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Italian Cubesats for Moon and Asteroid imaging

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Abstract

In the last decades, small satellites have consolidated their role in support to implement space missions in a fast cheap and effective way. Space science is one of the areas where Cubesat can be used to complement the investigations performed by the traditional sized satellites. Modularity, standardization, intensive use of state-of-the art COTS technologies allow to manage cheaper missions in shorter time-frames, thus providing better opportunities to access quasi and deep space, to a wider technical and scientific community. The Italian Space Agency promotes, funds and coordinates the national initiatives in this promising sector, both for autonomous missions and in international cooperation. ArgoMoon and LICIACube (Light Italian Cubesat for Imaging of Asteroids) are 6U Cubesat designed manufacture by the Italian company Argotec and managed by Italian Space Agency. ArgoMoon will be launched during the maiden flight of the NASA Space Launch System (SLS) named "Artemis1 mission", with the aim to collect pictures of the SLS last stage and of the other piggy-back nanosatellites. After the first mission phase, few orbital manoeuvres will move the satellite in a geocentric highly elliptic orbit, whose apogee is high enough to allow flybys and imaging of the Moon and of the surrounding environment. Instead, LICIACube flies as piggy-back on Double Asteroid Redirection Test (DART), NASA mission. DART has devoted to test the kinetic impact technique in the frame of the Planetary Defense program. DART will act as a kinetic impactor deflecting the orbit of the secondary asteroid of the binary system Didymos: the entire event will be witnessed and recorded by LICIACube that will separate from the main satellite 15 days before its impact on Dimorphos surface. LICIACube has on board cameras will capture images of impact effects, primarily the plume of ejecta, and of the not visible side of the secondary asteroid, so supporting the validation of kinetic impactor technique for trajectory deflection. Both these Cubesat will make use of the NASA Deep Space Network for Ground Communications.
Keywords: Cubsats, ArgoMoon, LICIACube, COTS, Imaging Software

Acronyms/Abbreviations

CA	Close Approach
DART	Double Asteroid Redirection
DSN	Deep Space Network
FoV	Field of View
GS	Ground Station
ICPS	Interim Cryogenic Propulsion Stage
IS	Imaging System
MATISSE	Multi-purpose Advanced Tool for the Solar System Exploration
MCC	Mission Control Center
NEA	Near Earth Asteroid
OBC&DH	On-Board Computer & Data Handling
OSW	On-Board Software
PHA	Potential Hazardous Asteroid
PL	Payload
PS	Propulsion System
RW	Reaction Wheel
SLS	Space Launch System
SOC	Scientific Operations Center
SSDC	Space Science Data Center

1. Introduction

In the context of robotic and human exploration, the use of small satellites is recurrent for the purpose of supporting and complementing larger space missions designed to reach solar system targets such as asteroids, Moon, and Mars. In particular, the small spacecrafts are suitable means of solar system exploration since they can be used with a stand-alone fleet capable of rendezvous with multiple targets or a swarm carried by a larger spacecraft and deployed at the destination (e.g. Moon, asteroid/comet, Mars). Furthermore, the standard dimensions also allow Cubesats to hitch a ride to orbit within a container, which simplifies the accommodation on the launcher and minimizes flight safety issues, increasing the number of launch opportunities as well as keeping the launch cost low. Cubesats in deep space represent a flexible and affordable solution, complementary to the traditional large size probes, to push the boundaries of space exploration due to their small volumes and high capabilities.

The Italian Space Agency (ASI) is increasing the interest in Cubesats and nanosatellites for small payload driven mission in deep space as well.

Currently, there are two missions in course which involved two Italian Cubsat in deep space: ArgoMoon and LICIACube (Light Italian Cubesat for Imaging of Asteroids), both are 6U Cubesat designed and manufacture by the Italian company Argotec on beneath by Italian Space Agency.

LICIACube has been launched on 24th November 2021 as piggy-back on Double Asteroid Redirection Test (DART) NASA mission.

Instead, ArgoMoon will be launched during the maiden flight of the NASA Space Launch System (SLS) named “Artemis1 mission", currently scheduled for the month of September 2022.

ArgoMoon and LICIACube have been developed for the Italian Space agency by Argotec Italian company; scientific teams are also involved in the missions’ preparation and implementation, with responsibilities in trajectory design (Polytechnic of Milan), Orbit Determination and Navigation (University of Bologna), science case study, payload development support and data exploitation (Italian Institute of Astrophysics and several other Italian Universities).

This paper provides an overview on the design of the satellites focusing on the main technological challenges and lessons learned during the development of Cubesats for Deep Space mission.

