Enhancing Space Operations: From Solar System Exploration to Advanced Space Situational Awareness with SPICE and AI/ML

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Abstract

Starion plays a crucial role in mission planning and operations support as the primary service provider for the European Space Agency's (ESA) solar system science exploration program. This abstract outlines Starion's transition from supporting ESA's solar system missions to pioneering advancements in Space Situational Awareness (SSA) through innovative use of the SPICE geometry system and state-of-the-art AI/ML algorithms.

In this context, Starion develops and maintains operational software for mission planning in solar system science missions such as Mars Express, BepiColombo, and JUICE. This software encompasses mission analysis, observation opportunity finding, operations scheduling, spacecraft trajectory and pointing planning, simulation and constraint checking, and operational products generation. These computations rely on SPICE, an information system developed by JPL at Caltech, which uses ancillary data to provide solar system geometry. Starion also leads the ESA SPICE Support Office, offering mission analysis and operations support for various ESA solar system missions using SPICE.

Drawing on its extensive mission operations experience with SPICE, Starion has created an innovative SSA solution. This solution is part of ASTRAL—a component-based ground segment offering—that ensures scalability, modernization, and cost-effectiveness. ASTRAL builds on Starion's strong operational heritage in ground segment development, mission automation, and operations preparation, adopting a security-by-design strategy. Its versatile architecture ensures seamless accessibility, improves user experience, and features modular, integrable plug-ins for customization to specific mission requirements. Powered by SPICE, the SSA solution can handle hundreds of thousands of bodies concurrently and perform geometry computations, further strengthening the system's capability to manage complex spatial data and operations.

This solution has been enhanced with AI/ML algorithms, achieving a robust and accurate orbit prediction model, crucial for collision risk assessment. The integration of AI/ML reduces uncertainty in predicting satellite trajectories and improves decision-making processes for collision avoidance maneuvers. It also incorporates flexible optimization of collision avoidance strategies and risk mitigation techniques, based on maneuvering for collision, which are vital for satellite operators to ensure the safety and longevity of space assets.

This presentation will showcase how Starion's advanced SSA solution, grounded in the proven SPICE system and augmented with AI/ML, provides significant value to mission operations. Attendees will gain insights into the practical implementation of secure, scalable, and modern solutions that increase the efficiency and reliability of space operations. This innovative approach highlights the importance of integrating advanced technologies to meet the dynamic demands of contemporary space missions.

Keywords: (maximum 6 keywords)
space debris, space situational awareness, optimisation, AI, ML, open-source

Acronyms/Abbreviations

SSA: Space Situational Awareness

ESA: European Space Agency
JPL: Jet Propulsion Laboratory
PoC: Probability of Collision
TLE: Two Line Elements

1. Introduction

Exploration of the solar system is fundamental to the understanding of our universe. Starion stands out as the main service provider for mission planning activities of the European Space Agency (ESA), playing a crucial role in the analysis and operational support of various solar system missions. In addition, we are in a time where satellites are multiplying rapidly in Low Earth Orbit (LEO), the urgency for reliable collision avoidance methods has never been higher. In this context, Starion has developed an innovative solution in the SSA domain, framed within its ASTRAL ground segment software, leveraging operational experience in the use of the SPICE information system developed by JPL, enhancing it with machine learning algorithms and advanced optimization.

2. Solar System Navigation Expertise

Starion provides engineering expertise and solutions for space and other critical infrastructures across Europe, pushing the boundaries of innovation. Starion teams work on world-leading space projects that deliver our company's vision of 'shaping the future of what is possible. Exploration of the solar system is fundamental to the understanding of our universe. Starion stands out as the main service provider for mission planning activities of the European Space Agency (ESA), being responsible for the development and maintenance of the operational software used for the scientific payload mission planning in planetary missions like Mars Express, BepiColombo and JUICE. The operational software includes features like mission analysis, observation opportunity finder, operations scheduling, spacecraft trajectory and pointing planning, simulation and constraint checking and operational products generation. Those computations are based on SPICE [1], an information system that uses ancillary data to provide Solar System geometry. For mission analysis, trajectories are converted to SPICE formats and propagated for science feasibility studies. In addition, for the spacecraft trajectory and pointing planning, the mission planning software implements the necessary flight dynamics algorithms and constraints checks allowing the generation and simulation of special spacecraft pointing requests compatible with the scientific payload objectives.

