Flight Dynamics and Navigation Performance of the BioSentinel Mission

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BioSentinel was one of ten CubeSats launched by the Space Launch System (SLS) as part of the Artemis I campaign on 16 November 2022. A lunar flyby gave BioSentinel the needed energy to escape the Earth-Moon system into heliocentric space. The biological payload contains yeast cells designed to measure radiation in deep space beyond the reach of Earth's magnetosphere. This paper discusses in detail the BioSentinel flight performance, as well as challenges and lessons learned prior to, and during the mission.

I. Introduction

The BioSentinel mission launched aboard the SLS Block 1 launch vehicle (LV) as part of the Artemis I campaign (see SLS and Artemis reference guides). The main purpose of this campaign was to place the Orion capsule into a distant retrograde orbit (DRO) around the Moon (Dawn et. al. 2018; Witze 2022), which succeeded. In addition, ten 6U CubeSats ride-shared with Artemis-I, placed in various azimuthal locations inside the Orion Stage Adapter (OSA), which connected the Orion capsule itself and the SLS's upper stage, namely the Interim Cryogenic Propulsion System (ICPS). Originally 13 CubeSats were to ride along inside the ICPS/OSA (Robinson e. at. 2020; McIntosh, Baker and Matus 2020); however, only ten were ready in time for encapsulation during 2021, among them BioSentinel. The payload, comprising 4U of the total 6U CubeSat volume, consists of a biology experiment. More precisely, the project attempts to measure DNA damage due to natural radiation in heliocentric space (far beyond that occurring in the radiation-shielded LEO regime) on the standard organism Saccharomyces cerevisiae (i.e., yeast). The DNA damage will then be compared to (a) an identical sample aboard the ISS, as well as (b) another identical sample on the ground (Tieze e. at. 2020; Padgen et al. 2021).

II. Pre-Launch Activities

Pre-launch activities included mission design updates, rehearsals and the development of a tracking schedule in coordination with the Artemis-I payload office and the Deep Space Network (DSN) for various potential launch dates. Nominal BioSentinel trajectories were computed for the opening and the closing of the various SLS launch windows (of variable duration), thereby bracketing the possible orbital behavior of the CubeSat. An important influence on the trajectories of the CubeSat secondaries was the uncertainty associated with deployment from the OSA. The OSA/ICPS was rotating at a rate of 1 rpm; there was also uncertainty in the spin axis attitude, which translated into an unknown clock angle of deployment. The wide dispersions in this angle and magnitude of deployment, plus the variable Sun-Earth-Moon geometry for different launch dates implied the existence of a non-negligible risk of a lunar impact, which was evaluated using Monte Carlo methods for various potential launch dates; please see Figure 1.

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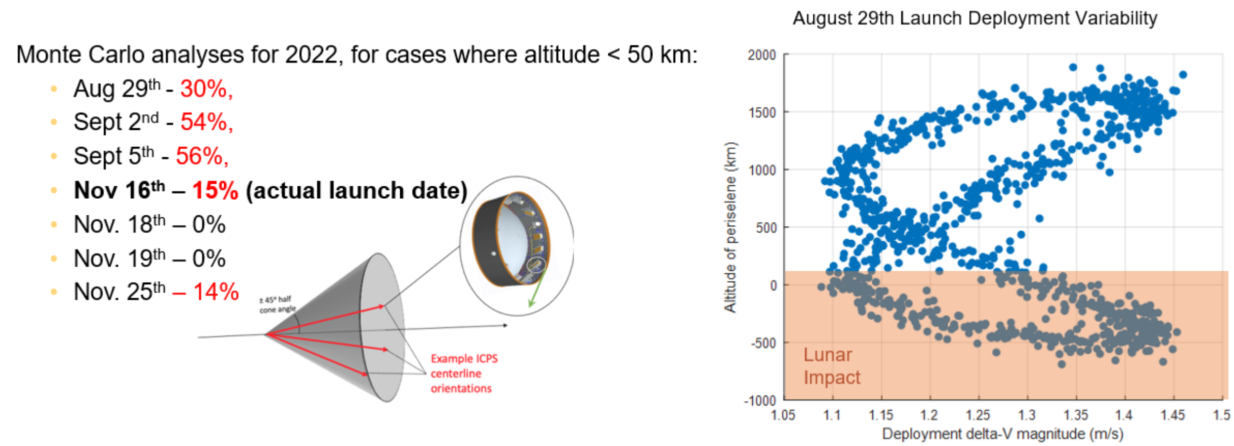
Figure I: BioSentinel lunar impact risk for various SLS launch dates, from Monte Carlo Analyses. The plot on the right shows resulting periselene altitude for all cases for a specific launch date of 29-Aug-2022, resulting a 30% risk of lunar impact. Image credit: ARC FD.



