuss which NAV team solution should be selected and uploaded to the LICIACube, confronting the robustness of each NAV solution. ASI's representatives were responsible of the final maneuver selection.
5. Finally, after the selection of the NAV solution, the MCC was responsible of converting the FMC direction and amplitude into telecommands to be uploaded to LICIACube at the next available communication window.

Due to the issues experienced by the probe during the initial commissioning, the timeline has been adapted by shifting the manoeuvre slots 1 day later for CAL1 and OM1. The collected radiometric data were analysed using the MONTE Orbit Determination tool to fit the model and reconstruct the spacecraft trajectory. During the operations, three different solutions were delivered to update the apriori value of the maneuvers OM1, OM2, and OM3. The results in Figure 8show the evolution of the estimated trajectory aimpoints at the B-plane, along with their 3-sigma uncertainty. As expected, the uncertainty decreases with time, due to the larger amount of data collected. Considering the propagated state and uncertainty were already compliant with the navigation requirements, the OM3 was aborted obtaining the expected values shown in green. This decision was made following a risk mitigation philosophy involving the acceptance of an already compliant state instead of trying to gain some better observation position with the risk of any system malfunctioning would have endangered the mission goals.

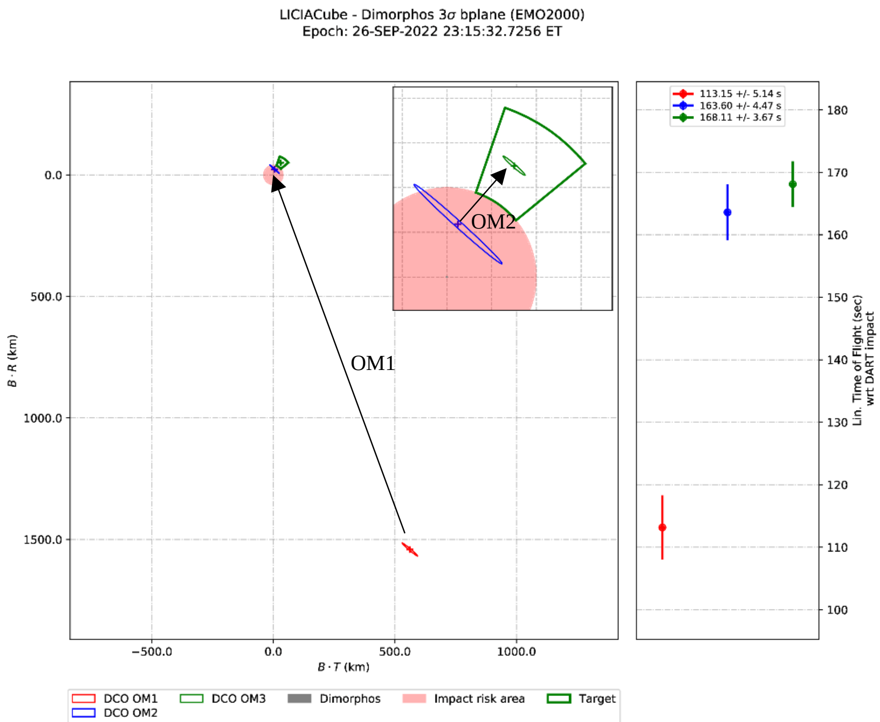

Figure 8 - LICIACube B-plane solution for OM1, OM2 and OM3 deliveries

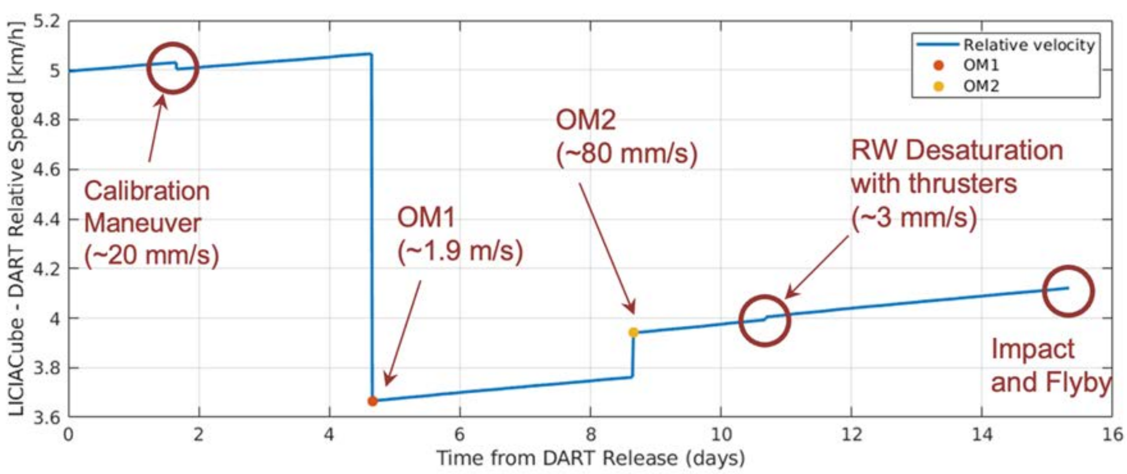

Figure 9 - Evolution of the LICIACube-DART relative speed, highlighting the different manoeuvres executed.

Figure 9 represents the evolution of the relative velocity between LICIACube and DART with the highlights of the different events. The two main orbital manoeuvres are indicated with the executed Δv, together with other critical steps handled by the FD team, such as a propulsion unit calibration and reaction wheels desaturation, which had reduced impact on the relative velocity. In Figure 10 the cubesat's trajectories relative to Dimorphos and DART respectively are depicted.

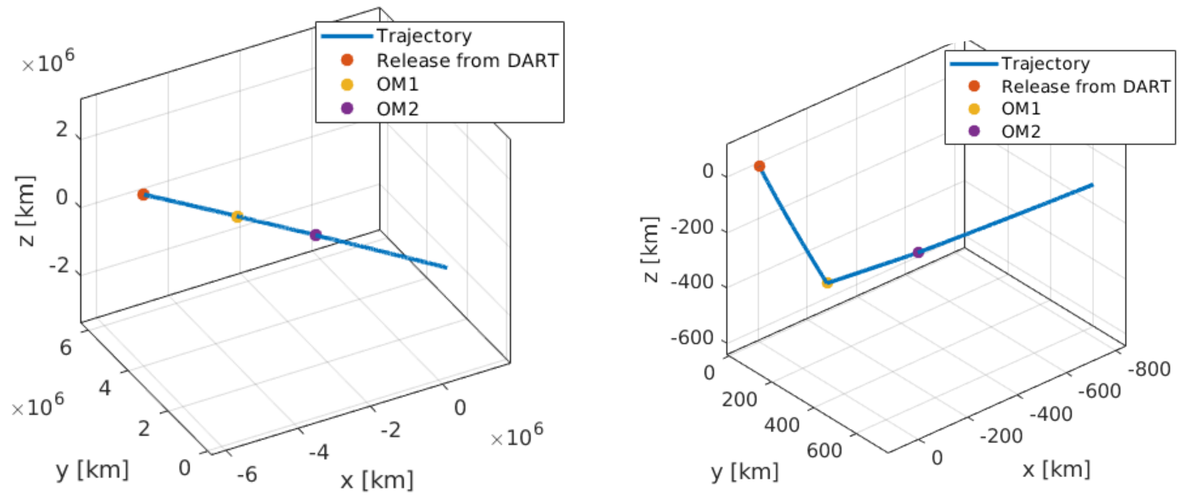

Figure 10 - LICIACube trajectory relative to Dimorphos (a) and DART (b)

A final consideration can be made on the "a posteriori" trajectory reconstruction, considering the whole set of collected data up to the S/C last received radiometric data, on October 24th, 2022. The two-way Doppler and range residuals (Figure 11) exhibit a noise level of 0.05 mm/s (at 60 s integration time) and 0.8 m, respectively, well below the a priori expected values of 0.3 mm/s and 5 m, respectively.