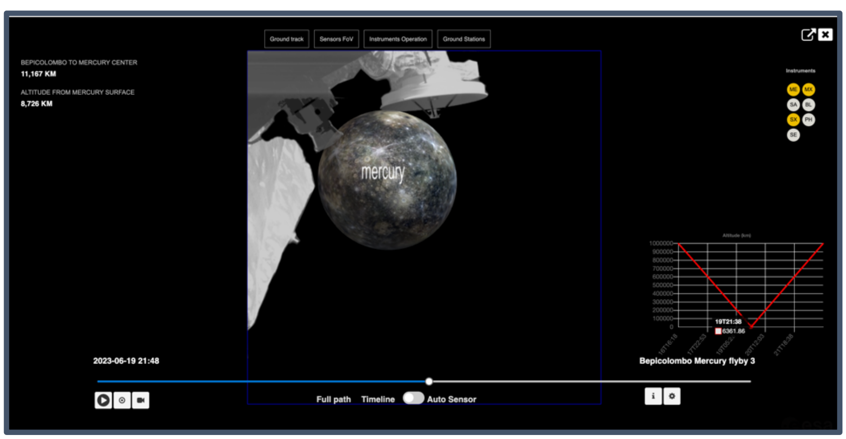

Figure 1: Example of a Mercury Flyby Mission Planning

3. SPICE

SPICE [1] is an information system that uses ancillary data to provide Solar System geometry. SPICE has a Technology Readiness Level of 9. I.e., the actual system is "flight proven" through successful mission operations. SPICE includes models for Earth oblateness, tide, atmospheric drag, relativistic corrections, and solar system masses and parameters and even Spacecraft Clock time correlations data.

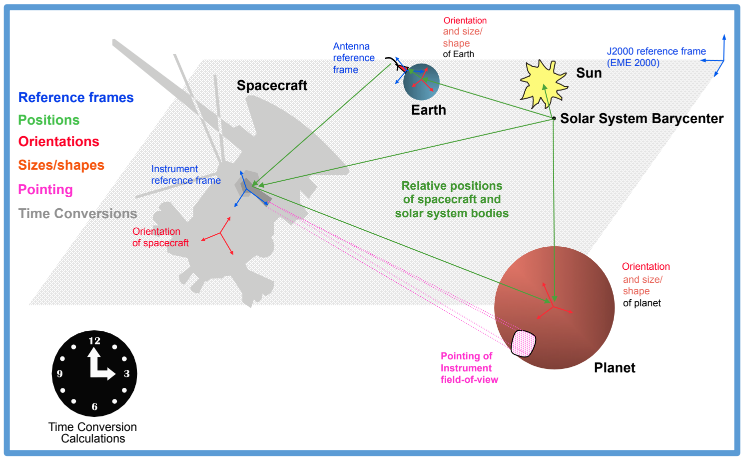

Figure 2: SPICE information system

Starion has been leading for many years the ESA SPICE Support Office, providing mission analysis and operations support for different ESA solar system missions, including:

- Develop and operate software to convert orbit, attitude, telemetry and spacecraft clock correlation data into the corresponding SPICE formats.
- Generate, develop, maintain and archive the SPICE Kernel Datasets (SKD) for the ESA Solar System Explorers.
- Provide consultancy and support to the Science Ground Segments and the Science Community of the planetary missions for SPICE and ancillary data management.
- Maintain study and support SPICE Kernel Datasets for a greater number of missions, constantly increasing