2. Mission Concepts: ArgoMoon and LICIACube

LICIACube and ArgoMoon Cubesats have been realized with the aim to collect several pictures the achievement of their corresponding mission objectives. Both Cubesats will act as a nano-eyewitness in deep space. ArgoMoon will inspect the Interim Cryogenic Propulsion Stage (ICPS) SLS rocket stage, as to the results of the dispenser operations. Instead, LICIACube, thanks to a suite of cameras accommodated on board, will get photos of the impact of the DART probe on the moon of the Dimorphos asteroid and will catch the plume ejecta evolution.

2.1 ArgoMoon: mission concept

The NASA mission Artemis 1 will represent the maiden flight for the Space Launch System (SLS) rocket, it has been designed and developed by NASA to bring the Orion capsule and to fly in deep space. The SLS is an American heavy-lift expendable vehicle developed by the NASA as part of NASA’s deep space exploration program. Instead, the Orion service module will perform several manoeuvres once in lunar orbit, to test flight capabilities before performing an Earth controlled re-entry, where the capsule will be recovered following a splashdown in the Pacific Ocean.

In order to demonstrate the possibility to achieve relevant scientific results with cheap and reliable platforms, NASA has offered to deploy thirteen Cubesats. during Artemis1 mission, hosted into appropriate dispensers accommodated in the Orion Stage Adapter OAS. Therefore, ICPS will provide the

final thrust to launch the Orion capsule towards the Moon and after the detachment of the Orion capsule, ICPS will follow a highly elliptical orbit that will bring the stage into a disposal heliocentric path after a Lunar flyby. During the coasting phase of the ICPS, the CubeSats will be deployed at different separation windows (Bus Stops) along different orbits according to their specific mission timelines.
One of these Cubsat is ArgoMoon and its mission objective consists in collecting significant amount of pictures of the launcher's ICPS, for technical and outreach purposes.
The ArgoMoon mission will be divided into two main phases: during the Phase 1 (Proximity Operations around the ICPS), within the first hours from the deployment, the satellite will take images of ICPS, performing autonomously flight around the target. Following Phase 1, the ArgoMoon satellite will be navigated from ground to perform a series of maneuvers and enter into a high eccentricity geocentric orbit with several Moon flybys. Finally, the probe is inserted into a heliocentric disposal orbit exploiting the last lunar flyby. The main objectives of the satellite are to take historically relevant pictures of the Artemis1 (Phase 1) and of the lunar surface, then to validate technologies in deep space (Phase 2).

2.2 LICIACube: mission concept

The primary objective of the LICIACube mission is to acquire multiple images of the Dimorphos asteroid, during and after the impact, along with the ejecta plume, with different phase angles to allow the reconstruction of the mass-velocity distribution and the size distribution of the ejecta [1][2], as well as the real shape of the asteroid. LICIACube imaging includes the non-impact hemisphere of the Dimorphos, the side not imaged by DART.
LICIACube satellite will be deployed by DART spacecraft roughly 15 days before the Dimorphos impact – actually foreseen on 26th September 2022 - with a velocity relative to DART of 1.19 m/s [3]. Once deployed in a heliocentric orbit, LICIACube will start its commissioning phase, powering and checking all the subsystems, before performing in-orbit tests and calibrating the payloads. Once tested the propulsion subsystem, three closed-loop maneuvers are scheduled to address the observation aimpoint at the Closest Approach (C/A) of Dimorphos, less than 200 sec after the DART impact. The satellite performs a flyby of the asteroid at a nominal distance of approximately 55 km from the impact region.
The scientific phase of the mission starts 240 seconds before the Dimorphos C/A, when the optical payload is capable to identify at least one body in the image. The first pictures will be acquired at a relative distance of about 1440 km from the binary system up to the C/A, with a spatial scale close to 1.4 m/px and it will continue to take pictures for about 5 minutes after the C/A. Since the science objectives are very challenging and the real brightness of the object is highly unknown, the LICIACube observation strategy has been designed to obtain data redundancy acquisition, increasing the dynamic range of the detectors on board.
The greatest challenge of the LICIACube mission is represented by achieving the goals with the limitations of a Cubesat platform, in particular the precision required to the navigation at the very high speed of the spacecraft relative to the target (approx. 6.5 km/sec), the pointing at a high rate and the very tiny schedule dense of events.

3. Cubesat Overview

ArgoMoon and LICIACube are both 6U class Cubesats with approximate mass of 14kg, whose design is based on the Argotec's Hawk6 platform. A brief summary of their configuration is hereafter reported.