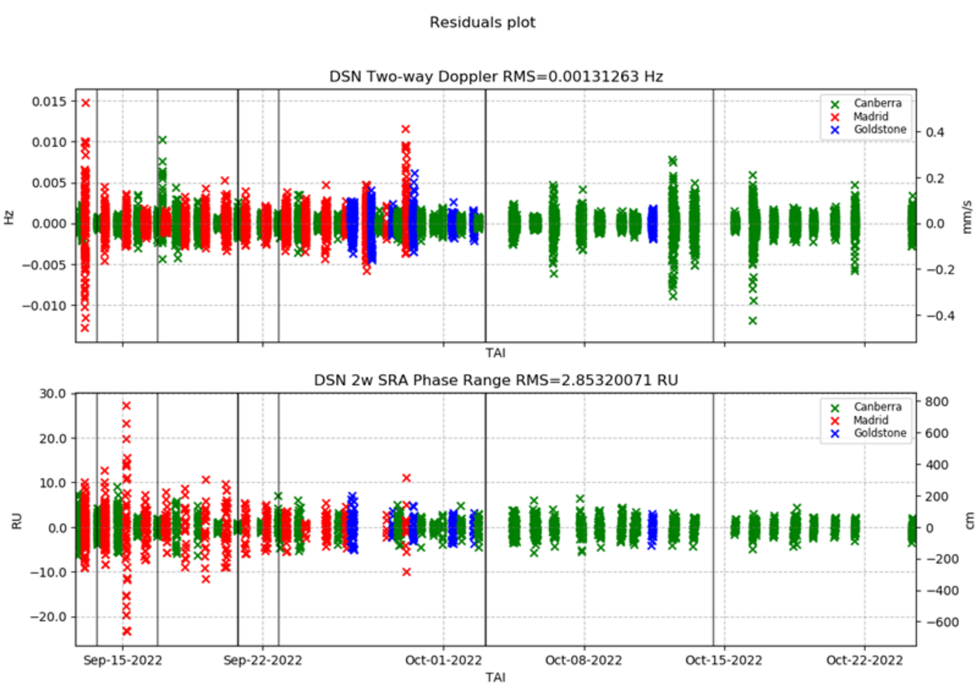

Figure 11 - Two-way Doppler (top) and range (bottom) residuals of the LICIACube mission

4. ArgoMoon operations: preliminary assessment

4.1 *Sequence of events*

Artemis-1 launch occurred on November 16th, at 06:47:44 UTC. According to the Deep Space Network, ArgoMoon - AGM was released by ICPS at 10:36 UTC (Launch Epoch + 3h 49m 44s). Communication with the satellite was successfully established at 10:37 UTC.

After the boot-up, the cubesat's ADCS sensors immediately detected an unexpected tumbling rate around body axes resulting in a global spin of about 11°/s: this was due to the ICPS contribution of 6°/s around its axis plus the rotation induced by the dispenser release, that resulted in an additional rate of 5°/s. The satellite rotation temporarily prevented the full opening of the solar panels (SPA), so that the power consumption during this tumbling phase led to rapid battery discharge. Consequently, AGM correctly commanded the activation of "Safe Mode" as per the intervention of the pre-loaded FDIR (Fault Detection, Isolation and Recovery) system. The solar panels were only partially exposed to the sun, since, at that moment, they were not fully deployed. The non-nominal situation has persisted for about 15 minutes, after which AGM finally entered a stable attitude and the SPA were fully deployed, thus allowing the full recharging of the battery. Unfortunately, this series of events have directly impacted the acquisition of ICPS images, which could not be performed as the spacecraft was not considered yet in a safe configuration.

The first telemetries received after the attitude stabilization showed that the spacecraft was healthy and the preliminary activities were performed by the Flight Control Team. These included the switch into Communication Mode, turning on the Star Tracker and the update of the on-board ephemerides.

The second and the third day of the mission have been devoted to the proper configuration of ArgoMoon propulsion system in preparation of the planned orbital manoeuvres. In addition to that, the first two images of the Earth have been shot through the two optical payloads on-board and successfully downloaded on ground. The outcome was absolutely remarkable: the target has been captured within the camera field of view, demonstrating a high-precision pointing capability of the small-sized platform.