Figure 3: ESA missions by ESA SPICE Support Office

4. ASTRAL

ASTRAL is a component-based satellite ground segment Starion solution, allowing customers a high degree of flexibility to integrate their own or third-party components and interface to other systems. Astral is operationally proven and offers a high degree of automation supporting multiple spacecraft, and includes an industry leading operations preparation environment. It can be deployed on servers, private cloud and public cloud infrastructures. Astral builds on Starion's longstanding operational heritage in ground segment development, mission automation and operations preparation. Astral provides an integrated environment for different ground segment systems, enabling end-toend support from preparation to operations with the same toolset providing major benefits:

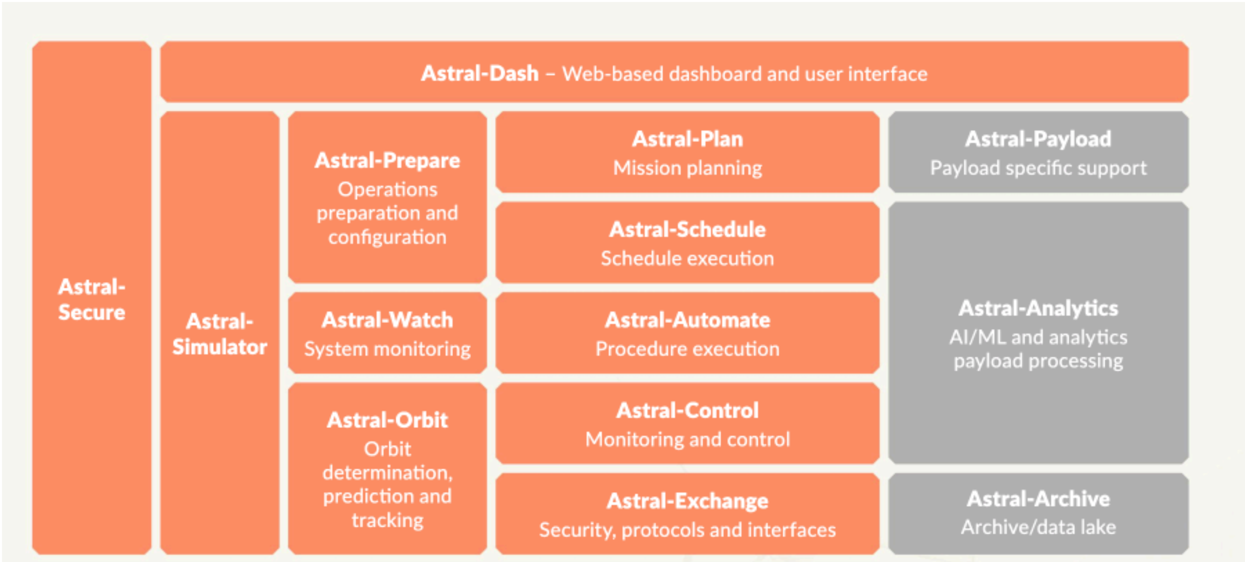

Figure 4: Astral consists of various components, each supporting different ground segment elements. Each element can be replaced by customer-provided or third-party components. The grey components tend to be mission specific and are not included as standard.

One of the ASTRAL components, Astral-Orbit, includes the SSA solution presented in this paper and described in next sections.

