Deep Space Navigation for the BioSentinel CubeSat Science Orbit

Jose Alvarellos (1), Andres Dono (2)

(1) *Flight Dynamics Team, ASRC Federal, NASA Ames Research Center*
(2) *Flight Dynamics Team Lead, Axient, NASA Ames Research Center*

ABSTRACT

BioSentinel is a 6U CubeSat active in heliocentric orbit, as of April 2024. The spacecraft was launched aboard the first SLS flight as part of the Artemis-I campaign in November 2022. After successful separation from the upper stage of SLS, it performed a lunar flyby which provided the necessary energy to achieve an Earth-trailing heliocentric orbit. This paper includes a description of the final science orbit as well as its evolution, the techniques and procedures utilized to perform the orbit determination and a description of the overall navigation campaign, with emphasis on the heliocentric orbit operations.

1 INTRODUCTION

The BioSentinel spacecraft is a CubeSat of the 6U form-factor currently (as of April 2024), active in heliocentric space. It carries a 4U astrobiology payload that consists of yeast cells, optical and microfluidics sensors, and a Linear Energy Transfer (LET) spectrometer that has the objective to measure deep space radiation from events such as coronal mass ejections and solar particle events. Along with the Orion capsule, BioSentinel was one of ten CubeSats placed in orbit by the inaugural launch of the Space Launch System (SLS) rocket on 16-Nov-2022, where upon separation from the Interim Cryogenic Propulsion System or ICPS (the upper stage of SLS) it was injected into a large (a = 195,499 km) and highly eccentric (e = 0.965) geocentric orbit. Approximately 5.2 days after separation, it performed a lunar flyby with a periselene altitude of 406 km, which was followed 26 minutes later by an eclipse lasting 36.5 minutes. The flyby provided the necessary energy to achieve a heliocentric orbit, in an Earth-trailing pattern. The navigation analysis/orbit determination (OD) consisted of a sequential Kalman-filter that utilized tracking data from the Deep Space Network (DSN [1]) and the ESA Estrack network. Many antennas were needed since the Artemis-I campaign included the injection of a total of ten CubeSats, as well as the Orion capsule, in orbit. Therefore, the scheduling process required more antenna assets than usual, due to simultaneous demands from the various missions. The processed tracking data was also refined with a smoother process to obtain more accurate solutions. We used Ansys' ODTK 7.0 to process the tracking data and perform the OD. The mission involved the processing of diverse set of tracking data types, including total count phase (TCP), Sequential Range, Doppler and Range formats. These measurements were used from BioSentinel separation until approximately four days past the flyby. The solar radiation pressure (SRP) coefficient, as well as the ΔV from the deployment (1.24 m/s) and the flyby, were modelled to obtain suitable solutions that could decrease the position and velocity uncertainties along the mission concept of operations. The final product each time resulted in updated ephemeris files that were used by the mission and the antenna networks as the mission progressed.

2 NAVIGATION PERFORMANCE IN HELIOCENTRIC SPACE

The preparation for the mission included various Monte Carlo simulations regarding the spacecraft deployment, which indicated that a non-negligible fraction of cases could result in lunar impact for some launch dates. Detailed information about the separation orbit and lunar flyby, and about the performances of the various BioSentinel sub-systems can be obtained from [2-3], and references therein. Science operations started in early December 2022, but unfortunately no yeast cell growth was observed [2]. However, the LET spectrometer continues to record valuable data. Table 1 below, reproduced from reference [3], shows the BioSentinel major sequence of events. In this paper we place the focus on the post-flyby orbit. Section II provides more details about navigation of a CubeSat in heliocentric orbit, and in section III we provide our conclusions.

Table 1. Major sequence of events for the BioSentinel mission (from [3]). Elapsed Time is measured from BioSentinel separation from ICPS.