The objective of the orbital manoeuvre was the insertion into an Earth high-elliptical orbit that allowed for multiple fly-bys of the Moon throughout the whole mission duration. The main orbital manoeuvre, consisting of 4 separate firings, was carried out in the backup slot for OTM1 (OTM1B). Preliminary telemetry analysis seemed to indicate that the manoeuvre performed nominally and within the expected uncertainty. However, further Orbit Determination analysis showed that the manoeuvre significantly underperformed, and TM analysis showed an anomaly of the AGM propulsion system. Following a new calculation of the UniBo Navigation Team, a second attempt has been tried, with a firing duration of 800 seconds. The result of this firing sequence has been a significant reduction in the plenum pressure, but the post-firing analyses showed that the actual delta-V produced by the manoeuvre have been lower than expected. It became clear that the further legs of the orbital manoeuvre could not be executed for lack of sufficient propellant, and therefore AGM would not be able to postpone entry into heliocentric orbit as planned. Thus, priority was given to correctly address the first - and unique - lunar flyby maximizing the AGM science return by capturing photos of the Moon, both during the approach and during the fly-by.

Over the course of the mission, about 50 photos of the Earth and the Moon were successfully acquired and downloaded. Interesting pictures show the far side of the Moon, with a clear view of the Jackson Crater (Figure 12). The images taken at the time of maximum proximity to Earth clearly show the area of South America, the Indian Ocean and the African continent, although partially characterized by cloud cover (Figure 13).

Since November 28th 2022, the momentum accumulated by the spacecraft has caused the inability to maintain a stable link with ground. At present day, despite the growing uncertainty in ArgoMoon orbit determination, AGM Flight Control Team is still carrying on search and recovery activities.