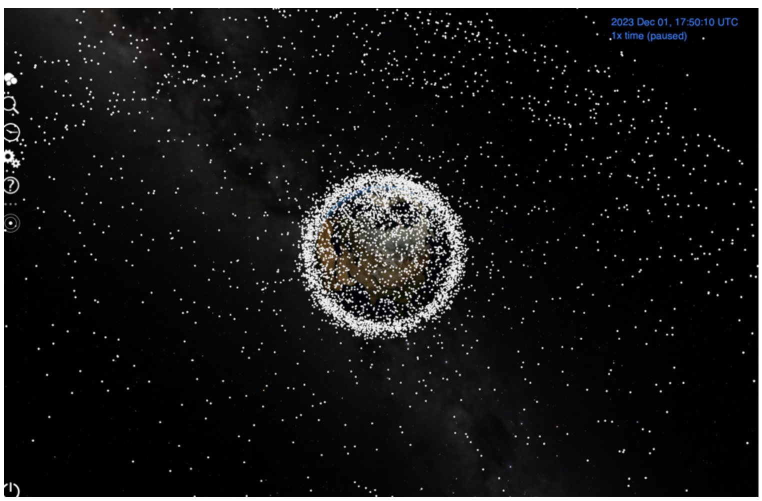

Figure 5: ASTRAL SSA 3D visualisation

5. SSA overview

The Starion SSA solution, enhanced with state-of-the art AI/ML algorithms, empowers a robust and accurate orbit prediction model, a critical aspect of the collision risk assessment. Additionally, risk mitigation techniques, based on manoeuvring for collision can be carried out to improve the decision-making process of satellite operators.

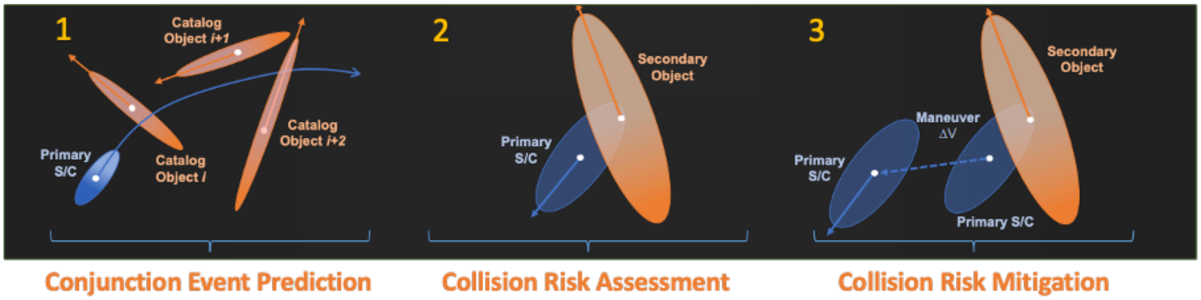

Figure 6: Starion SSA capabilities

2. SSA Implementation

The SSA solution is based on the use of the SPICE system [1], taking advantage of its extensive operational validation in a multitude of missions of the inner and outer solar system, in addition to its capabilities in orbital and geometric calculation, as well as its consistent principles based on scalability, recurrent and open source updating.

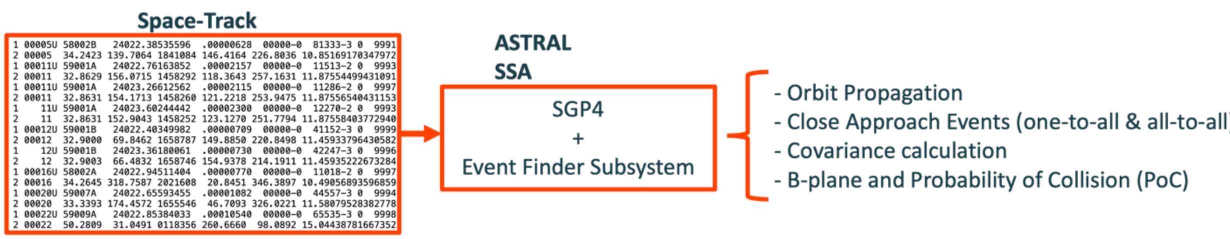

Figure 7: Starion SSA geometry finder

All this allows the incorporation of event conjunction prediction functionalities, where by means of the built-in SGP-4 analytical propagator, the trajectories and covariances of thousands of orbital objects are computed through the load of the associated TLEs and, subsequently, using the Geometric *Event Search subsystem,* B-plane diagrams *and collision probabilities (*PoC) are computed in a matter of seconds) for all objects considered to be below the established risk tolerances.

