

POLITECNICO DI TORINO

Master's Degree Course in Aerospace Engineering



Low Earth Orbit Constellation Deployment Optimization

Supervisors:

Prof. Manuela Battipede

Dr. Luigi Mascolo

Candidate:

Domenico Pio

Di Giamberardino

Industrial Supervisor:

Dr. Irene Cavallari

Eng. Marco Primavera

Eng. Francesco Di Pietro

ACADEMIC YEAR 2025/2026

*“The secret of man’s being is not only to live
but to have something to live for.”*

FËODOR MICHAJLOVIČ DOSTOEVSKIJ
The Brothers Karamazov

Abstract

The ongoing evolution of the space sector toward distributed architectures introduces new challenges in flight operations management, particularly during the orbital phasing phase required for precise relative positioning within constellations. In this context, this thesis, developed in collaboration with Telespazio at the Fucino Space Centre, addresses the design and validation of a finite-burn maneuver planner for highly constrained low-thrust satellite platforms. To evaluate the proposed planning strategy within a realistic operational framework, a high-fidelity flight dynamics simulator was developed using the *Orekit* library. The simulation environment relies on a robust numerical propagator and comprehensive perturbation modeling, including high-degree geopotential harmonics, atmospheric drag, solar radiation pressure, and third-body effects, ensuring physical consistency and dynamical accuracy. The core contribution of this work is the development of a maneuver planning architecture capable of managing both in-plane corrections, targeting semi-major axis and eccentricity, and out-of-plane maneuvers for inclination control at orbital nodes. To comply with stringent mission constraints, such as maximum burn durations, mandatory waiting intervals, low-thrust actuation limits, and eclipse-only firing windows, a dedicated sliding and vector clamping logic was implemented. This approach enables temporal discretization and redistribution of finite burns while preserving targeting accuracy and operational feasibility. The resulting maneuvers were assessed by comparing the achieved final orbital states against theoretical references obtained through a sequential quadratic programming (SQP) optimizer. The analysis demonstrates that the proposed planner achieves near-impulsive performance while respecting all operational constraints, bounding residual errors to the order of tens of meters in semi-major axis and 10^{-5} degrees in inclination. These results confirm the effectiveness of the approach and highlight its potential applicability to autonomous maneuver planning for next-generation distributed LEO systems.

Contents

Contents	V
List of Acronyms	IX
1 Introduction	1
1.1 Thesis Overview	4
2 Orbital Mechanics	7
2.1 Kepler's laws and Law of Universal Gravitation	7
2.2 Two-Body Problem	8
2.2.1 Constants of Motion	10
2.2.2 Trajectory Equation	10
2.3 Orbital Elements	12
2.3.1 Keplerian Elements	12
2.3.2 Alternative parameters	16
2.3.3 Equinoctial Elements	16
2.4 Reference Frames	17
2.4.1 Geocentric-Equatorial coordinate system	17
2.4.2 True of Date (TOD)	18
2.4.3 Satellite Coordinate System, RSW	19
2.4.4 Satellite Coordinate System, NTW	19
2.5 Orbital Perturbations	21
2.5.1 Non-sphericity of the Earth	22
2.5.2 Atmospheric Drag	26
2.5.3 Solar Radiation Pressure	29
2.5.4 Third-Body Perturbations	30

CONTENTS

2.5.5	Gauss's Variational Equations	31
2.6	Orbit Classification	33
2.7	Satellite Eclipse Conditions	35
3	Orbital Maneuvers	39
3.1	Propulsive Dynamics	39
3.1.1	Performance	40
3.1.2	Impulsive Orbital Maneuvers	44
3.2	Edelbaum Approximation	47
3.3	Phasing maneuvers	52
4	Phasing Problem	57
4.1	Implementation Methodology	60
4.1.1	Simulation Core	61
4.1.2	Firing Windows	69
4.1.3	Maneuver Scheduling and Waiting Constraints	73
4.1.4	Numerical Propagator	78
4.1.5	Implementation of Force Models	78
5	Simulations results	83
5.1	Window 1	89
5.2	Error Analysis	94
6	Conclusion and Future Work	99
A	Results	101
A.1	Window 2	101
A.2	Window 3	106
A.3	Window 4	110
A.4	Window 5	115
A.5	Window 6	119
A.6	Window 7	124
A.7	Window 8	128
A.8	Window 9	133
A.9	Window 10	137

A.10 Window 11	142
A.11 Window 12	146
A.12 Window 13	151
A.13 Window 14	155
A.14 Window 15	160
A.15 Window 16	164
A.16 Window 17	169
A.17 Window 18	173
A.18 Window 19	178
A.19 Window 20	182
A.20 Window 21	187
A.21 Window 22	191
A.22 Window 23	196
A.23 Window 24	200
A.24 Window 25	205
A.25 Window 26	209
A.26 Window 27	214
A.27 Window 28	218
A.28 Window 29	223
A.29 Window 30	227
A.30 Window 31	232
A.31 Window 32	236
Bibliography	241
List of Figures	245
List of Tables	255

List of Acronyms

2BP	Two-Body Problem
AOL	Argument of Latitude
ASI	Agenzia Spaziale Italiana
COEs	Classical Orbital Elements
COSMO-SkyMed	COntstellatIon of small Satellites for the Mediterranean basin Observation
CIO	Celestial Intermediate Origin
DSST	Draper Semi-analytical Satellite Theory
ECEF	Earth-Centered, Earth-Fixed
ECI	Earth-Centered Inertial
ENAV	Ente Nazionale per l'Assistenza al Volo
ESA	European Space Agency
EU	European Union
IERS	International Earth Rotation and Reference Systems Service
ITRF	International Terrestrial Reference Frame
GCC-I	Galileo Control Centre Italy
GEO	Geostationary Earth Orbit
GLONASS	Global'naya Navigatsionnaya Sputnikovaya Sistema
GPS	Global Positioning System
GVE	Gauss's Variational Equations

CONTENTS

HEO	High Earth Orbit
IRIDE	Italian Radar Imaging for the Development of Earth observation
IRIS²	Infrastructure for Resilience, Interconnectivity and Security by Satellite
LEO	Low Earth Orbit
LOF	Local Orbital Frame
LVLH	Local Vertical, Local Horizontal
MEO	Medium Earth Orbit
NLP	Non-Linear Problem
ODE	Ordinary Differential Equation
PNRR	National Recovery and Resilience Plan
R2BP	Restricted Two-Body Problem
RAAN	Right Ascension of the Ascending Node
SNAM	Società Nazionale Metanodotti
SQP	Sequential Quadratic Programming
SRP	Solar Radiation Pressure
SSO	Sun-Synchronous Orbit
TOD	True of Date
WGS84	World Geodetic System 1984

Chapter 1

Introduction

Great things are not done by impulse, but by a series of small things brought together.

Vincent van Gogh

The observation of the starry sky is historically rooted not only in scientific curiosity but also in humanity's search for answers and practical solutions. Understanding the motion of celestial bodies has always carried, beyond a metaphysical dimension, concrete implications for daily life. It is within this context, between ancestral fascination and innovation, that the work of Telespazio, the focal company of this project, is situated [1].

Founded in Italy in 1961 and now a pillar of the Space Alliance between Leonardo and Thales, Telespazio pursues the mission of "*bringing space closer to Earth*," delivering tangible benefits to citizens, institutions, and businesses through an Open Innovation approach. With over 3000 employees and an international network across fifteen countries, the company covers the entire lifecycle of space missions, from design and launch management to in-orbit satellite control and the provision of critical navigation and communication services.

The operational heart of this capability is the "Piero Fanti" Space Centre in Fucino, Abruzzo, operational since 1963. With its 370.000 square meters and approximately 170 antennas, it represents the world's most significant civilian teleport. Here, some 250 specialized engineers and technicians manage strategic

infrastructures of global importance. The centre hosts the Control Centre for the COSMO-SkyMed program and is one of the two primary sites managing the European Galileo satellite navigation system. In this latter role, the Galileo Control Centre Italy (GCC-I), spanning 6000 square meters, ensures the generation, management, and dissemination of precision signals, coordinating a worldwide network of approximately fifty ground stations.



Figure 1.1: Conceptual representation of a Low Earth Orbit satellite constellation for telecommunication services [3]

Beyond navigation, the Centre manages global satellite connectivity for major operators and broadcasters, ensuring multimedia distribution and broadband services. Its infrastructure also supports institutional and industrial entities such as Società Nazionale Metanodotti (SNAM), Agenzia Spaziale Italiana (ASI), and Ente Nazionale per l'Assistenza al Volo (ENAV), enabling operational services ranging from telemedicine and remote system supervision to distance learning. Participating in this reality means positioning oneself at the confluence of astronomy's millennial heritage and the technological frontiers of the future, where theoretical models of orbital dynamics are translated into essential services for contemporary society.

The operational excellence described above is currently facing a paradigm shift

in the aerospace sector: the transition from monolithic architectures to distributed systems. While traditional missions relied on large, single satellites, often in Geostationary Earth Orbit (GEO), to provide capacity, the *New Space Economy* is increasingly driven by satellite constellations in Low Earth Orbit (LEO).

Markets and Markets [2] estimated in its latest report that, by 2030, the LEO satellite market will reach significant growth peaks. The study projects a value of 20.69 billion dollars within five years, starting from 11.81 billion in 2025.

The strength of these new assets in the global space economy lies in their position. Being located between 160 and 2000 km from Earth, they can offer high-performance services, ensuring low latency, real-time Earth observation, and broadband connections even in the most remote areas.

The strategic importance of constellations lies in their geometry. By distributing sensors or communication nodes across multiple orbital planes, these systems ensure global coverage and high temporal resolution (revisit time), overcoming the physical limitations of a single satellite. This approach transforms space infrastructure into a resilient *System of Systems*, where the service is guaranteed not by an individual asset but by the collective coordination of the fleet. However, managing hundreds or thousands of satellites introduces unprecedented challenges in terms of orbital dynamics, collision avoidance, and fleet maintenance.

In this context, constellations can be employed for various tasks:

- **Global Internet:** Programs such as Starlink, OneWeb, and Amazon’s Kuiper aim to achieve total coverage.
- **Defense and Surveillance:** The defense sector has had to rethink its approach to intelligence gathering. Armies increasingly prefer LEO satellites for tactical communications and real-time observation, leveraging the dual-use nature of these technologies.
- **Emergency Management and Climate Monitoring:** This allows for the acquisition of high-resolution images crucial for rapid intervention.

An emblematic example is Starlink, a constellation with approximately seven thousand satellites already operational in low orbit and millions of active customers. The first launches took place in 2019, and the constellation is growing rapidly, with

plans to exceed forty thousand satellites. Starlink's primary competitive advantage stems from the fact that its operator, SpaceX, possesses the most mature launch system currently on the market, the Falcon-9, with over 450 launches and 400 first-stage recoveries; control over the supply chain indeed allows for significant economies of scale.

To address the need for strategic autonomy and secure connectivity in this domain, the European Union has established IRIS². Designed as the European response to non-EU mega-constellations like Starlink, Kuiper, and the Chinese Guowang, IRIS² constitutes the third pillar of the EU Space Programme, complementing *Galileo* for navigation and *Copernicus* for Earth observation. The infrastructure is engineered to integrate seamlessly with terrestrial 5G networks, implementing a dual-service model: a high-security layer dedicated to government institutional use and a commercial layer for the private sector. Full operational capability is projected to be achieved between 2027 and 2030

In this rapidly evolving landscape, Italy has positioned itself at the forefront with IRIDE, one of the most ambitious Earth Observation programs in Europe. Born as an initiative of the Italian Government with resources from the PNRR and managed by ESA in collaboration with ASI, IRIDE represents a unique "*constellation of constellations*" [4].

The evolution of the space landscape towards LEO mega-constellations thus necessitates novel mission analysis tools. In this context, this thesis presents a simulation framework for orbital maneuver planning, integrating a control logic that harmonizes multiple operational constraints. Specifically, the tool schedules maneuvers by accounting for illumination conditions (sunlight/eclipse) and orbital geometry (Argument of Latitude ranges). Furthermore, it ensures strict compliance with the mandatory waiting times between consecutive operations and the maximum burn duration of each thrust arc, ultimately enabling the successful acquisition of the target orbit.

1.1 Thesis Overview

The overall structure of the thesis is outlined as follows:

- **Chapter 2** establishes the theoretical foundation, starting with Kepler's

laws and Newton’s law of universal gravitation to discuss the two-body problem, derive the equations of motion, and describe orbital trajectories via conic sections. It then analyzes Classical Orbital Elements (COEs) and reference frames. Subsequently, the primary orbital perturbations are described, leading to the introduction of Gauss’s Variational Equations (GVE). Following this, orbits are classified based on altitude, inclination, and mission application. Finally, a brief overview of eclipse phenomena is provided.

- **Chapter 3** focuses on propulsion dynamics, beginning with the derivation of the Tsiolkovsky rocket equation. A comparative analysis of chemical versus electric propulsion performance is presented to highlight their respective advantages. The chapter then examines impulsive maneuvers (both in-plane and out-of-plane) and introduces the Edelbaum approximation for modeling finite-thrust trajectories. It concludes with a numerical example illustrating a standard phasing maneuver.
- **Chapter 4** details the specific problem statement and the algorithmic logic underlying the custom simulation software developed for this project. It begins by presenting the two solution approaches, including a concise description of the Sequential Quadratic Programming (SQP) optimization method used for the baseline. The discussion then moves to the numerical propagator, detailing the force models implemented and the operational constraints enforced during the simulation. Finally, the chapter analyzes the core software architecture, specifically the class responsible for the autonomous maneuver planning logic.
- **Chapter 5** presents and discusses the final simulation results, providing a quantitative validation of the proposed strategy through comparisons with the reference baseline.
- **Chapter 6** concludes with recommendations for future developments and potential applications of this work.

Chapter 2

Orbital Mechanics

*I can calculate the motion of heavenly bodies, but
not the madness of people.*

Isaac Newton

2.1 Kepler's laws and Law of Universal Gravitation

Between 1609 (*Astronomia Nova*) and 1619 (*Harmonices Mundi*), the German mathematician Johannes Kepler, based on the analysis of astronomical observations collected by the Danish astronomer Tycho Brahe, formulated the famous three laws describing the motion of the planets:

1. The orbit of each planet is an ellipse, with the Sun located at one of its foci.
2. The line joining a planet and the Sun sweeps out equal areas in equal times.
3. The square of a planet's orbital period is proportional to the cube of its mean distance from the Sun.

The second pillar of orbital mechanics is instead represented by Newton's contribution. In 1689, in the *Philosophiae Naturalis Principia Mathematica*, Newton analytically demonstrated the three aforementioned laws and formulated the **Law of Universal Gravitation**. This law states that in the Universe, two

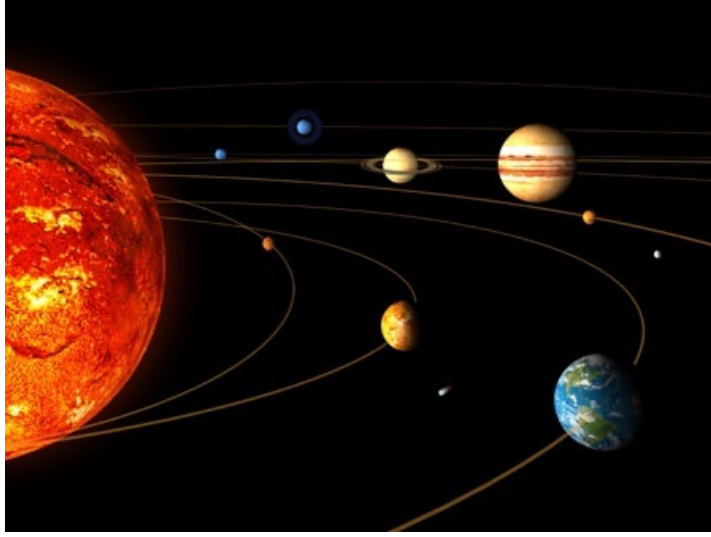


Figure 2.1: Solar System [5]

material bodies exert mutually an attractive and central force directly proportional to the product of their masses and inversely proportional to the square of their distance:

$$\mathbf{F} = -G \frac{mM}{r^3} \mathbf{r} \quad (2.1)$$

where $G = 6.67430 \cdot 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$ is the gravitational constant, while $\mathbf{r}$ is the radius vector between mass M and m . It is customary in the case of bodies orbiting around Earth, such as satellites, to substitute the gravitational parameter $\mu = GM$ within the equation. In case of the Earth: $\mu_{\oplus} = 3.986 \cdot 10^{14} \text{ m}^3 \text{ s}^{-2}$. The same can be applied to rotating bodies around other celestial objects by substituting the appropriate gravitational parameter.

2.2 Two-Body Problem

In Two-Body Problem (2BP) is the first approximated representation used in orbital mechanics to describe the motion of massive bodies under their mutual gravitational attraction. Also known as Kepler problem, this model simplifies the complexities of multi-body interactions by reducing the system to only two

bodies, allowing for an exact analytical solution. An additional simplification to this problem is the so-called **Restricted Two-Body Problem (R2BP)**, where one of the two bodies is considered to have a significantly smaller mass than the other. The assumptions underlying this model are:

- Distribution of the mass homogeneous and spherical
- Punctiform masses concentrated in the centres of the bodies
- $m \ll M$
- Only gravitational forces

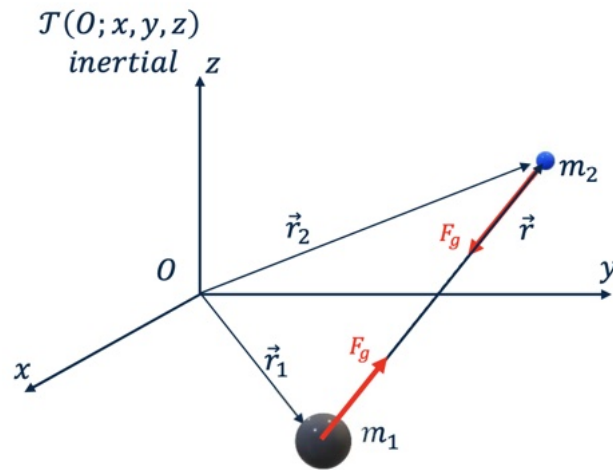


Figure 2.2: Representation of the 2BP in a generic inertial RF [6]

In the R2BP, the secondary body, such as a spacecraft, is assumed to experience the exclusive gravitational attraction of a primary body. Thanks to the simplifications made, it is possible to derive analytically the equation that governs its motion. Starting from equation (2.1) and under the assumptions of the previously presented R2BP, can be obtained:

$$\ddot{\mathbf{r}} + \frac{\mu}{r^2} \frac{\mathbf{r}}{r} = 0 \quad (2.2)$$

This formula describes the motion of the secondary body relative to the primary body and represents a second-order vector equation.

2.2.1 Constants of Motion

The R2BP is characterized by several constants of motion. Here, we recall:

- **Angular Momentum**

$$\mathbf{h} = \mathbf{r} \wedge \mathbf{v} \quad (2.3)$$

In the context of the R2BP, the trajectory is planar, meaning it lies within a plane. Since $\mathbf{r}$ and $\mathbf{v}$ define the orbital plane, $\mathbf{h}$ must be always perpendicular to it.

- **Specific Mechanic Energy**

$$\mathcal{E} = \frac{v^2}{2} - \frac{\mu}{r} \quad (2.4)$$

Where the first term represents kinetic energy, while the second term represents the potential energy associated with the Earth's gravitational field

2.2.2 Trajectory Equation

The equation of the trajectory in the R2BP describes the locus of points occupied by the secondary body during its orbit. By solving the equation of motion (2.2) and through several steps not reported here for simplicity, one can obtain it:

$$r = \frac{p}{1 + e \cos \nu} \quad (2.5)$$

Where ν is the true anomaly which defines the position of the satellite in its orbit, p is the semilatus rectum of the orbit and e the eccentricity, two parameters that define the amplitude and the shape of the trajectory. Formula (2.5) describes the locus of points characterizing the orbit of a satellite.

All possible orbits are conics. Specifically, a satellite can assume a circular, elliptical, parabolic, or hyperbolic orbit, as shown in Figure 2.3. In this work we are interested mainly in circular and elliptical orbits. The solution to the R2BP

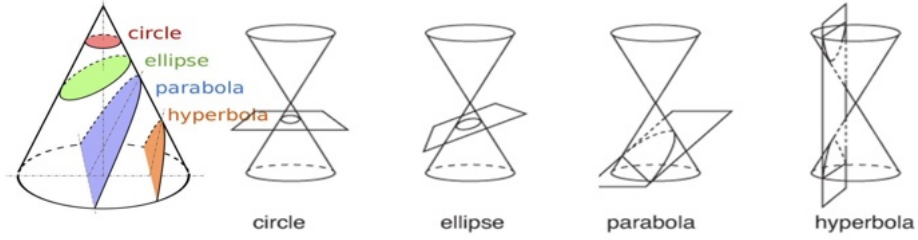


Figure 2.3: Conic sections [6]

is an orbit referred to as Kepler Orbit. In the case of an elliptical orbit, two important quantities can be defined: r_p and r_a , which are the radii of the periapsis and apoapsis, respectively.

$$\begin{cases} r_p = \frac{p}{1 + e \cos(0)} = \frac{p}{1 + e} & \text{per } \nu = 0 \\ r_a = \frac{p}{1 + e \cos(\pi)} = \frac{p}{1 - e} & \text{per } \nu = \pi \end{cases} \quad (2.6)$$

These two points represent the extremes of the ellipse along the major axis and can be obtained from equation (2.6)

Through geometric considerations, one can then write:

$$p = a(1 - e^2) \quad (2.7)$$

$$\begin{cases} r_p = a(1 - e) \\ r_a = a(1 + e) \end{cases} \quad (2.8)$$

Using equation (2.7) and (2.8) from which:

$$e = \frac{r_a - r_p}{r_a + r_p} \quad (2.9)$$

By comparing the trajectory equation and the equation of a conic section, we see immediately that the semilatus rectum p of the orbit depends only on the specific angular momentum $\mathbf{h}$ of satellite.

$$p = \frac{h^2}{\mu} \quad (2.10)$$

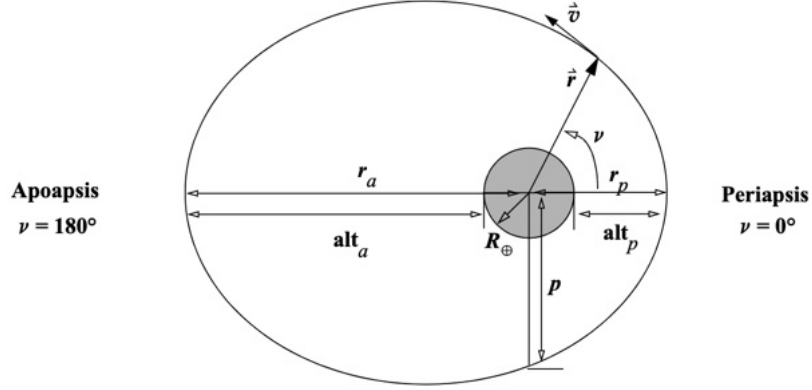


Figure 2.4: Elliptical Orbits [7]

2.3 Orbital Elements

A generic Keplerian orbit can be parameterized in various ways; in particular, given an inertial frame of reference and an arbitrary epoch (a specified point in time). The orbit and position of a body can be uniquely defined by employing six different parameters, which corresponds to the number of degrees of freedom of the problem.

2.3.1 Keplerian Elements

The shape and orientation of the orbit are uniquely determined by the body's position and velocity vectors at any given instant. Given an initial epoch, these six values define the orbit uniquely. However, utilizing position and velocity vectors, collectively known as the **state vector**, is highly impractical for orbital characterization. Instead, COEs, also known as *Keplerian elements*, are preferred. These parameters are inherently dependent on the position and velocity vectors and can be directly derived from them through analytical formulations.

- **Semi-major Axis (a)**

It defines the size of the orbit. While easily identified for an elliptical orbit, the semi-major axis tends toward infinity for a parabola. For a hyperbola, it assumes a negative value and represents half the distance between the vertices (periapses) of the two mathematically admissible orbital branches.

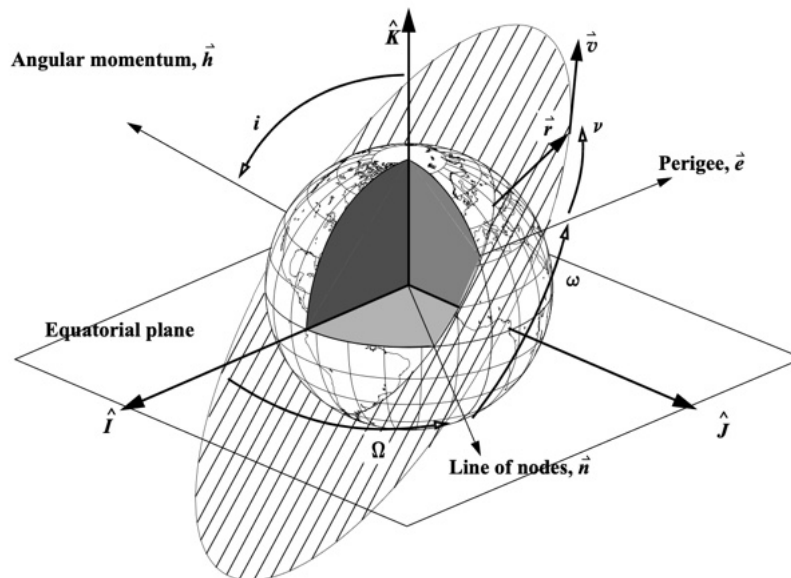


Figure 2.5: Keplerian Orbital Elements [7]

The geometric interpretation for the hyperbola is of secondary importance, as only one of the two branches is physically traversed by the spacecraft. The semi-major axis is directly related to the specific orbital energy:

$$a = -\frac{\mu}{2\mathcal{E}} \quad (2.11)$$

For an ellipse, $a > 0$ and $\mathcal{E} < 0$. For a parabola, $a \rightarrow \infty$ and $\mathcal{E} = 0$. For a hyperbola, $a < 0$ and $\mathcal{E} > 0$.

If the energy is positive, as in the case of a hyperbola, when $r \rightarrow \infty$ the spacecraft retains a non-zero velocity, referred to as the *hyperbolic excess velocity*: $V_\infty = \sqrt{2\mathcal{E}}$.

If the specific energy is zero, as in the case of a parabolic trajectory, the hyperbolic excess velocity is zero; thus, the spacecraft reaches infinity with zero residual velocity. If the energy is negative, as in the case of an elliptical orbit, the hyperbolic excess velocity becomes an imaginary number, indicating that infinity is not physically attainable (the orbit is closed).

- **Eccentricity $\mathbf{e}$**

It defines the shape of the orbit. It can be expressed as:

$$e = \sqrt{1 + 2\mathcal{E} \left(\frac{h}{\mu} \right)^2} \quad (2.12)$$

An eccentricity vector can also be defined by the expression:

$$\mathbf{e} = \frac{1}{\mu} \left[\left(v^2 - \frac{\mu}{r} \right) \mathbf{r} - (\mathbf{r} \cdot \mathbf{v}) \mathbf{v} \right] \quad (2.13)$$

Table 2.1: Classification of orbital trajectories based on conic sections.

Orbit Type	Specific Energy ($\mathcal{E}$)	Semi-major axis (a)	Eccentricity (e)
Circle	$\mathcal{E} < 0$	$a > 0$	$e = 0$
Ellipse	$\mathcal{E} < 0$	$a > 0$	$0 < e < 1$
Parabola	$\mathcal{E} = 0$	$a = \infty$	$e = 1$
Hyperbola	$\mathcal{E} > 0$	$a < 0$	$e > 1$

- **Inclination (i)**

It is defined as the angle between the orbital plane and the reference plane. To describe it, the Geocentric Equatorial Coordinate System is defined: centered at the Earth's center, with the $\hat{I}$ axis pointing toward the vernal equinox, the $\hat{J}$ axis perpendicular to $\hat{I}$ in the equatorial plane, and the $\hat{K}$ axis completing the right-handed triad toward the North Pole (Polaris). The inclination is given by:

$$\cos(i) = \frac{h_k}{h} \quad (2.14)$$

where h_k is the component of the specific angular momentum vector $\mathbf{h}$ along the $\hat{K}$ direction. ¹

- **Right Ascension of the Ascending Node (RAAN) (Ω)**

Defined as the angle between the line of nodes and the $\hat{I}$ axis. The node

¹The inclination i is conventionally defined in the range $0^\circ \leq i \leq 180^\circ$.

vector $\mathbf{n}$, which points toward the ascending node, is defined as:

$$\mathbf{n} = \hat{K} \times \mathbf{h} \quad (2.15)$$

The mathematical expression for the RAAN is given by:

$$\cos \Omega = \frac{n_I}{n} \quad (2.16)$$

where n_I is the component of the node vector along the $\hat{I}$ axis and n is its magnitude.²

- **Argument of Periapsis (ω)**

Defined as the angle between the line of nodes and the eccentricity vector $\mathbf{e}$ (which points toward the periapsis), measured in the direction of motion within the orbital plane. The mathematical definition is:

$$\cos \omega = \frac{\mathbf{n} \cdot \mathbf{e}}{ne} \quad (2.17)$$

where $\mathbf{n}$ is the node vector, $\mathbf{e}$ is the eccentricity vector, and n and e are their respective magnitudes.³

- **True Anomaly (ν)**

It defines the location of the spacecraft along the orbit and is given by the angle between the eccentricity vector $\mathbf{e}$ and the position vector $\mathbf{r}$. It is defined with respect to a time reference called the *epoch*; thus, it is typically expressed as the *true anomaly at epoch* t_0 . The mathematical definition is:

$$\cos \nu = \frac{\mathbf{e} \cdot \mathbf{r}}{er} \quad (2.18)$$

where $\mathbf{e}$ is the eccentricity vector and $\mathbf{r}$ is the position vector.⁴

²To uniquely determine the quadrant of Ω , the condition $n_J \geq 0$ must be checked: $0^\circ \leq \Omega < 180^\circ$ if $n_J \geq 0$, otherwise $180^\circ \leq \Omega < 360^\circ$.