Event	Date/Time (UTC)	Elapsed Time (days)	Notes
SLS Launch	16-Nov-2022 06:47:44	-0.155	44 mins. into launch window[1]
BioS Separation from ICPS	16-Nov-2022 10:30:42	0.0	
BioS Enters Lunar Hill Sphere[2]	20-Nov-2022 23:14:35	4.530	
BioS Closest Lunar Approach	21-Nov-2022 15:40:51	5.215	Periselene altitude = 406 km
Eclipse Starts	21-Nov-2022 16:06:56	5.233	
Eclipse Ends	21-Nov-2022 16:43:23	5.259	36.5 mins. duration
BioS Exits Lunar Hill Sphere	22-Nov-2022 19:47:29	6.387	1.9 days inside lunar Hill Sphere
Minimum post-Flyby dist. to Earth	24-Nov-2022 00:54:58	7.600	254,250 km from Earth
BioS Exits Earth's Hill Sphere	12-Dec-2022 10:30:00	26.000	Enters heliocentric space

As detailed in [2], a few days after the lunar flyby and eclipse BioSentinel momentarily decreased its distance to Earth (Table 1), although soon after, the distance to Earth continued monotonically increasing. On the 12th of December in 2022 (26 days after separation) BioSentinel exited the Earth's Hill sphere, which can be considered the boundary between the region where Earth's gravity dominates (inside) and where the Sun's gravity dominates (outside). The Earth's Hill sphere radius is given by

$$R_H = a\left(\frac{M_E}{3(M_E+M_S)}\right)^{1/3} \qquad (1)$$

where M_E and M_S are the masses of the Earth and Sun, respectively, and a is the Earth's semi-major axis. Using values from [4] we find $R_H = 1.497\text{x}10^6$ km; note that this is essentially the distance from the Earth's center to either L1 or the L2 point (Earth-Sun system). Figure 1 shows the plot of the C3 energy versus the elapsed time, for the first 180 days. Notice how prior to the lunar flyby, the C3 energy was negative (i.e., bound to Earth), as expected. The lunar flyby injected enough energy so that the C3 almost instantaneously became positive, with a maximum value of 2.375 km^2/s^2 at the flyby. Soon after, the C3 decreased to a local minimum of 0.086 km^2/s^2, occurring 15.6 days post-separation. Thereafter C3 monotonically increased so that 180 post-separation days its value is nearly 8.02 km^2/s^2.

Other important post-flyby events not mentioned in Table 1 above, and related to the concept of operations, are that the last tracking data pass from an ESA station occurred on the 24th of November, in 2022 from the Malargüe ground station, located in Argentina. Thereafter, BioSentinel used only DSN passes to obtain tracking data. Further, and starting at about the same time, the tracking data type received from DSN was and continues to be TCP only. For telemetry, tracking

[1] The launch window for the 16-Nov-2022 launch date was two hours [2].
[2] The lunar Hill sphere radius is $6.13\text{x}10^4$ km [2].

and control (TT&C), BioSentinel uses the X-band Iris version 2.1, which is a software-defined radio (SDR). In addition, the spacecraft has two low-gain antennas (LGAs) on its -Y body face and one medium-gain antenna (MGA) on its +Y body face [2].

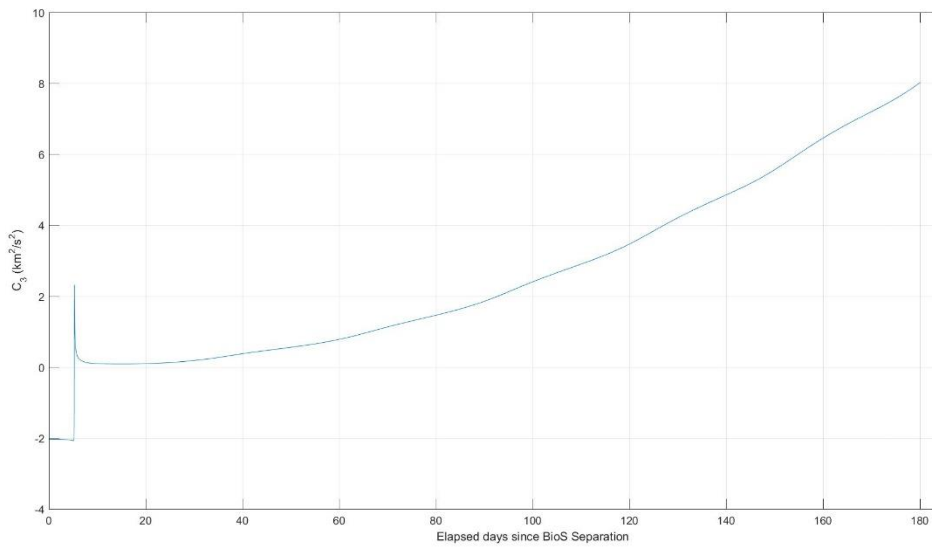

Figure 1. BioSentinel's C3 versus time for the first 180 days post-separation.