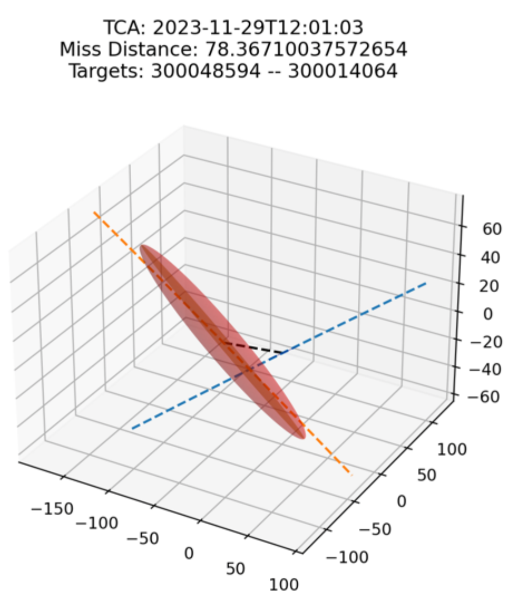

Figure 8: Calculation of TCA, "miss distance" and matrix of associated covariances, with ASTRAL-SSA

In those cases where an orbital conjunction is detected, highly accurate numerical integration will be used to reduce the positional error of each object involved, thus providing enough estimated points to be able to use Gaussian processes that approximate each of the coordinates of the orbit of the objects in question. Using this type of stochastic process, it is possible to significantly reduce the uncertainty around the positional state of the objects involved in a previously detected orbital conjunction [2] and thus reinforce the PoC calculation.

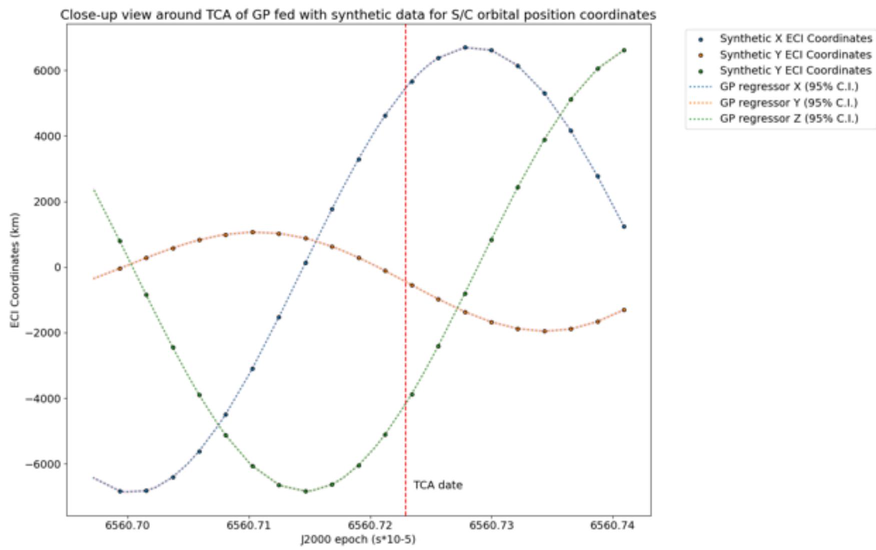

Figure 9: Fitting orbital coordinates with Gaussian process around TCA, offering the associated uncertainty

Finally, with the aim of optimizing collision avoidance maneuvers and thus improving the decision-making process of satellite operators, multi-objective optimization algorithms are integrated [3], which in turn allow the introduction of ranges to restrict any variable involved during the resolution of the problem.