3.1 ArgoMoon

The ArgoMoon subsystems on board are hereafter summarized:
Rangefinder (RF): checks the relative distance to the desired target in order to maintain safe distances and confirms the target is inside the FoVs of the cameras, acting in support of the proximity navigation function
Onboard Computer and Data Handling (OBC&DH): the core of the satellite checks and handles the interfaces with the other subsystems and manages the storing of the acquired pictures.
Image Recognition Software (IS): implemented in the OBC&DH, is able to track, recognize and point object/different targets (Earth, Moon, ICPS) in the FoV of the cameras.
Attitude Determination and Control System (ADCS): composed of star tracker, sun sensors, reaction wheels to determine and control the attitude of the satellite.
Propulsion System (PS): a small thruster and four cold-gas thrusters – volume of 1U – provide the necessary thrust to modify the satellite orbit, perform station keeping and control the attitude of the satellite.
Telemetry and Telecommand System (TMTC): in charge of coding the telemetry data coming from the subsystems and sending the data to ground through the use of four different patch antennas.
Electrical Power System (EPS): in charge of collecting the power from the Solar Panel Arrays (SPAs), handling the required power to the subsystems and storing the power in the battery pack of the satellite.

3.2 LICIACube

LICIACube platform [4] has been designed based on the primary scientific objectives to acquire images to study the plume evolution, for that aim:

- LICIACube images will measure the motion slow ejecta
- LICIACube images will allow the estimation of the plume density structure

The Attitude Determination and Control Subsystem (ADCS) and a high-performance Propulsion System (PS) has been selected based on improved performances, in order to allow the satellite to perform the requested orbital maneuvers.

The Argotec's HAWK platform, designed and built to be resilient in the extreme conditions is equipped with the following subsystem:

Structure Subsystem (SS): the LICIACube structure is made of aluminum alloy 7075-T651 in order for it shall ensure that the satellite is able to withstand the mechanical environment and space operational one. The Cubsat design has been thought to minimize mass and maximize, usable volume and offering the highest possible reliability. Since the SS has composed by primary structure, that provides the interface for all the satellite's subsystems and the secondary one that provides support to the internal subsystems. Both of them are linked by means of a set of 3x0.5 countersunk screws, leading to an easy structure assembly and dismount process.

Thermal Control Subsystem (TCS): that is in charge to keep all the subsystems within the thermal requirements during the overall mission according to the changing thermal loads and environment. The TCS exploits a completely passive architecture due to the very compact configuration and the absence of eclipses. Thus, thermal paint is applied on the external part of the structure to lower the absorption coefficient and to increase the emissivity to the deep space sink. In addition, gap fillers and thermal spreaders are inserted.

Electrical Power Subsystem (EPS): that provides, converts and conditions the power to all the subsystems. It includes the Battery (BAT), the Solar Panel Array (SPA) and the Power Conversions and Distribution Unit (PCDU), which is in charge to convert and distribute the power coming from the SPA to each subsystem, or store it in the BAT. Using three regulated voltages, the primary power source is provided by two wings of solar panels and the BAT will store enough energy to face events like eclipses or increased energy demand from the subsystems. The PCDU extracts the maximum electrical power available from the SPA, converting it in order to distribute the energy to the subsystems, protecting them from overcurrent.

On-Board Computer and Data Handling (OBC&DH): that provides communication among all the subsystems allowing their interaction. It represents the core of the satellite since it runs the On-Board Software (OSW) in order to monitor and control the LICIACube satellite. In addition, the OBC&DH interfaces the payload and the platform subsystems for Telemetry and Telecommand to properly manage the satellite and acts as the satellite mass-memory.

OSW, that is hosted in the OBC&DH: manages the system commands and telemetries and drives the autonomous navigation of the satellite. One of its main parts is represented by the Imaging System (IS)

Attitude Determination and Control Subsystem (ADCS): that is able to determine and control the satellite's attitude, in order to properly orient it. The ADCS main function is to stabilize and direct LICIACube in the desired direction despite the external torques acting on it. Three-axis control is necessary to correct the execution of the photographic shooting and the relative maneuvers in the proximity of Dimorphos. Such a technique allows to achieve a very accurate pointing and stability in order not to deteriorate the acquired images. The LICIACube ADCS is composed of a star tracker, Inertial Measurement Unit (IMU) and two sun sensors, that provide their input to the Attitude Determination Block, whose task is to reconstruct the satellite's attitude. That block also feeds the Momentum Control Block, which maintains the spacecraft's momentum within a safe dead band for the Reaction Wheels (RWs). RWs are able to control and modify the satellite's attitude by providing a maximum spin rate of approximately 18 deg/s, considering the mass of 14 kg of the 6U CubeSat. If the limit is exceeded, the Propulsion Subsystem is required to desaturate the wheels.

Propulsion Subsystem (PS): that provides orbital maneuvers and corrections, station keeping and RWs desaturation. The PS is also required since LICIACube will have to perform both braking and correction maneuvers to reach the nominal baseline, approach the impact scene and perform the scientific phase during the asteroid's fly-by. Thus, a cold gas PS will be embarked on LICIACube; it has four double canted thrusters for attitude control and two axial thrusters for orbital maneuver.