BioSentinel has a cold-gas propulsion system, which includes seven nozzles. There are two nozzles on the +Y body-face (one of which has been found to be inoperable [2]) and two nozzles on the -Y body face. In addition, there is one nozzle on each on the +Z and -Z body faces. All six nozzles are located near the +X body face and, along with three reaction wheels, are used for attitude control. Finally, there is one nozzle located in the middle of the +X body face. This seventh nozzle could have been used to apply a ΔV to the spacecraft soon after separation, in the event that the deployment from the ICPS main vehicle would have put BioSentinel in a lunar-impact trajectory. Initial orbit determination (IOD) analysis performed after deployment indicated that the periselene altitude would be close to 410 km, making a maneuver for collision avoidance unnecessary [2, 3], and as of the time of this writing (April 2024), the seventh nozzle has not been used. During routine operations, BioSentinel has the solar arrays pointed to the Sun (i.e., the -X body axis points to the sun). The cross-sectional area to the Sun is 0.316 m^2 [3]. However, during communication passes, the CubeSat is oriented so that the antennas point to Earth, when differential solar torques accumulate momentum which needs to be periodically dumped [2]. For instance, during the year 2023, there were 20 momentum desaturation maneuvers, and the typical ΔV imparted to the spacecraft was 2 mm/s per maneuver. These desaturation maneuvers, as well as the point-gravity of the Earth, Moon, Sun and the rest of the major planets, plus SRP are taken into account in the force model implemented in the aforementioned ODTK, plus in the Ansys' STK version 12.4 and the GMAT version 2020a that were used during the mission.

Figure 2 shows a sample plot of residual ratios since the 1st of December of 2023, for the various DSN communication passes, where in addition to command uploads and telemetry downloads, TCP tracking data is downloaded and used in the OD process. Note that most of the tracking data comes from the Madrid-Robledo DSN complex, with some data from the Goldstone complex as well[3]. Currently, OD is performed every three weeks to incorporate new tracking data and any necessary desaturation maneuvers occurred since the last trajectory update. The resulting

[3] Last tracking data from the Canberra complex was obtained December 2022.

heliocentric orbit solution obtained from the OD process is shown in Table 2, while the evolution of said orbit elements is shown in Figure 3. The trajectory is converted to the SPICE and periodically uploaded to the SPS system [5] and distributed to the rest of the Mission Operations team as well.

Table 2. BioSentinel heliocentric orbital elements with respect to the mean ecliptic and equinox of J2000.

Epoch	1-Dec-2023, 00:00:00 UTC
Semi-major axis, *a*	152,378,168 km (1.018585 AU)
Eccentricity *e*	0.0193878
Inclination *i*	0.239 deg
Longitude of the Ascending Node Ω	66.045 deg
Argument of perihelion ω	4.092 deg
True Anomaly υ	348.240 deg
Orbital period T_B	375.5 days
Perihelion distance *q*	149,423,893 km (0.998837 AU)
Aphelion distance *Q*	155,332,443 km (1.038333 AU)