³To uniquely determine the quadrant of ω , the condition $e_k \geq 0$ must be checked: $0^\circ \leq \omega < 180^\circ$ if $e_k \geq 0$, otherwise $180^\circ \leq \omega < 360^\circ$.

⁴To uniquely determine the quadrant of ν , the sign of the radial velocity must be checked: if $\mathbf{r} \cdot \mathbf{v} \geq 0$, then $0^\circ \leq \nu < 180^\circ$; if $\mathbf{r} \cdot \mathbf{v} < 0$, then $180^\circ \leq \nu < 360^\circ$.

The orbital parameters a and e define the geometry of the orbit (shape and size), while the parameters i , Ω , and ω define the spatial orientation of the orbit. These constitute the set of COEs; however, depending on the specific application or to avoid mathematical singularities, alternative sets may be utilized.

2.3.2 Alternative parameters

In some cases, classical orbital elements are not suitable for defining certain specific orbits. Therefore, the following alternative parameters are introduced:

- *Longitude of Periapsis*: $\Pi = \Omega + \omega$
which is used for equatorial orbits ($i = 0$), where there is no line of nodes, and Ω is therefore undefined.
- *Argument of Latitude*: $u = \omega + \nu$
which is employed for circular orbits ($e=0$) where ω is undefined, as the periapsis cannot be identified.
- *True Longitude*: $l = \Omega + \omega + \nu$
it is used in the specific case of orbits with zero eccentricity and inclination ($i = e = 0$), for which it is not possible to define ω and Ω . This applies, for example, to a geostationary orbit.

2.3.3 Equinoctial Elements

The equinoctial elements are a set of alternative orbital parameters, useful to avoid singularities in the equations of motion for either circular or equatorial orbits. The transformation from Keplerian elements is given by:

$$\left\{ \begin{array}{lcl} a & = & a \\ e_x & = & e \cos(\omega + \Omega) \\ e_y & = & e \sin(\omega + \Omega) \\ h_x & = & \tan\left(\frac{i}{2}\right) \cos(\Omega) \\ h_y & = & \tan\left(\frac{i}{2}\right) \sin(\Omega) \\ \lambda_v & = & \nu + \omega + \Omega \end{array} \right. \quad (2.19)$$

The conversion equations from and to Keplerian elements given above hold only when both sides are unambiguously defined, i.e. when orbit is neither equatorial nor circular. When orbit is either equatorial or circular, the equinoctial parameters are still unambiguously defined whereas some Keplerian elements (more precisely ω and Ω) become ambiguous. For this reason, equinoctial parameters are the recommended way to represent orbits.⁵

2.4 Reference Frames

The first requirement for describing an orbit is to choose a suitable reference frame. To define any reference frame, we need to specify:

- The origin of the reference frame;
- The orientation of the fundamental plane (the X–Y plane);
- The principal direction (i.e., the direction of the X axis);
- The direction of the Z axis, which is perpendicular to the fundamental plane.

The Y axis is always chosen so that (X,Y,Z) form a right-handed set of coordinate axes.

2.4.1 Geocentric-Equatorial coordinate system

The Earth-Centered Inertial (ECI) is a frame centered at the Earth’s center of mass. Unlike the Earth-Centered, Earth-Fixed (ECEF) frame, the ECI system does not rotate with the Earth; its axes are fixed relative to the stars (neglecting long-term precession). The fundamental plane coincides with the Earth’s equatorial plane, where the $\hat{I}$ axis points toward the Vernal Equinox. The $\hat{K}$ axis is aligned with the Earth’s rotation axis pointing North, and $\hat{J}$ completes the right-handed triad. This frame is essential for the characterization of Earth-orbiting spacecraft. ECEF primary axis is always aligned with the Greenwich meridian (principal direction). For this coordinate system, it is necessary define an epoch (J2000).⁶

⁵However, two of the components are singular for an orbital inclination of 180 degrees.

⁶ITRF system is frequently called the Earth-Centered, Earth- Fixed (ECEF) coordinate frame. The term “Earth-fixed” describes a terrestrial reference system whose net global orientation



Figure 2.6: Geocentric Equatorial System (IJK) [7]

2.4.2 True of Date (TOD)

TOD reference frame is a geocentric system used to describe the state of a satellite by accounting for the instantaneous orientation of the Earth's axis at the epoch of interest. As its name implies, this reference frame is not fixed in absolute space. Instead, it varies continuously depending on the specific instant (epoch) at which the position is calculated, incorporating the actual and complex physical motions of the Earth's rotation axis, specifically precession⁷ and nutation.⁸

The TOD frame is defined as follows:

- Z_{TOD} : directed along the true Earth rotation axis at the current date, accounting for both precession and nutation effects;
- X_{TOD} : directed toward the true vernal equinox of date;
- Y_{TOD} : completes the right-handed orthogonal triad.

Since the TOD frame does not rotate with the Earth itself, it can be considered a *quasi-inertial* frame. For numerical orbital propagation applications, the TOD

remains unchanged over time with respect to the crust of the Earth.

⁷Precession is the long-term, secular conical motion of the Earth's rotational axis (with a cycle of approximately 26,000 years) caused by the gravitational torque of the Sun and Moon on the Earth's equatorial bulge.

⁸Nutation refers to the smaller, short-term periodic oscillations (with a principal period of 18.6 years) superimposed on the precessional motion, arising from continuous variations in these gravitational forces.

frame provides an effective compromise between rigorous modeling of the Earth's orientation and computational simplicity. For this reason, it has been adopted as the primary reference frame for the simulations conducted in this study.

2.4.3 Satellite Coordinate System, RSW

The satellite coordinate system applies to studies of relative motion. The system moves with the satellite and is sometimes called the Gaussian coordinate system and is sometimes given the letters RTN (radial, transverse, and normal) or Local Vertical, Local Horizontal (LVLH). The R axis always points out from the satellite along the Earth's radius vector to the satellite as it moves through the orbit. The S axis points in the direction of (but not necessarily parallel to) the velocity vector and is perpendicular to the radius vector, an important additional requirement. The W axis is normal to the orbital plane. Figure 2.7 shows this system. The S axis is usually not aligned with the velocity vector except for circular orbits or for elliptical orbits at apogee and perigee. The coordinate system applies to all orbit types. Relative positions or displacements of satellite orbits use the RSW coordinate system. Radial positions and displacements are parallel to the position vector (along the R axis). Along-track or transverse displacements are normal to the position vector (along the S axis). Some confusion may exist with in-track displacements, which we'll define with the NTW coordinate system in the next subsection. Finally, cross-track positions are normal to the plane defined by the current position and velocity vectors (along the W axis). These orientations mainly provide reference points for describing the satellite's position from a sensor site and are often used to describe orbital errors.

2.4.4 Satellite Coordinate System, NTW

Figure 2.7 shows this system, which is valid for all orbit types. In this system, the T axis is tangential to the orbit and always points to the velocity vector. The N axis lies in the orbital plane, normal to the velocity vector. The W axis is normal to the orbital plane (as in the RSW system). We define in-track or tangential displacements as deviations along the T axis. In-track errors are not the same as along-track variations in the RSW system. One way to remember the distinction

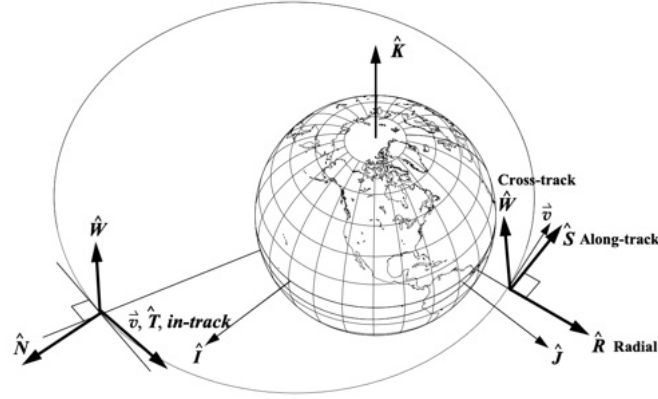


Figure 2.7: Satellite Coordinate Systems, RSW and NTW [7]

is that the in-track errors are in the direction of the velocity, whereas along-track variations are simply along the velocity vector. We use this coordinate system to analyze drag effects on the orbit because drag always acts along the velocity vector.

Table 2.2: Coordinate Systems Summary

System	Symbol	Origin	Fundamental Plane	Principal Direction	Example Use
Interplanetary systems					
Heliocentric	XYZ	Sun	Ecliptic	Vernal equinox	Patched conic
Solar system	$(XYZ)_{\text{ICRF}}$	Barycenter	varies	varies	Planetary motion
Earth-based systems					
Geocentric	IJK	Earth	Earth equator	Vernal equinox	General
Earth	$(IJK)_{\text{GCRF}}$	Earth	varies	varies	Perturbations
Body-fixed	$(IJK)_{\text{ITRF}}$	Earth	Earth equator	Greenwich meridian	Observations
Earth-Moon	$(IJK)_s$	Barycenter	Invariable plane	Earth	Restricted 3-body
Topocentric horiz.	SEZ	Site	Local horizon	South	Radar obs.
Topocentric equat.	$(IJK)_t$	Site	Parallel to Earth eq.	Vernal equinox	Optical obs.
Satellite-based systems					
Perifocal	PQW	Earth	Satellite orbit	Periapsis	Processing
Satellite radial	RSW	Satellite	Satellite orbit	Radial vector	Rel. motion, Pert.
Satellite normal	NTW	Satellite	Satellite orbit	Normal to velocity	Perturbations
Equinoctial	EQW	Satellite	Satellite orbit	Calculated vector	Perturbations

2.5 Orbital Perturbations

The 2BP assumes a perfectly central gravitational field and neglects all secondary influences. In practice, the motion of an Earth-orbiting satellite is affected by several small forces, generally referred to as *perturbations*. These perturbations cause slow variations of the orbital elements over time, leading the trajectory to deviate from the ideal Keplerian solution. The equation of motion can therefore be expressed as:

$$\ddot{\mathbf{r}} = -\frac{\mu}{r^3}\mathbf{r} + \mathbf{a}_p \quad (2.20)$$

where $\mathbf{a}_p$ represents the vector sum of all perturbing accelerations.

This type of vector differential equation cannot be solved in closed-form; therefore, the solution is typically approached via three main classes of methods: general perturbation methods (analytical), special perturbation methods (numerical), and semi-analytical methods.

In the first case, the method is analytical: the perturbative terms are expanded into series and each term of the expansion is integrated. This yields an analytical solution describing the trajectory as a function of time under the influence of the perturbing agents considered. While computationally efficient, these solutions can become complex to manage for high-order perturbations.

The second case refers to a series of numerical methods aimed at integrating the equations of motion directly. These are capable of generating a specific trajectory (termed special) given the spacecraft's initial conditions.

To bridge the gap between the speed of analytical expansions and the precision of numerical integration, *Semi-analytical methods* were developed. An example is the **Draper Semi-analytical Satellite Theory**.

The DSST separates the orbital dynamics into two distinct components:

1. **Mean Elements:** These represent the long-term evolution of the orbit (secular and long-period variations), filtered from high-frequency noise.
2. **Short-Period Variations:** These are small, periodic oscillations that occur within a single orbital period.

The DSST determines the evolution of the mean orbital elements by integrating only the averages equations of motion (typically in the form of Gauss's

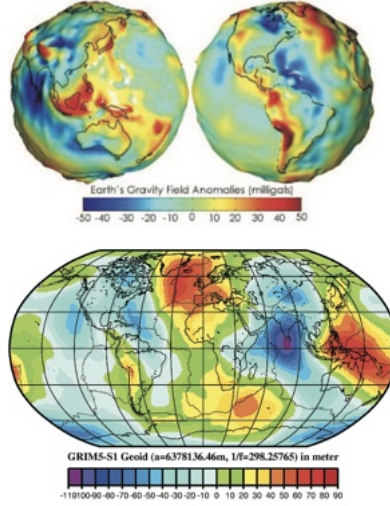


Figure 2.8: Geoid and Earth's gravity field model derived from U.S. GRACE satellite data [8]

Variational Equations, see 2.5.5).

2.5.1 Non-sphericity of the Earth

One of the fundamental simplifying assumptions made in the 2BP was the perfect sphericity of the central body. This allowed the planet's entire mass to be modeled as a point mass concentrated at its center, ensuring that gravitational effects acted with perfect spherical symmetry on any orbiting body. In reality, the Earth's shape is significantly different. It is an oblate spheroid, flattened at the poles with a prominent equatorial bulge where a greater concentration of mass is located. This additional mass exerts a non-uniform gravitational pull on satellites, disturbing the ideal Keplerian trajectory. This phenomenon represents the primary source of orbital perturbations arising from the planet's non-sphericity. As a first approximation, the Earth can be described as an ellipsoid of revolution, where the semi-major axis corresponds to the equatorial radius and the semi-minor axis to the polar radius. However, its actual shape is significantly more complex; for instance, the equator itself is not perfectly circular but exhibits a slight ellipticity (or triaxiality) that must be accounted for in high-precision models. The physical

shape of the Earth is accurately represented by the **Geoid**, which is defined as the equipotential surface of the Earth's gravity field that best fits the global mean sea level in a least-squares sense. Essentially, it represents the mass distribution at sea level and provides a mathematical formulation for it. Indeed, this gravitational potential can be expressed as a spherical harmonic series expansion:

$$U(r, \phi, \lambda) = -\frac{\mu}{r} \left\{ 1 - \sum_{n=2}^{\infty} J_n \left(\frac{R_E}{r} \right)^n P_n(\sin \phi) - \sum_{n=2}^{\infty} \sum_{m=1}^n \left(\frac{R_E}{r} \right)^n P_n^m(\sin \phi) [C_{nm} \cos(m\lambda) + S_{nm} \sin(m\lambda)] \right\} \quad (2.21)$$

where R_E is the Earth's equatorial radius, ϕ is the geocentric latitude, λ is the longitude, P_n and P_n^m are the Legendre polynomials, J_n are the zonal harmonic coefficients, C_{nm} and S_{nm} are the tesseral and sectorial harmonic coefficients.

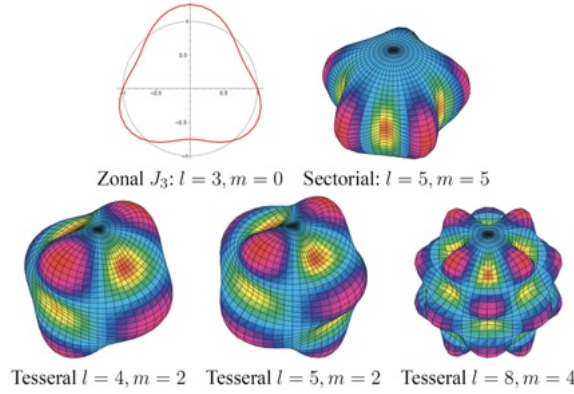


Figure 2.9: Harmonics' effects [9]

The J_n coefficients are referred to as zonal harmonics; they describe the symmetries or asymmetries of the Earth's gravitational field relative to the equatorial plane. Specifically, even-degree harmonics ($n = 2, 4, \dots$) characterize the symmetric features of the field, while odd-degree harmonics ($n = 3, 5, \dots$) represent the asymmetric ones. The most significant terms are J_2 and J_3 : the former accounts for the Earth's polar flattening (oblateness), whereas the latter describes the

higher mass concentration in the Southern Hemisphere, often referred to as the "*pear-shaped*" component of the Earth's gravity field. The coefficients C_{nm} and S_{nm} are associated with deviations of the Earth's gravitational field from axial symmetry. They are further classified into two subcategories: when $n = m$, they are referred to as sectorial harmonics, while when $0 < m < n$, they are known as tesseral harmonics. As an example, the C_{22} and S_{22} coefficients describe the ellipticity of the Earth's equatorial mass distribution. It should be noted that if these coefficients were all identically zero, the potential would reduce to:

$$V_G = -\frac{\mu}{r} \quad (2.22)$$

which is the gravitational potential derived under the spherical Earth assumption.

In general, the effects of sectorial and tesseral harmonics are averaged out and therefore largely canceled by the fact that a satellite completes several revolutions around the Earth within one day. This rapid variation in orbital longitude mitigates the influence of longitudinal asymmetries in the Earth's gravitational field. This assumption is no longer valid in the case of geostationary satellites, which maintain an almost fixed position with respect to the Earth's surface and are therefore significantly affected by east–west perturbations associated with sectorial and tesseral harmonics. Zonal harmonics, on the other hand, remain relevant in all orbital regimes. Each of these harmonics describes a specific characteristic of the planet's shape. The accuracy of the representation increases as more terms and consequently more harmonic coefficients are included in the series expansion. Nevertheless, for a fundamental understanding of the Earth's geometry and its primary orbital effects, the first few terms are generally sufficient.

Truncating the expansion at the dominant term, $J_2 = 1.08263 \times 10^{-3}$, provides the quadrupole contribution to the potential:

$$U_{J_2} = -\frac{\mu}{r} J_2 \left(\frac{R_E}{r} \right)^2 \frac{1}{2} (3 \sin^2 \phi - 1) \quad (2.23)$$

By taking the gradient of U_{J_2} , we obtain the corresponding acceleration in

the Earth-Centered Inertial (ECI) frame:

$$\mathbf{a}_{J_2} = \frac{3J_2\mu R_E^2}{2r^5} \begin{bmatrix} x \left(5\frac{z^2}{r^2} - 1 \right) \\ y \left(5\frac{z^2}{r^2} - 1 \right) \\ z \left(5\frac{z^2}{r^2} - 3 \right) \end{bmatrix} \quad (2.24)$$

Averaging the equations of motion over one orbital period yields the classical expressions:

$$\dot{\Omega} = -\frac{3}{2}J_2n \left(\frac{R_E}{a} \right)^2 \frac{\cos i}{(1-e^2)^2} \quad (2.25a)$$

$$\dot{\omega} = \frac{3}{4}J_2n \left(\frac{R_E}{a} \right)^2 \frac{4 - 5\sin^2 i}{(1-e^2)^2} \quad (2.25b)$$

where $n = \sqrt{\mu/a^3}$ is the mean motion. These relations describe a westward regression of the ascending node and a rotation of the line of apsides, both depending on altitude and inclination.

The dependence on inclination in Eq.(2.25), expressed via the cosine function, reveals the differing behaviors of prograde (direct) and retrograde orbits.

Prograde orbits⁹, defined by an inclination range of $0^\circ \leq i < 90^\circ$, correspond to a positive cosine value. This results in a negative rate of change for the RAAN ($\dot{\Omega} < 0$), leading to a *westward regression* of the line of nodes. In contrast, retrograde orbits have an inclination between $90^\circ < i \leq 180^\circ$, where the cosine is negative. Consequently, these orbits experience an increase in the RAAN, translating into an *eastward precession* (positive rotation) of the line of nodes.

A similar analysis applies to the rotation of the Line of Apsides, described by Eq.(2.25b). In this case, the sign of the variation is governed by the term $(4 - 5\sin^2 i)$, which introduces a specific threshold known as the *critical inclination* ($i_{crit} \approx 63.4^\circ$). For orbits with an inclination below this threshold ($0^\circ \leq i < 63.4^\circ$), the rate $\dot{\omega}$ is positive, resulting in the perigee advancing in the direction of the satellite's motion. Conversely, for steeper inclinations ($63.4^\circ < i \leq 116.6^\circ$), the

⁹Physically, prograde orbits move in the direction of Earth's rotation (eastward). For an observer on the ground, a LEO satellite in a prograde orbit typically exhibits an apparent motion from West to East. Conversely, retrograde orbits move against Earth's rotation, resulting in an apparent motion from East to West.

term becomes negative, causing the Line of Apsides to regress.

At the exact critical inclination, the perturbative effects vanish ($\dot{\omega} = 0$), a property exploited by specific orbital regimes, such as Molniya orbits, to maintain a stable apogee location over a specific hemisphere.

2.5.2 Atmospheric Drag

Satellites at altitudes below 1000 km are subject to aerodynamic forces due to the tenuous atmospheric layers present at those heights. The presence of atomic oxygen in these regions is particularly significant, leading to both aerodynamic drag and material erosion. Quantifying the effect of drag in the upper atmosphere is highly complex, as it depends strongly on solar activity and the resulting atmospheric density variations.

Atmospheric drag is the primary cause of *orbital decay*. By exerting a non-conservative force opposite to the velocity vector, drag reduces the total specific energy of the orbit, leading to a progressive reduction of the semi-major axis. The perturbing acceleration due to aerodynamic drag is expressed by the following fluid dynamic relation:

$$\mathbf{a}_D = -\frac{1}{2}\rho v_{rel}^2 \frac{C_D S}{m} \hat{\mathbf{v}}_{rel} \quad (2.26)$$

where:

- ρ is the atmospheric density;
- v_{rel} is the magnitude of the velocity of the spacecraft relative to the atmosphere;
- C_D is the drag coefficient;
- S is the cross-sectional area (wet area) perpendicular to the flow;
- m is the spacecraft mass.

The drag coefficient is generally higher than those typically considered for aeronautical applications (typically $C_D \approx 2.0 - 2.2$), as both the geometries of spacecraft and the nature of the molecular impacts encountered in orbit are

fundamentally different. Indeed, at these altitudes, the atmosphere is in the *free molecular flow* regime.

To analyze the effect on the orbital geometry, we consider the time-rate of change of the specific mechanical energy E :

$$E = -\frac{\mu}{2a} \implies \frac{dE}{dt} = \frac{\mu}{2a^2} \frac{da}{dt} \quad (2.27)$$

The rate of change of energy corresponds to the work done by the drag force per unit time (power dissipation). Assuming a circular orbit where the velocity vector is antiparallel to the drag force, and approximating the relative velocity with the orbital velocity ($v_{rel} \approx v = \sqrt{\mu/a}$):

$$\begin{aligned} \frac{dE}{dt} &= \mathbf{a}_D \cdot \mathbf{v} \\ &= -\left(\frac{1}{2}\rho v^2 \frac{C_D S}{m}\right) v \\ &= -\frac{1}{2}\rho v^3 \frac{C_D S}{m} \end{aligned} \quad (2.28)$$

By equating this expression with Eq.(2.27) and substituting $v = \sqrt{\mu/a}$, we obtain the rate of decay of the semi-major axis:

$$\dot{a} = -\sqrt{\mu a} \rho \frac{S C_D}{m} \quad (2.29)$$

In this context, the *Ballistic Coefficient* ($B.C.$) is often defined as the ability of a body to overcome air resistance:

$$B.C. = \frac{m}{S C_D} \quad (2.30)$$

Eq.(2.29) demonstrates that orbital decay is directly proportional to atmospheric density and inversely proportional to the ballistic coefficient: the greater the mass relative to the area, the smaller the drag effect.

The Harris-Priester Density Model

The accurate estimation of aerodynamic drag depends critically on the modeling of atmospheric density ρ . While simple static models assume a spherically symmetric distribution dependent only on altitude, the real upper atmosphere is dynamic and strongly influenced by solar heating. The absorption of Extreme Ultraviolet radiation creates a significant density variation between the day and night sides of the Earth, a phenomenon known as the **diurnal bulge**.

The Harris-Priester model (used in our simulation) addresses this anisotropy by modifying static density profiles to account for the bulge's position and intensity. It determines the density at a specific location by interpolating between tabulated minimum (night-time) and maximum (day-time) density profiles.

The density ρ at a given altitude h is computed using the following relation [10]:

$$\rho(h) = \rho_{\min}(h) + [\rho_{\max}(h) - \rho_{\min}(h)] \cos^n \left(\frac{\psi}{2} \right) \quad (2.31)$$

where:

- $\rho_{\min}(h)$ and $\rho_{\max}(h)$ are the minimum and maximum density values at altitude h , obtained from standard tables corresponding to the current mean solar flux ($F_{10.7}$).
- n is an empirical exponent (typically $2 \leq n \leq 6$) that defines the sharpness of the bulge profile.
- ψ is the angle between the satellite position vector $\mathbf{r}_{sat}$ and the unit vector pointing to the center of the diurnal bulge $\mathbf{u}_B$.

A key feature of the Harris-Priester model is the definition of the bulge's center, or *apex*. Due to the thermal inertia of the atmosphere, the point of maximum density does not align perfectly with the sub-solar point (local noon) but lags behind by approximately 2 hours (around 14:00 local time).

Consequently, the apex coordinates are defined in the Equatorial frame as:

$$\begin{cases} \delta_B = \delta_{\odot} \\ \alpha_B = \alpha_{\odot} + \lambda \end{cases} \quad (2.32)$$

where $\delta_{\odot}$ and $\alpha_{\odot}$ are the declination and right ascension of the Sun, respectively, and $\lambda \approx 30^\circ$ represents the phase lag angle due to the atmosphere's delayed thermal response. This geometric approach allows the model to capture the significant density variations encountered by the satellite throughout its orbit without the high computational cost of full thermospheric physics models.

2.5.3 Solar Radiation Pressure

Like atmospheric drag, solar radiation pressure is a non-conservative perturbation; however, its effects become increasingly significant at higher altitudes. One of the main challenges in modeling solar radiation pressure lies in the variability of solar activity and the associated fluctuations in solar flux. The mean solar radiation flux at 1 AU, known as the solar constant, is given by:

$$SF = 1367 \text{ W/m}^2. \quad (2.33)$$

Solar radiation pressure arises from the transfer of momentum carried by electromagnetic radiation. For a radiation flux SF , the corresponding pressure is:

$$p_{srp} = \frac{SF}{c} \approx 4.56 \times 10^{-6} \text{ N/m}^2, \quad (2.34)$$

where c is the speed of light.

Introducing the reflectivity coefficient C_R and the area exposed to the Sun $A_{\odot}$, the force due to solar radiation pressure acting on a spacecraft can be expressed as:

$$\mathbf{F}_{SRP} = -p_{srp} C_R A_{\odot} \frac{\mathbf{r}_{sc\odot}}{|\mathbf{r}_{sc\odot}|}, \quad (2.35)$$

where $\mathbf{r}_{sc\odot}$ is the position vector of the Sun relative to the spacecraft.

The coefficient C_R accounts for the optical properties of the spacecraft surface and typically ranges between 0 and 2. A value of $C_R = 1$ corresponds to complete absorption of the incident radiation, while values approaching 2 represent nearly specular reflection, as in the case of a perfectly reflecting surface normal to the incident flux. The effective illuminated area $A_{\odot}$ depends on the spacecraft geometry and attitude.

Finally, the acceleration due to solar radiation pressure is obtained from

Newton's second law:

$$\mathbf{a}_{SRP} = -\frac{p_{srp} C_R A_{\odot}}{m} \frac{\mathbf{r}_{sc\odot}}{|\mathbf{r}_{sc\odot}|^2}. \quad (2.36)$$

2.5.4 Third-Body Perturbations

While the Earth's gravity dominates the motion of a satellite in LEO, the gravitational attraction of other celestial bodies, primarily the Sun and the Moon, introduces non-negligible perturbations. Although these effects are small in low orbits compared to J_2 or drag, they are included in high-fidelity dynamic models to ensure long-term propagation accuracy.

The perturbing acceleration due to an i -th external body (point mass approximation) is given by the difference between the acceleration exerted by the body on the satellite and the acceleration exerted on the central body (Earth).

The equation of motion is expressed as:

$$\mathbf{a}_{3B,i} = \mu_i \left(\frac{\mathbf{d}_i}{d_i^3} - \frac{\mathbf{r}_i}{r_i^3} \right) \quad (2.37)$$

where:

- μ_i is the gravitational parameter of the perturbing body (Sun or Moon);
- $\mathbf{r}$ is the geocentric position vector of the satellite;
- $\mathbf{r}_i$ is the geocentric position vector of the third body;
- $\mathbf{d}_i = \mathbf{r}_i - \mathbf{r}$ represents the position vector of the third body relative to the satellite (pointing from the spacecraft to the perturbing body).

Two distinct terms can be identified in Eq.(2.37):

1. **Direct Effect** $\left(\frac{\mu_i}{d_i^3} \mathbf{d}_i \right)$: Represents the direct gravitational pull of the third body on the satellite.
2. **Indirect Effect** $\left(-\frac{\mu_i}{r_i^3} \mathbf{r}_i \right)$: Represents the acceleration of the Earth (the center of the coordinate system) due to the third body. Since the equations of motion are written in an Earth-Centered frame, which is non-inertial because the Earth itself is accelerating towards the Sun/Moon, this term must be subtracted to obtain the correct relative motion.

For LEO satellites, the Sun's perturbation is generally stronger than the Moon's, but both are orders of magnitude smaller than the Earth's oblateness effects. However, they play a crucial role in the long-term evolution of the eccentricity and inclination.

2.5.5 Gauss's Variational Equations

Depending on convenience, two different ways of projecting the perturbing accelerations can be employed.

The first reference frame (RTN) is defined by:

- radial direction a_r ;
- tangential direction a_t (along the local horizontal);
- direction normal to the orbital plane a_w .

The second reference frame (TNW) is defined by:

- direction along the velocity vector a_v ;
- direction lying in the orbital plane and normal to the velocity a_n (directed inward);
- direction normal to the orbital plane a_w .

The transformation between these components is given by:

$$a_r = \frac{h}{pv} [(e \sin \nu) a_v - (1 + e \cos \nu) a_n] \quad (2.38a)$$

$$a_t = \frac{h}{pv} [(1 + e \cos \nu) a_v + (e \sin \nu) a_n] \quad (2.38b)$$

Defining the mean angular velocity as:

$$n = \sqrt{\frac{\mu}{a^3}} \quad (2.39)$$

and the mean anomaly as:

$$M = n(t - t_p) \quad (2.40)$$

The mean anomaly represents the true anomaly that would be obtained at the same time from the passage at periapsis if the orbit were circular.