Telemetry Tracking & Command (TT&C): which is constituted by an X-Band Transponder connected to a Solid-State Power Amplifier (SSPA) and to a Low Noise Amplifier (LNA), providing power and signal to the 4 patch antennas. They are located on two opposite sides of the satellite (i.e. SPA side and radiator side), to provide the following information:

- Telemetry and remote-control data (e.g. health and status, in-orbit corrections);
- Payload data (i.e. scientific data);

- Ranging (i.e. pure tones for phase-based distance estimation).

Harness (HNS), that is an assembly of electrical wires required to connect the subsystems, to transmit signals or electrical power.

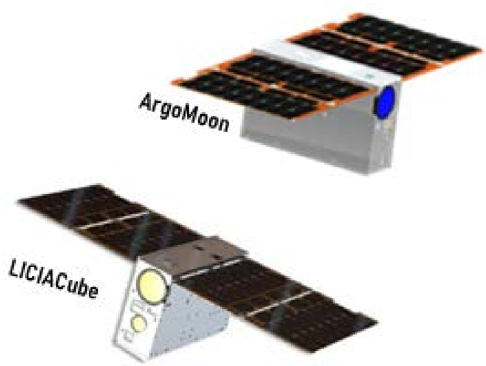

Fig. 1. 3D view of LICIACube and ArgoMoon spacecraft with deployed Solar Array

3.3 Payload overview

The payload has been designed for both LICIACube and ArgoMoon missions, in order to meet the objectives mission and for fitting available weight and volume that has been qualified to fly in Deep Space. For what concern ArgoMoon's Payload subsystem has been developed in order to be customize on ArgoMoon mission constrains. It is composed of two optical cameras with different Fields of View (FoV) to take pictures of the desired target (ICPS, Moon and Earth) and a Range Finder to measure its relative distance from ICPS during proximity maneuvers. The configuration with multiple optics and different FoV optimizes the tracking performance of the system while keeping the high resolution of the pictures from long distances.
The payload operates in a guaranteed visible spectrum due to the lens coating that filters undesired frequencies. Each optic is equipped with a high-speed CMOS image sensor with a resolution of 4096x3072 pixels commanded by dedicated electronics that can handle picture in different formats (RAW, GreyScale, RGB) according to the commands from the OBC and depending on the mission needs.
The RF is also part of the PL and is essential to evaluate the distance from the target in order to respect the safety limits imposed by NASA that established a forbidden area below 100 meters from ICPS. This component can measure distances up to 5 km with a resolution of 0.1 m.
The customization of the LICIACube platform is mainly based on the primary objective of obtaining significant pictures of the DART impact, therefore the optical properties of the two cameras have been designed considering the DART high velocity impact on Dimorphos (approximately 6 km/s) and Closest approach (CA) distance of about 55 km after it will be release by the dispenser. The two on board cameras are:
LEIA (LICIACube Explorer Imaging for Asteroid): the principal payload is catadioptric camera composed of 2 reflective elements and 3 refractive elements with a FoV of ±2.06° on the sensor diagonal, IFoV 25 µrad/px (see Table 1). 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 highly miniaturized, compact and high-performance camera. 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. The detector is connected with On-Board Computer & Data Handling (OBC&DH) via Spacewire interface, in order to reach an adequate transfer rate for shot pictures. The same SpW interface shall be used for payload commanding and telemetry as well.
LUKE (LICIACube Unit Key Explorer): is the secondary instrument, it is the Gecko imager from SCS space, is a catoptric camera composed by 4 refractive element and 2 reflective elements. The detector is a CIMOS sensor (CMV2000) with 2048 x 1088 pixel. It is interfaced with the NanoCU, the data elaboration unit of the camera, through a flexible PCB, to minimize any mechanical stress. The detector is able to operate in the NIR and visible spectral range from 400 nm to 900 nm. The NanoCU is connected with On-Board Computer & Data Handling (OBC&DH) via SPI interface. The same interface is used for payload commanding and telemetry. LUKE is a RGB camera with a Bayer pattern filter and its focal length (70.55 mm) is designed to work in focus between 400 nm to infinity (Table1). The FoV is ±5° and IFoV 78 µrad/px with a spatial scale about 4 m/px at 51 km. Moreover, the hardware is capable of directly integrating the image data to the integrated mass storage.
The suite of the payload will obtain images of the Didymos system with both LUKA e LEIA cameras during the flyby.
The primary camera will acquire pictures from a high distance providing high level of details of the frame field, meanwhile, the second one will take pictures to the CA by pointing at the ejecta cone and possibly the target surface if not obscured by ejecta.
The current imaging plan [5] is to collect sets of three images at the maximum frame rate and different integration times, in order to maximize the dynamics of the acquired imaging data (pictures) of the impact plume and surface.
The proximity operation and image acquisition at the asteroid have been used to select the flyby aimpoint for the trajectory design and Orbit Determination (OD)

constraints, to accomplish the different mission objectives.