Figure 12 - ArgoMoon pictures of the Moon, at the distance of 18573 km

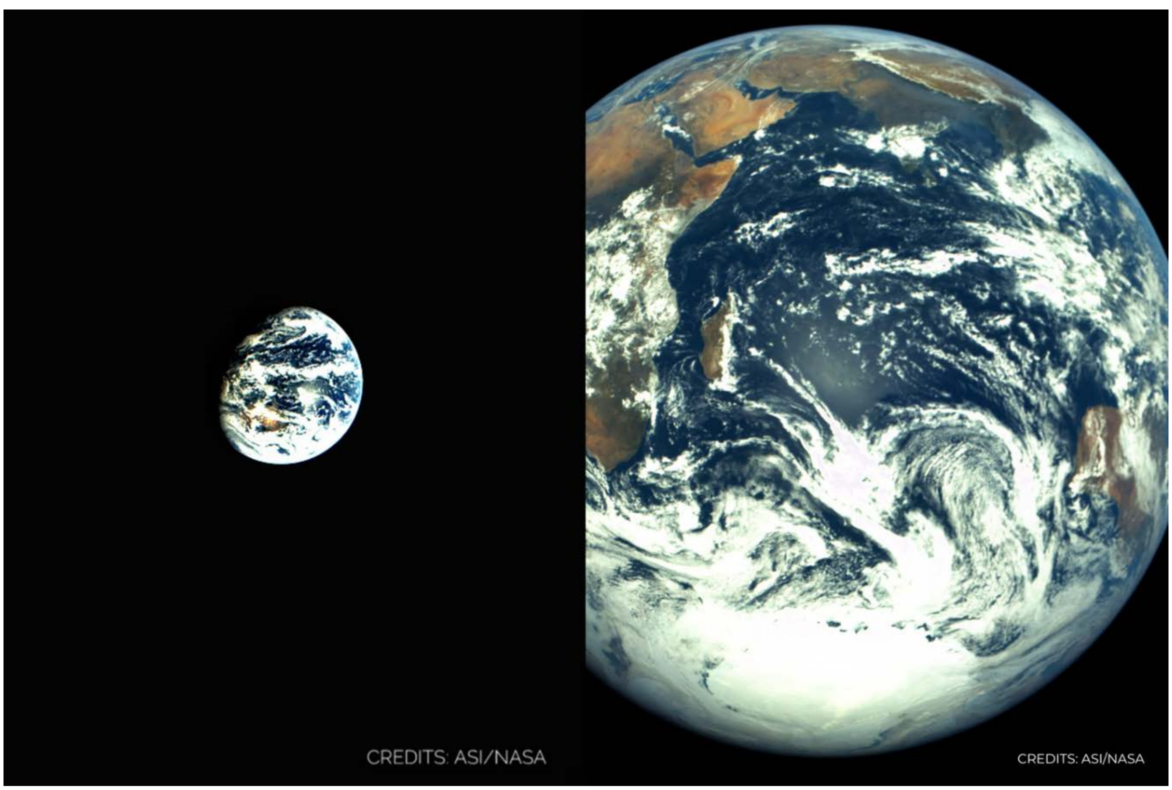

Figure 13 - ArgoMoon pictures of the Earth, at the distance of 149.789 km - PL = 2, RGB 1536 x 2048 (a) and 237378 km PL1, ID41, RGB 2048x1536 (b)

4.2 *Discussion*

The navigation strategy for ArgoMoon was designed on the peculiar cislunar orbit. The manoeuvres were set at the apoapses and periapses, to exploit the lower manoeuvre cost, and few days before and after the Moon flybys, to correctly target the Moon closest approach and cleanup the perturbations amplification.

Similarly to LICIACube, the navigation timeline during the first days of the mission was very tight, so the DCOs were set about 48 hours before each planned manoeuvre, while after the first Moon fly-by the computation time was conveniently increased to 96 hours.

Due to the experienced release issues the reconstruction model had to be adapted to include the additional unplanned desaturations, and the OTM1 had to be executed to its backup slot (OTM1B). Once received the radiometrics and telemetry data, a thruster problem was highlighted by comparing the expected trajectory after the OTM1 with the reconstructed one. Promptly reacting to this contingency scenario, a new orbital manoeuvre, called STM0, was computed by the Navigation Team, prepared, commanded and executed in less than 24h (Figure 13). AGM managed to correctly perform the flyby, taking some spectacular pictures of the Moon's surface.

After the flyby, the Orbit Determination allowed to reconstruct the trajectory and verified that the S/C was leaving the Earth-Moon system, entering into a heliocentric orbit.

Figure 14 depicts an example of the residuals generated in the OD analysis. Once fitted, the Doppler and range data are characterized by a noise level close to 0.1 mm/s (at 60 s integration time) and 1 m, respectively.