The variation of the orbital elements as a function of the components of the perturbing acceleration is given by Gauss' equations:

$$\begin{aligned}\dot{a} &= \frac{2a^2}{\sqrt{\mu p}} \left[(e \sin \nu) a_r + \frac{p}{r} a_t \right] \\ &= \frac{2a^2 V}{\mu} a_v\end{aligned}\tag{2.41a}$$

$$\begin{aligned}\dot{e} &= \sqrt{\frac{p}{\mu}} \left[\sin \nu a_r + \frac{r}{p} (e \cos^2 \nu + 2 \cos \nu + e) a_t \right] \\ &= \frac{1}{V} \left[2(e + \cos \nu) a_v - \frac{a \sin \nu}{r} a_n \right]\end{aligned}\tag{2.41b}$$

$$\dot{i} = \frac{r \cos(\nu + \omega)}{\sqrt{\mu p}} a_w\tag{2.41c}$$

$$\dot{\Omega} = \frac{r \sin(\nu + \omega)}{\sqrt{\mu p} \sin i} a_w\tag{2.41d}$$

$$\begin{aligned}\dot{\omega} &= -\dot{\Omega} \cos i + \frac{\sqrt{p/\mu}}{e} \left[-\cos \nu a_r + \left(1 + \frac{r}{p} \right) \sin \nu a_t \right] \\ &= -\dot{\Omega} \cos i + \frac{1}{eV} \left[2 \sin \nu a_v + \left(1 + \frac{r}{p} \right) \cos \nu a_n \right]\end{aligned}\tag{2.41e}$$

$$\begin{aligned}\dot{M} &= n - \frac{2r}{\sqrt{\mu a}} a_r - \sqrt{1 - e^2} (\dot{\omega} + \dot{\Omega} \cos i) \\ &= n - \frac{2\sqrt{1 - e^2}}{V} \left[\frac{er \sin \nu}{p} a_v - a_n \right] - \sqrt{1 - e^2} (\dot{\omega} + \dot{\Omega} \cos i)\end{aligned}\tag{2.41f}$$

Looking at Eq.(2.41a) for the semi-major axis, it can be seen that the only acceleration component affecting the variation of a is the one along the velocity vector. Therefore, to enlarge the orbit, it is most effective to thrust parallel to the velocity.

To change the eccentricity e , both the components along the velocity $\mathbf{a}_v$ and normal to it $\mathbf{a}_n$ are effective. However, their effectiveness depends on the position

along the orbit. At periapsis ($\nu = 0$), thrusting along the normal direction does not change e , whereas thrusting along the velocity is effective. Similarly, at points where $e + \cos \nu = 0$, thrusting along $\mathbf{a}_v$ has no effect.

An important observation is that if one wants to change the geometry of the orbit (its shape and size), the thrust must be applied in the orbital plane.

The equations for the variation of the inclination i and the RAAN Ω indicate that, to change the orbital plane, thrust must be applied perpendicular to it (a_w). At the ascending node ($\nu = -\omega$), thrusting out-of-plane changes the inclination i but not Ω . At the antinodes, i.e., 90° of true anomaly away from the nodes, thrusting perpendicular to the orbital plane changes Ω but not i .

The argument of periapsis ω changes when Ω varies. Changes in the mean anomaly M depend on thrust components applied in the orbital plane.

2.6 Orbit Classification

Several classifications of orbits can be made. The first is based on the orbit altitude h :

- **LEO**: $180 \text{ km} < h < 2000 \text{ km}$. These orbits are used for Earth observation, space tourism, and missions such as the ISS.
- **Medium Earth Orbit (MEO)**: $2000 \text{ km} < h < \text{GEO}$. These are used for communications, since the higher the orbit, the larger the portion of the Earth the satellite can observe.
- **GEO**: radius $r = 42164 \text{ km}$. GEO is equatorial and has an orbital period T equal to a sidereal day, slightly shorter than a solar day (Sidereal = 86164 s, Solar = 86400 s). When the Earth completes a rotation relative to the fixed stars (i.e., around its axis), it has moved slightly relative to the Sun. The difference between a solar and a sidereal day corresponds to this small angle (approximately 1° per day). GEO orbits are circular as well, ensuring that a spacecraft remains fixed relative to a point on the Earth. They are mainly used for communications.
- **High Earth Orbit (HEO)**: $h > \text{GEO}$.

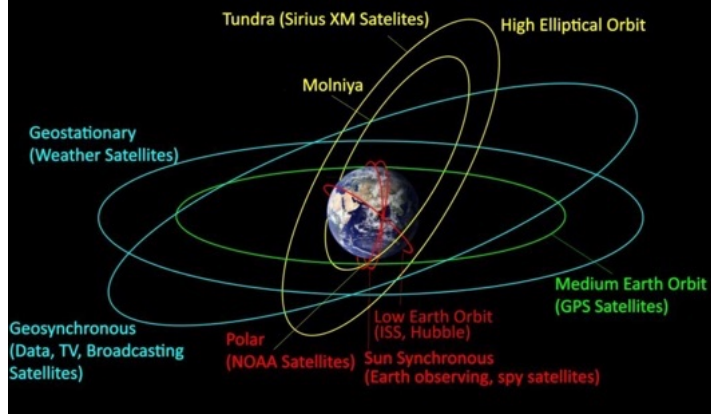


Figure 2.10: Orbit Classification [11]

Another classification is based on inclination, i.e., the angle between the orbital plane and the equatorial plane:

- **Equatorial:** zero inclination (e.g., GEO).
- **Polar:** inclination of 90° . These are important because they pass over every point on Earth. During the orbit, the satellite moves from a positive to a negative latitude, with maximum latitude determined by the orbit inclination (for example, if $i = 30^\circ$, the satellite reaches maximum Latitude $= \pm 30^\circ$). Considering that the Earth rotates around its axis during the orbit, such an orbit allows full Earth coverage. For this reason, polar orbits are used for Earth monitoring.
- **Sun-Synchronous Orbit (SSO):** exploit the nodal precession caused by J_2 to maintain a constant local solar time of passage over each point on Earth. By selecting a suitable combination of inclination and semi-major axis, the regression rate of the ascending node is synchronized with the apparent annual motion of the Sun:

$$\dot{\Omega}_{SSO} \approx \frac{0.9856^\circ}{day} = 1.991 \cdot 10^{-7} rad/s \quad (2.42)$$

- **Molniya Orbit:** these have a special inclination of about 64° , such that the rotation of the perigee (caused by the planet's oblateness, which would

otherwise shift the perigee in the same direction as the spacecraft rotation) and, consequently, the apogee, cancels out. They are very useful because to cover a specific region of the Earth, the spacecraft can be positioned with the apogee over that area. The satellite moves slowly near apogee, providing extended coverage, while completing the rest of the orbit quickly to return to the area of interest. Molniya orbits are used, for example, by the Russian “Global Positioning System (GPS)” system Global’naya Navigatsionnaya Sputnikovaya Sistema (GLONASS).

2.7 Satellite Eclipse Conditions

One of the constraints of the problem under analysis is the feasibility of performing maneuvers during eclipses, as certain clients serviced by Telespazio require strict adherence to this operational constraint. Therefore, a brief overview of this phenomenon is presented below.

Given the position of the Sun, this problem consists of determining the points along the trajectory (if any) where the satellite is located within the shadow cone cast by the central body it is orbiting. This problem can be solved with varying levels of approximation, depending on the desired geometric accuracy in describing the shadow cast by the planet (or, more generally, the primary attractor). However, knowledge of the relative Earth-Sun position at any given observation epoch is a prerequisite.

In the **cylindrical model**, it is assumed that the shadow cast by the planet corresponds to a right cylinder of infinite height, with its base located at the Earth and its axis coinciding with the Sun-Planet line. The boundary of this cylinder (i.e., its lateral surface) represents the interface separating spatial points in full sunlight from those in total shadow. Consequently, the cylindrical model predicts an instantaneous transition of the satellite from a state of full illumination to one of total eclipse.

However, it is well known that all Earth-orbiting satellites experience conditions of so-called *partial eclipse* (or penumbra) as they transition from the illuminated side to the shadowed (nocturnal) side of the Earth. To account for these partial eclipse conditions, a **conical shadow model** must be adopted.

The plane shown in Figure 2.11 is the one passing through the center of mass of the Sun, the center of mass of the Earth, and the satellite, which is treated as a point mass. The figure also depicts the trace of the *fundamental plane*, defined as the plane passing through the satellite and perpendicular to the axis of the shadow cone. The distance of the fundamental plane from the Earth's center of mass (representing the occulting body, assumed to be spherical with radius $R_\oplus$) is denoted by r_0 and is given by the following relation:

$$r_0 = \frac{|\mathbf{r} \cdot \mathbf{r}_\odot|}{|\mathbf{r}_\odot|} \quad (2.43)$$

where $\mathbf{r}$ and $\mathbf{r}_\odot$ denote the position vectors of the satellite and the Sun, respectively, in the planetocentric frame. The distance l of the satellite from the shadow cone axis is, evidently (where $r = |\mathbf{r}|$ is the Earth-satellite distance):

$$l = \sqrt{r^2 - r_0^2} \quad (2.44)$$

The intersections of the penumbra and umbra cones with the fundamental plane correspond to two circles of radii l_1 and l_2 , whose values are given by the following relations:

$$l_1 = c_1 \tan \phi_1 \quad (2.45)$$

$$l_2 = c_2 \tan \phi_2 \quad (2.46)$$

where c_1 and c_2 are defined as:

$$c_1 = r_0 + \frac{R_\oplus}{\sin \phi_1} \quad (2.47)$$

$$c_2 = r_0 - \frac{R_\oplus}{\sin \phi_2} \quad (2.48)$$

while the angles ϕ_1 and ϕ_2 satisfy the equations:

$$\phi_1 = \arcsin \left(\frac{R_\odot + R_\oplus}{|\mathbf{r}_\odot|} \right) \quad (2.49)$$

$$\phi_2 = \arcsin \left(\frac{R_{\odot} - R_{\oplus}}{|\mathbf{r}_{\odot}|} \right) \quad (2.50)$$

where $R_{\odot} \approx 6.96 \cdot 10^5$ km indicates the mean radius of the Sun.

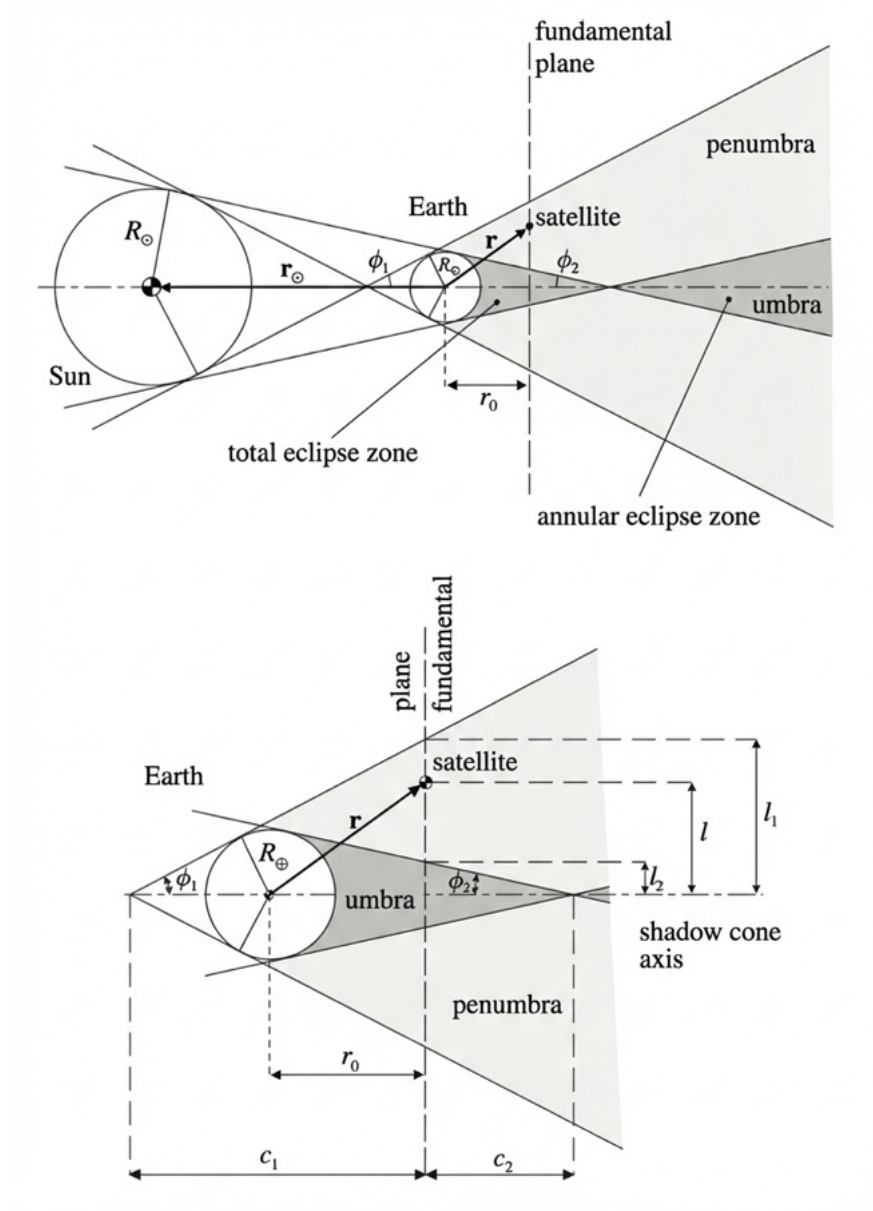


Figure 2.11: Conical shadow model (not to scale) [12]

Once the problem has been geometrically defined, it is possible to identify the conditions under which the satellite is in shadow or penumbra. Indeed, if $\mathbf{r} \cdot \mathbf{r}_\odot \geq 0$, the satellite is completely illuminated, as it is located in the region between the Sun and the Earth (day side), and therefore experiences no eclipse. If, on the other hand, $\mathbf{r} \cdot \mathbf{r}_\odot < 0$, it is necessary to verify whether the satellite is still illuminated or is in shadow. To this end, it is sufficient to check the distance l of the satellite from the Sun-Earth axis, as defined by Eq.(2.44). Specifically:

$$\text{if } \begin{cases} l > l_1 & \text{the satellite is completely illuminated} \\ |l_2| < l < l_1 & \text{the satellite is in penumbra} \\ l < |l_2| & \text{the satellite is in shadow and } \begin{cases} l_2 < 0 & \text{total eclipse} \\ l_2 > 0 & \text{annular eclipse} \end{cases} \end{cases}$$

Chapter 3

Orbital Maneuvers

Newton's Third Law. The only way humans have figured out how to move forward is to leave something behind.

Interstellar

3.1 Propulsive Dynamics

Space propulsion is governed by Newton's **Third Law of Motion**, often referred to as the law of action and reaction. In an isolated system, linear momentum is conserved. Since space is (nearly) a vacuum, providing no external medium for momentum exchange, the spacecraft system is considered isolated. Therefore, the only way to generate thrust is to expel part of the system's own mass: the propellant. Consider a one-dimensional analysis where the spacecraft system has a velocity v at time t . Over an infinitesimal time interval dt , the spacecraft expels a propellant mass dm_p , changing its velocity to $v + dv$. This mass dm_p is ejected with a relative velocity c with respect to the spacecraft (corresponding to an absolute velocity of $v - c$). Assuming the system is isolated and the velocities are collinear, the principle of conservation of momentum leads to the definition of thrust T :

$$T = \dot{m}_p c \quad (3.1)$$

where c is the **effective exhaust velocity** and $\dot{m}_p$ is the propellant mass flow rate.

3.1.1 Performance

The primary objective of propulsion is to modify the spacecraft's velocity; therefore, the focus is not merely on the thrust itself, but on the cumulative effect it exerts on the system. The **total impulse** (I_{tot}) is defined as the integral of the thrust over the time interval between the start and the end of the maneuver:

$$I_{tot} = \int_{t_0}^{t_f} T dt \quad (3.2)$$

The total propellant mass (m_p) consumed during a given maneuver is expressed as the integral of the propellant mass flow rate:

$$m_p = \int_{t_0}^{t_f} \dot{m}_p dt \quad (3.3)$$

The **specific impulse** (I_{sp}) is defined as the ratio between the total impulse provided by the system and the weight of the consumed propellant mass at the Earth's surface:

$$I_{sp} = \frac{I_{tot}}{m_p g_0} \quad (3.4)$$

In the scenario where both thrust and mass flow rate remain constant during the maneuver, the expression for specific impulse simplifies as follows:

$$I_{sp} = \frac{I_{tot}}{m_p g_0} = \frac{T \Delta t}{\dot{m}_p \Delta t g_0} = \frac{T}{\dot{m}_p g_0} = \frac{c}{g_0} \quad (3.5)$$

This parameter serves as a measure of the efficiency with which the expelled propellant mass is utilized. Physically, the specific impulse can be interpreted as the duration for which a given amount of propellant can provide a thrust equal to its weight on Earth. From a practical standpoint, a higher I_{sp} implies that the

system can either maintain a specific thrust for a longer duration or generate a greater thrust for a shorter period, given a fixed mass of propellant.

An additional fundamental parameter is introduced:

$$\Delta V = \int_{t_0}^{t_f} \frac{T}{m(t)} dt \quad (3.6)$$

This ΔV represents the velocity increment that the system would achieve if thrust T were the only force acting upon it and if it were perfectly aligned with the velocity vector. By substituting the definition of thrust, the integral becomes:

$$\Delta V = \int_{t_0}^{t_f} \frac{T}{m(t)} dt = \int_{t_0}^{t_f} \frac{c \dot{m}_p}{m(t)} dt \quad (3.7)$$

Assuming a constant effective exhaust velocity c , the integration yields the **Tsiolkovsky rocket equation**:

$$\Delta V = c \ln \left(\frac{m_0}{m_f} \right) \quad (3.8)$$



Figure 3.1: Raptor 3, an example of chemical propulsion [13]

This equation relates the initial mass (m_0) and the final mass (m_f) based on the required ΔV and the velocity c . It implies that for a given maneuver, the engine's effective exhaust velocity should be comparable to the required ΔV . The higher the value of c , the lower the propellant mass required to complete the maneuver.

Chemical Propulsion

In chemical propulsion, a propellant mass flow $\dot{m}_p$ undergoes a reaction, releasing chemical energy that is converted into kinetic energy through the expansion and acceleration of the exhaust gases. The resulting kinetic power at the nozzle exit is therefore given by:

$$\dot{m}_p \frac{u_e^2}{2} = \eta \dot{m}_p E_{ch} \quad (3.9)$$

where E_{ch} represents the energy per unit mass released by the reaction, and η is the efficiency factor, accounting for the fraction of chemical energy effectively converted into enthalpy. Neglecting the initial energy of the propellant at the combustion chamber inlet, we obtain:

$$P_T = \dot{m}_p \frac{c^2}{2} \approx \dot{m}_p \frac{u_e^2}{2} \approx \dot{m}_p E_{ch} \quad (3.10)$$

yielding:

$$c \approx \sqrt{2E_{ch}} \quad (3.11)$$

This relation demonstrates that c is fundamentally limited by the chemical energy of the reaction: the energy source used to accelerate the propellant mass, which must exchange momentum with the spacecraft, is the energy stored within the propellant itself.

On the other hand, the fact that the energy is contained within the propellant makes this class of thrusters highly scalable. Thrust scalability is achieved by simply increasing or decreasing the mass flow rate while maintaining the same effective exhaust velocity.

Electric Propulsion

In electric propulsion, conversely, the propellant mass flow $\dot{m}_p$ passes through the thruster where it receives a specific electric power input P_E . The thruster converts this available electric power into the kinetic power of the propellant beam:

$$\eta P_E \approx \dot{m}_p \frac{c^2}{2} = T \frac{c}{2} = P_T \quad (3.12)$$

While chemical thrusters exhibit very high efficiencies in converting chemical energy into kinetic energy, this is not necessarily the case for electric thrusters. Indeed, the conversion from electric to kinetic form is often accompanied by significant losses. The effective exhaust velocity is given by:

$$c = \sqrt{\frac{2\eta P_E}{\dot{m}_p}} \quad (3.13)$$

Theoretically, arbitrarily large values of effective exhaust velocity c can be achieved either by increasing the input power P_E or by decreasing the mass flow rate $\dot{m}_p$ (and consequently the thrust T).

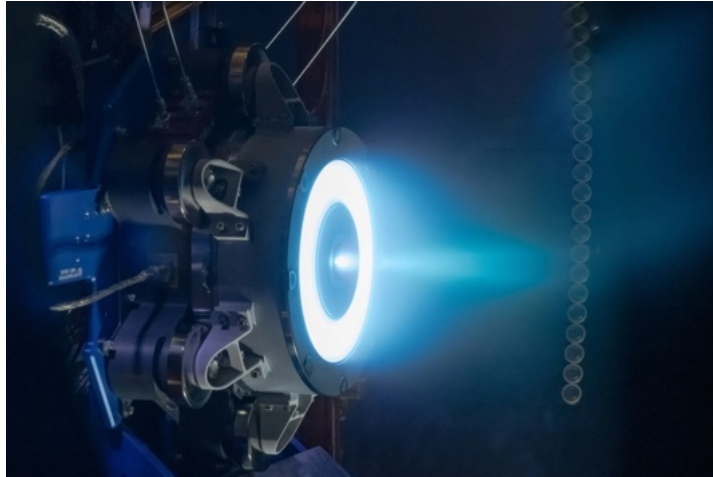


Figure 3.2: Hall Thruster [14]

This highlights the fundamental trade-off between the two technologies.

Chemical propulsion is capable of generating arbitrarily large thrust levels but is constrained by a limited specific impulse. Electric propulsion, on the other hand, offers specific impulses far superior to those of chemical propulsion, but with the disadvantage of requiring an onboard electrical power source and generating significantly lower thrust.

If high thrust levels were desired with electric propulsion, extremely high P_E would be required. However, since the power generator has its own mass (the power processing unit and solar arrays/nuclear source), increasing power increases dry mass, which penalizes the overall acceleration of the spacecraft system.

Consequently, rapid maneuvers such as orbital injection are generally not feasible with electric propulsion due to these thrust limitations. For interplanetary transfers, however, electric propulsion allows achieving the same ΔV with drastically reduced propellant consumption, provided that a longer mission duration compared to chemical propulsion is acceptable.

3.1.2 Impulsive Orbital Maneuvers

Orbital maneuvers are required to transfer a spacecraft from one orbit to another. These changes can be dramatic, such as the transfer from a Low-Earth parking orbit to an interplanetary trajectory, or quite small, as in the final stages of a rendezvous operation.

When the operation involves brief firings of onboard rocket motors, these are classified as *impulsive maneuvers*. In this approximation, the magnitude and direction of the velocity vector are assumed to change instantaneously. This idealization allows for decoupling the trajectory analysis from the numerical integration of the equations of motion with active thrust. The assumption is valid when the burn time is negligible compared to the coasting time (i.e., for high-thrust chemical propulsion). Each impulsive maneuver results in a velocity increment $\Delta \mathbf{V}$. Depending on the vector geometry, maneuvers are often categorized as [15]:

- **Pumping maneuvers:** Changes in the magnitude of the velocity vector (changing the orbital energy/semi-major axis).
- **Cranking maneuvers:** Changes in the direction of the velocity vector (changing the orbital plane).

- **Combined maneuvers:** Simultaneous changes in both magnitude and direction.

Recalling Gauss's planetary equations 2.5.5, a brief analysis is conducted on the effects induced by an applied thrust vector $\mathbf{F} = [F_T, F_N, F_W]^T$ on the orbital parameters. The following near-circular orbit assumptions are established:

- $e \rightarrow 0$
- $a = r$
- $V = a \cdot n$

where e is the eccentricity of the orbit, a is the semi-major axis, r is the orbital radius, V is the linear velocity, and n is the orbital angular speed (mean motion).

With these assumptions, as demonstrated in [7], the Gauss equations for the description of the orbital elements assume the following formulation:

$$\frac{de_X}{dt} = \frac{\sin u}{V} F_N + \frac{2 \cos u}{V} F_T \quad (3.14)$$

$$\frac{de_Y}{dt} = \frac{\cos u}{V} F_N + \frac{2 \sin u}{V} F_T \quad (3.15)$$

$$\frac{da}{dt} = \frac{2a}{V} F_T \quad (3.16)$$

$$\frac{di}{dt} = \frac{\cos u}{V} F_W \quad (3.17)$$

$$\frac{d\Omega}{dt} = \frac{\sin u}{V \sin i} F_W \quad (3.18)$$

$$\frac{du}{dt} = -\frac{\cos i \sin u}{V \sin i} F_W \quad (3.19)$$

where u is the Argument of Latitude. In Eqs. (3.14) and (3.15) we exploited the fact that:

$$\frac{de_X}{dt} = \cos \omega \frac{de}{dt} - e \sin \omega \frac{d\omega}{dt} \quad (3.20)$$

$$\frac{de_Y}{dt} = \sin \omega \frac{de}{dt} + e \sin \omega \frac{d\omega}{dt} \quad (3.21)$$

$$\frac{d\omega}{dt} = \frac{du}{dt} - \frac{d\nu}{dt} \quad (3.22)$$

Considering impulsive maneuvers, the system can be reformulated as demonstrated in [23]:

$$\Delta e_X = \frac{\sin u}{V} \Delta V_N + \frac{2 \cos u}{V} \Delta V_T \quad (3.23)$$

$$\Delta e_Y = \frac{\cos u}{V} \Delta V_N + \frac{2 \sin u}{V} \Delta V_T \quad (3.24)$$

$$\Delta a = \frac{2a}{V} \Delta V_T \quad (3.25)$$

$$\Delta i = \frac{\cos u}{V} \Delta V_W \quad (3.26)$$

$$\Delta \Omega = \frac{\sin u}{V \sin i} \Delta V_W \quad (3.27)$$

$$\Delta \alpha = -\frac{\cos i \sin u}{V \sin i} \Delta V_W \quad (3.28)$$

where ΔV_N , ΔV_T , and ΔV_W indicate respectively the radial, tangential, and out-of-plane (normal to the orbital plane) components of the impulsive velocity variation vector $\Delta \mathbf{V}$.

These equations explicitly demonstrate how a specific $\Delta \mathbf{V}$ component impacts the individual orbital elements. In particular, Equation 3.25 highlights that an impulse applied purely in the tangential direction directly and most efficiently alters the semi-major axis a . Similarly, an out-of-plane impulse ΔV_W can be strategically exploited to correct the Right Ascension of the Ascending Node Ω and the inclination i , as shown in Equations 3.27 and 3.26.

Conversely, Equation 3.28, although expressing a direct mathematical relationship between the out-of-plane velocity increment and the variation of the Argument of Latitude u , does not represent a practical tool for orbital control strategies. Indeed, for near-polar orbits ($i \rightarrow 90^\circ$), the $\cos i$ term approaches zero, rendering the effect of ΔV_W on u strictly negligible. Furthermore, out-of-plane

maneuvers are inherently expensive in terms of propellant consumption. Therefore, adjusting the Argument of Latitude is operationally achieved by modifying the semi-major axis via in-plane maneuvers and exploiting the resulting natural orbital drift, which is a far more efficient alternative.

3.2 Edelbaum Approximation

Unlike chemical propulsion, where maneuvers can be considered impulsive (i.e. all the thrust required to achieve the desired ΔV is delivered in a time short compared to the transfer duration) in electric propulsion the thrust is applied continuously over time. This is due to the low thrust levels, which invalidate the impulsive maneuver assumption: the required ΔV is provided over a relatively long period, during which the orbital parameters can no longer be assumed constant within the engine firing window.

The use of low-thrust propulsion therefore requires a new approach to describe the equations of motion. First, it is convenient to introduce the approximations proposed by Edelbaum [17], a classical solution for a control problem with electric propulsion.

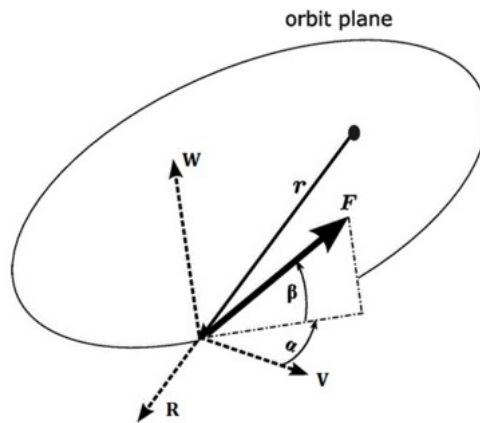


Figure 3.3: Thrust Component Directions [16]

- Orbits are assumed to be nearly circular, such that the eccentricity can be

approximated as zero ($e \approx 0$). This also implies that the orbital parameters (semimajor axis and semilatus rectum) can be approximated by the instantaneous radius of the trajectory ($r \approx a \approx p$). Consequently, the spacecraft speed at any instant is approximately equal to the circular velocity: $V^2 \approx \mu/r$.

- For a nearly circular orbit, the true, eccentric, and mean anomalies can be considered equivalent ($\nu \approx E \approx M$).
- Small inclination changes are considered ($i \approx 0$). If the initial orbital plane is used as the reference plane, one can also approximate $\cos i \approx 1$ and $\sin i \approx i$.
- Thrust and accelerations are small ($T/m \ll \mu/r^2$).
- Thrust and acceleration components are decomposed into an orthogonal set (Figure 3.3):

- $a_V = a_T \ll \mu/r^2$: acceleration along the velocity direction, tangent to the trajectory;
- $a_R \ll \mu/r^2$: radial acceleration component;
- $a_W \ll \mu/r^2$: out-of-plane component, in the direction of $\mathbf{h}$.

Given the small accelerations, the spacecraft experiences gradual changes in velocity and orbital parameters over multiple revolutions around the Earth. The objective is to determine the optimal thrust directions T to achieve the desired orbital changes.

Since the trajectories must remain circular, no action is taken to change the eccentricity or argument of perigee, which would require adjusting the thrust angle α . Therefore, the optimization problem focuses exclusively on controlling the angle β , the out-of-plane thrust direction affecting inclination and RAAN, and the thrust component parallel to the velocity vector to modify the semimajor axis.

To describe the variation of orbital parameters, differential equations are used as functions of the orthogonal components of a perturbing acceleration T/m , introduced previously. These equations are known as the *Lagrange planetary equations* in Gauss form, as already discussed.

These equations can be rewritten by considering the simplifications previously introduced. Furthermore, the orthogonal acceleration components are expressed in terms of the control angle β , and the argument of latitude is introduced, $u = \omega + \nu$, representing the angle between the ascending node and the spacecraft position.