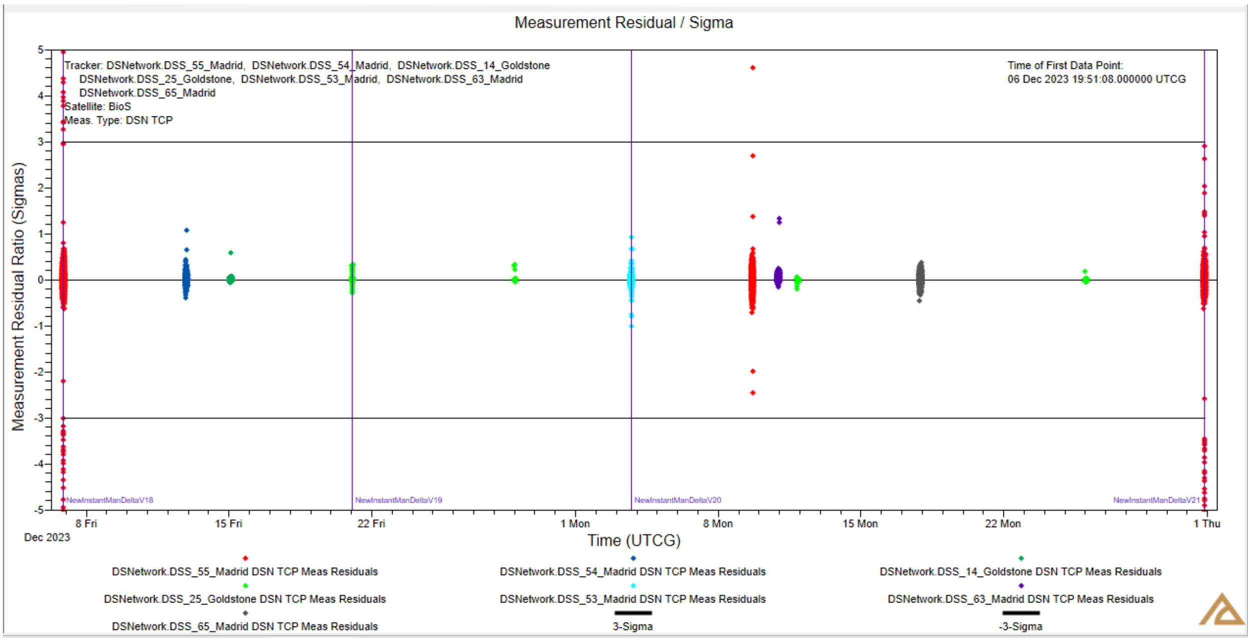

Figure 2. Residual ratios since 1-Dec-2023; the vertical lines represent momentum dumps.

BioSentinel is currently in an Earth-trailing orbit and its current orbital period is about 376 days. Notice from Figure 3 that its semi-major axis is slowly growing as a result of the gravitational pull of the Earth, which is ahead of the CubeSat. However, as its distance to Earth increases, the effect naturally becomes weaker, and its effect on the semi-major axis decreases. BioSentinel last passed perihelion on the 12th of December 2023, and will pass aphelion on the 19th of June, in 2024.

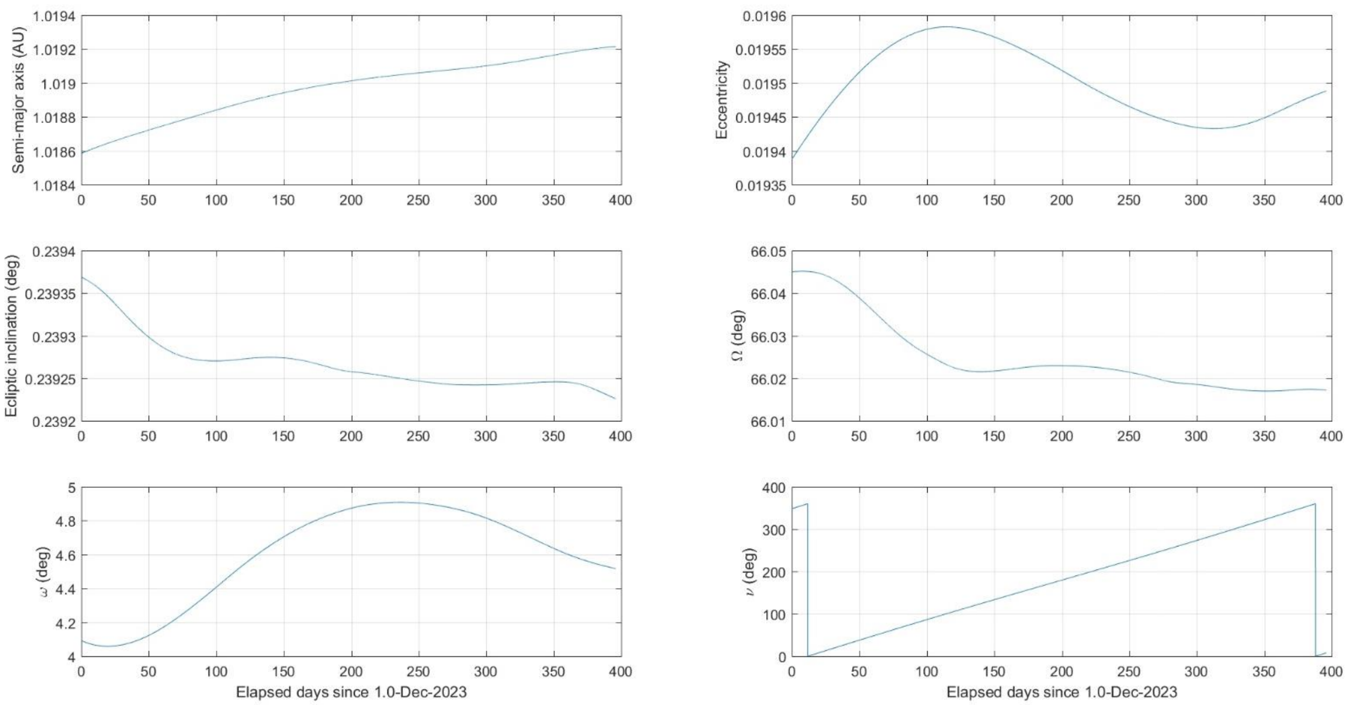

Figure 3. Evolution of the BioSentinel heliocentric orbital elements (mean ecliptic and equinox of J2000).