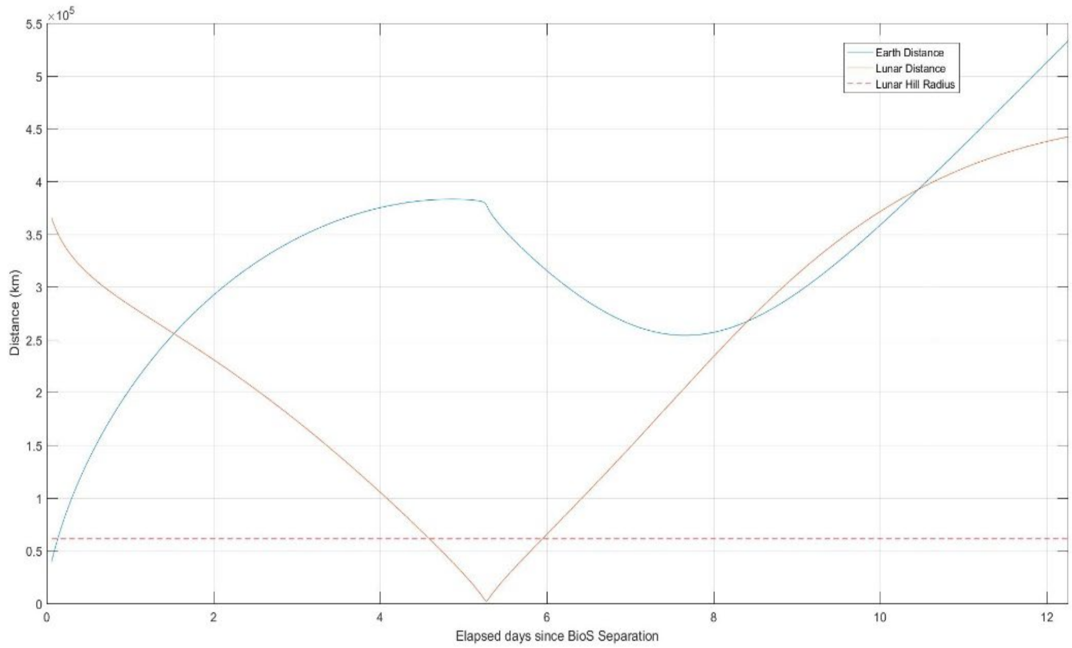
III. Launch and LEOPS

After four attempts, on November 16th 2022 SLS Block 1 launched 44 minutes into its two-hour launch window, in SLS launch period 28. BioSentinel successfully deployed from the OSA/ICPS 3.7 hours post-launch, in the so-called Bus Stop 1 region, at an altitude a few thousand km higher than GEO: it was the second CubeSat in the deployment order. Thereafter the mission team started to receive telemetry and tracking data from the DSN and ESA stations. Soon after deployment, however the CubeSat went tumbling and entered safe mode. The mission team recovered the spacecraft and after four tracking passes, the navigation team solved for an initial ephemeris which was sent to the DSN for better tracking. All four solar panels were nominally deployed soon after. By propagating this first ephemeris solution, the navigation team determined that BioSentinel avoided impact with a margin of a few hundred km from the lunar surface. More tracking data over the next few days allowed for a more refined orbit solution, namely[2] 530 km × 377,711 km × 30°.3; in addition, we were able to ascertain that the deployment speed from the OSA was 1.24 m/s. This implied a periselene altitude of 406 km, occurring 5.4 days post-launch; therefore, BioSentinel operators avoided any trajectory correction maneuvers. A lunar eclipse lasting 36.5 minutes occurred soon after the flyby. BioSentinel's distance to Earth underwent a temporary minimum (2.54×10^5 km) two days after flyby, after which it increased monotonically ever since; please see Figure 2.

To a greater or lesser degree, tracking data of various types (DSN Doppler; DSN sequential ranging; as well as Doppler and Ranging, and TCP – total count phase) were obtained from all 14 antennas in the Deep Space Network, as well as from the ESA antennas Goonhilly (UK), New Norcia (Australia) and Malargüe (Argentina). Over the course of the next two weeks the mission operators corroborated that the subsystems were functioning as expected: IRIS radio, solar arrays, patch low and medium gain antennas, EPS, C&DH, and the Propulsion system. Science operations started 5-Dec-2022, a week before BioSentinel exited the Earth's Hill sphere.