3. Results

To demonstrate the operational capabilities of the module, results of each of the components described in the previous section are shown based on real use cases. First, it is iterated with each of the objects available on the *Space-Track* platform, amounting to a total of approximately 25000 objects, with the aim of evaluating the efficiency and robustness when detecting orbital conjunction events with the set of them, obtaining times in the vicinity of *30 s* in the case of One-to-all detection, which allows for continuous re-evaluation in practice of collision probabilities with each update of available orbital states.

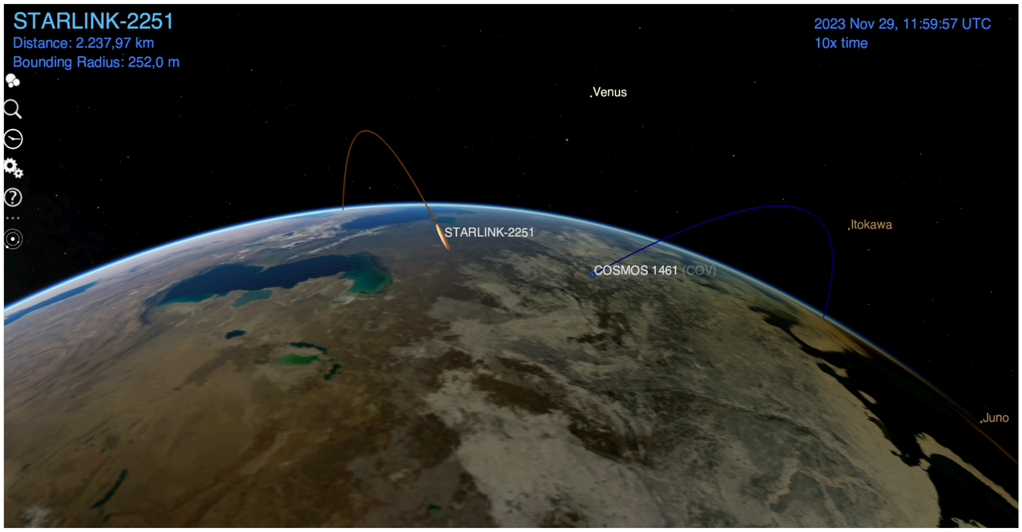

Figure 10: Visualization of conjunction event between orbital objects along with the uncertainty ellipsoid associated with each of them

On the other hand, in order to reproduce a realistic operation to show the capabilities of the error reduction and positional uncertainty component, 6 different real orbital objects in low Earth orbit are chosen, achieving a reduction in positional error of 47.6% and 61.2% for the associated uncertainty, considering each of the 6 days prior to the date of maximum approach (*TCA*). with respect to the classical methods based on SGP-4.

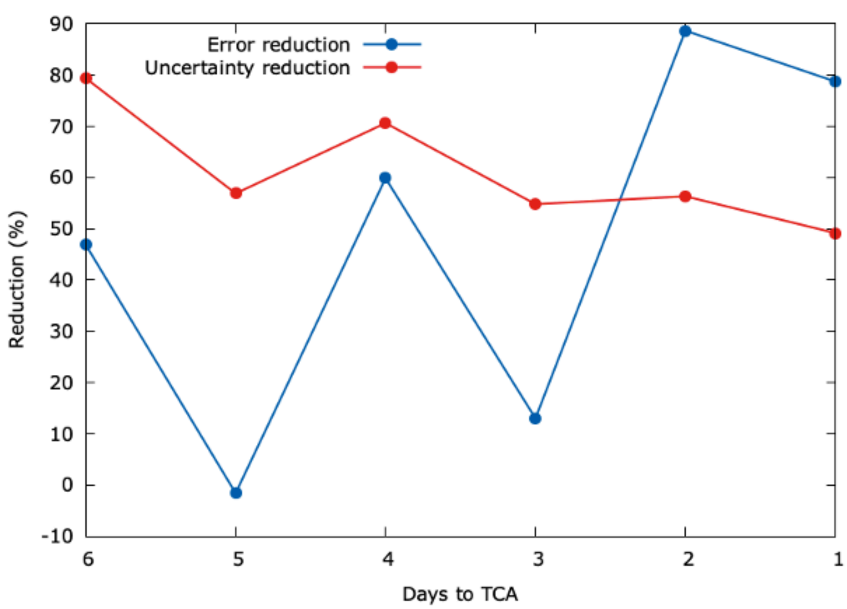

Figure 11: Reduction of average positional error and uncertainty in TCA with respect to the SGP-4-based method for 6 satellites in low Earth orbit