In Figure 4 we show the position of BioSentinel in the inner solar system on 5-Apr-2024. The synodic period of BioSentinel *S*, is related to the orbital periods of the Earth (T_E) and BioSentinel (T_B) by the simple relation [6]

$$\frac{1}{S} = \frac{1}{T_E} - \frac{1}{T_B} \qquad (2)$$

Making use of Kepler's Third Law, and the binomial theorem (using the small parameter Δa = 0.018585 AU i.e., the difference between BioSentinel's and Earth's semi-major axes), we obtain

$$S \approx \frac{2}{3\Delta a} \qquad (3)$$

Plugging the values from above we obtain the synodic period of BioSentinel $S \cong 36$ years, after which time the CubeSat will again approach Earth. In the time corresponding to *S/2*, BioSentinel will be at its most distant from Earth (approximately 300x10^6 km), since at that instant, it will be behind the Sun as seen from Earth.

The distance to Earth since separation from ICPS is shown in Figure 5; each dot represents a ground station pass. Currently there occurs one DSN pass per week. The density of passes was much higher earlier in the mission, as can be seen in Fig. 5. The small, local minimum seen near the origin (at 7.6 days) represents the post-flyby minimum distance to Earth (see Table 1 and [3]).

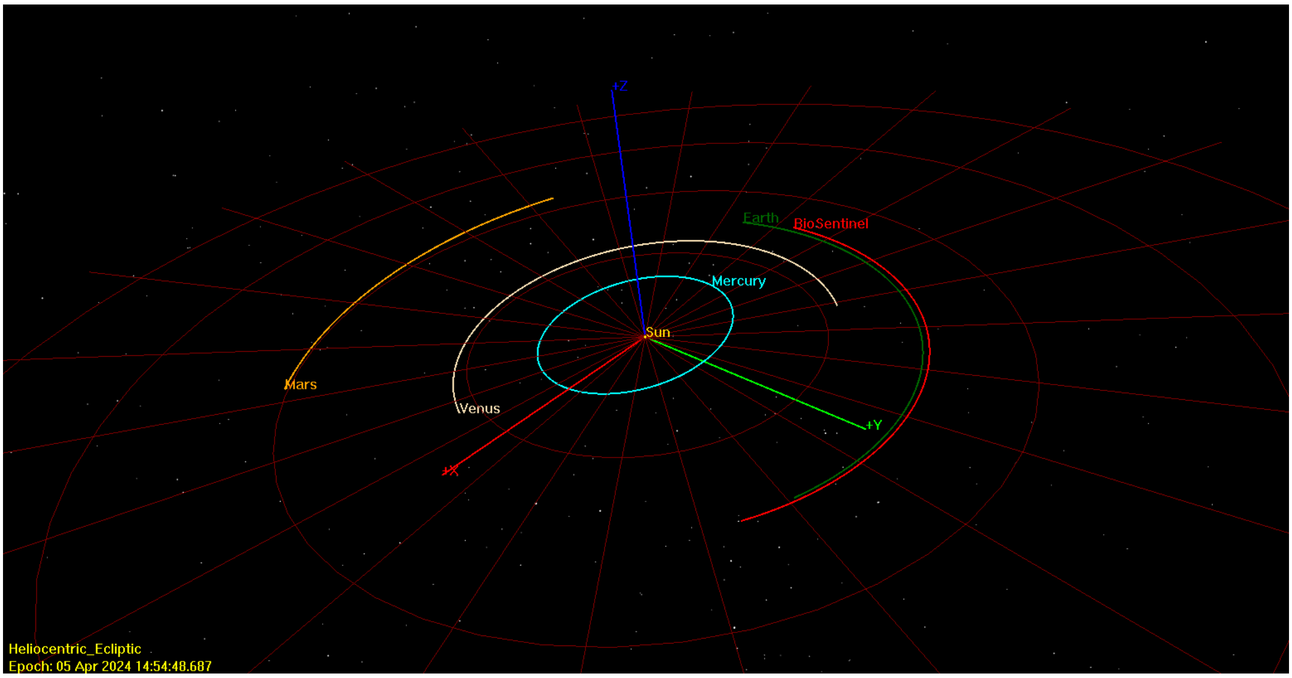

Figure 4. The position of BioSentinel in the inner solar system for Epoch 5-Apr-2024, 14:54:49 UTC (mean ecliptic and equinox of J2000)

