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An overview of the ArgoMoon and LICIAcube flight dynamics operations

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Abstract CubeSats are becoming a reliable alternative for low-cost space applications in deep space, as mission companions or as standalone missions. The use of CubeSats in deep space requires to address many operational challenges, particularly those related to navigation. LICIACube and ArgoMoon are the first two 6U CubeSat missions to the outer space funded and managed by the Italian Space Agency, whose spacecrafts have been developed and operated by Argotec. The flight dynamics operations of both missions were performed by the flight dynamics team of the University of Bologna using NASA/JPL's navigation software MONTE. This paper gives a brief presentation of the flight dynamics operations of ArgoMoon and LICIACube and presents the obtained results highlighting the challenges of cis-lunar and deep space CubeSat navigation as well as the achieved successes.

Introduction

The CubeSat standard identifies a category of small satellites whose design is based on an elementary form factor of 1 U, that corresponds to a cube of 10 cm of latus [1]. The use of compact and lightweight spacecraft (S/C) enables a reduction of costs (design, assembly, integration, and launch) without sacrificing research objectives. Many CubeSats have been launched in Low Earth Orbit (LEO) [2], demonstrating that this small satellite technology is also trustworthy for complex missions other than educational or technological demonstrations. These characteristics made CubeSats appealing for deep space and cis-lunar exploration [3], either as stand-alone missions or as companions to conventional, larger spacecrafts. Two recent and relevant cis-lunar and deep space CubeSat missions, that successfully proved the capabilities of the platform and ground teams to operate in the outer space, are LICIACube and ArgoMoon.

Light Italian CubeSat for Imaging of Asteroids (LICIACube)

LICIACube is a 6U CubeSat mission of the Italian Space Agency (ASI) [4] that participated to the Double Asteroid Redirection Test (DART) mission of NASA [5]. The DART mission aimed to perform a technology demonstration to examine asteroid redirection by performing a controlled high velocity impact [6]. The objective of LICIACube was to take thorough and relevant photos of the effects of DART impact on Dimorphos. LICIACube was equipped with an active attitude determination and control system, a cold-gas orbital Propulsion System (PS), and a star tracker, while the core of the scientific payload was composed of two optical cameras [7]. LICIACube was placed into DART as a secondary payload and, after a cruise of 10 months, it was released into space on September 11, 2022, 15 days before the planned impact [8].

LICIACube ground-based navigation has been performed by the Radio Science and Planetary Exploration Laboratory (RSLab) of the University of Bologna (UNIBO), and independently also by the NASA's Jet Propulsion Laboratory (JPL), both using the NASA/JPL's orbit determination software MONTE [9]. The navigation strategy was based on two-way radiometric observables, Doppler and range, acquired by the Deep Space Network (DSN) [10]. The navigation aimed to fly LICIACube through a specific region of the Dimorphos B-plane defined from the mission high-level scientific requirements. The primary navigation requirements were to maintain the nominal trajectory and fly-by conditions to prevent collisions with the impact ejecta debris, maintain the impact scene within the cameras field of view, and prevent the saturation of the reaction wheels during the high-rate rotation phase to point at Dimorphos near the closest approach. The mission timeline included a calibration maneuver (CAL1) to check the thrusters, a targeting maneuver (Orbital Maneuver 1 - OM1) to address the aimpoint, and two clean-up maneuvers (OM2, OM3) to clear potential trajectory deviations during the operations.

On the first hours after the LICIACube deployment from DART, the acquired Doppler data showed a signature compatible with a tumbling motion caused by the S/C, which entered in safe mode because of the release event. However, the tumbling motion was then successfully damped by the CubeSat before the end of the first tracking pass. To properly fit the data of the first two tracking passes, a Doppler bias of ~1.86 Hz had to be estimated. Then, a commanded re-configuration of the LICIACube transponder during the second pass removed the latter bias, leaving only a small residual bias of ~0.025 Hz to be estimated. The Doppler biases were caused by a quantization error on the on-board digital IRIS [11] transponder. Stochastic accelerations were implemented and estimated to fit the data to the noise level. A detailed inspection of the stochastic accelerations shown signatures currently attributed to larger than expected non-gravitation accelerations. Despite the challenges, the team managed to design all the necessary maneuvers to reach the target point and to reconstruct the trajectory of LICIACube, satisfying all the navigation requirements. Figure 1 reports the Orbit Determination (OD) solutions of OM1, OM2, and OM3 deliveries, on the Dimorphos B-plane. As can be seen from the presented results, after OM2, the predicted trajectory and its 3-σ state uncertainty were widely contained in the requirement region and, as consequence, OM3 was scrubbed.