Finally, a case, although realistic, highly expensive from the point of view of orbital deviation, is chosen with the aim of demonstrating the performance of the optimization module for collision avoidance, giving as input data the orbital state of an object two orbits before the point of maximum approach, as well as the desired position range of the object at that point. with a horizontal displacement of between 100 and 200 km from the initial point of maximum approach, in addition to the number of manoeuvres to be carried out (2, non-impulsive), the target variable to be minimised (delta-V), and leaving the initial and final times of the manoeuvres as unrestricted variables, as well as the magnitude of the change in speed itself. The execution time of this problem, considering the inclusion of all kinds of orbital perturbations in the numerical calculations, is below *10 s*, converging to the final solution that sets the vectors and times of both ignitions, with a total fuel cost in the vicinity of *70 m/s* for a final "*miss distance"* of *120 km.*

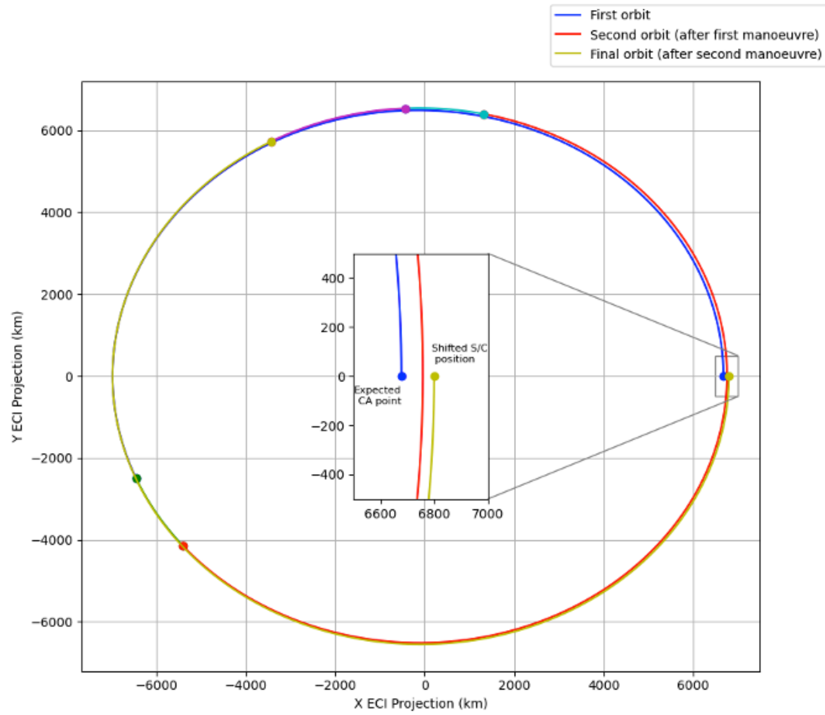

Figure 12: Trajectory of the orbital object projected in the X-Y ECI plane, showing both optimized maneuvers

4. Conclusions

Starion's ASTRAL SSA solution offers an effective, robust and remarkably optimized response to face the current challenges in the field of SSA, offering high added value to the landscape of the ground segment in space operations. The combination of operational expertise, advanced technology and modular approach ensures an adaptive, safe and scalable solution for detecting conjunction events, visualizing them, refining the collision probability calculation and optimizing collision avoidance maneuvers for current and future space missions in Earth orbit.

References

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