Finally, the J_2 perturbation must be included in Eq. 2.41d by considering the time derivative of the RAAN, $\dot{\Omega}$, as introduced in Eq. 2.25

$$\frac{da}{dt} = 2 \frac{a}{V} \frac{T}{m} \cos \beta, \quad (3.29)$$

$$\frac{di}{dt} = \frac{1}{V} \frac{T}{m} \cos u \sin \beta, \quad (3.30)$$

$$\frac{d\Omega}{dt} = \frac{1}{V \sin i} \frac{T}{m} \sin u \sin \beta - J_2 \frac{3}{2} \left(\frac{R_T}{a} \right)^2 \frac{V}{a} \cos i. \quad (3.31)$$

These equations can also be rewritten using the argument of latitude u as the independent variable, taking into account the relation between du and dt given by:

$$\frac{dt}{du} = \sqrt{\frac{a^3}{\mu}}. \quad (3.32)$$

Thus, Eqs.3.29-3.31 become:

$$\frac{da}{du} = 2a \frac{T/m}{\mu/a^2} \cos \beta, \quad (3.33)$$

$$\frac{di}{du} = \frac{T/m}{\mu/a^2} \cos u \sin \beta, \quad (3.34)$$

$$\frac{d\Omega}{du} = \frac{T/m \sin u}{\mu/a^2 \sin i} \sin \beta - J_2 \frac{3}{2} \left(\frac{R_T}{a} \right)^2 \cos i. \quad (3.35)$$

In the more general case of a maneuver performed over multiple revolutions, the total maneuver time becomes significant, and the time variation of the spacecraft mass must also be considered:

$$\frac{dm}{dt} = -\frac{T}{c}. \quad (3.36)$$

In his work, Edelbaum proposed control laws in terms of the angles α and β that minimize the ΔV for an electric propulsion maneuver over a single revolution, under the simplifying assumptions described. In particular, the small variations of orbital elements per revolution allow linearizing both the changes in orbital parameters and the equations of motion and control. These solutions consist of determining the optimal thrust direction for each position of the spacecraft along its trajectory.

Regarding the sole change in semimajor axis, while keeping the orbital eccentricity constant, the optimal control law requires that the thrust be parallel to the velocity vector, applied continuously over one or multiple revolutions depending on the required Δa . The thrust direction is aligned with the velocity vector for a positive increase of the semimajor axis, or opposite for a decrease.

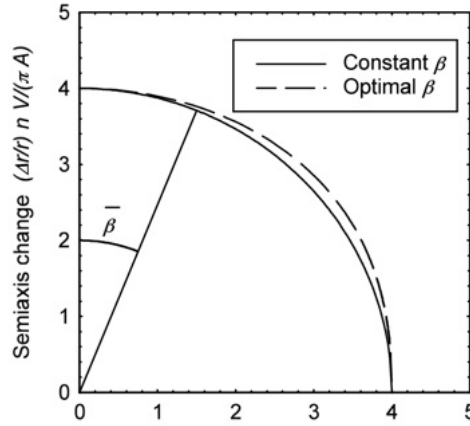


Figure 3.4: Normalized Variations of Semimajor Axis and Inclination [16]

For a combined change of semimajor axis and inclination, the maneuver becomes an out-of-plane maneuver. If eccentricity variations are not considered, the condition $\tan \alpha_{\text{opt}} = 0$ is imposed, and the control is performed through β to maximize $\dot{a} + k\dot{i}$, a linear combination of the temporal variations of the two parameters to be changed. The constant k depends on the magnitude of the desired variations. This leads to the control equation:

$$\tan \beta_{\text{opt}} = k \cos u \quad (3.37)$$

The resulting control law for β is sinusoidal, with larger values at the nodes and smaller values at the antinodes. Edelbaum proposed a simplification of this result, using an intermediate β constant in magnitude, with its sign changing every half orbit. As shown in Figure 3.4., this piecewise-constant control angle approximation yields a suboptimal solution that closely approaches the optimal one.

A different scenario arises when large changes in orbital parameters are required, i.e., maneuvers executed over multiple revolutions rather than a single one. For this case, Edelbaum proposed to consider all orbits, including transfer orbits, as nearly circular. This allows leveraging the single-revolution results and applying a constant thrust angle β for each revolution. The analysis, using ΔV as the independent variable, leads to the following result:

$$V \sin \beta = V_0 \sin \beta_0 = \text{constant} \quad (3.38)$$

Since the product between the sine of the thrust angle and the velocity is constant, β will be smaller where the velocity is high, and larger where the velocity is low. This is consistent with simple plane-change maneuvers using chemical propulsion, where it is preferable to apply out-of-plane thrust when the velocity magnitude is smaller, i.e., at greater distances from the central body, to change the inclination more efficiently.

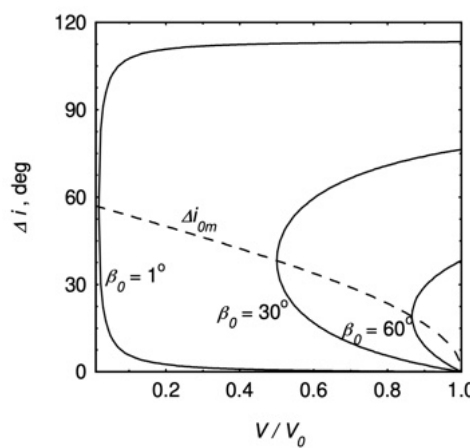


Figure 3.5: Optimal Maneuvers for Inclination and Semimajor Axis Changes [16]

The value of ΔV for the maneuver is independent of the trajectory followed. For any inclination change smaller than 2 radians, we have:

$$\Delta V = \sqrt{V_0^2 + V_1^2 - 2V_0V_1 \cos\left(\frac{\pi}{2}\Delta i\right)}. \quad (3.39)$$

For inclination changes greater than 2 radians, ΔV does not increase and remains the same, since an inclination change of 2 radians corresponds to a plane change at zero cost at infinity:

$$\Delta V = V_0 + V_1. \quad (3.40)$$

In the case where $\Delta i = 0$:

$$\Delta V = |V_0 - V_1|. \quad (3.41)$$

The mission duration can instead be derived from the propellant mass required for the maneuver:

$$m_p = m_0 - m_f = m_0 \left(1 - \exp\left(-\frac{\Delta V}{c}\right)\right), \quad (3.42)$$

from which:

$$\Delta t = \frac{m_p}{\dot{m}_p} = \frac{m_0 (1 - \exp(-\frac{\Delta V}{c}))}{T/c}. \quad (3.43)$$

3.3 Phasing maneuvers

Phasing maneuvers are used to change the position of a spacecraft in its orbit. If two spacecraft, destined to rendezvous, are at different locations in the same orbit, then one of them may perform a phasing maneuver in order to catch the other one. Communications and weather satellites in geostationary earth orbit use phasing maneuvers to move to new locations above the equator. In that case, the rendezvous is with an empty point in space rather than with a physical target. In Figure 3.6, phasing orbit 1 might be used to return to P in less than one period of the main orbit. This would be appropriate if the target is ahead of

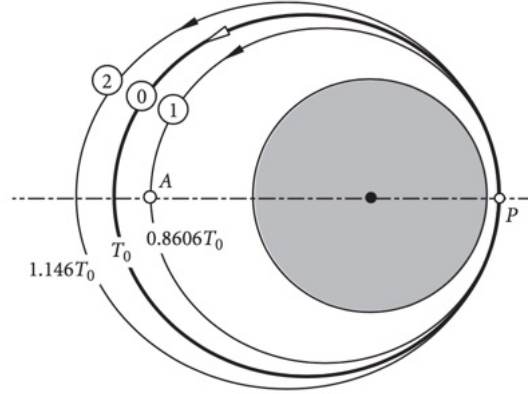


Figure 3.6: Main orbit (0) and two phasing orbits, faster (1) and slower (2). T_0 is the period of the main orbit. [15]

the chasing vehicle. Note that a retrofire is required to enter orbit 1 at P. That is, it is necessary to slow the spacecraft down in order to speed it up, relative to the main orbit. If the chaser is ahead of the target, then phasing orbit 2 with its longer period might be appropriate. A forward fire of the thruster boosts the spacecraft's speed in order to slow it down.

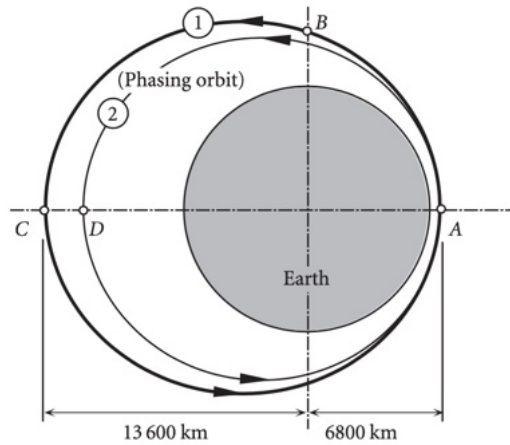


Figure 3.7: Phasing maneuver. [15]

An example [15] is provided below (3.7): Spacecraft at A and B are in the

same orbit (1). At the instant shown, the chaser vehicle at A executes a phasing maneuver so as to catch the target spacecraft back at A after just one revolution of the chaser's phasing orbit (2). The required total delta-v must be determined.

From the Figure 3.7,

$$r_A = 6800 \text{ km}, \quad r_C = 13600 \text{ km}$$

Orbit 1:

The eccentricity of orbit 1 is

$$e_1 = \frac{r_C - r_A}{r_C + r_A} = 0.3333$$

Evaluating the orbit equation at A, we find

$$r_A = \frac{h_1^2}{\mu} \frac{1}{1 + e_1 \cos 0} \Rightarrow h_1 = 60116 \text{ km}^2/\text{s}$$

The period:

$$T_1 = \frac{2\pi a_1^{3/2}}{\sqrt{\mu}} = 10252 \text{ s}$$

Since A is perigee, there is no radial velocity component there. The speed, directed entirely in the transverse direction, is found from the angular momentum formula,

$$v_{A1} = \frac{h_1}{r_A} = 8.8406 \text{ km/s}$$

The phasing orbit must have a period T_2 equal to the time it takes the target vehicle at B to coast around to point A on orbit 1. We can determine the flight time by calculating the time Δt_{AB} from A to B and subtracting that result from the period T_1 of orbit 1. At B the true anomaly is $\nu_A = 90^\circ$:

$$\tan \frac{E_B}{2} = \frac{\sqrt{1 - e_1}}{\sqrt{1 + e_1}} \tan \frac{\nu_B}{2} \Rightarrow E_B = 1.2310 \text{ rad}$$

Then, from Kepler's equation, we get

$$\Delta t_{AB} = \frac{T_1}{2\pi} (E_B - e_1 \sin E_B) = 1495.7 \text{ s}$$

Thus, the time of flight of the target spacecraft from B to A is

$$\Delta t_{BA} = T_1 - \Delta t_{AB} = 8756.3 \text{ s}$$

Orbit 2:

The period of orbit 2 must equal t_{BA} so that the chaser will arrive at A when the target does. That is $T_2 = 8756.3 \text{ s}$. This, together with the period formula yields the semimajor axis of orbit 2 $\Rightarrow a_2 = 9182.1 \text{ km}$. Since $2a_2 = r_A + r_D$, we find

$$r_D = 2a_2 - r_A = 11564 \text{ km}$$

Therefore, point A is indeed the perigee of orbit 2, the eccentricity of which can now be determined:

$$e_2 = \frac{r_D - r_A}{r_D + r_A} = 0.25943$$

Evaluating the orbit equation at point A of orbit 2 yields its angular momentum,

$$r_A = \frac{h_2^2}{\mu} \frac{1}{1 + e_2 \cos 0} \quad \Rightarrow \quad h_2 = 58426 \text{ km}^2/\text{s}$$

Finally, we can calculate the speed at perigee of orbit 2,

$$v_{A2} = \frac{h_2}{r_A} = 8.5921 \text{ km/s}$$

At the beginning of the phasing maneuver,

$$\Delta v_A = v_{A2} - v_{A1} = -0.24851 \text{ km/s}$$

At the end of the phasing maneuver,

$$\Delta v_A = v_{A1} - v_{A2} = 0.34851 \text{ km/s}$$

The total delta-v, therefore, is

$$\Delta V_{\text{total}} = |-0.24851| + |0.24851| = 0.4970 \text{ km/s}$$

Chapter 4

Phasing Problem

*Non exiguum temporis habemus, sed multum
perdimus.*

Lucius Anneo Seneca, De Brevitate Vitae

The phasing problem can be divided into two main parts:

- In the first part, the problem is addressed through a constrained optimization approach based on the SQP method, aimed at defining an optimal maneuver strategy. The orbital dynamics are simulated using a DSST propagator that incorporates gravity J_2 and atmospheric drag force models, using impulsive maneuvers to determine the resulting ΔV for each individual batch. The problem is discretized into batches; within each batch, a specific number of orbits is allocated. The strategy focuses on the median orbit, allowing maneuvers only within specific Argument of Latitude (AOL) ranges and eclipse. The primary objective is to minimize the total ΔV required to reach the target orbit while strictly adhering to these operational constraints. Given the local convergence nature of the SQP algorithm, the selection of the initial guess is critical. The final solution vector provides the specific AOLs for maneuver execution, as well as the tangential (raising or braking) and normal components of the velocity increment.
- In the second phase, leveraging the outputs from the first part, a maneuver

planner is developed. The various operation batches are simulated using a numerical propagator (incorporating all the typical force models of the LEO environment) alongside finite thrust maneuvers. These operations are subject to multiple strict constraints: execution is restricted to eclipse phases and specific AOL ranges, while firm limits are also imposed on the maximum burn duration and the mandatory waiting times between consecutive maneuvers.

The entire project has been developed in a Java environment, leveraging the Orekit framework [19], a library for the development of space flight dynamics applications. In this thesis, only the second part is investigated in detail.

Brief description of the SQP method

Before proceeding, a brief overview of the SQP optimizer is provided, as it has become one of the most successful methods for solving nonlinear constrained optimization problems [20]. As with most optimization techniques, SQP is not a single algorithm, but rather a conceptual framework from which several specific algorithms have evolved.

The nonlinear programming problem (NLP) to be solved is defined as:

$$\begin{aligned} & \underset{\mathbf{x}}{\text{minimize}} && f(\mathbf{x}) \\ & \text{subject to:} && \mathbf{h}(\mathbf{x}) = \mathbf{0} \\ & && \mathbf{g}(\mathbf{x}) \leq \mathbf{0} \end{aligned}$$

where $f : \mathbb{R}^n \rightarrow \mathbb{R}$, $\mathbf{h} : \mathbb{R}^n \rightarrow \mathbb{R}^m$, and $\mathbf{g} : \mathbb{R}^n \rightarrow \mathbb{R}^p$.

Such problems arise in a wide variety of applications in science, engineering, industry, and management.

In the NLP formulation, the problem is quite general and includes linear and quadratic programming as special cases, in which the constraint functions $\mathbf{h}$ and $\mathbf{g}$ are affine and f is linear or quadratic. Although these problems are important and widespread, the main strength of the SQP method lies in its ability to handle nonlinear constraints. For this reason, it is assumed that the NLP problem contains at least one nonlinear constraint function.

The fundamental idea behind SQP is to model the NLP at a given approximate

solution $\mathbf{x}_k$ by means of a quadratic programming subproblem, and then use the solution of this subproblem to construct an improved approximation $\mathbf{x}_{k+1}$. This process is iterated, generating a sequence of approximations that ideally converges to an optimal solution $\mathbf{x}^*$.

The key to understanding the performance and theoretical foundations of SQP lies in the fact that, with an appropriate choice of the quadratic subproblem, the method can be interpreted as a natural extension of Newton and quasi-Newton methods to constrained optimization. Consequently, SQP methods are expected to share the typical characteristics of Newton-type methods: rapid convergence when the iterates are close to the solution, but potentially irregular behavior when they are far from it, requiring careful control strategies. While this analogy generally holds, the presence of constraints significantly increases both the analytical and implementation complexity of SQP methods.

Two additional properties of the SQP method are worth emphasizing. First, SQP is not a feasible-point method; that is, neither the initial point nor the subsequent iterates are required to be feasible (where feasibility means satisfying all NLP constraints). This represents a substantial advantage, as finding a feasible point in the presence of nonlinear constraints can be nearly as difficult as solving the NLP itself. Second, SQP methods can be easily modified to ensure that linear constraints, including simple bounds, are always satisfied.

A key function, one that plays a central role in all of the theory of constrained optimization, is the scalar-valued **Lagrangian function** defined by:

$$\mathcal{L}(\mathbf{x}, \mathbf{u}, \mathbf{v}) = f(\mathbf{x}) + \mathbf{u}^T \mathbf{h}(\mathbf{x}) + \mathbf{v}^T \mathbf{g}(\mathbf{x}) \quad (4.1)$$

where $\mathbf{u} \in \mathbb{R}^m$ and $\mathbf{v} \in \mathbb{R}^p$ are the *multiplier vectors*. Given a vector $\mathbf{x}$, the set of active constraints at $\mathbf{x}$ consists of the inequality constraints, if any, satisfied as equalities at $\mathbf{x}$.

Let B_k be an approximation of the Hessian of the Lagrangian function $\mathcal{H}\mathcal{L}(\mathbf{x}_k, \mathbf{u}_k, \mathbf{v}_k)$, and let $\mathbf{d}_x = \mathbf{x} - \mathbf{x}_k$. We can write the quadratic subproblem as:

$$\begin{aligned}
& \underset{\mathbf{d}_x}{\text{minimize}} && \nabla \mathcal{L}(\mathbf{x}_k, \mathbf{u}_k, \mathbf{v}_k)^T \mathbf{d}_x + \frac{1}{2} \mathbf{d}_x^T B_k \mathbf{d}_x \\
& \text{subject to:} && \nabla \mathbf{h}(\mathbf{x}_k)^T \mathbf{d}_x + \mathbf{h}(\mathbf{x}_k) = \mathbf{0} \\
& && \nabla \mathbf{g}(\mathbf{x}_k)^T \mathbf{d}_x + \mathbf{g}(\mathbf{x}_k) \leq \mathbf{0}.
\end{aligned} \tag{4.2}$$

In the problem of interest, the objective function to be minimized, $f(\mathbf{x})$, is the sum of the ΔV of the maneuvers required to reach the target orbit. This minimization must be performed while satisfying a set of operational and physical conditions, expressed as nonlinear inequality constraints in the standard form $\mathbf{g}(\mathbf{x}) \geq \mathbf{0}$. Specifically, these constraints are:

- **Orbital element accuracy:** The allowable relative error with respect to the target for each orbital element must not be exceeded.
- **Operational windows:** Maneuvers are restricted to be executed exclusively during the eclipse phases of the orbit and within predefined ranges of the Argument of Latitude.
- **Thruster capacity:** The magnitude of each individual maneuver (calculated as the vector norm of the tangential and normal thrust components) must remain strictly within the maximum capacity specified by the manufacturer.

The main challenge in formulating this problem lies in properly normalizing, scaling, and transforming all these heterogeneous conditions into a suitable mathematical framework.

4.1 Implementation Methodology

Considering a single batch of the first problem, an initial orbit and a target orbit are given, together with their associated epochs. The primary objective is to verify whether a finite-thrust maneuver planner can reproduce the orbital transfers solved using impulsive maneuvers, and to thoroughly analyze any resulting discrepancies.

Problem Constraints

It is worth summarizing the three fundamental pillars that govern the maneuver planner's logic:

- **Eclipse and Geometric Constraints:** The propulsion system can only be ignited when the spacecraft is within the Earth's shadow (eclipse) or within specific Argument of Latitude (AOL) ranges. This is the most restrictive operational constraint, designed to preserve the spacecraft's power balance and ensure optimal solar array pointing during non-thrusting phases.
- **Hardware Saturation Limits:** To prevent thermal degradation and system stress, a strict physical upper bound is imposed on the maximum duration of a single continuous burn (maximum Δt_{burn}). The planner must therefore manage the orbital error without exceeding the engine's operational capabilities.
- **Rigorous Maneuver Scheduling:** Spacecraft operations require incompressible physical delays. The planner accounts for thermal cooldowns ($t_{recovery}$) and attitude slew times (t_{prep}) between consecutive ignitions. Furthermore, an absolute deadline is enforced: every maneuver must be entirely completed safely before the current valid geometric window closes.

4.1.1 Simulation Core

The core of the simulation resides within the central scheduling algorithm, where maneuvers are evaluated, planned, and executed to reach the target orbit within the predefined operational window.

Since the first phase of the problem utilizes a DSST propagator, both the initial and target orbits are expressed in terms of mean Keplerian elements. However, the maneuver planner relies on a high-fidelity numerical propagator that naturally operates on osculating elements. To bridge this theoretical gap, a dedicated mathematical transformation routine is introduced, which accurately translates the instantaneous orbital state from mean to osculating elements and vice versa.

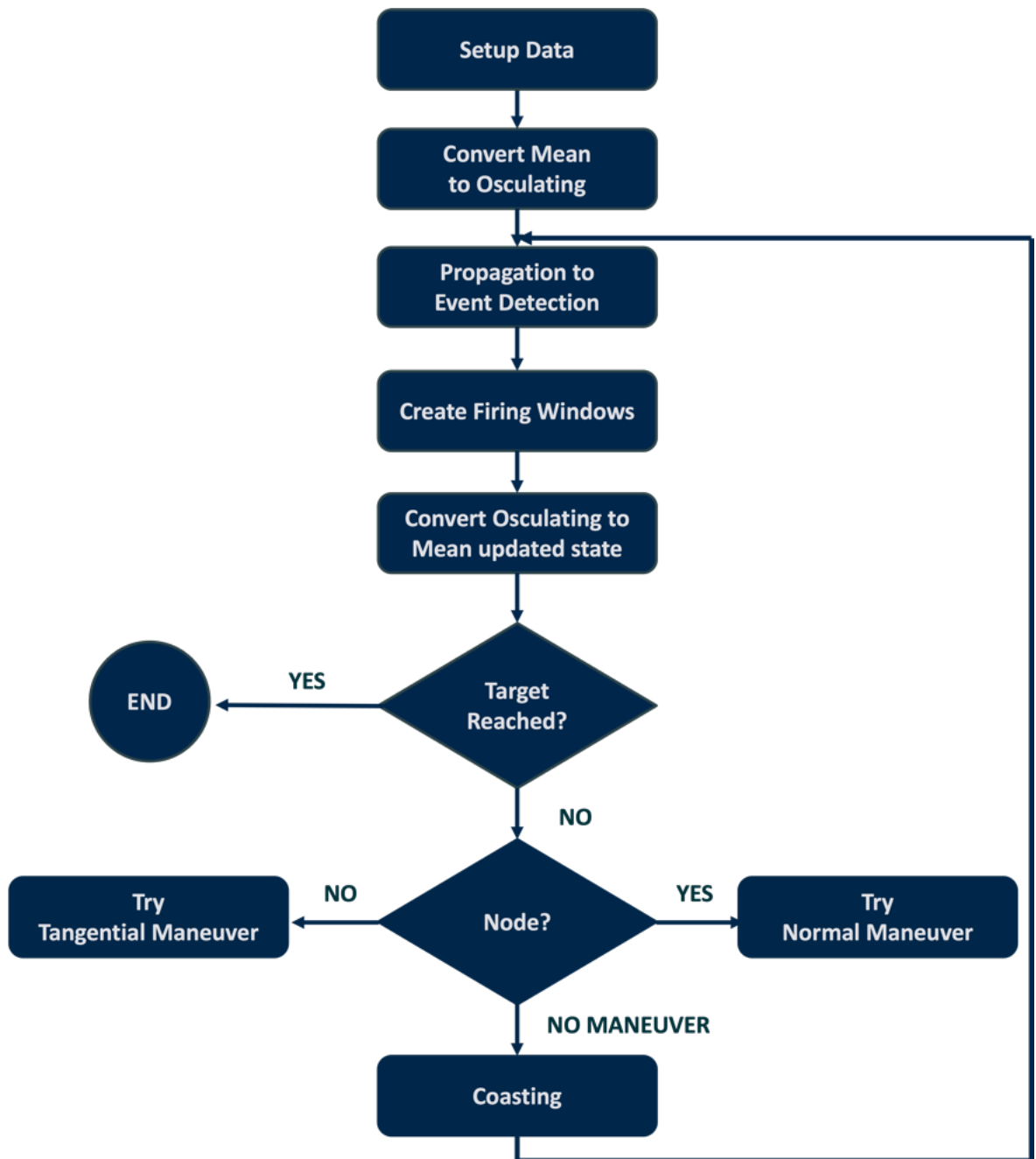


Figure 4.1: Evolution of the Semi-Major Axis (a) during Window 1.

Once the elements are converted into the osculating framework, the main simulation loop is initialized and remains active until the available operational window expires. At each iteration, an exploratory propagation is performed in order to detect relevant geometric events such as eclipses, AOL ranges, and orbital node crossings.

Dedicated event handlers are attached to the propagator, enabling the precise identification of these events along the trajectory. The detected events are subsequently processed by a dedicated firing window construction routine, which combines the geometric constraints to generate candidate maneuver execution intervals.

The exploratory propagation spans a duration equal to approximately 1.5 orbital periods of the target orbit. This ensures that the algorithm always captures the next valid maneuver opportunity immediately following the previously executed maneuver, while preventing missed events.

Once the candidate firing windows are generated, the planner sequentially evaluates each interval to determine whether a feasible maneuver can be scheduled within it. Windows whose duration is below a minimum operational threshold are automatically discarded, preventing the execution of excessively short burns that would be impractical from both propulsion and attitude-control perspectives.

To evaluate mission progress, the propagated osculating state is periodically converted back into mean orbital elements and compared with the target state. If the prescribed tolerances on the semi-major axis and inclination are satisfied, the control loop terminates and the simulation concludes.

To prevent the scheduling of multiple maneuvers within the same geometric opportunity, a logical execution flag is enforced within each iteration of the loop, ensuring that at most one maneuver is executed per detected window.

Out-of-Plane Maneuvers

If a valid firing window contains an orbital node, the algorithm evaluates the feasibility of performing an out-of-plane maneuver to correct the inclination. Since short and fragmented burns are propellant-inefficient, the system first estimates the normal velocity increment required to correct the inclination error. Assuming a near-circular orbit, this quantity can be approximated as

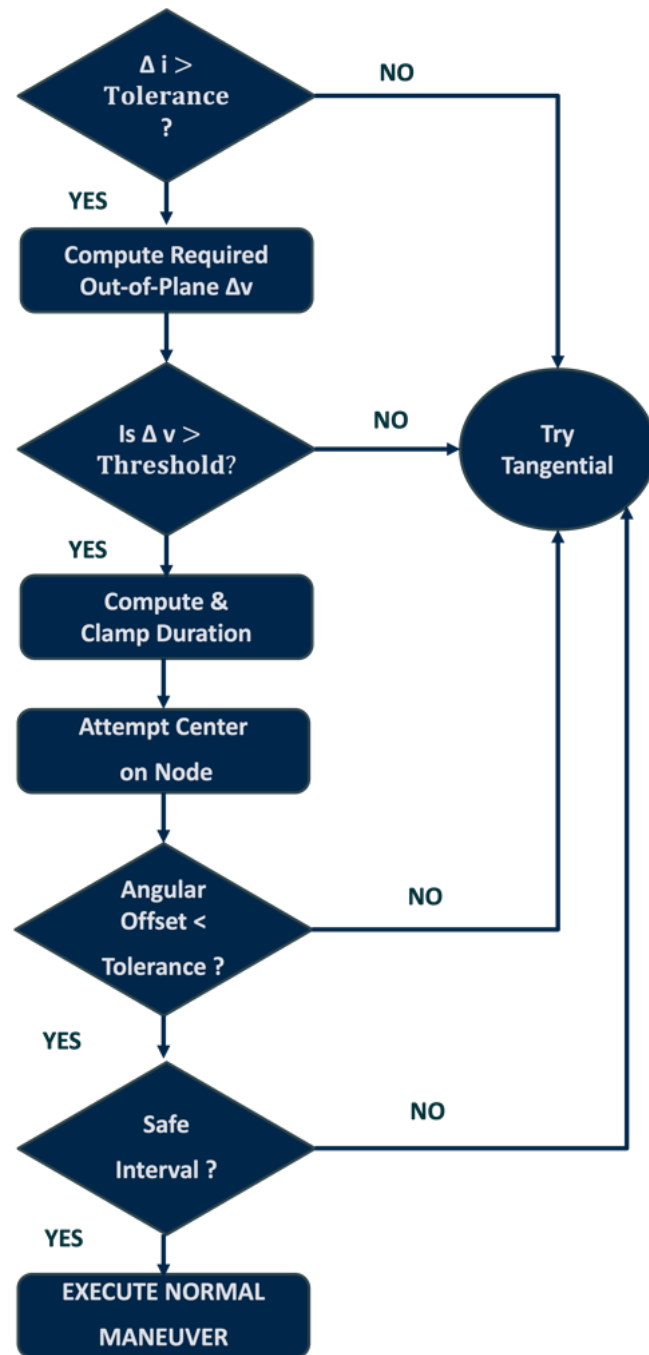


Figure 4.2: Evolution of the Semi-Major Axis (a) during Window 1.

$$\Delta V_{N,\text{req}} = (i_{\text{target}} - i_{\text{current}}) \sqrt{\frac{\mu_{\oplus}}{a_{\text{current}}}} \quad (4.3)$$

where:

- i_{target} is the target mean inclination,
- i_{current} is the current mean inclination,
- a_{current} is the current mean semi-major axis,
- $\mu_{\oplus}$ is the Earth's gravitational parameter.

A maneuver is considered only if the inclination error exceeds a predefined threshold, preventing unnecessary corrections for negligible deviations.

Once a candidate node is identified within the firing window, the algorithm determines the earliest physically feasible ignition time, considering propulsion system constraints such as thermal limits and re-ignition waiting intervals. The desired burn duration is then computed from the required $\Delta V_{N,\text{req}}$, using the current propulsion performance and spacecraft mass.

The actual maneuver duration is determined conservatively by selecting the minimum value among the following constraints:

1. **Ideal Duration:** The time required to fully correct the inclination error.
2. **Available Window Duration:** The residual time available before the firing window closes.
3. **Propulsion System Limits:** Maximum allowable burn duration imposed by hardware and thermal constraints.

If the available time inside the firing window is insufficient to execute a meaningful burn, the maneuver is skipped.