On September 26, 2022, LICIACube flew by Dimorphos at a distance of ~58 km and at a relative velocity of ~6.1 km/s [8], successfully acquiring the images before and after the DART impact on the asteroid including the ejection plume.

ArgoMoon

NASA selected 10 CubeSats as secondary payloads of the Space Launch System (SLS) for the Artemis-1 mission. Among them, ASI's ArgoMoon was chosen as an essential technological demonstrator [12]. The ArgoMoon S/C is based on the same 6U CubeSat platform of LICIACube, and the main goals of the mission were to autonomously fly around the Interim Cryogenic Propulsion Stage (ICPS), to capture images of the stage, and to confirm that the other CubeSats

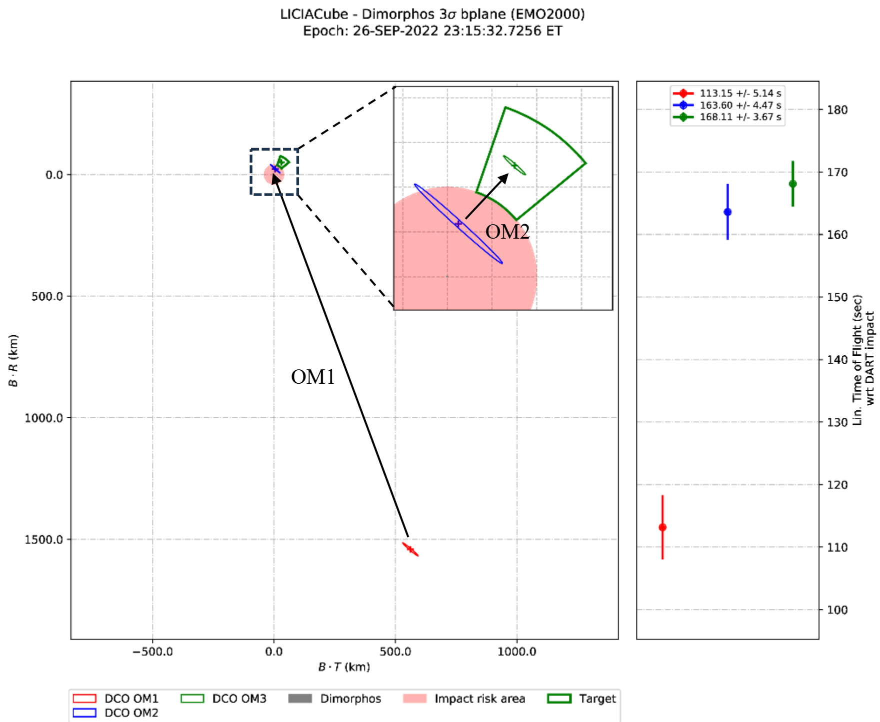

Figure 1: LICIACube predicted trajectory and 3-σ uncertainties mapped to the Dimorphos B-plane for the OD solutions of OM1, OM2 and OM3 deliveries.

were deployed during the first six hours of the mission. After the deployment, the mission foresaw a highly elliptical geocentric orbit for 180 days, with multiple encounters with the Moon.
As for LICIACube, the cis-lunar radiometric navigation of ArgoMoon was performed by the RSLab of UNIBO [13] using MONTE and exploited two-way radiometric data, Doppler and range, acquired by the DSN and the European Space Tracking (ESTRACK). The flight path control aimed to follow the reference trajectory through a dedicated optimal control strategy [13]. The ArgoMoon navigation requirements were designed to guarantee the correct pointing of the S/C from the DSN stations, prevent impacts with Earth and Moon, and allow the S/C disposal in a heliocentric orbit at the end of the mission.