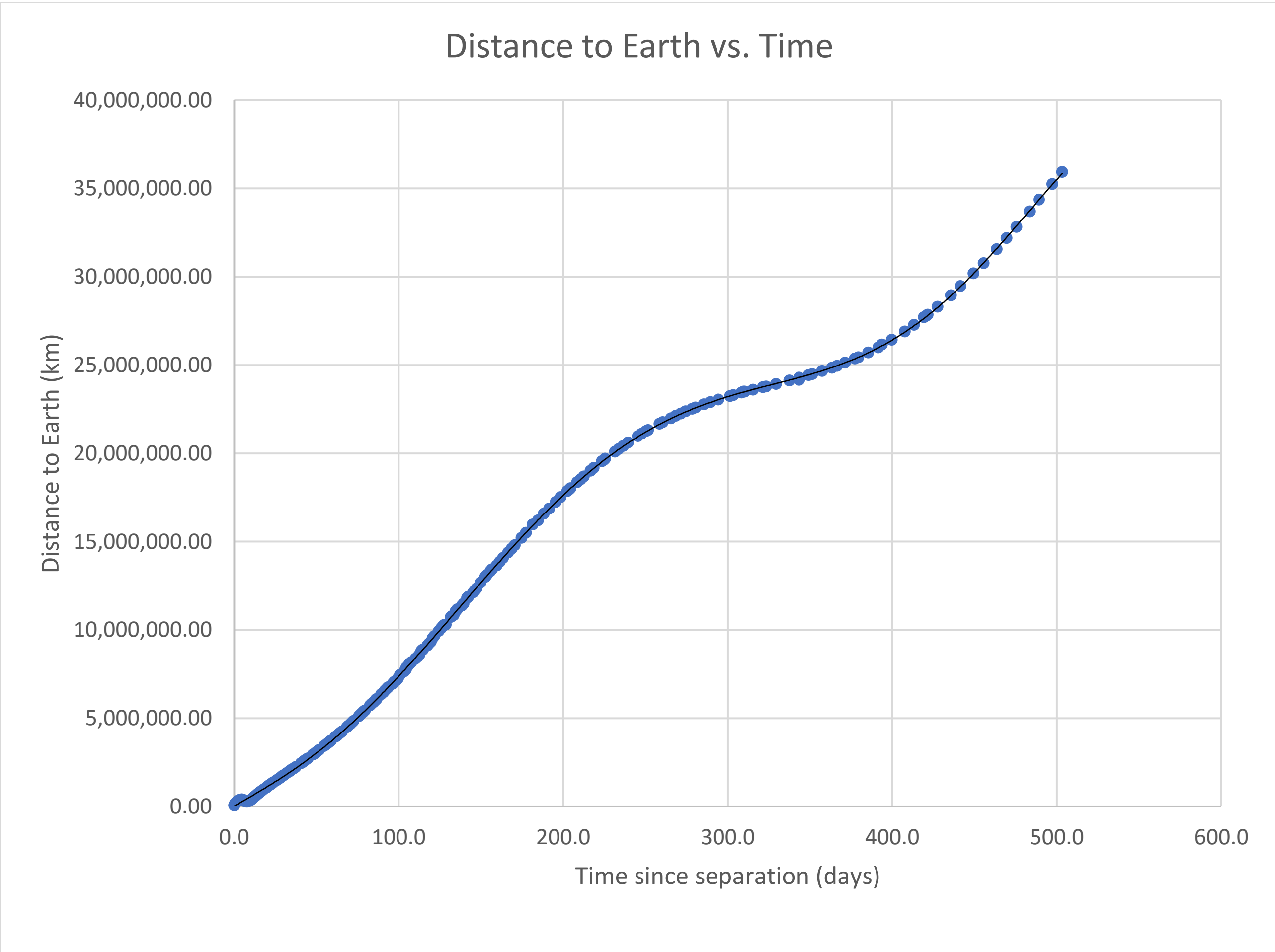

Figure 5. BioSentinel distance to Earth since separation from ICPS.