Table 2
Design parameters of LEIA and LUKE.

	Focal length (mm)	FoV (°)	IFoV (μrad/ px)	Spatial scale at 55.3 km (m/px)
LEIA	220	± 2.06	25	1.38
LUKE	70.55	± 5	78	4.31

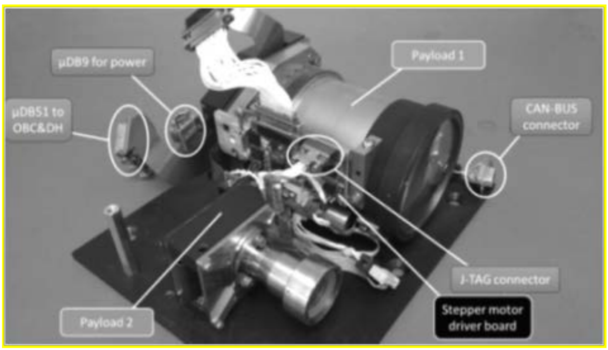

Fig.2 Payload Ground model

4. CubeSat Development Challenges

The ArgoMoon and LICIACube satellites have to deal with constraints that most Cubesats have not dealt with yet. The technical challenges and the limitations of a deep space 6U CubeSat platform make the fulfilment of the scientific objectives extremely complex. Concerning LICIACube, one of the first obstacle to overcome is the long cruise to reach the Didymos binary system. In fact, during the maximum 11 months of cruise required to reach the target, LICIACube will face a severe environment, being subjected to extreme temperature changes and to a significant radiation dose.
Similarly, ArgoMoon will operate outside of LEO, in a deep space environment, in agreed with the Space Launch System (SLS) program requirements and ECSS standards. ArgoMoon will operate outside the Earth’s magnetic field, crossing the Van Allen radiation belts multiple times during its operational lifetime
In order to match these constraints, the ArgoMoon platform relies on novel technologies for Cubesat applications, since two of the main subsystems (OBC&DH and EPS) have been fully designed by Argotec to match the constraints of a deep space radiation environment linked to the small amount of available volume inside the structure. Furthermore, the core part of the OBC&DH is the Imaging Software Algorithm aimed at processing, tracking and identifying the targets in the field of view of the cameras.

The OBC&DH has been designed with a flexible architecture to meet a broad variety of mission scenarios. It is a compact unit – volume of 0.5U – based on two main components, a Field Programmable Gate Array (FPGA) that hosts the interfaces with all subsystem, and a Central Processing Unit (CPU) connected to the FPGA capable of supporting the elaboration of the inputs from the satellite and providing instructions to all subsystems. The OBC has been integrated together with the Electrical Power Subsystem (EPS) control and power distribution boards inside an aluminum box (Power and Data Handling Unit), providing additional mitigation from external radiation in addition to the main structure of the CubeSat.
The EPS has been designed to guarantee certain flexibility as a general-purpose power distribution subsystem, which has been entirely customized for the ArgoMoon mission. It is composed of two deployable wings of 2 solar panels each able to provide a total amount of 80W and a battery pack with a configuration of 7s2p and a capacity of approximately 120Wh. The EPS manage the significant amount of power with a high efficiency and distribute it to each subsystem.
The EPS design is safe and reliable considering that the mission/system performances are assured even when the loss of a solar wing (i.e. no deployment) or the loss of a string of the battery will occur.
Since the space sector is becoming more competitive, the space segment requires spacecraft that perform better at a lower cost and with faster development times in order to satisfy. Traditionally, most of spacecraft components are specifically manufactured and tested for use in space to be sure that they can withstand the intense radiation and harsh environmental conditions that spacecraft are exposed to.
Traditional 'space-qualified' parts make our satellite reliable, but it also comes with they undergo extensive design, testing and qualification processes, they cost much more than their commercial off-the-shelf (COTS) counterparts. COTS parts are ready-made in large batches for Earth-based commercial applications and are starting to be used for space applications.
It is relevant to consider that both Cubsats procurement and development of subsystems are based on High Reliability Commercial-Off-The-Shelf (COTS)