Normal maneuvers are theoretically optimal only when centered exactly on the line of nodes. However, operational constraints may prevent perfect alignment. To increase the number of usable opportunities, a sliding logic is implemented. The algorithm initially attempts to center the burn on the node crossing. If this is not possible due to window boundaries or propulsion constraints, the maneuver

is shifted within the firing window while maintaining the maximum possible proximity to the node.

To ensure acceptable efficiency, the angular displacement between the node and the actual center of the burn is evaluated through the corresponding shift in the AOL. If the displacement exceeds a small predefined tolerance, the maneuver is rejected. Once validated, the thrust direction is determined using a LVLH Local Orbital Frame. The thrust is applied purely along the normal axis ($\mathbf{K}$), with the sign determined by the node type and the required inclination correction:

- **Inclination Increase** ($\Delta i > 0$): Northward thrust ($+\mathbf{K}$) at the ascending node, or Southward thrust ($-\mathbf{K}$) at the descending node.
- **Inclination Decrease** ($\Delta i < 0$): Southward thrust ($-\mathbf{K}$) at the ascending node, or Northward thrust ($+\mathbf{K}$) at the descending node.

The ascending or descending branch of the orbit is identified dynamically by evaluating the vertical component of the inertial velocity vector (v_z) at the maneuver ignition epoch. A positive value ($v_z > 0$) indicates the ascending branch, while a negative value ($v_z < 0$) indicates the descending branch.

Finally, the propellant consumption and the achieved ΔV are evaluated using the Tsiolkovsky rocket equation, accounting for the spacecraft mass variation during the burn.

In-Plane Maneuvers

If the operational window does not contain an orbital node, or if no valid out-of-plane maneuver is scheduled, the algorithm evaluates the feasibility of an in-plane tangential maneuver. These maneuvers are primarily used to correct the semi-major axis while simultaneously shaping the eccentricity vector.

The required tangential velocity increment is first estimated as

$$\Delta V_{T,\text{req}} = (a_{\text{target}} - a_{\text{current}}) \frac{n}{2} \quad (4.4)$$

where n is the mean motion of the current orbit. A positive value corresponds to an orbit-raising maneuver, while a negative value results in a braking maneuver. In the LVLH frame, the thrust is therefore applied along the tangential axis $\mathbf{J}$:

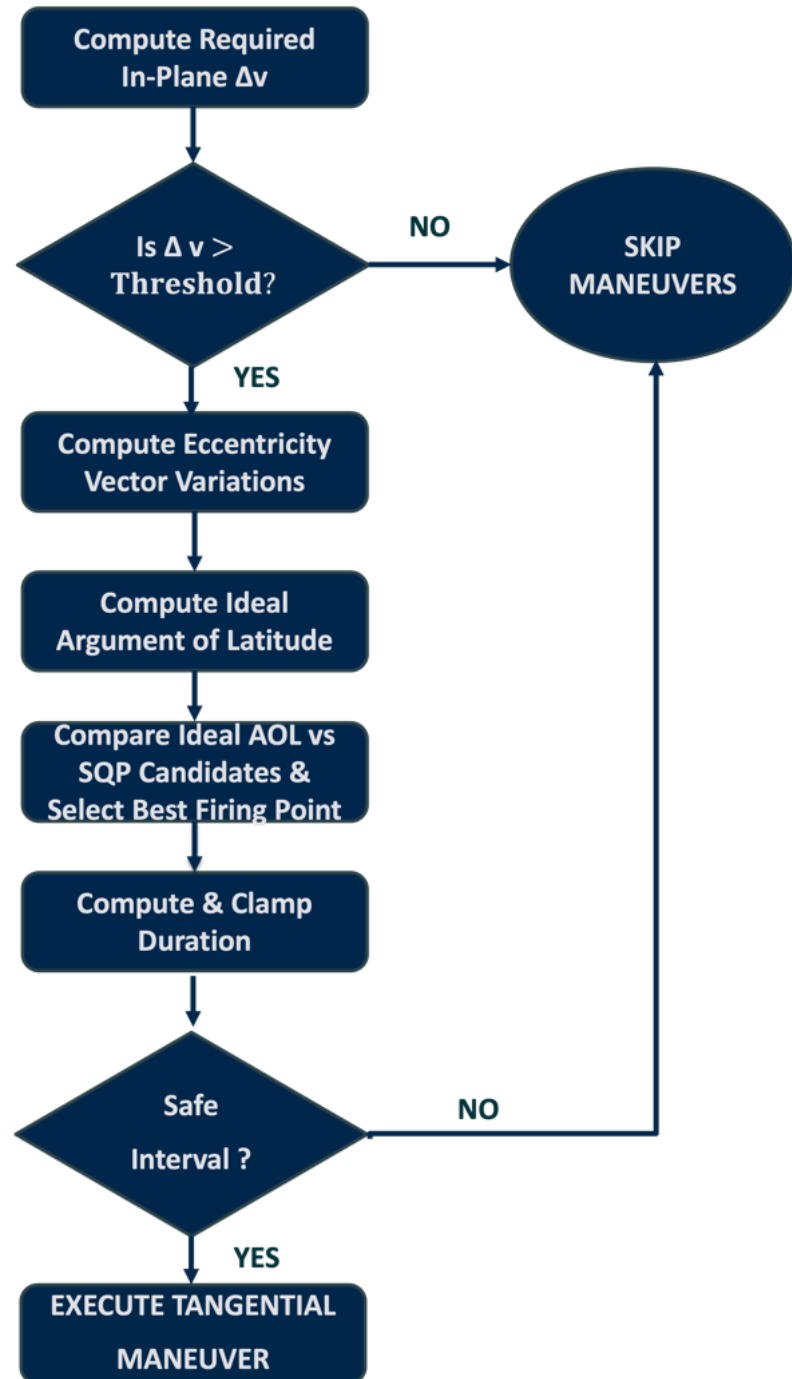


Figure 4.3: Evolution of the Semi-Major Axis (a) during Window 1.

- **Raising:** thrust in the $+\mathbf{J}$ direction.
- **Braking:** thrust in the $-\mathbf{J}$ direction.

To simultaneously manage the orbital shape, the algorithm also considers the evolution of the eccentricity vector. The current eccentricity components are obtained from the mean orbital elements as

$$e_{x,\text{current}} = e_{\text{current}} \cos(\omega_{\text{current}}) \quad (4.5)$$

$$e_{y,\text{current}} = e_{\text{current}} \sin(\omega_{\text{current}}) \quad (4.6)$$

where e_{current} is the magnitude of the mean eccentricity and ω_{current} is the argument of perigee. The target components are defined analogously, allowing the eccentricity error vector to be written as

$$\begin{cases} \Delta e_x = e_{x,\text{target}} - e_{x,\text{current}} \\ \Delta e_y = e_{y,\text{target}} - e_{y,\text{current}} \end{cases} \quad (4.7)$$

From this error vector, the algorithm derives the theoretically optimal Argument of Latitude for the maneuver:

$$u_{\text{opt}} = \text{atan2}(\text{sgn}(\Delta V_{T,\text{req}})\Delta e_y, \text{sgn}(\Delta V_{T,\text{req}})\Delta e_x) \quad (4.8)$$

This angle represents the geometrically ideal location for applying the tangential thrust in order to simultaneously correct the semi-major axis and drive the eccentricity vector toward its target value.

Rather than enforcing execution exactly at u_{opt} , which may not coincide with the available firing window, the algorithm compares this ideal direction with two predefined candidate AOL locations supplied by the external SQP optimization module. The candidate whose angular distance from u_{opt} is smallest is selected as the preferred maneuver location.

A strict geometric validation is then performed. If the selected candidate lies outside the currently open firing window, the maneuver center is clamped to the closest point of the window. The angular displacement between the desired candidate and the clamped point is evaluated, and if this shift exceeds a predefined

tolerance, the maneuver opportunity is rejected in order to avoid inefficient burns.

If the geometric constraints are satisfied, the algorithm proceeds with the temporal feasibility analysis. The earliest physically allowed ignition time is computed considering propulsion system constraints such as cooling intervals and minimum re-ignition times. The maneuver duration is then determined by selecting the minimum value among:

1. the duration required to deliver the desired ΔV ,
2. the remaining time available inside the firing window,
3. the propulsion system operational limits.

Finally, the maneuver is centered around the selected Argument of Latitude whenever possible. If the ideal centering would violate the temporal boundaries of the firing window, a time-clamping procedure shifts the burn start while preserving the largest possible alignment with the target geometry.

Once all constraints are satisfied, the finite burn is injected into the numerical propagator, and the resulting ΔV and propellant consumption are evaluated through the Tsiolkovsky rocket equation. The propagation then continues with a short post-maneuver stabilization phase before the planner resumes the search for subsequent maneuver opportunities.

4.1.2 Firing Windows

Orbital maneuvers are allowed only within specific AOL ranges or under prescribed illumination conditions (sunlight or eclipse). One of the primary reasons for executing operations during eclipse phases is that the spacecraft's solar array configuration does not yield a favorable solar aspect angle while in the firing attitude. Consequently, performing a thrust maneuver in sunlight would merely reduce the optimal sun-pointing duration without facilitating battery recharge or allowing for an extended firing duration.

To identify the orbital intervals during which the spacecraft is not illuminated by the Sun, the software leverages Orekit's native *Detector* mechanism. This approach relies on the continuous monitoring of a switching function $g(t)$ during

numerical integration. The architecture is composed of two elements: the physical detector and the logical customized handler.

Eclipse Detector Configuration

The event detection mechanism is established by defining the geometry of the occultation problem. The detection logic is specifically configured to trigger events based on the total shadow cone (umbra). Mathematically, a switching function $g(t)$ is formulated such that it yields a positive value when the spacecraft is fully illuminated or in penumbra, and a negative value when it is strictly inside the umbra.

A dedicated event-handling routine is implemented to act as a passive observer. Instead of interrupting the numerical propagation upon event detection, it simply records the relevant orbital data and allows the simulation to proceed continuously.

To ensure robustness, an initialization sequence evaluates the switching function at the beginning of the propagation. This manages the edge case where the simulation starts with the spacecraft already inside an eclipse region. By assessing the initial sign of the switching function, the system sets an internal flag that enables the post-processing algorithm to correctly determine whether the first recorded boundary crossing corresponds to an exit from or an entry into the shadow.

Whenever the switching function $g(t)$ crosses zero, an event is triggered, and the following key parameters are stored:

1. **Relative Time:** The elapsed time since the reference epoch t_{ref} at the start of the propagation window.
2. **Orbital Position (AOL):** The instantaneous spacecraft state is converted into a circular orbital formulation to accurately extract the Argument of Latitude.
3. **Crossing Direction:** The slope of the switching function $g(t)$ at the zero-crossing is evaluated to identify the nature of the transition. For eclipse detection specifically:
 - *Decreasing slope:* Transition from light to shadow (eclipse entry).

- *Increasing slope*: Transition from shadow to light (eclipse exit).

This passive event-logging architecture is applied not only to eclipse conditions but also to the detection of specific AOL ranges and orbital nodes. The aggregated data allows for the construction of a highly accurate map of operational windows along the entire propagated trajectory, which the algorithm subsequently uses to rigorously enforce the physical constraints on maneuver execution.

AOL Detector Configuration

In addition to eclipses, the maneuvering strategy requires the definition of operational windows based on the spacecraft's geometric position along the orbit. Since the considered orbits may be nearly circular, the use of angular parameters such as the True Anomaly (ν) or the Mean Anomaly (M) may become ambiguous, as the argument of perigee is ill-defined in low-eccentricity conditions. For this reason, a custom detector has been developed based on the Argument of Latitude (AOL) ($u = \omega + \nu$), which provides a non-singular angular parametrization along the orbit.

The main challenge in creating an Orekit detector lies in defining a continuous switching function $g(u)$ that changes sign exactly at the boundaries of the interval of interest $[u_{start}, u_{end}]$. The implemented class adopts a quadratic (parabolic) function of the form:

$$g(u) = \sigma \cdot (u - u_{start}) \cdot (u - u_{end}) \quad (4.9)$$

where:

- u is the current spacecraft AOL, normalized in the interval $[0, 2\pi]$;
- σ is a sign correction factor computed in the constructor to handle angular wrap-around at $0^\circ/360^\circ$ (e.g., an arc starting at 350° and ending at 10°).

This mathematical formulation ensures that $g(u)$ has two roots exactly at the start and end angles of the arc. The interpretation of the crossing direction (*slope*) is fundamental for event identification:

- *Increasing*: the function transitions from negative to positive values, indicating entry into the valid maneuver arc.

- *Decreasing*: the function transitions from positive to negative values, indicating exit from the arc.

In this way the numerical integrator can therefore detect zero crossings with arbitrary precision, triggering the correct events.

Construction of Firing Windows

Following a preliminary numerical propagation, after which the spacecraft state is immediately reset to its initial condition to serve merely as a predictive sweep, the recorded discrete events are processed to construct continuous time intervals during which maneuvers are permitted.

The algorithm operates in three sequential phases:

- **Interval Reconstruction:** The detected orbital events are inherently discrete, corresponding strictly to the zero-crossing timestamps of the switching functions. The algorithm's primary task is to convert these discrete timestamps into continuous time intervals. A significant challenge in this phase is the correct handling of the boundary conditions: if the simulation begins while the spacecraft is already inside a region of interest (e.g., already in eclipse or within a valid AOL range), no explicit "entry" event will be recorded at the initial epoch. The logic infers the true initial state by evaluating the sign of the switching function at the start of the propagation and coupling it with the slope of the first recorded crossing. This ensures that no valid operational window is lost or incorrectly truncated at the simulation boundaries.
- **Opportunity Aggregation:** In accordance with the mission requirements discussed previously, both geometrically constrained windows (AOL ranges) and eclipse phases constitute valid opportunities for maneuver execution. These disparate intervals are aggregated into a unified timeline and processed through a consolidation routine. If two valid windows overlap or are strictly adjacent, they are merged into a single, continuous maneuver block. This consolidation prevents unnecessary fragmentation of the timeline, which would otherwise complicate the subsequent simulation stages. Naturally,

intervals that are strictly separated in time are maintained as distinct and independent maneuver opportunities.

- **Classification (Type Assignment):** Finally, each reconstructed time window is analyzed to determine the optimal type of maneuver that can be executed within its bounds. The algorithm cross-references the maneuver windows with the recorded orbital node crossing events. If a window encompasses an orbital node, it is classified as suitable for out-of-plane (normal) maneuvers, which are physically efficient only in these specific locations. Conversely, if no node is present within the interval, the window is designated strictly for in-plane (tangential) maneuvers.

4.1.3 Maneuver Scheduling and Waiting Constraints

The enforcement of required waiting times between maneuvers is not treated as a simple fixed delay, but is formulated as a *constrained scheduling problem*. The objective of this routine is to determine whether a feasible time interval exists in which the orbital geometry (e.g., node crossing, eclipse) and the spacecraft operational readiness favorably intersect.

The decision algorithm implements a temporal set intersection logic that can be decomposed into three distinct phases: computation of maneuver-dependent setup times, projection of absolute operational deadlines, and resolution of the resulting Min–Max intersection.

The waiting time required between two consecutive maneuvers ($k - 1$ and k) depends on the specific sequence of operations. The algorithm first evaluates the maneuver-dependent technical waiting interval, composed of two operational contributions:

$$\Delta t_{tech}^{min} = t_{recovery,min}^{(k-1)} + t_{prep,min}^{(k)} \quad (4.10)$$

where:

- $t_{recovery}$ represents the recovery time required after the previous maneuver (e.g., propulsion thermal cooldown or power system stabilization).
- t_{prep} represents the preparation time required before the next maneuver (e.g.,

attitude slew maneuver, actuator settling, sensor stabilization).

In practical spacecraft operations, both quantities may also define an upper operational bound, producing a maximum allowable waiting time

$$\Delta t_{tech}^{max} = t_{recovery,max}^{(k-1)} + t_{prep,max}^{(k)} \quad (4.11)$$

To guarantee safe spacecraft operation and prevent propulsion duty-cycle violations, a global safety constraint t_{duty} is introduced as a lower bound on the waiting time.

The earliest instant at which the spacecraft can physically ignite the thruster again is therefore

$$t_{ready} = t_{end}^{(k-1)} + \max(\Delta t_{tech}^{min}, t_{duty}) \quad (4.12)$$

while the latest acceptable ignition time imposed by the maneuver-dependent timeout constraint is

$$t_{timeout} = t_{end}^{(k-1)} + \Delta t_{tech}^{max} \quad (4.13)$$

Once the spacecraft readiness bounds are determined, these temporal constraints are projected onto the absolute timeline of the geometric maneuver opportunity window

$$[w_{start}, w_{end}]$$

which represents the time interval in which the orbital geometry allows the maneuver to be executed.

A critical operational requirement concerns the finite duration of the maneuver, Δt_{burn} . It is not sufficient for the maneuver to start within the geometric window; the burn must also be fully completed before the window closes. The latest valid ignition epoch is therefore computed as

$$w_{deadline} = w_{end} - \Delta t_{burn} \quad (4.14)$$

Note on Maneuver Duration: The parameter Δt_{burn} is dynamically validated by a dedicated constraint function prior to scheduling. This ensures

that the requested burn duration respects the physical saturation limits of the propulsion system, preventing hardware degradation or overheating based on the current spacecraft mass and propulsion characteristics.

The valid operational interval for maneuver ignition is obtained by solving the following Min–Max temporal intersection problem:

1. Start Time Determination (t_{start}^*)

Ignition can occur only once both the geometric window is open and the spacecraft has completed all preparation phases:

$$t_{start}^* = \max(w_{start}, t_{ready}) \quad (4.15)$$

2. End Time Determination (t_{end}^*)

The opportunity to initiate the burn ends at the earliest of two strict limits: the closure of the geometric window adjusted for maneuver duration, or the operational timeout associated with the maneuver sequence:

$$t_{end}^* = \min(w_{deadline}, t_{timeout}) \quad (4.16)$$

3. Feasibility Check

The maneuver is feasible if and only if a valid temporal intersection exists between the readiness interval and the geometric window:

$$\text{isFeasible} \iff t_{start}^* \leq t_{end}^* \quad (4.17)$$

If this inequality evaluates to false, the spacecraft becomes ready too late to execute the burn within the current opportunity window. In this case, the maneuver is marked as infeasible and the planner automatically defers execution to the next available orbital opportunity.

Numerical Examples of Scheduling Logic

To illustrate the practical behavior of the temporal intersection logic, two demonstrative operational scenarios are presented.

Scenario A: Complex Transition (Feasible) In this scenario, the spacecraft must perform a normal maneuver (plane change) immediately after an in-plane orbit-raising burn. This transition demands a significant attitude reorientation (slew maneuver), which dominates the scheduling constraints.

Initial Conditions ($t = 0$ set at $t_{end}^{(k-1)}$):

- **Transition:** Raising $\rightarrow$ Normal.
- **Burn Duration** (Δt_{burn}): 120 s.
- **Constraints:**
 - $t_{recovery}$ (Thermal cooldown): 60 s.
 - t_{prep} (Attitude slew and settling): 540 s.
 - t_{duty} (Minimum duty cycle rest): 300 s.
- **Geometry** ($[w_{start}, w_{end}]$): The orbital node is accessible between $t = 400$ s and $t = 1000$ s.

Algorithm Execution:

1. Readiness Calculation:

$$\begin{aligned}\Delta t_{tech} &= 60 + 540 = 600 \text{ s} \\ t_{ready} &= 0 + \max(600, 300) = \mathbf{600} \text{ s}\end{aligned}$$

The satellite completes preparations at $t = 600$. Note that while the geometric window opened earlier at $t = 400$, the system was unavailable due to ongoing attitude control operations.

2. Deadline Projection:

$$w_{deadline} = 1000 - 120 = \mathbf{880} \text{ s}$$

Igniting the thruster after $t = 880$ would result in the burn continuing outside the permitted orbital node limits.

3. Intersection:

$$t_{start}^* = \max(400, 600) = 600 \text{ s}$$

$$t_{end}^* = \min(880, \infty) = 880 \text{ s}$$

Since $600 \leq 880$, the maneuver evaluates as **FEASIBLE** and is cleared for execution within the interval $[600, 880]$ s.

Scenario B: Violation of Duration Constraint (Infeasible) Here, a secondary raising maneuver is requested during a brief perigee pass. Although the spacecraft prepares quickly, the geometric window closes before the full burn can be accommodated.

Initial Conditions:

- **Transition:** Raising $\rightarrow$ Raising.
- **Burn Duration** (Δt_{burn}): 250 s.
- **Constraints:**
 - Setup time (Δt_{tech}): 100 s.
 - Minimum rest (t_{duty}): 400 s.
- **Geometry:** Short visibility window at $[300 \text{ s}, 600 \text{ s}]$.

Algorithm Execution:

1. Readiness Calculation:

$$t_{ready} = 0 + \max(100, 400) = \mathbf{400 \text{ s}}$$

The waiting time is strictly bounded by the hardware duty cycle constraint (e.g., battery recharge time).

2. Deadline Projection:

$$w_{deadline} = 600 - 250 = \mathbf{350 \text{ s}}$$

To finish before the window closes at $t = 600$, the engine must ignite no later than $t = 350$.

3. Intersection:

$$t_{start}^* = \max(300, 400) = 400 \text{ s}$$

$$t_{end}^* = 350 \text{ s}$$

Since t_{start}^* (400) is strictly greater than t_{end}^* (350), the feasibility check evaluates to **FALSE**.

Result: The maneuver is **INFEASIBLE** for the current window and is successfully intercepted and skipped by the planner.

4.1.4 Numerical Propagator

The simulation of the orbital dynamics is performed using a numerical propagator, which solves the equations of motion by numerically integrating the accelerations acting on the spacecraft. The core of this propagation relies on an ODE integrator configured with an adaptive step-size strategy. This architectural choice is essential to dynamically balance computational accuracy and execution time, ensuring strict error control especially in scenarios characterized by highly non-linear, time-varying perturbations.

4.1.5 Implementation of Force Models

The fidelity of an orbital simulation strongly depends on the accurate modeling of the accelerations acting on the spacecraft. The implementation strategy adopted for each of the main perturbations discussed in the previous chapter is detailed below.

Non-Spherical Gravitational Field

To model the Earth's non-spherical gravity field, the simulation architecture loads fully normalized spherical harmonic coefficients up to a user-configured degree and order (n,m).

The permanent tide system (e.g., Tide-Free or Zero-Tide) is intrinsically defined by the selected gravity model dataset and is rigorously preserved by the simulation without additional transformations. The distinction between permanent tide systems is rooted in geodetic conventions and relies on the nominal Love numbers of the Earth¹, as defined in the International Earth Rotation and Reference Systems Service (IERS) 2010 [21].

The computation of the geopotential acceleration relies on the Holmes–Featherstone algorithm. This specific mathematical formulation is selected to ensure numerical robustness for high-degree gravity field expansions. By employing a stable recursive evaluation of fully normalized associated Legendre functions, the algorithm effectively mitigates numerical underflow and overflow issues that typically arise in classical implementations at high degrees [22].

Geometrically, the gravity field is defined in an Earth-fixed reference frame corresponding to the ITRF, consistent with the IERS 2010 conventions and based on a CIO transformation paradigm. The simulation algorithm automatically handles the necessary frame transformations between the inertial propagation frame and the rotating Earth-fixed frame at each integration step, ensuring a dynamically consistent evaluation of the geopotential.

For the definition of the central body’s geometry, a reference ellipsoid based on WGS84 parameters is adopted, encompassing the equatorial radius, flattening, and nominal angular velocity. This guarantees perfect geometric consistency across all perturbation models (such as drag and solar radiation pressure) that depend on the Earth’s shape.

Regarding non-static effects, time-varying perturbations related to the solid crust, oceans, and poles are suppressed to reduce the computational burden. Consequently, the logic evaluates only the static geopotential, consistent with the selected permanent tide convention.

¹Love numbers, named after the British mathematician A.,E.,H. Love, are dimensionless parameters that quantify a planetary body’s rigidity and its susceptibility to deformation under tidal forces. In particular, the second-degree potential Love number k_2 characterizes the variation in the Earth’s external gravitational potential induced by tidal mass redistribution. It provides the theoretical basis for the permanent tide corrections applied to the spherical harmonic coefficients in geopotential models.

Third-Body Gravitational Attraction

To model the gravitational influence of external celestial bodies, primarily the Sun and the Moon, the simulation adopts a dynamic approach based on a configurable list of perturbing masses. For each requested celestial body, the algorithm retrieves precise astronomical ephemerides, specifically the time-varying position and velocity vectors relative to the central body.

At each numerical integration step, the dynamic model computes the differential gravitational acceleration exerted by the third body on the spacecraft with respect to the Earth. This formulation continuously updates the relative geometry between the central body, the satellite, and the external masses, effectively solving the perturbed N-body problem and integrating these external forces into the spacecraft's equations of motion.

Atmospheric Drag

Following the theoretical formulation of the Harris–Priester model, the simulation translates these physical principles into a robust computational architecture. The construction of the aerodynamic drag force relies on the combination of three distinct modeling layers: the spacecraft aerodynamic representation, the Earth shape model, and the atmospheric physics.

First, the interaction between the spacecraft and the atmospheric flow adopts an isotropic spherical approximation, commonly referred to as the *cannonball model*. This representation is characterized by a constant drag coefficient (C_D) and a fixed effective cross-sectional area irrespective of the spacecraft's instantaneous attitude. This conceptual abstraction successfully decouples the vehicle's aerodynamic sensitivity from the underlying atmospheric density formulation.

A critical aspect of the physical implementation is the integration of the Earth's geometric model. An oblate spheroid formulation, configured with the equatorial radius and the flattening of the central body, provides the precise reference surface for the atmosphere generator. This step is strictly necessary because the atmospheric density is intrinsically a function of the *geodetic altitude*, rather than the simple geocentric radius. By rigorously referencing the ellipsoidal Earth model, the density estimation properly accounts for planetary oblateness, ensuring accurate predictions across different latitudes, particularly highlighting

the gradient between polar and equatorial regions.

Furthermore, the solar ephemerides are continuously evaluated to allow the Harris–Priester atmospheric model to dynamically compute the position of the apex of the *diurnal bulge* (the localized atmospheric expansion due to solar heating) with respect to the spacecraft’s instantaneous position.

Finally, these fundamental components are mathematically aggregated to compute the instantaneous perturbing acceleration vector at each numerical integration step. The dynamic algorithm combines the local atmospheric density with the spacecraft’s ballistic coefficient, applying the resulting aerodynamic force strictly opposite to the spacecraft’s velocity vector relative to the co-rotating atmosphere.

Solar Radiation Pressure (SRP)

Similarly to the atmospheric drag implementation, the SRP model is constructed by coupling the physical properties of the spacecraft with the celestial geometry of the radiation source, the target body, and the occulting body.

The interaction between the solar photon flux and the spacecraft surfaces is modeled using an isotropic radiation approach. This formulation assumes a spherical spacecraft geometry with a fixed effective cross-sectional area and a single global reflectivity coefficient (C_R), which consolidates both specular and diffuse reflection components. This isotropic assumption implies that the effective area exposed to the Sun remains constant regardless of the spacecraft’s instantaneous attitude.

A crucial physical feature of the SRP model is the rigorous geometric representation of the Earth as an occulting body. Instead of treating the central body as a point mass or a perfect sphere, the simulation employs an oblate spheroid model. This precise geometric formulation allows the propagation algorithm to dynamically compute the *shadow function* (or illumination ratio) at each integration step. Consequently, the simulator accurately determines the satellite’s entry and exit times across the umbra and penumbra regions, automatically attenuating or entirely nullifying the SRP force during eclipse phases.

Ultimately, the dynamic model integrates the Sun as the photon source, the oblate Earth as the occulting body, and the spacecraft as a radiation-sensitive

target. This synthesis ensures that the computed perturbing acceleration vector remains strictly consistent with the instantaneous relative geometry of the Sun–Earth–spacecraft system throughout the propagation.

Chapter 5

Simulations results

One test result is worth one thousand expert opinions.

Wernher von Braun

The following chapter presents the results obtained for the phasing of a LEO satellite on a sun-synchronous orbit. The problem has been divided into 32 maneuver windows, each consisting of 28 orbits, spanning a timeframe from February 1st to March 31st, 2026. All orbits are defined with respect to the TOD reference frame. To comply with the mission analysis constraints, maneuvers will be executed exclusively during eclipse periods.

Furthermore, since the satellite operates in a Sun-Synchronous Orbit (SSO), it is particularly interesting to note the constant geometry of the illumination conditions: the eclipse phase consistently encompasses one of the two orbital nodes. This specific geometric property is highly advantageous, as it guarantees that out-of-plane maneuvers (which must be performed at the nodes to efficiently correct the inclination) can always be executed without violating the strict eclipse firing constraint.

The resolution of the problem via the SQP optimizer provides several baseline parameters for each window: the initial and target orbits, the tangential and normal ΔV components, and the AOL at which the equivalent impulsive maneuver, which conceptually encapsulates the cumulative effect of all the finite burns performed

over the 28 orbits, is located.

Given the intrinsic physical differences between the impulsive mathematical approach and the realistic finite-burn model, and considering that the SQP solver yields a locally optimal solution, the high-fidelity results generated by our numerical simulation will be extensively compared against this theoretical baseline.

The key mission parameters, operational constraints, numerical integrator settings, and the physical parameters of the spacecraft employed in the simulation are detailed in the subsequent tables.

Table 5.1: Numerical Integrator Configuration.

Parameter	Value
Integrator Type	Dormand-Prince 8(5,3)
Min Integration Step (Δt_{min})	0.001 <i>s</i>
Max Integration Step (Δt_{max})	300.0 <i>s</i>
Position Error Tolerance	1.0 <i>m</i>

Table 5.2: Operational Constraints on Maneuver Duration.

Maneuver Type	Max Duration [s]
Raising (In-Plane)	1200.0
Braking (In-Plane)	1200.0
Out-of-Plane (Normal)	1200.0

Table 5.3: Force Model and Spacecraft Physical Parameters.

Parameter	Value / Model
<i>Gravitational Forces</i>	
Geopotential Degree (n)	2
Geopotential Order (m)	0
Third Bodies	Sun, Moon
<i>Atmospheric Drag</i>	
Drag Coefficient (C_D)	2.2
Cross-Sectional Area (A_{drag})	3.6 m^2
<i>Solar Radiation Pressure</i>	
Reflection Coefficient (C_R)	1.5
Cross-Sectional Area (A_{SRP})	3.6 m^2
<i>Spacecraft & Propulsion</i>	
Satellite Mass (m)	235.0 kg
Thrust (T)	0.016 N
Specific Impulse (I_{sp})	1200 s

Table 5.4: Maneuver Waiting Time Constraints configured in the planner.