Finally in Figures 6 and 7 we show BioSentinel's position and velocity 3σ uncertainties, both expressed in the Radial, In-Track and Cross-Track (RIC), components respectively. The vertical lines represent desaturation maneuvers. Note how In-Track is typically the largest position uncertainty component; conversely radial is typically the largest velocity uncertainty component.

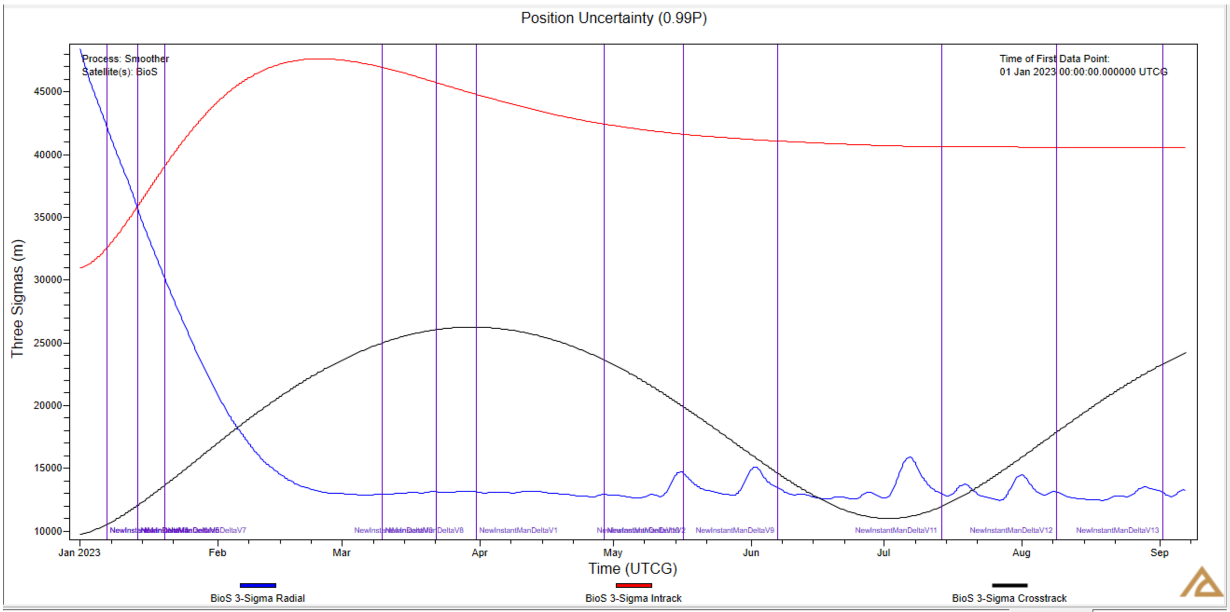

Figure 6. BioSentinel's sample position uncertainties in heliocentric space (RIC).