- ADCS
- Radio
- Range Finder
- Antennas

and subsystem High Reliability New Design

- Optical Payload
- Propulsion System
- OBC&DH
- PCDU
- Battery
- Solar Panels

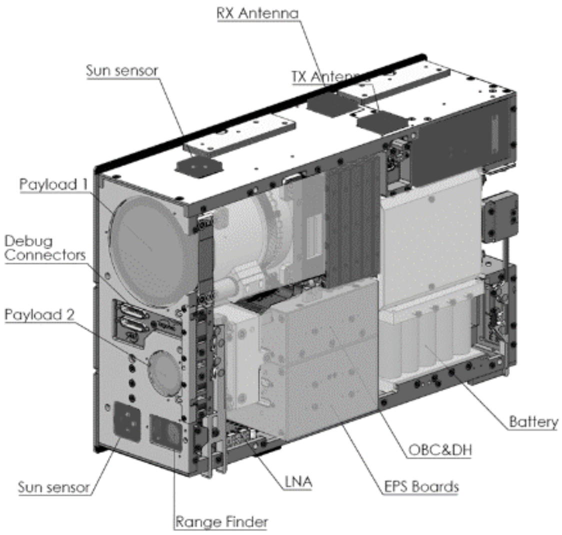

Fig.3 Cubesat configuration

5. Imaging System (IS)

The core part of the OBC&DH is the Imaging Software Algorithm (IS) aimed at processing, tracking and identifying the targets in the field of view of the cameras. The Imaging Subsystem (IS) is aimed at processing the picture acquired with the vision unit of the Payload, in order to recognize the objects in the field of view and support autonomously proximity flight around the target. Both the imaging systems, for ArgoMoon and LICIACube missions have been developed by Argotec.

5.1 ArgoMoon IS

The main target of ArgoMoon, is to image it has to be identified is the Interim Cryogenic Propulsion Stage (ICPS) of the Space Launch System (SLS), where ArgoMoon will be deployed from. The identification of ICPS will make it possible to track and maintain it in the center of the field of view, thus allowing ArgoMoon to take detailed pictures in accordance with the mission goals. ArgoMoon imaging algorithms consist into three main steps, planned to be used in different mission phases:

- **IS1** – Visual Confirmation the object is in view and rough pointing;
- **IS2** – Fine Pointing and MTI (Multiple Target Identification);
- **IS3** – Target Confirmation.

IS1 merges the information commanded to the OBC for the shooting with the pictures metadata and it gives confirmation the target is in view, by comparing the luminance channel with respect to a threshold evaluated from the OBC, thus working with filtered information. Once the object is confirmed to be in view (see Fig. 4) and the rough position has been estimated, each photograph is filtered and analyzed to detect the center of area of the target and the associated dispersion.

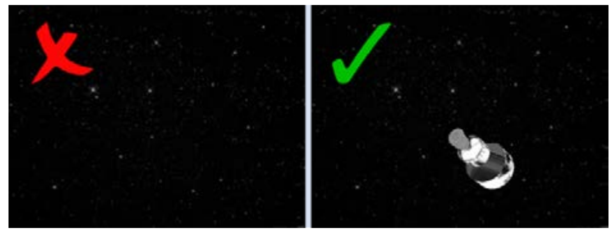
Fig.4 IS1 target confirmation

IS2 is able to ensure the level of pointing required by the mission. A Multiple Target Identification (MTI) algorithm has been developed. This allows ArgoMoon to identify multiple targets (see Fig.5), label them and calculate their estimated centers of areas and dispersion (with IS2 performances). The starfield is filtered, while the three main objects are considered. After this identification, different solutions can be applied in order to select the proper target.

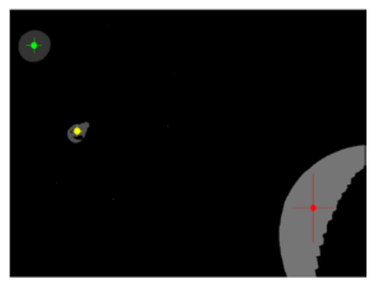
Fig.5 IS2 output, the objects are recognized

For all the IS strategies, once the target is detected, the target pointing vector is computed and sent to the ADCS via the OBC&DH-ADCS link in the shape of a quaternion. The photograph information will be combined with the output of a predictor algorithm that will consider the motion of the satellite during the shooting. This will produce a rotation of the satellite, until the target in the central position of the camera. Confirmation will be provided by IS2 run on a newly acquired picture.

5.2 LICIACube IS

The main modules of the LICIACube navigation system are:

- The Imaging Subsystem (IS) module, that processes and manages the image I acquired from the Payload, in order to recognize the two asteroids and to give a feedback to the Trajectory

Recognition module, in terms of targets position within the image. For each target, the IS provides the offset of the object centroid (Cg) with respect to the centre of the image.

- The Trajectory Recognition module is aimed at estimating the actual trajectory on which the satellite is traveling using the Cg to minimize the error between the nominal orbit and the other 2σ trajectories. The time at which the satellite will be at C/A and its distance from the asteroid at C/A characterize the different trajectories, where the pair (tN, dN) identifies the nominal one. The set of (2σ + 1) calculated trajectories constitutes the trends from which the Trajectory Recognition module will choose the best trajectory. The purpose is to compensate for the uncertainty arising from on-board time and ephemeris. Θ is the angle formed by the vector of the satellite velocity w.r.t. the asteroid at a certain time instant and the straight line connecting the satellite and the asteroid. The inputs of the block are Cg and the satellite attitude information provided by ADCS.
- The Tracking Loop module takes as input the IS result in addition to the angle Θ, in order to derive the desired pointing quaternion q0 to track Dimorphos.
- The Attitude Control module is designed to control the angular velocity of the reaction wheels of the ADCS via a PD controller. It gets the current quaternion (q) and body rate (ω) from the ADCS and by combining them with q0, calculates the torque T to control the ADCS.