Maneuver Type	Min Before [s]	Max Before [s]	Min After [s]	Max After [s]
Raising	1000.0	1200.0	1000.0	1200.0
Braking	1000.0	1200.0	1000.0	1200.0
Out-of-Plane	1300.0	1500.0	1300.0	1500.0

Note: Extended Re-ignition Interval is set to **3600.0 s**.

Consistent with the problem's formulation and the algorithmic design of

the maneuver planner, a distinct operational pattern emerges and systematically repeats across all 32 maneuver windows.

Because the spacecraft starts relatively far from the target state at the beginning of each window, both the tangential (in-plane) and normal (out-of-plane) corrections initially operate in a saturation regime. During this phase, the planner commands the maximum allowed burn duration (1200 s) to maximize the rate of error reduction. As the orbital discrepancies decrease and the satellite approaches the desired target, the algorithm naturally transitions into a trimming phase. It begins to execute significantly shorter, high-precision burns to safely stabilize the orbit. A critical observation arises regarding the spatial execution of tangential maneuvers. During the long, saturated burns, the thrust spans a wide orbital arc (approximately 20 minutes of flight). Consequently, it is often geometrically impossible to perfectly center the maneuver on the ideal AOL dictated by the SQP without violating the boundaries of the available operational window (e.g., the eclipse condition). The algorithm handles this by clamping the maneuver within the allowable limits, resulting in a slight offset from the ideal center. Conversely, during the shorter trimming burns, the finite-burn model closely approximates an impulsive maneuver, allowing the planner to execute the thrust exactly at the optimal AOL and maximizing the eccentricity correction efficiency.

Finally, the normal maneuvers exhibit absolute structural consistency: to decrease the inclination while strictly adhering to the "eclipse-only" firing constraint, the out-of-plane burns are systematically and correctly executed at the descending node ($\text{AOL} \approx 180^\circ$). This confirms that the planner flawlessly handles the geometric constraints of the SSO environment throughout the entire mission timeline.

Regarding the evolution of the semi-major axis, the maneuver campaign can be structurally divided into three macroscopic phases.

During the initial maneuver windows, the orbital strategy is characterized by a rapid ascent phase. In this stage, the target semi-major axis experiences substantial increases of approximately 1.0 to 1.2 km between consecutive windows, requiring exclusively raising maneuvers.

However, starting from Window 9, the mission profile undergoes a significant strategic shift. The algorithm begins to command braking maneuvers. Throughout

this central portion of the campaign, the semi-major axis variations stabilize at a more moderate average magnitude of approximately 500 m per window. This interplay of raising and braking burns is crucial for tracking the precise phase and eccentricity targets dictated by the optimizer.

Concurrently with these in-plane variations, the orbital inclination strictly follows the previously discussed monotonically decreasing trend, ensuring that the necessary Sun-Synchronous conditions are continuously preserved.

Finally, the concluding maneuver windows of the simulation present a highly demanding scenario. The mission profile dictates very large variations in the target semi-major axis (exceeding 2.5 km in the final stages). Consequently, the spacecraft is compelled to execute high-intensity, saturated maneuvers to bridge this significant gap and achieve the final designated mission orbit.

The evaluation of the required ΔV firmly demonstrates the high fidelity of the simulation. The cumulative ΔV values obtained from our simulation are extremely close to the theoretical estimations provided by the SQP optimizer, being at most only slightly higher.

This minor, systematic discrepancy is a direct consequence of the fundamental differences in the modeling approaches. While the initial optimization problem assumes mathematically ideal, impulsive maneuvers, our simulation employs a rigorous numerical propagator combined with a finite-duration continuous thrust model.

When dealing with finite maneuvers executed by a low-thrust propulsion system, it is physically necessary to account for the inherent execution losses. As the engine fires continuously for extended periods, the spacecraft travels along a significant orbital arc, moving away from the mathematically optimal ignition point. This geometric deviation inevitably introduces *gravity losses* and steering inefficiencies, requiring the spacecraft to expend a slightly higher ΔV to achieve the same orbital correction compared to an ideal impulsive burn. Therefore, the slightly higher ΔV consumption is not an algorithmic error, but rather the validation of a highly realistic operational model.

The evolution of the eccentricity magnitude (e) exhibits a distinct, non-monotonic profile that perfectly complements the semi-major axis strategy to solve the phasing problem.

As observed in the data, during the first two windows, the target eccentricity

undergoes a slight decrease. This is immediately followed by a prolonged phase of continuous eccentricity build-up, reaching its peak magnitude during the central portion of the mission campaign (around Windows 20-22). Finally, in the concluding maneuver windows (Windows 29-32), a drastic and rapid reduction of the eccentricity is commanded, dropping the value to its absolute minimum by the end of the simulation.

The high-fidelity simulation flawlessly tracks this complex eccentricity profile. As documented in the residual error tables, the final discrepancies on the eccentricity vector components (Δe_x and Δe_y) consistently remain in the order of 10^{-5} or 10^{-6} across all windows. This confirms the extreme accuracy of the tangential firing logic and proves that the sliding and clamping mechanisms implemented in the maneuver planner successfully maximize the eccentricity correction efficiency, even during saturated burns.

The error in the RAAN consistently manifests as a tightly bounded, negative value (averaging approximately -0.001°). In a Sun-Synchronous Orbit, the nodal line is subject to a continuous secular precession ($\dot{\Omega}$) driven by the Earth's oblateness (J_2 harmonic). Nevertheless, an accumulated error of 10^{-3} degrees over weeks of operation is virtually negligible, confirming the excellent preservation of the required SSO sun-illumination geometry.

Conversely, the individual residual errors for the Argument of Perigee and the True Anomaly display higher magnitudes and variance. This phenomenon is a well-known mathematical artifact of near-circular orbits. Since the eccentricity of the target orbit is strictly maintained in the 10^{-3} regime, the orbit's geometry approaches a perfect circle. In this configuration, the physical location of the perigee (and consequently the line of apsides) becomes mathematically ill-defined (singularity as $e \rightarrow 0$). Consequently, even microscopic discrepancies in the eccentricity vector components (e_x, e_y) translate into large, highly sensitive angular displacements in ω and, symmetrically, in ν .

5.1 Window 1

Table 5.5: Window 1

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-02-01T00:00:00	2026-02-02T19:38:30	2026-02-02T19:38:30
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 812 284.284 m	6 813 876.428 m	6 813 854.647 m
Eccentricity	e	0.002204	0.002126	0.002123
Inclination	i	97.4064°	97.4049°	97.4049°
Arg. of Perigee	ω	270.0000°	254.4567°	255.0747°
RAAN	Ω	0.0000°	1.8537°	1.8522°
True Anomaly	ν	0.0000°	28.4273°	29.8506°

Table 5.6: Target State Errors Summary - Window 1

Parameter	Symbol	Error
Semi-Major Axis	Δa	−21.780 m
Inclination	Δi	0.000037°
Eccentricity X	Δe_x	0.000023
Eccentricity Y	Δe_y	−0.000003
RAAN	$\Delta \Omega$	−0.001482°
Arg. of Perigee	$\Delta \omega$	0.618°
True Anomaly	$\Delta \nu$	1.423°
Arg. of Latitude	Δu	2.041°

SIMULATIONS RESULTS

Table 5.7: Normal Maneuvers Summary - Window 1. SQP ΔV : 0.288677 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL ($^\circ$)	Thrust Z
2026-02-01 00:59:31	2026-02-01 01:19:31	1200.00	0.081702	0.081702	180.147	1.0
2026-02-01 02:32:54	2026-02-01 02:52:54	1200.00	0.081703	0.163405	180.147	1.0
2026-02-01 04:09:58	2026-02-01 04:22:36	758.12	0.051617	0.215023	180.147	1.0
2026-02-01 12:01:15	2026-02-01 12:05:12	237.63	0.016180	0.231202	180.147	1.0
2026-02-01 19:48:17	2026-02-01 19:52:08	231.15	0.015739	0.246942	180.147	1.0
2026-02-02 03:35:18	2026-02-02 03:39:12	234.72	0.015982	0.262924	180.147	1.0
2026-02-02 11:22:24	2026-02-02 11:26:15	230.88	0.015722	0.278646	180.147	1.0
2026-02-02 19:09:29	2026-02-02 19:13:20	230.87	0.015721	0.294366	180.147	1.0

Table 5.8: Tangential Maneuvers Summary - Window 1. SQP AOL: 159.57° , v_{Tan} SQP: 1.21 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]
2026-02-01 05:34:17	2026-02-01 05:54:17	1200.0	RAISING	120.95	197.96	164.28	159.40	0.081704	0.08
2026-02-01 07:07:40	2026-02-01 07:27:40	1200.0	RAISING	120.97	197.98	164.26	159.42	0.081704	0.16
2026-02-01 08:41:04	2026-02-01 09:01:04	1200.0	RAISING	120.97	197.98	164.23	159.42	0.081705	0.25
2026-02-01 10:14:27	2026-02-01 10:34:27	1200.0	RAISING	120.97	197.99	164.21	159.43	0.081706	0.33
2026-02-01 13:21:15	2026-02-01 13:41:15	1200.0	RAISING	120.99	198.01	164.01	159.45	0.081706	0.41
2026-02-01 14:54:38	2026-02-01 15:14:38	1200.0	RAISING	120.98	198.00	164.00	159.43	0.081707	0.49
2026-02-01 16:28:02	2026-02-01 16:48:02	1200.0	RAISING	120.98	198.00	164.02	159.43	0.081707	0.57
2026-02-01 18:01:26	2026-02-01 18:21:26	1200.0	RAISING	120.98	198.00	164.06	159.44	0.081708	0.65
2026-02-01 21:08:15	2026-02-01 21:28:15	1200.0	RAISING	121.00	198.03	163.95	159.46	0.081709	0.74
2026-02-01 22:41:39	2026-02-01 23:01:39	1200.0	RAISING	120.99	198.01	164.04	159.44	0.081709	0.82
2026-02-02 00:15:03	2026-02-02 00:35:03	1200.0	RAISING	120.99	198.02	164.20	159.45	0.081710	0.90
2026-02-02 01:48:28	2026-02-02 02:08:28	1200.0	RAISING	120.99	198.02	164.43	159.45	0.081710	0.98
2026-02-02 04:55:18	2026-02-02 05:15:18	1200.0	RAISING	121.01	198.05	164.64	159.47	0.081711	1.06
2026-02-02 06:30:55	2026-02-02 06:46:30	935.6	RAISING	129.46	189.52	165.16	159.46	0.063710	1.13
2026-02-02 08:10:41	2026-02-02 08:13:34	172.8	RAISING	153.93	165.02	165.81	159.47	0.011765	1.14
2026-02-02 09:44:20	2026-02-02 09:46:46	145.8	RAISING	154.79	164.15	165.82	159.47	0.009927	1.15
2026-02-02 12:49:28	2026-02-02 12:55:18	350.6	RAISING	148.23	170.74	166.36	159.48	0.023872	1.17
2026-02-02 14:24:30	2026-02-02 14:27:05	154.9	RAISING	154.51	164.45	166.93	159.48	0.010550	1.18
2026-02-02 15:57:56	2026-02-02 16:00:29	153.3	RAISING	154.55	164.39	167.60	159.47	0.010437	1.19
2026-02-02 17:31:15	2026-02-02 17:34:00	164.7	RAISING	154.19	164.76	168.75	159.47	0.011214	1.20

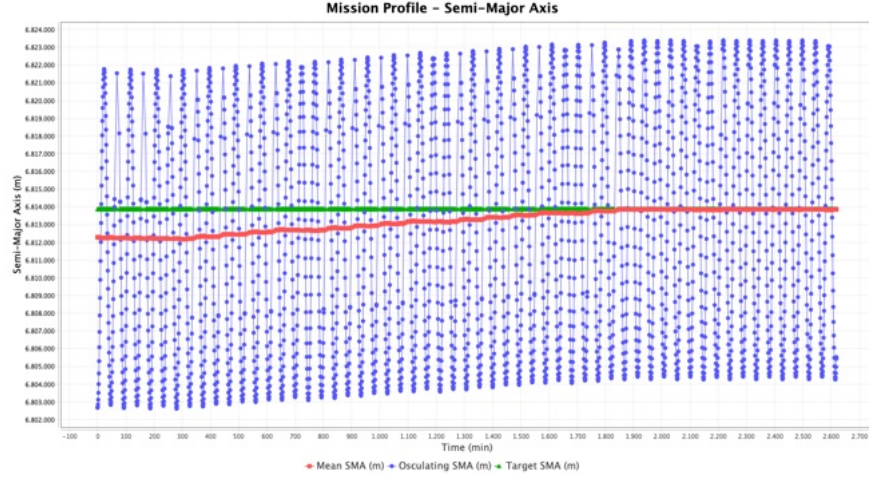


Figure 5.1: Evolution of the Semi-Major Axis (a) during Window 1.

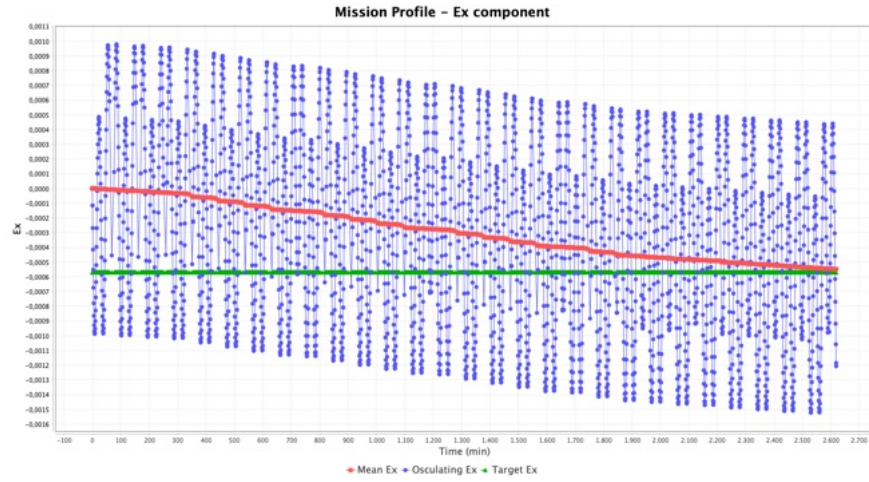


Figure 5.2: Evolution of the x-component of the eccentricity vector (e_x) for Window 1.

SIMULATIONS RESULTS

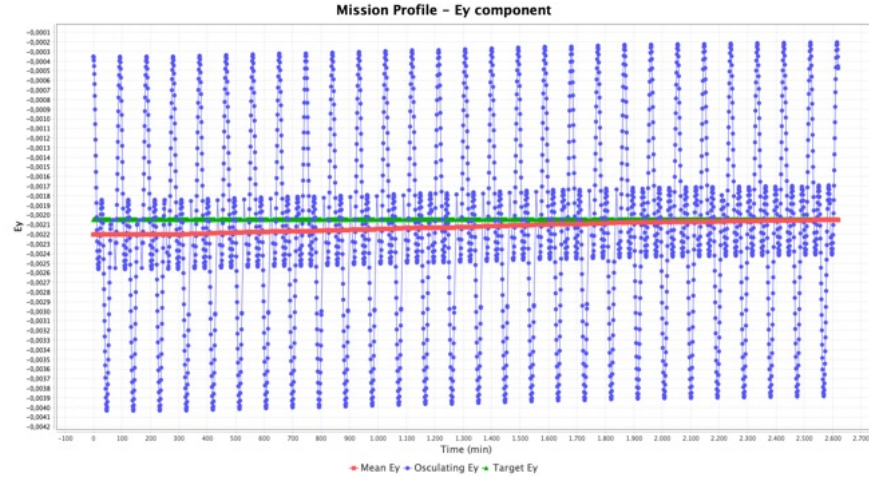


Figure 5.3: Evolution of the y-component of the eccentricity vector (e_y) for Window 1.

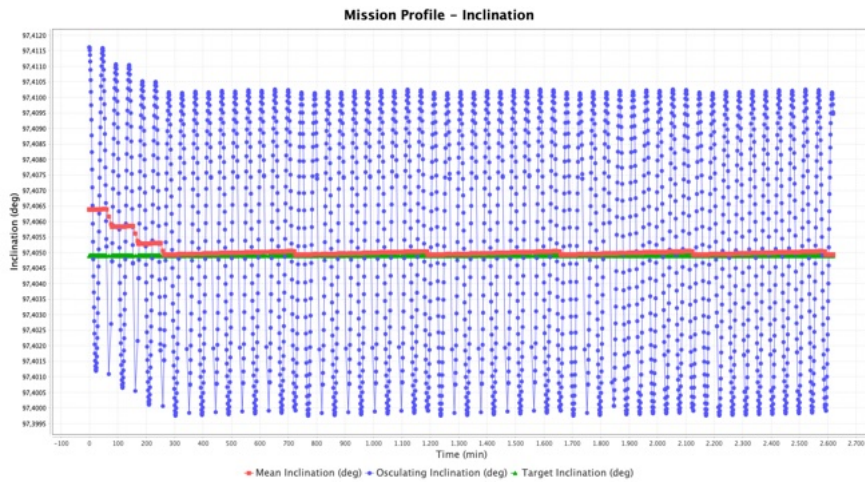


Figure 5.4: Evolution of the orbital Inclination (i) in Window 1.

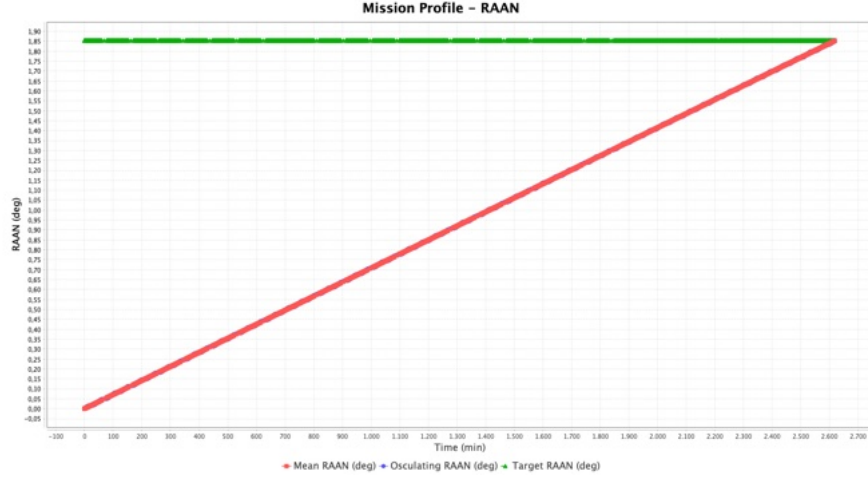


Figure 5.5: Evolution of the RAAN (Ω) during Window 1.

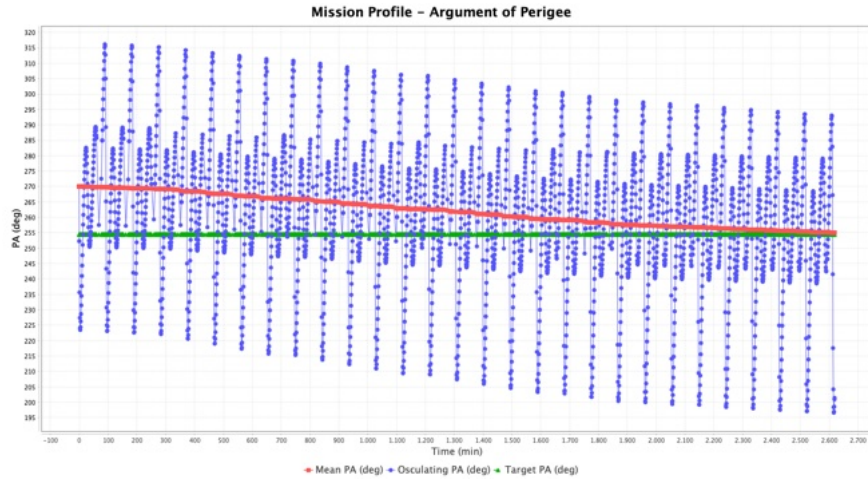


Figure 5.6: Evolution of the Argument of Perigee (ω) during Window 1.

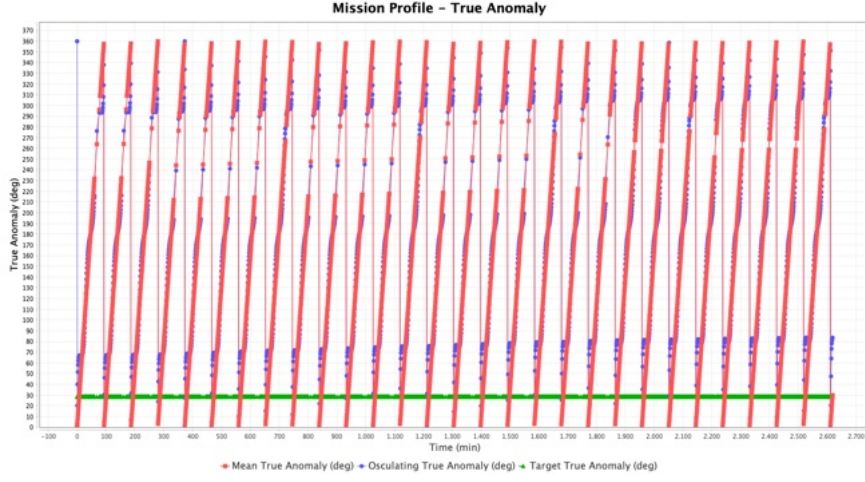


Figure 5.7: Evolution of the True Anomaly (ν) throughout Window 1.

The results regarding the remaining windows are available for consultation in A

5.2 Error Analysis

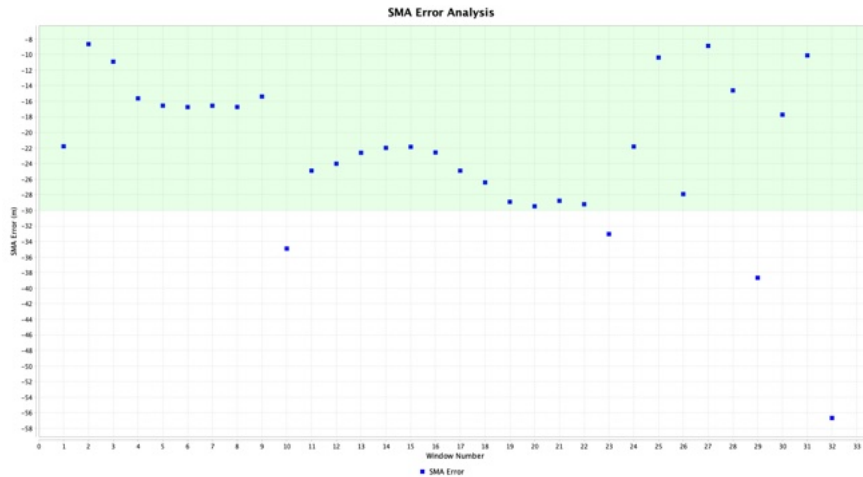


Figure 5.8: Analysis of the Semi-Major Axis error (Δa) across all 32 simulated maneuver windows.

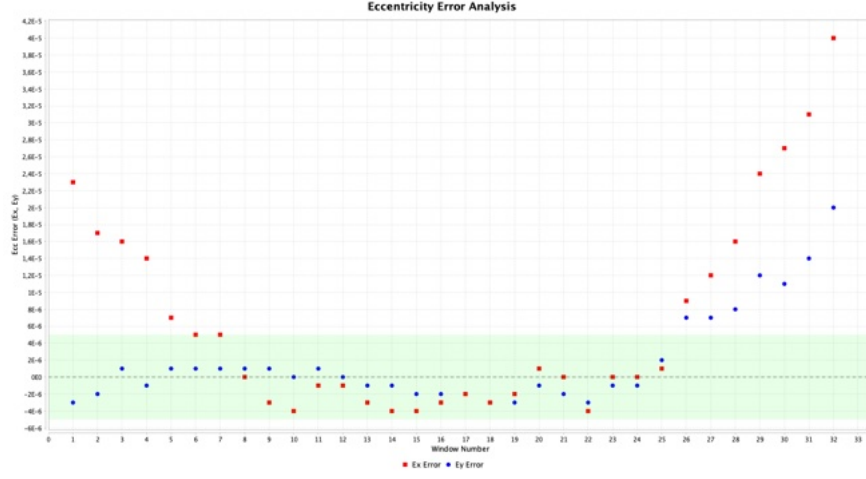


Figure 5.9: Progression of the eccentricity vector errors (Δe_x , Δe_y) throughout the operational windows.

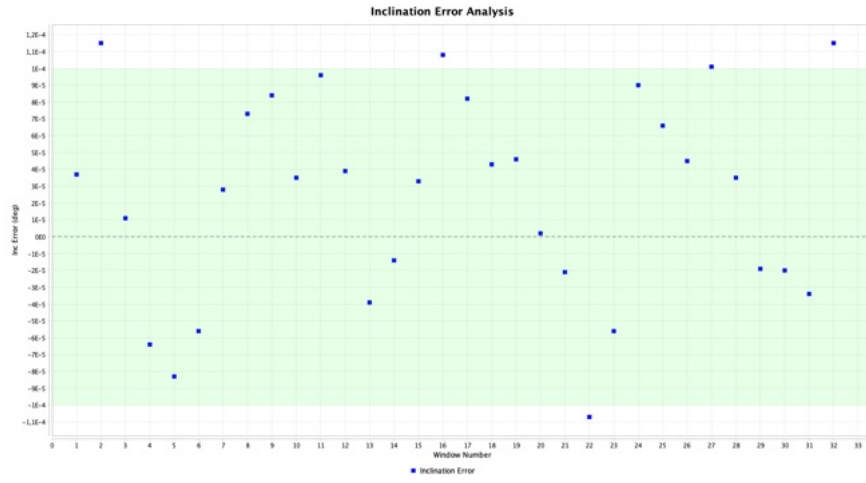


Figure 5.10: Distribution of the orbital Inclination error (Δi) over the mission timeline.

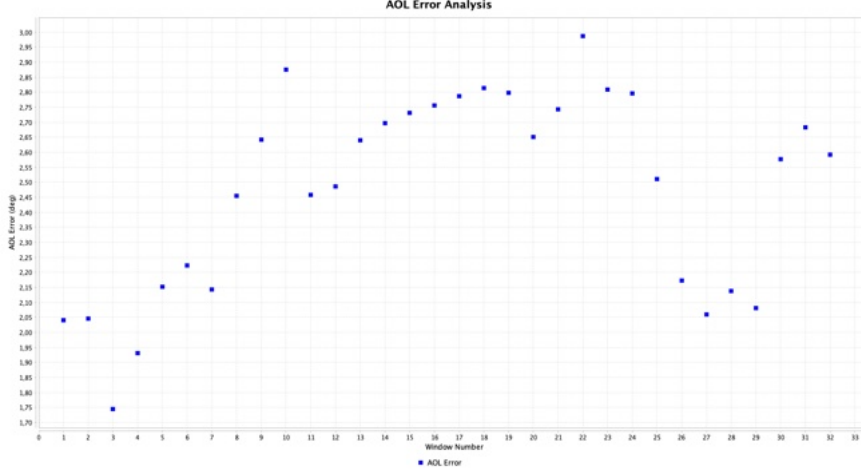


Figure 5.11: Trend of the Argument of Latitude error (Δu) recorded at the target maneuver points across the sequential simulation windows.

The tracking errors evaluated during this orbital transfer are characterized by an overall excellent stability across the different windows. Specifically:

- **Semi-Major Axis Error:** The error in the semi-major axis remains consistently negative throughout the operations, fluctuating predominantly between -8 m and -30 m, with a peak degradation reaching -56.66 m towards the final windows, where the target orbit is furthest from the initial injection orbit. Nevertheless, an error on the order of tens of meters for LEO is entirely acceptable and well within the mission's *phasing* requirements.
- **Inclination Error:** The control of the orbital plane proves to be extremely robust. The inclination error is almost entirely confined within a strict tolerance band of $\pm 1.0 \times 10^{-4}$ deg for the entire duration of the operations. This confirms that the SSO inclination does not undergo uncontrolled secular drifts, maintaining the strict conditions required for a Sun-Synchronous Orbit.
- **Eccentricity Vector Error (E_x, E_y):** The evolution of the eccentricity vector exhibits two distinct behaviors. The E_y component is remarkably stable and remains near zero for the entire duration of the simulation. Conversely, the E_x component shows a transient dynamic: it starts near

2.3×10^{-5} , safely returns within the $\pm 5 \times 10^{-6}$ tolerance band during the central phase of the operations, and then exhibits a slight divergence in the final stages, reaching 4.0×10^{-5} . This accumulation on E_x is primarily due to the imperfect centering of the maneuvers with respect to the AOL suggested by the SQP optimizer. Additionally, the varying magnitude of the maneuvers executed at that specific point introduces further control errors. Nevertheless, considering that these absolute values remain exceedingly low, the overall eccentricity control is still considered highly satisfactory.

- **Argument of Latitude (AOL) Error:** The AOL, which combines the true anomaly and argument of perigee errors, represents the primary metric for the along-track deviation. The error varies from an initial value of 2.04° up to a peak of 2.99° , before stabilizing around $2.5^\circ - 2.6^\circ$ in the final windows. Although this angular drift represents a longitudinal phase offset relative to the nominal target, its stabilization below the 3° threshold represents an excellent result, even more so considering that it always remains confined within this range of values.

Chapter 6

Conclusion and Future Work

The analysis of the simulation campaign demonstrates that the developed finite-burn maneuver planner achieves orbital targeting performances that remain highly consistent with the ideal impulsive solutions provided by the SQP optimizer, while enforcing realistic operational constraints. Across the maneuver windows, the semi-major axis error remains bounded within a few tens of meters, with a stable and non-divergent behavior, confirming the robustness of the forward-propagation targeting strategy. The inclination error remains centered around zero and consistently on the order of 10^{-5} – 10^{-4} degrees, demonstrating excellent cross-track control accuracy and absence of secular drift. These results confirm that the introduction of finite-burn modeling, thrust limitations, and operational constraints does not compromise orbital precision, but rather enables a physically consistent and operationally realistic maneuver execution framework.