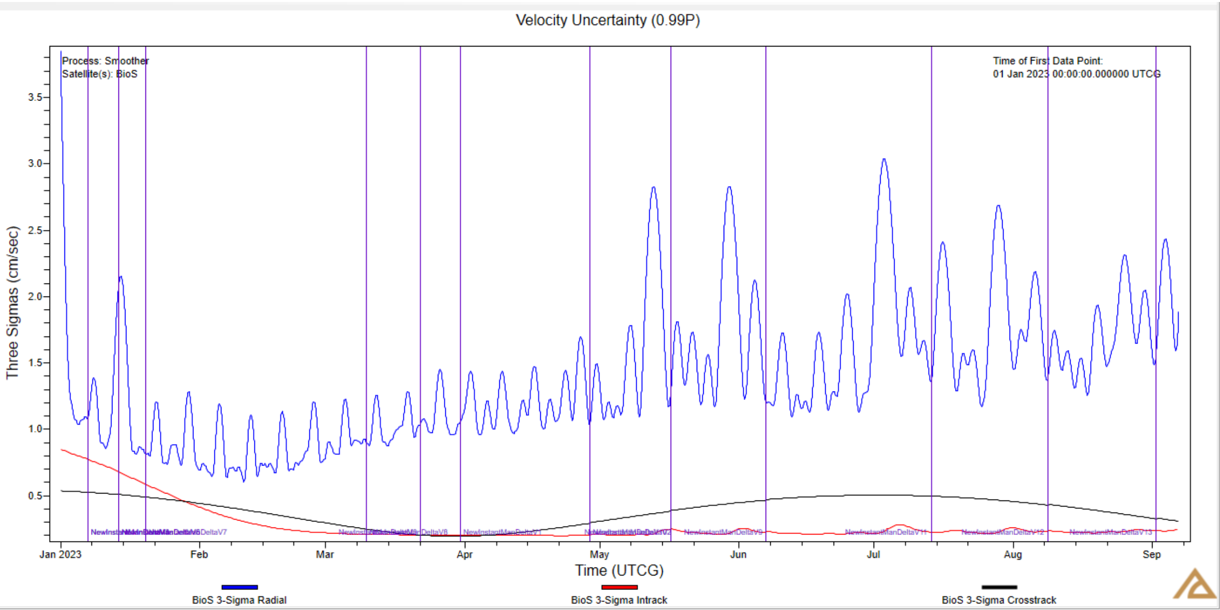

Figure 7. BioSentinel's sample velocity uncertainties in heliocentric space (RIC).

4 CONCLUSIONS

The BioSentinel mission has completed its first year and a half of ongoing spacecraft operations and measurements successfully. The flight dynamics team has guided the spacecraft from its deployment in Earth orbit, through a lunar flyby and to its final science orbit, in an Earth-trailing heliocentric orbit. Since then, the tracking data has been processed regularly every few weeks, showing an stable orbit configuration.

This paper has covered mostly the science orbit navigation. The spacecraft contains the biological payload more distant from Earth in history. The science is being carried out regularly measuring space radiation with the LET instrument. The navigation team continues to process TCP data from the DSN to compute orbital predictions as well as to keep track of the spacecraft. In addition, desaturation maneuvers that occur regularly are monitored and modeled. Details about these procedures have been explained herein.

5 ACKNOWLEDGEMENTS

The authors of this paper would like to thank the rest of the NASA Ames Research Center (ARC) Flight Dynamics Team, especially Nahum Alem for his help with the orbit determination scripts of the FDS, Laura Plice, for her contributions during all the phases of the mission, and Paul Levinson-Muth and Dylan Morrison-Fogel for their help with the internal reviews. We would also like to extend our gratitude to all the ARC Mission Ops BioSentinel team, in particular to Matt Napoli and Marcie Smith. In addition, we would like to acknowledge the contributions of the Space Exploration Engineering team that helped prior to and during the mission, especially Lisa Policastri, Ryan Lebois and John Carrico. We would also like to thank following individuals: Charles Miyamoto and Gerhard Kruizinga from NASA JPL for all the support during the preparations prior to launch and during the campaign navigation phase; Robert Stough from the Marshall Space Flight Center (MSFC) for all their insights regarding the ICPS orientation and orbit determination. Thanks also to C. Markwardt of GSFC for the doy websites. Finally, thanks also to R. Mathur of York Space Systems for relevant discussions.

6 REFERENCES

[1] Slobin, S. D. "Deep Space Network 301; Coverage and Geometry". DSN No. 810-005, 301, Rev. M, September 2020

[2] Napoli, M., Kong, C., Homan, J., Fusco, J., Nakamura, R., Padgen, M., Wu, S., Shi, P., Benton, J., Heher, D., Stevenson, T., Dono-Perez, A., Alvarellos, J. 2023. "BioSentinel: Mission Summary and Lessons Learned from the First Deep Space Biology Cubesat Mission". SSC23-I-02.

[3] Dono-Perez, A., J. L. Alvarellos, Alem, N., Napoli, M., Policastri, L. and Lebois, R. 2024. "Flight Dynamics and Navigation Performance of the BioSentinel Mission", 2024-1273. AIAA SciTech Forum, Orlando Fl.

[4] Murray, C. D., Dermott, S. F. 1999. "Solar System Dynamics". Cambridge University Press.

[5] Bui, B. "Service Preparation Subsystem (SPS) User Interface Portal User Guide". DSN No. 887-000117, Rev. A, December 2018.

[6] Roy, A. E. 1978. "Orbital Motion". A. Hilger Lmdt.

[7] Bryant, S. "TRK-2-34 DSN Tracking System Data Archival Format". DSN No. 820-013, TRK-2-34, Rev. O. October 2015.