ArgoMoon was successfully launched on November 16, 2022, at 06:47:44 UTC by the SLS. The S/C was released from ICPS after 3 hours and 49 minutes and the first signal acquisition successfully occurred at 10:37 UTC. During its mission, ArgoMoon performed 4 orbital maneuvers (Orbit Trim Maneuver 1B - OTM1B, Statistical Trim Maneuver 0 - STM0, STM1, STM2). However, no maneuver reached the commanded ΔV, showing a significantly underperforming thruster. Moreover, after STM0, a signature on the stochastic accelerations raised the doubt that the S/C thruster could have been leaking, but this assumption is still under investigation. A successful fly-by of the Moon was accomplished on November 21 at 16:07 UTC, about 48 minutes earlier than scheduled. Due to the differences between the commanded ΔV and that actually produced by thruster, the error on the B-plane with respect to the reference trajectory was of 5000 km, as can be seen from UBO007-10 of Figure 2. After the Moon’s fly-by, ArgoMoon flew by the Earth at ~166000 km on November 24, 2022, at 18:38 UTC. The S/C was unable to follow a geocentric orbit due to the altered geometry of the Moon's fly-by, effectively entering into a heliocentric orbit.

During the operations, the navigation team delivered a total of 10 OD solutions (UBO001 to UBO010) and 5 orbital maneuvers (where 4 of them have been commanded and executed, and one used as backup) [14]. The quality of the ArgoMoon radiometric data were mostly affected by the

S/C's rotational dynamics, the IRIS radio design and configuration, and the on-board activates (for example safe mode, reboot, desaturation maneuvers).

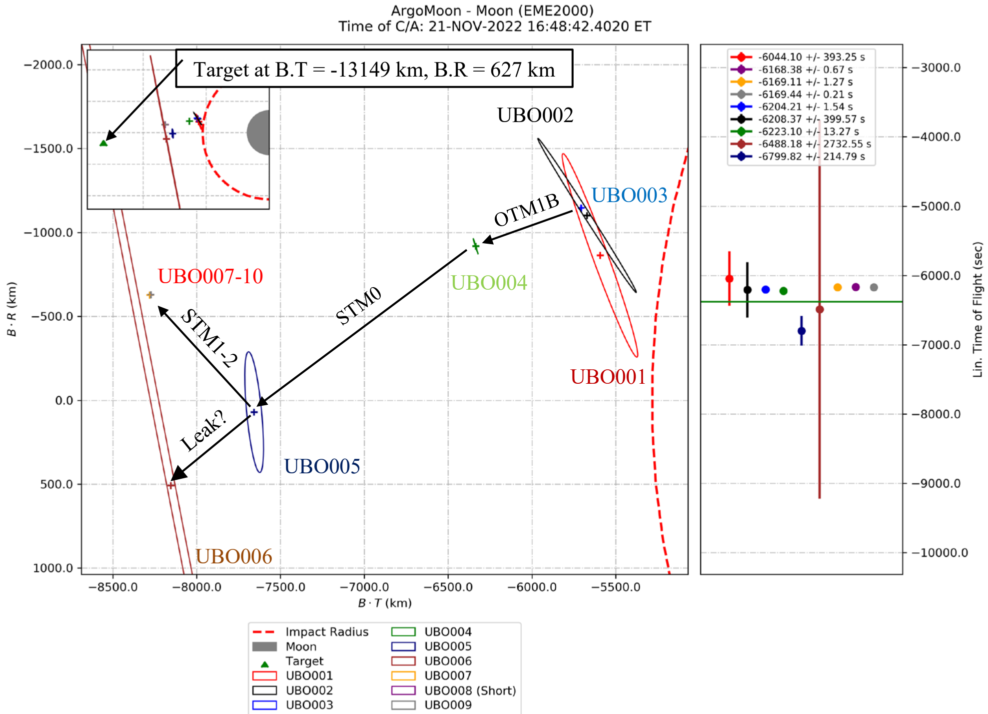

Figure 2: Summary of the delivered ArgoMoon OD solutions mapped on the Moon B-plane.

Conclusions

Using CubeSats in deep space requires addressing many operational challenges, particularly those related to the navigation, given the platform limitations related to the off-the-shelf components that are employed in the CubeSat philosophy and the strong requirements, similar to classical large deep space missions.

The navigation of LICIACube and ArgoMoon has proven the capability of CubeSats platforms to operate in deep space and achieve complex objectives. The navigation results show a performance on the residuals as good as any typical deep space mission. The Doppler and range residuals of LICIACube show a Root Mean Square (RMS) of 0.05 mm/s and 80 cm, respectively, while ArgoMoon had a RMS of 0.1 mm/s on Doppler and 30 cm on range. For both missions, the UNIBO navigation team was able to fulfill the navigation requirements, even with a very stringent contingency timeline, proving the reliability of the designed navigation procedures. Thanks to the obtained success, the pioneering flights carried on by LICIACube and ArgoMoon will surely provide a relevant heritage for the upcoming deep space and cis-lunar CubeSats missions.

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