While an iterative redistribution of the required ΔV could theoretically minimize the residual errors on the Keplerian elements and further align the propellant costs with the ideal theoretical values, the current forward-propagation approach was deliberately chosen to reflect actual operational dynamics. By enforcing realistic mission constraints, such as maximum burn durations, finite low-thrust levels, eclipse-only firing limitations, and mandatory waiting time between maneuvers, the developed model successfully bridges the gap between theoretical trajectory optimization and practical spacecraft operations.

Furthermore, the algorithmic architecture of the maneuver planner has been

designed to be highly modular and adaptable. Its applicability is not strictly confined to the specific Sun-Synchronous phasing problem addressed in this study. The core logic governing the targeting windows, node detection, and vector clamping can be easily generalized to support a wide range of missions in LEO.

Building upon the foundation established in this thesis, two primary avenues for future research and development emerge:

- **Constraint Formulation and High-Fidelity Optimization:** As a foundational step for future developments, work must focus on finding a rigorous mathematical definition for all operational limitations to formulate them as explicit equality and inequality constraints. Once this mathematical framework is established, the realistic trajectories and finite-burn distributions generated by the current planner can be directly utilized as a robust initial guess for a full-scale, continuous-thrust SQP optimization.
- **Comprehensive Comparative Analysis:** Following the successful implementation of the aforementioned finite-burn optimizer, it would be highly beneficial to conduct a definitive three-way comparative analysis. This would involve evaluating the discrepancies in final state precision and total propellant costs among (1) the theoretical impulsive optimized solution, (2) the finite-burn maneuver planner developed in this study, and (3) the fully optimized finite-burn solver utilizing our initial guess. Analyzing these differences will provide profound insights into the trade-offs between mathematical optimality and practical operational fidelity.

Overall, this work demonstrates that high-fidelity operational realism and accurate orbital targeting are not mutually exclusive objectives. Instead, they represent complementary components of a next-generation maneuver planning framework capable of supporting increasingly autonomous and distributed space systems. The results obtained confirm that finite-burn planners can achieve near-impulsive performance while preserving physical consistency and operational feasibility, thus providing a solid foundation for future autonomous guidance and optimization architectures.

Appendix A

Results

A.1 Window 2

Table A.1: Window 2

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-02-02T19:38:30	2026-02-04T15:17:01	2026-02-04T15:17:01
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 813 876.428 m	6 815 272.385 m	6 815 263.727 m
Eccentricity	e	0.002126	0.002122	0.002116
Inclination	i	97.4049°	97.4032°	97.4033°
Arg. of Perigee	ω	254.4567°	239.4581°	239.8997°
RAAN	Ω	1.8537°	3.7057°	3.7042°
True Anomaly	ν	28.4273°	52.9394°	54.5442°

RESULTS

Table A.2: Target State Errors Summary - Window 2

Parameter	Symbol	Error
Semi-Major Axis	Δa	-8.658 m
Inclination	Δi	0.000115°
Eccentricity X	Δe_x	0.000017
Eccentricity Y	Δe_y	-0.000002
RAAN	$\Delta \Omega$	-0.001516°
Arg. of Perigee	$\Delta \omega$	0.442°
True Anomaly	$\Delta \nu$	1.605°
Arg. of Latitude	Δu	2.046°

Table A.3: Normal Maneuvers Summary - Window 2. SQP ΔV : 0.304232 m/s .

Start Time (UTC)	End Time (UTC)	Duration (s)	$\Delta V \text{ [m/s]}$	$\Sigma \Delta V \text{ [m/s]}$	AOL ($^\circ$)	Thrust Z
2026-02-02 20:34:44	2026-02-02 20:54:44	1200.00	0.081702	0.081702	180.147	1.0
2026-02-02 22:08:09	2026-02-02 22:28:09	1200.00	0.081703	0.163405	180.147	1.0
2026-02-02 23:41:34	2026-02-03 00:01:34	1200.00	0.081704	0.245109	180.147	1.0
2026-02-03 02:56:36	2026-02-03 03:00:12	215.80	0.014693	0.259802	180.147	1.0
2026-02-03 10:43:46	2026-02-03 10:47:16	210.42	0.014327	0.274129	180.147	1.0
2026-02-03 20:04:11	2026-02-03 20:08:03	232.14	0.015807	0.289936	180.147	1.0
2026-02-04 05:25:05	2026-02-04 05:28:29	204.20	0.013904	0.303841	180.147	1.0

Table A.4: Tangential Maneuvers Summary - Window 2. SQP AOL: 156.50° , v_{Tan} SQP: 1.08 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma\Delta V$ [m/s]
2026-02-03 01:08:49	2026-02-03 01:28:49	1200.0	RAISING	117.88	194.92	156.43	156.34	0.081704	0.08
2026-02-03 04:15:40	2026-02-03 04:35:40	1200.0	RAISING	117.96	195.01	156.29	156.43	0.081705	0.16
2026-02-03 05:49:05	2026-02-03 06:09:05	1200.0	RAISING	117.95	195.00	156.18	156.42	0.081705	0.25
2026-02-03 07:22:31	2026-02-03 07:42:31	1200.0	RAISING	117.95	195.01	156.07	156.42	0.081706	0.33
2026-02-03 08:55:56	2026-02-03 09:15:56	1200.0	RAISING	117.95	195.01	155.96	156.43	0.081706	0.41
2026-02-03 12:02:48	2026-02-03 12:22:48	1200.0	RAISING	117.97	195.03	155.79	156.44	0.081707	0.49
2026-02-03 13:36:14	2026-02-03 13:56:14	1200.0	RAISING	117.96	195.02	155.69	156.43	0.081708	0.57
2026-02-03 15:09:40	2026-02-03 15:29:40	1200.0	RAISING	117.96	195.02	155.58	156.44	0.081708	0.65
2026-02-03 16:43:06	2026-02-03 17:03:06	1200.0	RAISING	117.96	195.03	155.48	156.44	0.081709	0.74
2026-02-03 18:16:32	2026-02-03 18:36:32	1200.0	RAISING	117.96	195.03	155.39	156.44	0.081709	0.82
2026-02-03 21:23:25	2026-02-03 21:43:25	1200.0	RAISING	117.97	195.05	155.34	156.45	0.081710	0.90
2026-02-03 22:56:52	2026-02-03 23:16:52	1200.0	RAISING	117.97	195.04	155.27	156.45	0.081711	0.98
2026-02-04 00:38:41	2026-02-04 00:41:56	195.6	RAISING	150.17	162.73	155.22	156.45	0.013322	0.99
2026-02-04 02:12:35	2026-02-04 02:14:56	141.2	RAISING	151.91	160.98	155.19	156.45	0.009611	1.00
2026-02-04 03:45:54	2026-02-04 03:48:30	155.8	RAISING	151.44	161.45	155.38	156.44	0.010608	1.01
2026-02-04 06:51:12	2026-02-04 06:56:59	346.9	RAISING	145.33	167.61	156.26	156.47	0.023618	1.04
2026-02-04 08:26:21	2026-02-04 08:28:44	143.4	RAISING	151.86	161.07	156.56	156.46	0.009763	1.05
2026-02-04 09:59:46	2026-02-04 10:02:12	146.2	RAISING	151.75	161.15	157.22	156.45	0.009956	1.06
2026-02-04 11:33:06	2026-02-04 11:35:45	159.1	RAISING	151.34	161.56	158.31	156.45	0.010836	1.07
2026-02-04 13:06:32	2026-02-04 13:09:12	159.7	RAISING	151.32	161.59	160.06	156.45	0.010877	1.08
2026-02-04 14:40:00	2026-02-04 14:42:38	158.9	RAISING	151.35	161.56	163.21	156.45	0.010821	1.09

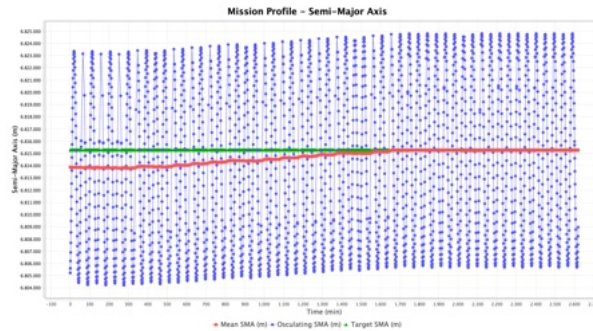


Figure A.1: Evolution profile of the Semi-Major Axis (a) during Window 2.

RESULTS

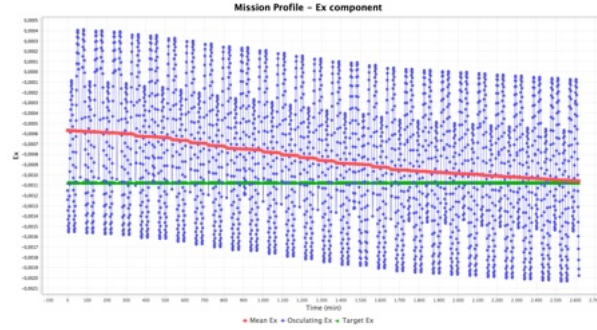


Figure A.2: Evolution of the x-component of the eccentricity vector (e_x) for Window 2.

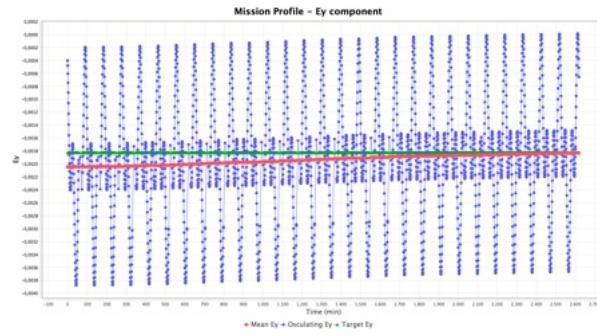


Figure A.3: Evolution of the y-component of the eccentricity vector (e_y) for Window 2.

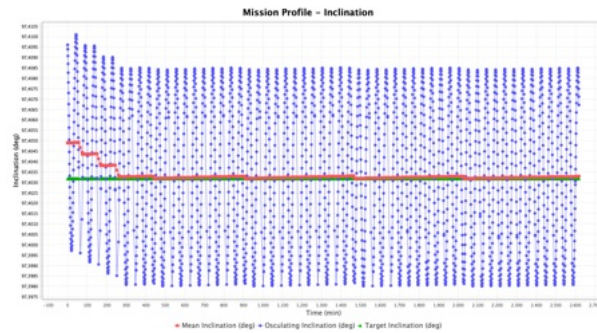


Figure A.4: Evolution of the orbital Inclination (i) in Window 2.

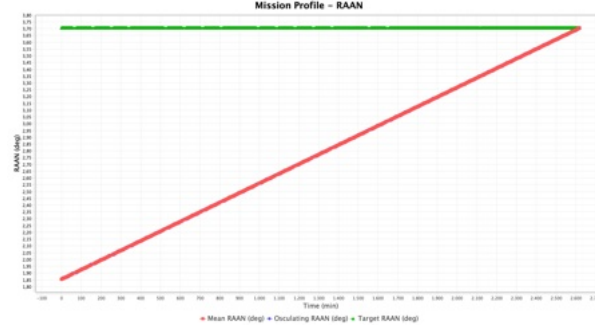


Figure A.5: Evolution of the RAAN (Ω) during Window 2.

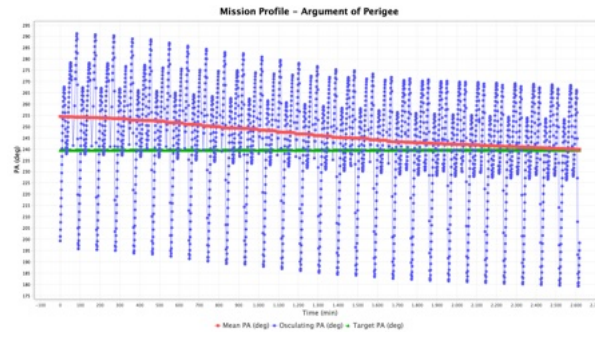


Figure A.6: Evolution of the Argument of Perigee (ω) during Window 2.

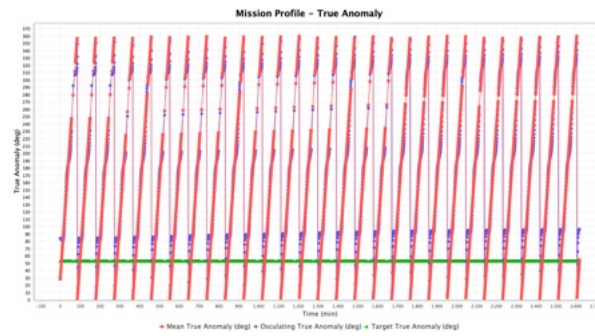


Figure A.7: Evolution of the True Anomaly (ν) throughout Window 2.

A.2 Window 3

Table A.5: Window 3

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-02-04T15:17:01	2026-02-06T10:55:32	2026-02-06T10:55:32
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 815 272.385 m	6 816 519.133 m	6 816 508.223 m
Eccentricity	e	0.002122	0.002209	0.002197
Inclination	i	97.4032°	97.4021°	97.4021°
Arg. of Perigee	ω	239.4581°	225.7190°	225.9966°
RAAN	Ω	3.7057°	5.5562°	5.5546°
True Anomaly	ν	52.9394°	73.2224°	74.6900°

Table A.6: Target State Errors Summary - Window 3

Parameter	Symbol	Error
Semi-Major Axis	Δa	−10.911 m
Inclination	Δi	0.000011°
Eccentricity X	Δe_x	0.000016
Eccentricity Y	Δe_y	0.000001
RAAN	$\Delta \Omega$	−0.001571°
Arg. of Perigee	$\Delta \omega$	0.278°
True Anomaly	$\Delta \nu$	1.468°
Arg. of Latitude	Δu	1.745°

Table A.7: Normal Maneuvers Summary - Window 3. SQP ΔV : 0.170272 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL ($^\circ$)	Thrust Z
2026-02-04 16:10:49	2026-02-04 16:30:49	1200.00	0.081702	0.081702	180.147	1.0
2026-02-04 17:46:09	2026-02-04 18:02:22	973.24	0.066264	0.147966	180.147	1.0
2026-02-05 04:46:47	2026-02-05 04:50:04	196.66	0.013390	0.161357	180.147	1.0
2026-02-06 07:15:45	2026-02-06 07:19:04	198.88	0.013542	0.174899	180.147	1.0

Table A.8: Tangential Maneuvers Summary - Window 3. SQP AOL: 160.87°, v_{Tan} SQP: 0.99 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]
2026-02-04 19:12:42	2026-02-04 19:32:42	1200.0	RAISING	122.29	199.41	152.18	160.79	0.081703	0.08
2026-02-04 20:46:09	2026-02-04 21:06:09	1200.0	RAISING	122.33	199.45	151.93	160.83	0.081704	0.16
2026-02-04 22:19:36	2026-02-04 22:39:36	1200.0	RAISING	122.33	199.46	151.62	160.84	0.081705	0.25
2026-02-04 23:53:03	2026-02-05 00:13:03	1200.0	RAISING	122.33	199.46	151.28	160.84	0.081705	0.33
2026-02-05 01:26:31	2026-02-05 01:46:31	1200.0	RAISING	122.33	199.46	150.91	160.84	0.081706	0.41
2026-02-05 02:59:58	2026-02-05 03:19:58	1200.0	RAISING	122.33	199.47	150.50	160.85	0.081706	0.49
2026-02-05 06:06:54	2026-02-05 06:26:54	1200.0	RAISING	122.36	199.50	150.20	160.87	0.081707	0.57
2026-02-05 07:40:21	2026-02-05 08:00:21	1200.0	RAISING	122.34	199.48	149.67	160.85	0.081708	0.65
2026-02-05 09:13:49	2026-02-05 09:33:49	1200.0	RAISING	122.34	199.48	149.05	160.86	0.081708	0.74
2026-02-05 10:47:17	2026-02-05 11:07:17	1200.0	RAISING	122.34	199.49	148.32	160.86	0.081709	0.82
2026-02-05 12:27:18	2026-02-05 12:34:13	415.2	RAISING	147.52	174.22	147.40	160.86	0.028273	0.85
2026-02-05 14:02:54	2026-02-05 14:05:34	160.5	RAISING	155.73	166.05	147.14	160.89	0.010929	0.86
2026-02-05 15:36:32	2026-02-05 15:38:53	141.1	RAISING	156.34	165.41	147.19	160.88	0.009605	0.87
2026-02-05 17:09:54	2026-02-05 17:12:27	153.1	RAISING	155.95	165.80	147.35	160.88	0.010428	0.88
2026-02-05 18:43:21	2026-02-05 18:45:56	155.0	RAISING	155.90	165.87	147.55	160.88	0.010557	0.89
2026-02-05 20:16:50	2026-02-05 20:19:24	154.3	RAISING	155.92	165.84	147.79	160.88	0.010509	0.90
2026-02-05 21:50:18	2026-02-05 21:52:53	154.1	RAISING	155.93	165.84	148.10	160.88	0.010493	0.91
2026-02-05 23:23:47	2026-02-05 23:26:21	154.1	RAISING	155.93	165.84	148.51	160.88	0.010490	0.92
2026-02-06 00:57:15	2026-02-06 00:59:49	154.0	RAISING	155.93	165.84	149.04	160.88	0.010486	0.93
2026-02-06 02:30:43	2026-02-06 02:33:17	153.9	RAISING	155.94	165.84	149.75	160.89	0.010482	0.94
2026-02-06 04:04:12	2026-02-06 04:06:46	153.9	RAISING	155.94	165.84	150.71	160.89	0.010478	0.95
2026-02-06 05:37:40	2026-02-06 05:40:14	153.8	RAISING	155.94	165.84	152.08	160.89	0.010475	0.96
2026-02-06 08:43:10	2026-02-06 08:48:37	326.6	RAISING	150.40	171.41	158.30	160.90	0.022240	0.98
2026-02-06 10:18:10	2026-02-06 10:20:34	144.6	RAISING	156.25	165.55	163.72	160.90	0.009845	0.99

RESULTS

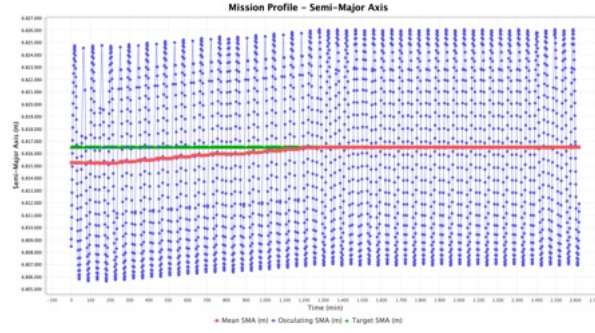


Figure A.8: Evolution of the Semi-Major Axis (a) during Window 3.

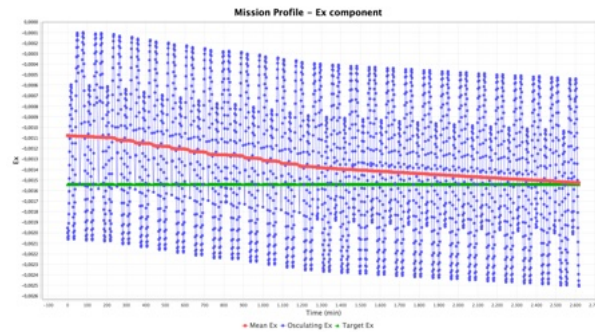


Figure A.9: Evolution of the x-component of the eccentricity vector (e_x) for Window 3.

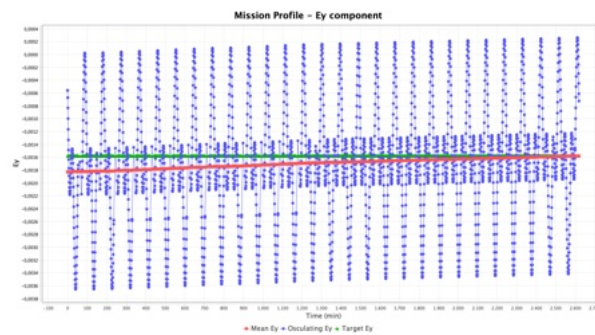


Figure A.10: Evolution of the y-component of the eccentricity vector (e_y) for Window 3.

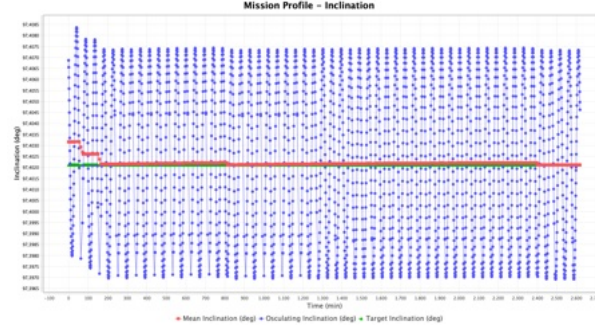


Figure A.11: Evolution of the orbital Inclination (i) in Window 3.

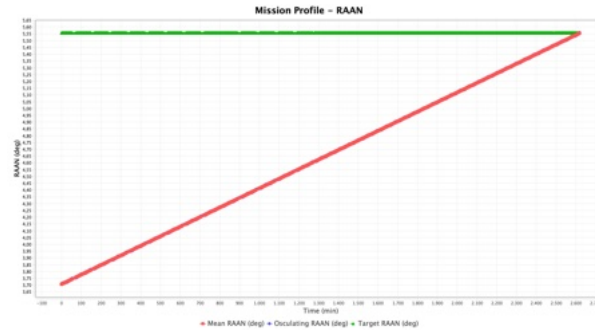


Figure A.12: Evolution of the RAAN (Ω) during Window 3.

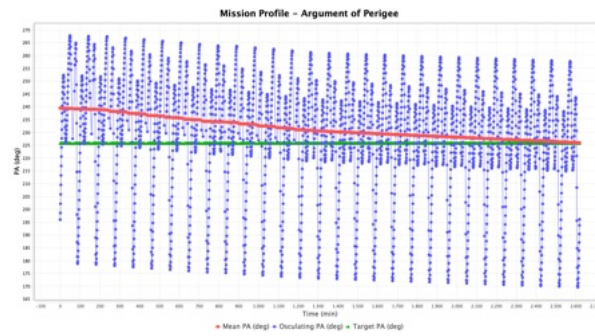


Figure A.13: Evolution of the Argument of Perigee (ω) during Window 3.

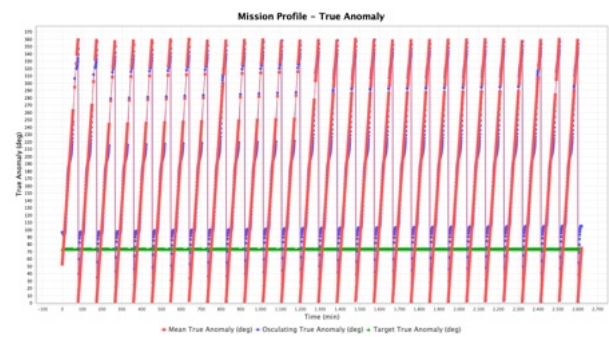


Figure A.14: Evolution of the True Anomaly (ν) throughout Window 3.

A.3 Window 4

Table A.9: Window 4

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-02-06T10:55:32	2026-02-08T06:34:03	2026-02-08T06:34:03
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 816 519.133 m	6 817 600.407 m	6 817 584.784 m
Eccentricity	e	0.002209	0.002329	0.002317
Inclination	i	97.4021°	97.3998°	97.3998°
Arg. of Perigee	ω	225.7190°	213.4570°	213.6669°
RAAN	Ω	5.5562°	7.4051°	7.4035°
True Anomaly	ν	73.2224°	89.4130°	91.1342°

Table A.10: Target State Errors Summary - Window 4

Parameter	Symbol	Error
Semi-Major Axis	Δa	-15.623 m
Inclination	Δi	-0.000064°
Eccentricity X	Δe_x	0.000014
Eccentricity Y	Δe_y	-0.000001
RAAN	$\Delta \Omega$	-0.001627°
Arg. of Perigee	$\Delta \omega$	0.210°
True Anomaly	$\Delta \nu$	1.721°
Arg. of Latitude	Δu	1.931°

Table A.11: Normal Maneuvers Summary - Window 4. SQP ΔV : 0.292595 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL (°)	Thrust Z
2026-02-06 11:47:39	2026-02-06 12:07:39	1200.00	0.081702	0.081702	180.147	1.0
2026-02-06 13:21:08	2026-02-06 13:41:08	1200.00	0.081703	0.163405	180.147	1.0
2026-02-06 14:54:36	2026-02-06 15:14:36	1200.00	0.081704	0.245109	180.147	1.0
2026-02-06 16:28:49	2026-02-06 16:47:19	1109.94	0.075572	0.320681	180.147	1.0

RESULTS

Table A.12: Tangential Maneuvers Summary - Window 4. SQP AOL: 157.81° , v_{Tan} SQP: 0.89 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma\Delta V$ [m/s]
2026-02-06 17:55:44	2026-02-06 18:15:44	1200.0	RAISING	119.24	196.40	143.97	157.76	0.081705	0.08
2026-02-06 19:29:14	2026-02-06 19:49:14	1200.0	RAISING	119.30	196.46	143.58	157.82	0.081705	0.16
2026-02-06 21:02:42	2026-02-06 21:22:42	1200.0	RAISING	119.30	196.46	143.09	157.83	0.081706	0.25
2026-02-06 22:36:11	2026-02-06 22:56:11	1200.0	RAISING	119.30	196.47	142.55	157.83	0.081706	0.33
2026-02-07 00:09:40	2026-02-07 00:29:40	1200.0	RAISING	119.30	196.47	141.93	157.83	0.081707	0.41
2026-02-07 01:43:09	2026-02-07 02:03:09	1200.0	RAISING	119.30	196.48	141.22	157.84	0.081707	0.49
2026-02-07 03:16:38	2026-02-07 03:36:38	1200.0	RAISING	119.30	196.48	140.40	157.84	0.081708	0.57
2026-02-07 04:50:07	2026-02-07 05:10:07	1200.0	RAISING	119.31	196.48	139.41	157.84	0.081709	0.65
2026-02-07 06:23:37	2026-02-07 06:43:37	1200.0	RAISING	119.31	196.49	138.21	157.84	0.081709	0.74
2026-02-07 08:05:51	2026-02-07 08:08:21	149.8	RAISING	153.03	162.67	136.70	157.85	0.010200	0.75
2026-02-07 09:39:29	2026-02-07 09:41:43	133.8	RAISING	153.54	162.15	136.65	157.85	0.009110	0.75
2026-02-07 11:12:51	2026-02-07 11:15:20	149.1	RAISING	153.05	162.64	136.77	157.85	0.010151	0.76
2026-02-07 12:46:20	2026-02-07 12:48:51	151.0	RAISING	152.99	162.71	136.89	157.85	0.010283	0.78
2026-02-07 14:19:50	2026-02-07 14:22:20	150.1	RAISING	153.02	162.68	137.05	157.85	0.010223	0.79
2026-02-07 15:53:19	2026-02-07 15:55:49	149.9	RAISING	153.03	162.67	137.26	157.85	0.010208	0.80
2026-02-07 17:26:49	2026-02-07 17:29:19	149.9	RAISING	153.03	162.68	137.53	157.85	0.010207	0.81
2026-02-07 19:00:19	2026-02-07 19:02:49	149.9	RAISING	153.03	162.68	137.89	157.85	0.010204	0.82
2026-02-07 20:33:48	2026-02-07 20:36:18	149.8	RAISING	153.04	162.67	138.37	157.85	0.010199	0.83
2026-02-07 22:07:18	2026-02-07 22:09:48	149.7	RAISING	153.04	162.67	139.00	157.86	0.010195	0.84
2026-02-07 23:40:48	2026-02-07 23:43:17	149.6	RAISING	153.04	162.67	139.89	157.86	0.010190	0.85
2026-02-08 01:14:17	2026-02-08 01:16:47	149.6	RAISING	153.05	162.67	141.15	157.86	0.010185	0.86
2026-02-08 02:47:47	2026-02-08 02:50:16	149.5	RAISING	153.05	162.67	143.07	157.86	0.010181	0.87
2026-02-08 04:21:17	2026-02-08 04:23:46	149.5	RAISING	153.05	162.67	146.22	157.86	0.010178	0.88
2026-02-08 05:54:46	2026-02-08 05:57:16	149.4	RAISING	153.06	162.67	152.19	157.86	0.010175	0.89

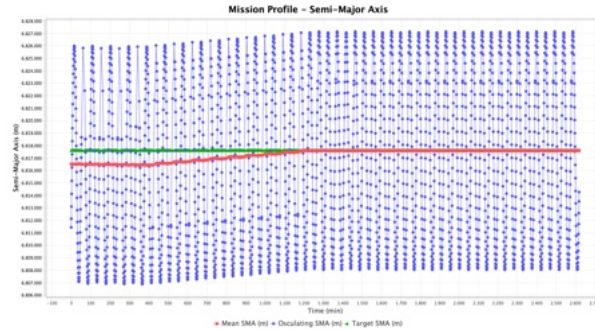


Figure A.15: Evolution of the Semi-Major Axis (a) during Window 4.

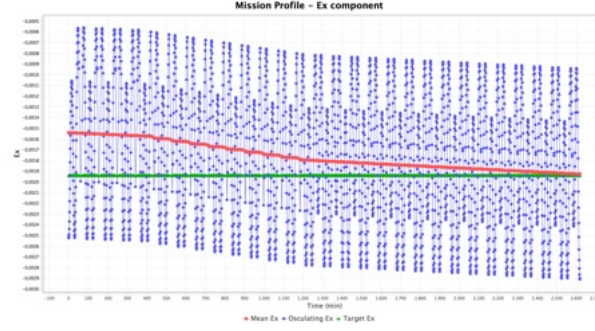


Figure A.16: Evolution of the x-component of the eccentricity vector (e_x) for Window 4.