6. Mission Operation

6.1 ArgoMoon

After the first phase of the mission, where the spacecraft will autonomously perform relative navigation with respect to ICPS, the spacecraft will be navigated from ground, to follow the reference trajectory. During this phase, the navigation process will require a precise Orbit Determination (OD), to reconstruct the past spacecratf trajectory and predict its future evolution. Whenever the actual trajectory deviates too much from the reference, a Flight Path Control (FPC) will be executed to compute trajectory correction maneuvers. The main navigation requirements are to prevent impacts with the Earth and the Moon, and to guarantee the spacecraft disposal into a heliocentric trajectory. The OD will estimate the spacecraft trajectory using the radiometric observables, Doppler and range, acquired by the Deep Space Network (DSN) and Estrack. The FPC is based on an optimal control strategy designed to reduce the dispersion with respect to the reference trajectory and minimize the total required ΔV. Before the launch, a covariance analysis was performed to assess the expected navigation performance and its robustness. The results of the analysis show that the reference translunar trajectory can be successfully flown, and that the navigation performance is strongly dependent on the uncertainties of the ArgoMoon's Propulsion Subsystem (PS) and the injection in orbit by the launcher. Moreover, the first days of the mission are expected to be challenging due to the tight operations timeline.

6.2 LICIACube

After the LICIACube release from DART, the spacecraft will be navigated from ground to target the desired state during the flyby of Didymos. Three different maneuvers are planned to control the trajectory, a first large orbital maneuver and two smaller correction maneuvers. In addition, a beginning small-thrust maneuver will be executed to check the state of the thrusters after the year of cruise to the Didymos system.

The LICIACube orbit determination relies on ranging and Doppler radiometric observables acquired during two 1.5h daily passes. Opportunistic optical observables of Didymos and DART can be used to enhance the relative orbit reconstruction. The expected navigation performance was assessed through numerical simulations. The Dimorphos B-plane uncertainty at the delivery DCO is almost circular with a 10km of radius, and 5.1 sec of time uncertainty [5]. After the flyby, OD will be limited to the heliocentric trajectory reconstruction to ensure the DSN pointing capability to the spacecraft and allow the downlink of the data acquired during the science phase.

7. Ground Segment

This section provides a description of LICIACube and ArgoMoon Ground Segment (GS) in terms of setting up and communication strategy among satellites and Earth. The architecture design of GS has been thinking in order to make it feasible to manage for broad variety of small sat mission.

The GS consists of all the ground system elements that are used to support the satellite operations during nominal and contingency cases from the Launch phase until the end of mission. It is responsible for acquiring and processing spacecraft telemetry and packets into raw science and ancillary data products. It consists of all the ground system elements that are used to support the satellite operations during nominal and contingency cases from the Launch phase until the end of mission, such as the Argotec Mission Control System (MCC) located in Turin, the DSN Ground Station System and the Ground Communication System (network connection between DSN and Argotec MCC). The MCC is connected to the NASA Deep-Space Network (DSN), and will support both LICIACube and ArgoMoon operations. The ARG-MCC is operated by the Argotec Flight Control Team (FCT) to provide real-time spacecraft control and telemetry monitoring, operations scheduling, Ground Segment control, and satellite navigation. The ARG-MCC is composed of a Front Room and a Back Room for engineering support. The Front Room positions are responsible for real-time operations and safety of the mission, while the back room supports the front room to facilitate meeting mission objectives and provide needed recommendations for their assigned system. To support operations a series of tools have been developed in-house. Argotec developed a Ground Segment Software Suite called ASP (Argotec Service Platform) composed of a Telemetry and Events visualization tool (MARGOT) and a Mission Planning Tool. These tools allow for real-time monitoring of the satellite, from each of the FCT positions, while allowing real-time management of the satellite resources and timelines, for STP (Short Term Planning) and LTP (Long Term Planning).