[2] Perigee height × apogee height × inclination with respect to Earth's equator, in the J2000 frame.

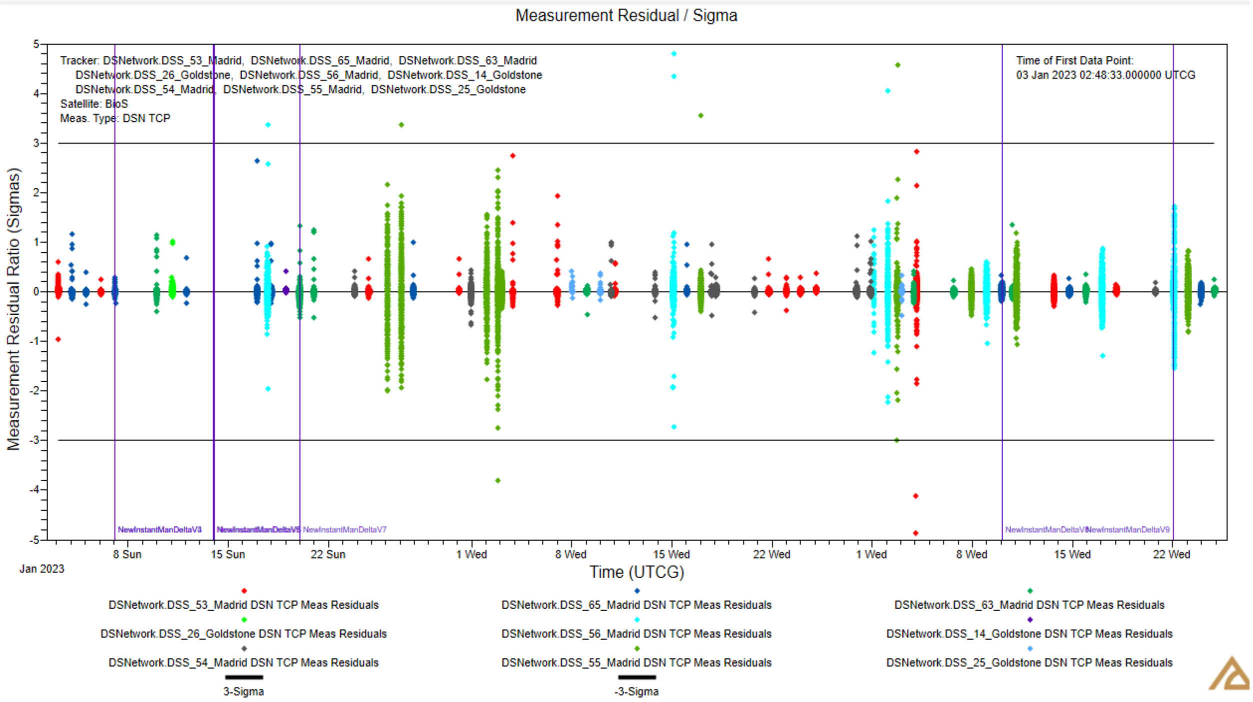
Figure II: BioSentinel distances to the Earth (blue) and Moon (red) versus time since its deployment. The minimum distance to the Moon was approximately 2,140 km (406 km from the lunar surface). The minimum post-flyby Earth distance was approximately 254,060 km, after which point it monotonically increased. The red dashed line at the bottom represents the lunar Hill radius (61,274 km; BioSentinel spent approximately 1.9 days inside the Moon's Hill sphere). Image credit: ARC FD.



IV. Current Status

The lunar flyby provided the necessary energy to achieve an Earth-trailing heliocentric orbit, eventually reaching a heliocentric semi-major axis of 1.02 AUT. The Linear Energy Transfer (LET) spectrometer is functioning nominally, BioSentinel continues to serve as a radiation detector in heliocentric space. Routine Mission Ops continues with, among other things, TT&C with the DSN antennas (a few passes per week, routinely providing TCP tracking-data), momentum dumps and periodic orbit determination activities to continue refining BioSentinel's trajectory in its Earth trailing orbit (BioSentinel will reach aphelion June 10th, 2023); please see Figure 3.

Figure III: Residual ratios of TCP-type tracking data for BioSentinel in its heliocentric orbit; note how most residual rations are withing +/- 3σ. Vertical lines represent momentum-dump maneuvers (ΔV's typically on the order of 10^{-4} m/s). Image credit: ARC FD.



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