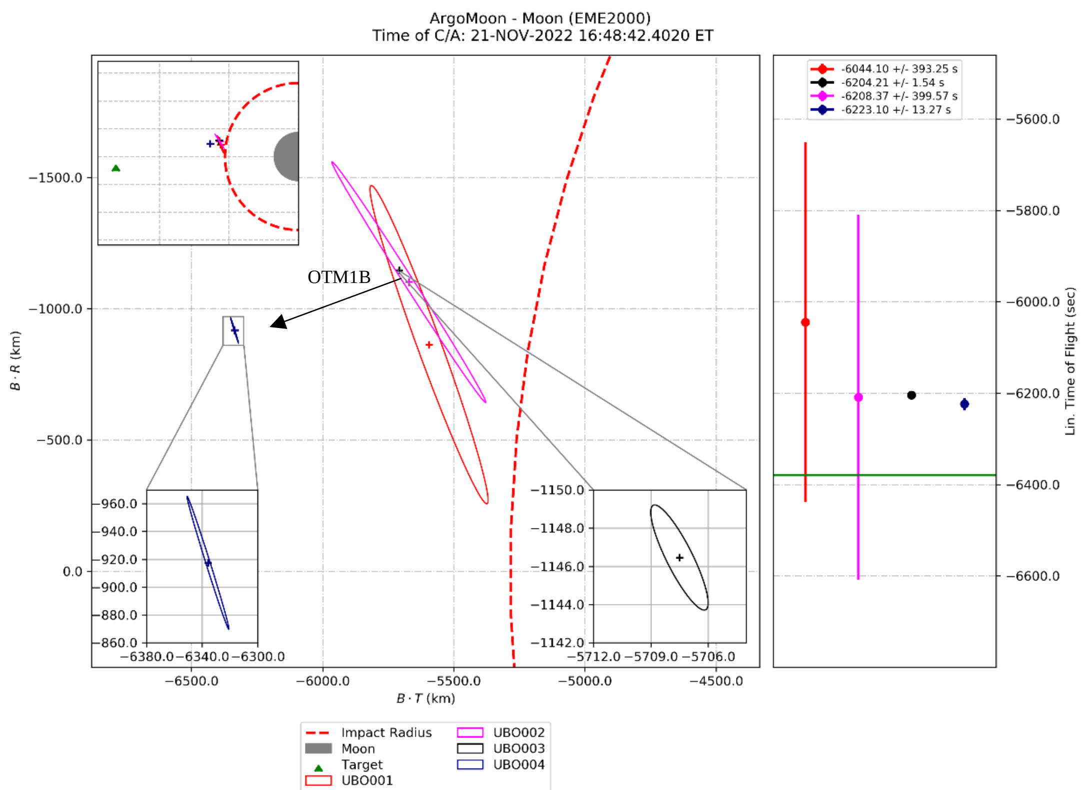

Figure 13 - ArgoMoon B-plane solutions for the first 3 navigation deliveries.

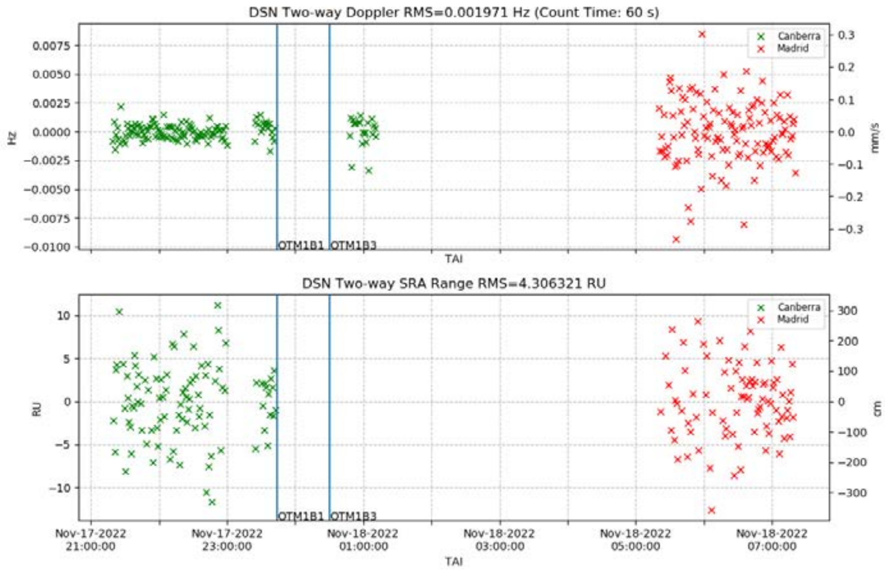

Figure 14 - Example of two-way Doppler (top) and range (bottom) residuals of the ArgoMoon mission

5. Conclusions

At the beginning of the present decade, the first missions of small satellites beyond Earth orbits have been implemented. In November 2022, Artemis1 mission towards the Moon allowed the release of ten cubesats and, among them, the Italian 6U cubesat ArgoMoon operated and manoeuvred to in the cislunar environment. Few months before, the Italian 6U nanosatellite LICIACube participated in the NASA DART mission and succeed in the challenging goal to flyby the binary asteroid system Didymos and to capture unique pictures of the impacted asteroid Dimorphos, with the aim of supporting the orbit deflection measurement and with scientific investigation purposes. Both missions' profiles had strong and specific challenges, that were assessed and handled during the mission preparation and then implementation by the Operations teams. To achieve the imaging goals, the optimization of trajectories played a crucial role, as well as Orbit Determination, due to the need of a precise positioning and safe guidance despite the tight mission timeline. The final success has been made possible by an accurate preparation of the operational procedures and then by a strict coordination between the different operational tasks, to be often executed in real time. The experience gained during the operations of both two missions establish a solid and unique background for the space community in Italy, that could pave the way for future similar challenges for Deep Space Exploration.

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