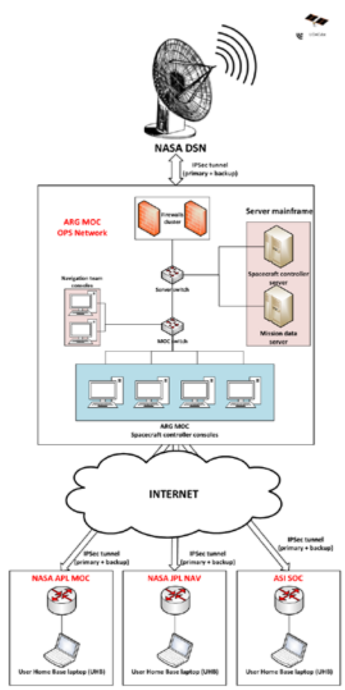

Fig.6 LICIACube Ground Data System (LCC-GS)

LICIACube's Ground segment is shown in Fig.7 and consists of the following distinct elements:

- Mission Control Center (MCC)
- Ground Station System (GSS)
- Ground Communication System (GCS)
- Scientific Operations Center (SOC)
- Applied Physics Laboratory (APL)

LICIACube shall provide telemetry and scientific communication data to the DSN Ground Stations' antennas system in order to exchange telemetry (TM), telecommands (TC) and Ranging information with the JPL Mission Operation Center (MOC). The information shall be passed through the internet via the NASA Johnson Space Center (JSC). From internet, TM/TC and Ranging measurements shall finally be forwarded to the ARG-MCC.

The ASI Space Science Data Center (SSDC) infrastructure, stores LICIACube mission data and documentation and hosts the science planning functions and image data processing pipelines. The MCC is managed by the Argotec Company and is located at its premises. It will be responsible for the delivery to the LICIACube SOC of raw-from-telemetry data format, as well as house-keeping and system data as received by the spacecraft.

The LICIACube SOC will make available the raw and calibrated data (and derived products when and if available) in FITS format (compliant to what described by [6] to the DART SOC in order to share them within the Investigation Team. This sharing is assured by automatically loading, as soon as they are generated, raw and calibrated FITS images of both LICIACube payloads, on the SOC website and SFTP. The section where these images will be uploaded are access restricted to the members of the team.

In addition, after the end of the mission, LICIACube SOC will provide the PDS4-compliant LCC archive to the DART SOC, for publication to the PDS. The work of making the dataset PDS4-compliant as it is originally generated, will be also useful to include these data in MATISSE (https://tools.ssdc.asi.it/Matisse), the SSDC scientific webtool expressly designed to search, visualize and analyse planetary exploration data directly projected over the 3D shade model of the target object.

Ground Station System (GSS) is the DSN Antenna System which will act as an interface between the ARG-MCC and LICIACube.

Ground Communication System (GSS) contains all the interconnections between Ground Systems and creates a communication link between the GS and SOC. Ground Station System and the Mission Control System will be connected via Space Link Extension Protocols.

APL is the center that will be responsible for DART operations and they will be responsible for DART

Mission Operation Center (DART-MOC), constantly in communication with ARG-MCC.

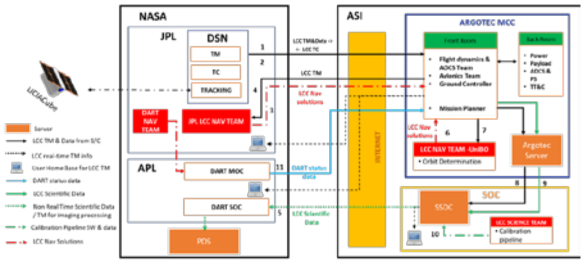

Fig.7 Data flow and communication of the LICIACube Mission and Science Operations Center. Acronyms are intended as follows: Applied Physics Laboratory (APL), Jet Propulsion Laboratory (JPL), Deep Space Network (DSN), Telemetry (TM), Telecommands (TC), Navigation (NAV), LICIACube (LCC), Attitude and Orbital Control System (AOCS), Attitude Determination & Control Subsystem (ADCS), Propulsion Subsystem (PS), Telemetry Tracking & Command (TT&C). Numbers near the arrows have the only scope to identify the corresponding links

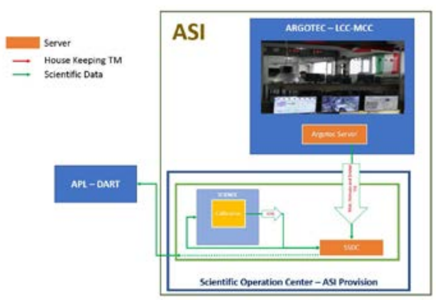

Fig.8 Data flow and communication of the LICIACube Mission Control Center and Science Operations Center

8. Conclusions

The Italian Cubesats ArgoMoon and LICIACube, whose main features and design have been described in this paper, are at the end of the development phase and are now ready to operate. Their respective missions will represent relevant milestones for the national technical and scientific communities, under the promotion, coordination and guidance of the Italian Space Agency. Several companies and international partners from Europe and the U.S. have been involved in the project, under Italian leadership. The overall result is a broad growth in experience and heritage on miniaturized space hardware which will represent a landmark and a guideline for the future of space exploration based on small satellite platforms.
The results of this missions will strongly contribute to future of Space Exploration based on small satellite platforms in Deep Space.

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