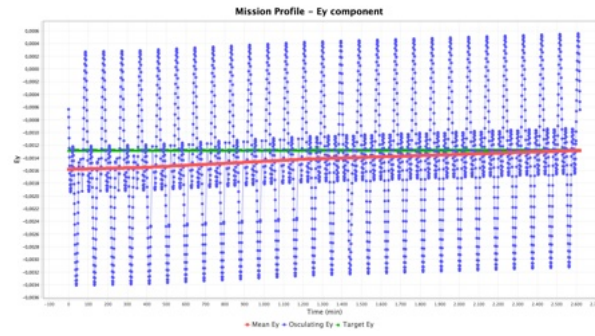


Figure A.17: Evolution of the y-component of the eccentricity vector (e_y) for Window 4.

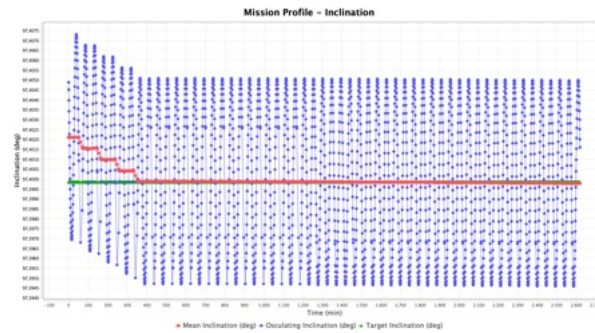


Figure A.18: Evolution of the orbital Inclination (i) in Window 4.

RESULTS

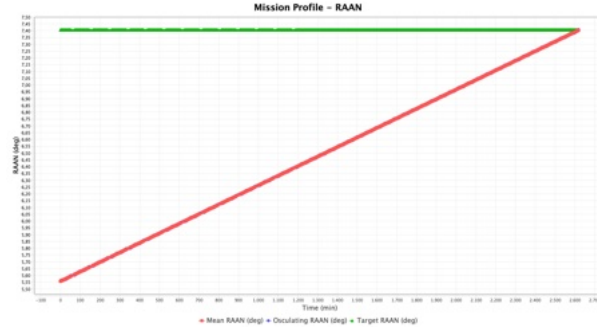


Figure A.19: Evolution of the RAAN (Ω) during Window 4.

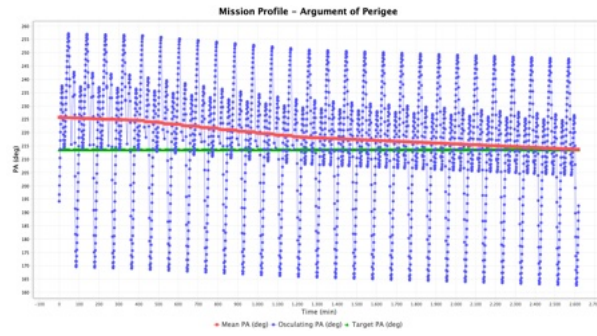


Figure A.20: Evolution of the Argument of Perigee (ω) during Window 4.

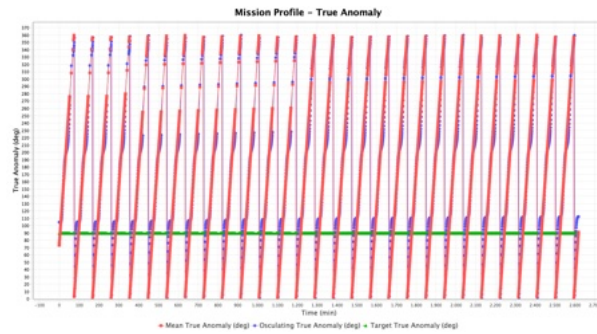


Figure A.21: Evolution of the True Anomaly (ν) throughout Window 4.

A.4 Window 5

Table A.13: Window 5

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-02-08T06:34:03	2026-02-10T02:12:34	2026-02-10T02:12:34
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 817 600.407 m	6 818 106.021 m	6 818 089.465 m
Eccentricity	e	0.002329	0.002438	0.002431
Inclination	i	97.3998°	97.3970°	97.3969°
Arg. of Perigee	ω	213.4570°	203.8621°	203.9034°
RAAN	Ω	7.4051°	9.2525°	9.2509°
True Anomaly	ν	89.4130°	101.1324°	103.2430°

Table A.14: Target State Errors Summary - Window 5

Parameter	Symbol	Error
Semi-Major Axis	Δa	−16.556 m
Inclination	Δi	−0.000083°
Eccentricity X	Δe_x	0.000007
Eccentricity Y	Δe_y	0.000001
RAAN	$\Delta \Omega$	−0.001584°
Arg. of Perigee	$\Delta \omega$	0.041°
True Anomaly	$\Delta \nu$	2.111°
Arg. of Latitude	Δu	2.152°

RESULTS

Table A.15: Normal Maneuvers Summary - Window 5. SQP ΔV : 0.349184 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL ($^\circ$)	Thrust Z
2026-02-08 07:25:10	2026-02-08 07:45:10	1200.00	0.081702	0.081702	180.146	1.0
2026-02-08 08:58:39	2026-02-08 09:18:39	1200.00	0.081703	0.163405	180.146	1.0
2026-02-08 10:32:09	2026-02-08 10:52:09	1200.00	0.081704	0.245109	180.146	1.0
2026-02-08 12:05:38	2026-02-08 12:25:38	1200.00	0.081704	0.326813	180.146	1.0
2026-02-08 13:40:21	2026-02-08 13:57:55	1053.50	0.071730	0.398543	180.146	1.0
2026-02-09 13:10:00	2026-02-09 13:13:18	197.49	-0.013447	0.385096	180.146	-1.0

Table A.16: Tangential Maneuvers Summary - Window 5. SQP AOL: 160.22 $^\circ$, v_{Tan} SQP: 0.56 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]
2026-02-08 15:07:28	2026-02-08 15:27:28	1200.0	RAISING	121.67	198.90	135.15	160.24	0.081705	0.08
2026-02-08 16:40:59	2026-02-08 17:00:59	1200.0	RAISING	121.72	198.95	134.11	160.29	0.081706	0.16
2026-02-08 18:14:29	2026-02-08 18:34:29	1200.0	RAISING	121.72	198.96	132.84	160.29	0.081706	0.25
2026-02-08 19:47:59	2026-02-08 20:07:59	1200.0	RAISING	121.73	198.96	131.34	160.29	0.081707	0.33
2026-02-08 21:25:16	2026-02-08 21:37:42	746.0	RAISING	136.30	184.33	129.54	160.30	0.050798	0.38
2026-02-08 23:03:40	2026-02-08 23:06:19	158.5	RAISING	155.22	165.42	128.29	160.32	0.010789	0.39
2026-02-09 00:37:25	2026-02-09 00:39:33	128.0	RAISING	156.19	164.43	128.13	160.31	0.008716	0.40
2026-02-09 02:10:47	2026-02-09 02:13:12	145.7	RAISING	155.62	165.00	128.15	160.31	0.009920	0.41
2026-02-09 03:44:16	2026-02-09 03:46:44	148.6	RAISING	155.53	165.10	128.14	160.31	0.010118	0.42
2026-02-09 05:17:46	2026-02-09 05:20:14	147.7	RAISING	155.56	165.07	128.13	160.31	0.010054	0.43
2026-02-09 06:51:17	2026-02-09 06:53:44	147.4	RAISING	155.57	165.06	128.14	160.31	0.010036	0.44
2026-02-09 08:24:47	2026-02-09 08:27:14	147.4	RAISING	155.57	165.06	128.18	160.32	0.010038	0.45
2026-02-09 09:58:17	2026-02-09 10:00:45	147.4	RAISING	155.57	165.06	128.24	160.32	0.010038	0.46
2026-02-09 11:31:47	2026-02-09 11:34:15	147.4	RAISING	155.57	165.07	128.33	160.32	0.010036	0.47
2026-02-09 14:37:24	2026-02-09 14:42:39	314.9	RAISING	150.20	170.47	129.60	160.33	0.021441	0.49
2026-02-09 16:12:23	2026-02-09 16:14:40	136.9	RAISING	155.92	164.74	128.92	160.33	0.009319	0.50
2026-02-09 17:45:54	2026-02-09 17:48:10	136.9	RAISING	155.92	164.73	129.28	160.32	0.009319	0.51
2026-02-09 19:19:19	2026-02-09 19:21:46	147.2	RAISING	155.58	165.07	129.93	160.32	0.010025	0.52
2026-02-09 20:52:49	2026-02-09 20:55:16	147.8	RAISING	155.57	165.09	130.83	160.33	0.010065	0.53
2026-02-09 22:26:19	2026-02-09 22:28:46	147.1	RAISING	155.59	165.07	132.27	160.33	0.010019	0.54
2026-02-09 23:59:49	2026-02-10 00:02:16	147.0	RAISING	155.60	165.06	134.91	160.33	0.010009	0.55
2026-02-10 01:33:20	2026-02-10 01:35:47	147.0	RAISING	155.60	165.06	140.84	160.33	0.010008	0.56

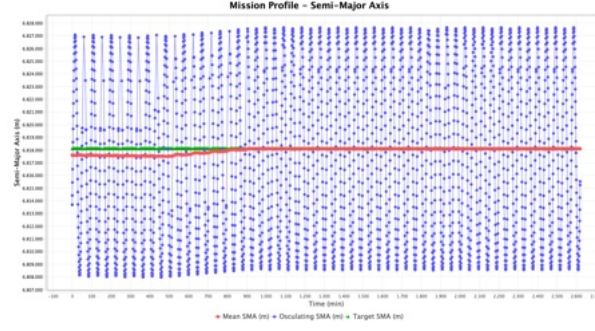


Figure A.22: Evolution of the Semi-Major Axis (a) during Window 5.

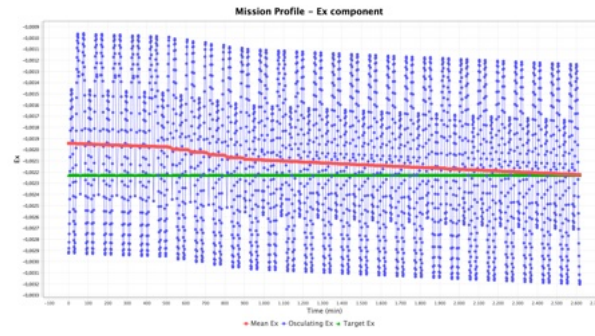


Figure A.23: Evolution of the x-component of the eccentricity vector (e_x) for Window 5.

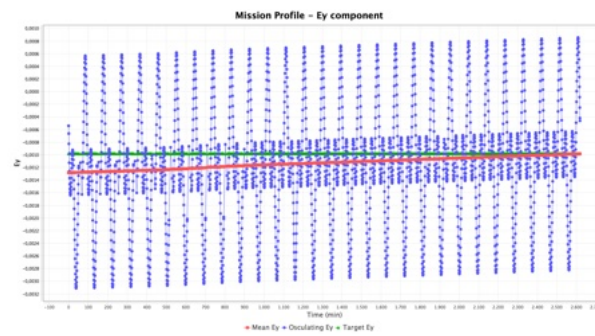


Figure A.24: Evolution of the y-component of the eccentricity vector (e_y) for Window 5.

RESULTS

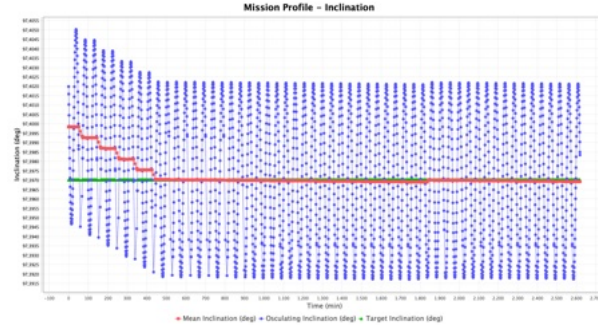


Figure A.25: Evolution of the orbital Inclination (i) in Window 5.

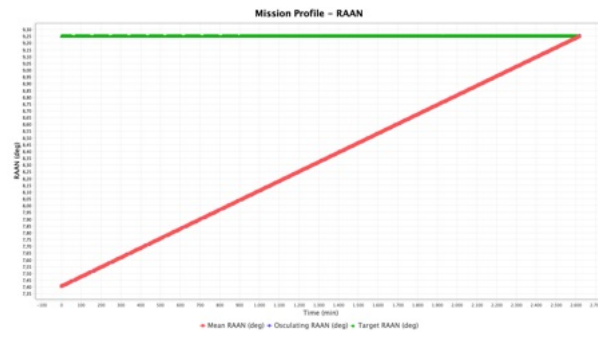


Figure A.26: Evolution of the RAAN (Ω) during Window 5.

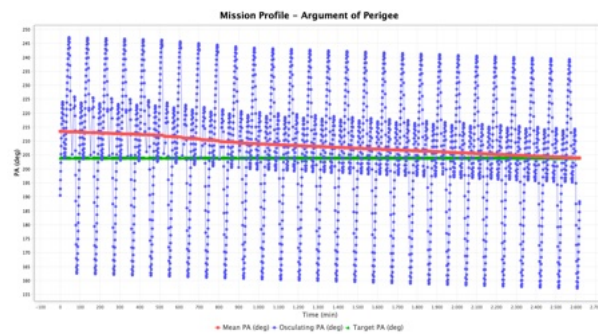
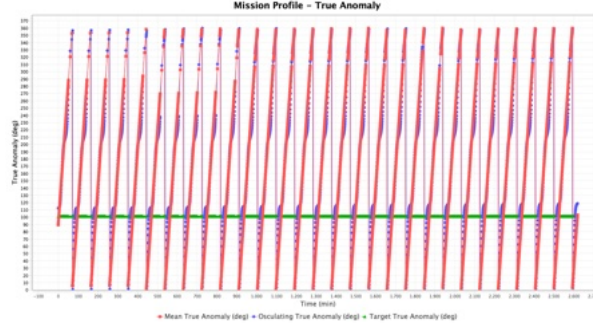


Figure A.27: Evolution of the Argument of Perigee (ω) during Window 5.

Figure A.28: Evolution of the True Anomaly (ν) throughout Window 5.

A.5 Window 6

Table A.17: Window 6

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-02-10T02:12:34	2026-02-11T21:51:05	2026-02-11T21:51:05
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 818 106.021 m	6 818 441.818 m	6 818 425.081 m
Eccentricity	e	0.002438	0.002548	0.002543
Inclination	i	97.3970°	97.3943°	97.3943°
Arg. of Perigee	ω	203.8621°	195.3312°	195.3312°
RAAN	Ω	9.2525°	11.0988°	11.0972°
True Anomaly	ν	101.1324°	110.8385°	113.0613°

RESULTS

Table A.18: Target State Errors Summary - Window 6

Parameter	Symbol	Error
Semi-Major Axis	Δa	-16.737 m
Inclination	Δi	-0.000056°
Eccentricity X	Δe_x	0.000005
Eccentricity Y	Δe_y	0.000001
RAAN	$\Delta \Omega$	-0.001538°
Arg. of Perigee	$\Delta \omega$	-0.000°
True Anomaly	$\Delta \nu$	2.223°
Arg. of Latitude	Δu	2.223°

Table A.19: Normal Maneuvers Summary - Window 6. SQP ΔV : 0.335830 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL ($^\circ$)	Thrust Z
2026-02-10 03:03:07	2026-02-10 03:23:07	1200.00	0.081702	0.081702	180.146	1.0
2026-02-10 04:36:38	2026-02-10 04:56:38	1200.00	0.081703	0.163405	180.146	1.0
2026-02-10 06:10:08	2026-02-10 06:30:08	1200.00	0.081704	0.245109	180.146	1.0
2026-02-10 07:43:38	2026-02-10 08:03:38	1200.00	0.081704	0.326813	180.146	1.0
2026-02-10 09:20:42	2026-02-10 09:33:34	771.53	0.052532	0.379345	180.146	1.0
2026-02-11 07:14:36	2026-02-11 07:17:56	199.53	-0.013586	0.365759	180.145	-1.0

Table A.20: Tangential Maneuvers Summary - Window 6. SQP AOL: 162.44° , v_{Tan} SQP: 0.46 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma\Delta V$ [m/s]
2026-02-10 10:46:05	2026-02-10 11:06:05	1200.0	RAISING	123.95	201.23	127.58	162.55	0.081705	0.08
2026-02-10 12:19:36	2026-02-10 12:39:36	1200.0	RAISING	123.96	201.24	125.93	162.56	0.081706	0.16
2026-02-10 13:53:06	2026-02-10 14:13:06	1200.0	RAISING	123.96	201.25	123.97	162.56	0.081706	0.25
2026-02-10 15:33:34	2026-02-10 15:39:39	364.8	RAISING	150.82	174.32	121.65	162.56	0.024842	0.27
2026-02-10 17:08:51	2026-02-10 17:11:25	154.5	RAISING	157.62	167.57	121.03	162.59	0.010521	0.28
2026-02-10 18:42:31	2026-02-10 18:44:46	135.3	RAISING	158.23	166.95	120.90	162.59	0.009214	0.29
2026-02-10 20:15:57	2026-02-10 20:18:21	144.6	RAISING	157.93	167.25	120.87	162.59	0.009847	0.30
2026-02-10 21:49:27	2026-02-10 21:51:53	146.3	RAISING	157.88	167.30	120.82	162.59	0.009959	0.31
2026-02-10 23:22:57	2026-02-10 23:25:23	145.7	RAISING	157.90	167.29	120.78	162.59	0.009924	0.32
2026-02-11 00:56:28	2026-02-11 00:58:54	145.6	RAISING	157.90	167.28	120.75	162.59	0.009912	0.33
2026-02-11 02:29:59	2026-02-11 02:32:24	145.5	RAISING	157.90	167.28	120.73	162.59	0.009910	0.34
2026-02-11 04:03:29	2026-02-11 04:05:55	145.5	RAISING	157.91	167.28	120.73	162.59	0.009908	0.35
2026-02-11 05:37:00	2026-02-11 05:39:26	145.5	RAISING	157.91	167.28	120.75	162.60	0.009906	0.36
2026-02-11 08:42:41	2026-02-11 08:47:48	306.9	RAISING	152.72	172.50	121.87	162.61	0.020895	0.38
2026-02-11 10:17:36	2026-02-11 10:19:54	138.1	RAISING	158.16	167.06	120.99	162.61	0.009403	0.39
2026-02-11 11:51:07	2026-02-11 11:53:24	136.3	RAISING	158.21	166.99	121.14	162.60	0.009284	0.40
2026-02-11 13:24:33	2026-02-11 13:26:59	145.3	RAISING	157.92	167.28	121.50	162.60	0.009894	0.41
2026-02-11 14:58:04	2026-02-11 15:00:30	145.9	RAISING	157.90	167.31	121.95	162.60	0.009936	0.42
2026-02-11 16:31:35	2026-02-11 16:34:00	145.4	RAISING	157.92	167.29	122.65	162.60	0.009900	0.43
2026-02-11 18:05:05	2026-02-11 18:07:31	145.3	RAISING	157.92	167.29	123.81	162.60	0.009893	0.44
2026-02-11 19:38:36	2026-02-11 19:41:01	145.3	RAISING	157.93	167.29	126.01	162.61	0.009891	0.45
2026-02-11 21:12:07	2026-02-11 21:14:32	145.2	RAISING	157.93	167.29	131.32	162.61	0.009889	0.46

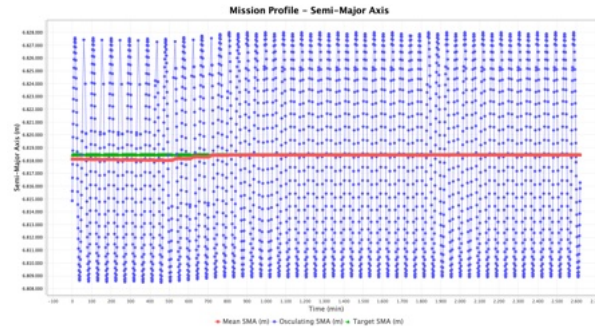


Figure A.29: Evolution of the Semi-Major Axis (a) during Window 6.

RESULTS

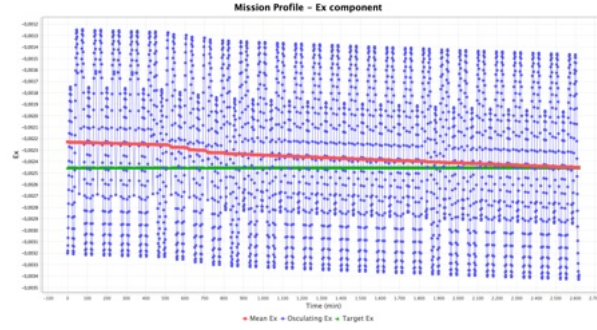


Figure A.30: Evolution of the x-component of the eccentricity vector (e_x) for Window 6.

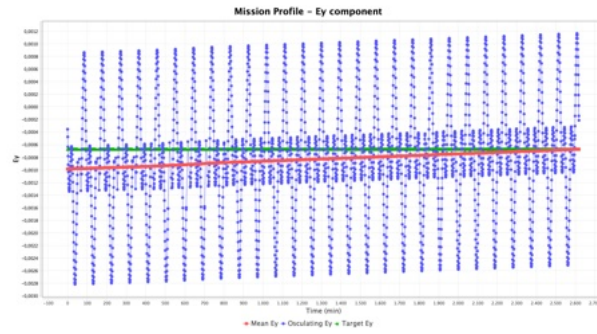


Figure A.31: Evolution of the y-component of the eccentricity vector (e_y) for Window 6.

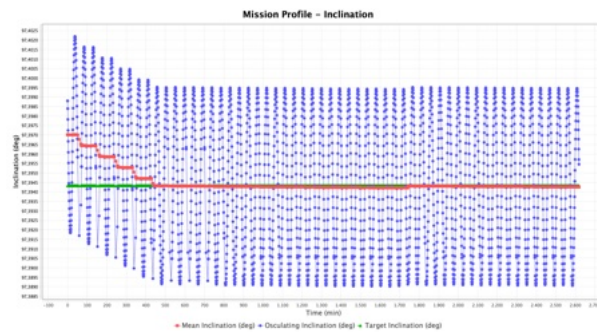


Figure A.32: Evolution of the orbital Inclination (i) in Window 6.

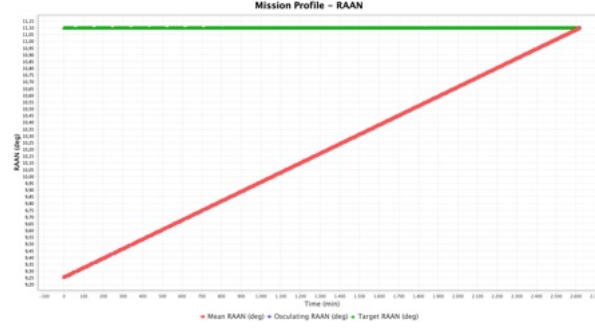


Figure A.33: Evolution of the RAAN (Ω) during Window 6.

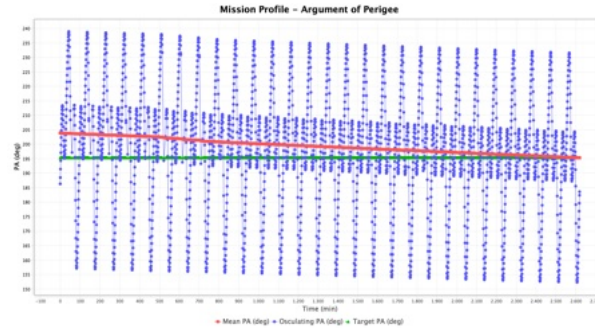


Figure A.34: Evolution of the Argument of Perigee (ω) during Window 6.

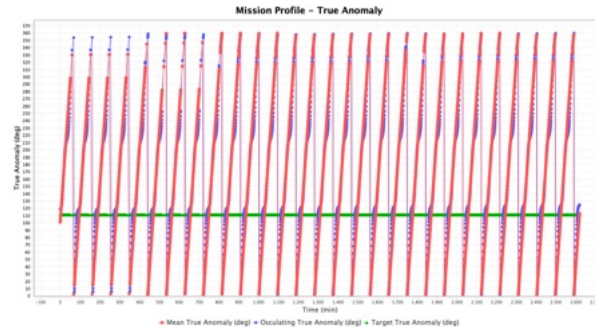


Figure A.35: Evolution of the True Anomaly (ν) throughout Window 6.

A.6 Window 7

Table A.21: Window 7

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-02-11T21:51:05	2026-02-13T17:29:36	2026-02-13T17:29:36
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 818 441.818 m	6 818 847.580 m	6 818 831.018 m
Eccentricity	e	0.002548	0.002677	0.002671
Inclination	i	97.3943°	97.3922°	97.3922°
Arg. of Perigee	ω	195.3312°	187.2085°	187.1923°
RAAN	Ω	11.0988°	12.9440°	12.9425°
True Anomaly	ν	110.8385°	119.3144°	121.4734°

Table A.22: Target State Errors Summary - Window 7

Parameter	Symbol	Error
Semi-Major Axis	Δa	−16.563 m
Inclination	Δi	0.000028°
Eccentricity X	Δe_x	0.000005
Eccentricity Y	Δe_y	0.000001
RAAN	$\Delta \Omega$	−0.001511°
Arg. of Perigee	$\Delta \omega$	−0.016°
True Anomaly	$\Delta \nu$	2.159°
Arg. of Latitude	Δu	2.143°

Table A.23: Normal Maneuvers Summary - Window 7. SQP ΔV : 0.291318 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL ($^\circ$)	Thrust Z
2026-02-11 22:41:20	2026-02-11 23:01:20	1200.00	0.081702	0.081702	180.145	1.0
2026-02-12 00:14:50	2026-02-12 00:34:50	1200.00	0.081703	0.163405	180.145	1.0
2026-02-12 01:48:21	2026-02-12 02:08:21	1200.00	0.081704	0.245109	180.145	1.0
2026-02-12 03:24:33	2026-02-12 03:39:10	877.44	0.059742	0.304851	180.145	1.0

Table A.24: Tangential Maneuvers Summary - Window 7. SQP AOL: 162.88 $^\circ$, v_{Tan} SQP: 0.49 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]
2026-02-12 04:50:56	2026-02-12 05:10:56	1200.0	RAISING	124.39	201.71	121.89	163.01	0.081705	0.08
2026-02-12 06:24:27	2026-02-12 06:44:27	1200.0	RAISING	124.41	201.73	120.13	163.03	0.081705	0.16
2026-02-12 07:57:58	2026-02-12 08:17:58	1200.0	RAISING	124.41	201.73	118.06	163.04	0.081706	0.25
2026-02-12 09:35:03	2026-02-12 09:47:56	772.4	RAISING	138.16	187.94	115.64	163.04	0.052590	0.30
2026-02-12 11:13:43	2026-02-12 11:16:19	155.6	RAISING	158.05	168.08	113.94	163.07	0.010592	0.31
2026-02-12 12:47:27	2026-02-12 12:49:37	130.7	RAISING	158.85	167.28	113.77	163.06	0.008897	0.32
2026-02-12 14:20:52	2026-02-12 14:23:14	142.5	RAISING	158.47	167.66	113.76	163.06	0.009704	0.33
2026-02-12 15:54:22	2026-02-12 15:56:47	144.7	RAISING	158.40	167.73	113.72	163.07	0.009851	0.34
2026-02-12 17:27:53	2026-02-12 17:30:17	144.0	RAISING	158.42	167.71	113.68	163.07	0.009808	0.35
2026-02-12 19:01:25	2026-02-12 19:03:48	143.8	RAISING	158.43	167.71	113.65	163.07	0.009794	0.36
2026-02-12 20:34:56	2026-02-12 20:37:20	143.8	RAISING	158.43	167.71	113.63	163.07	0.009793	0.37
2026-02-12 22:08:27	2026-02-12 22:10:51	143.8	RAISING	158.44	167.71	113.63	163.07	0.009790	0.38
2026-02-12 23:41:58	2026-02-12 23:44:22	143.7	RAISING	158.44	167.71	113.65	163.07	0.009787	0.39
2026-02-13 01:15:29	2026-02-13 01:17:53	143.7	RAISING	158.44	167.71	113.69	163.07	0.009784	0.40
2026-02-13 02:49:00	2026-02-13 02:51:24	143.7	RAISING	158.44	167.71	113.76	163.07	0.009782	0.41
2026-02-13 04:22:32	2026-02-13 04:24:55	143.6	RAISING	158.45	167.71	113.88	163.08	0.009780	0.42
2026-02-13 05:56:03	2026-02-13 05:58:26	143.6	RAISING	158.45	167.71	114.05	163.08	0.009779	0.42
2026-02-13 07:29:34	2026-02-13 07:31:57	143.6	RAISING	158.45	167.71	114.29	163.08	0.009778	0.43
2026-02-13 09:03:05	2026-02-13 09:05:29	143.6	RAISING	158.45	167.71	114.65	163.08	0.009778	0.44
2026-02-13 10:36:36	2026-02-13 10:39:00	143.6	RAISING	158.45	167.71	115.19	163.08	0.009777	0.45
2026-02-13 12:10:07	2026-02-13 12:12:31	143.6	RAISING	158.45	167.71	116.02	163.08	0.009777	0.46
2026-02-13 13:43:38	2026-02-13 13:46:02	143.6	RAISING	158.45	167.71	117.40	163.08	0.009776	0.47
2026-02-13 15:17:10	2026-02-13 15:19:33	143.6	RAISING	158.46	167.71	120.00	163.08	0.009775	0.48
2026-02-13 16:50:41	2026-02-13 16:53:04	143.5	RAISING	158.46	167.71	126.28	163.08	0.009773	0.49

RESULTS

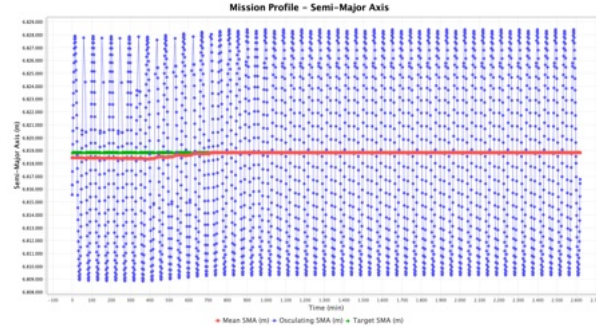


Figure A.36: Evolution of the Semi-Major Axis (a) during Window 7.

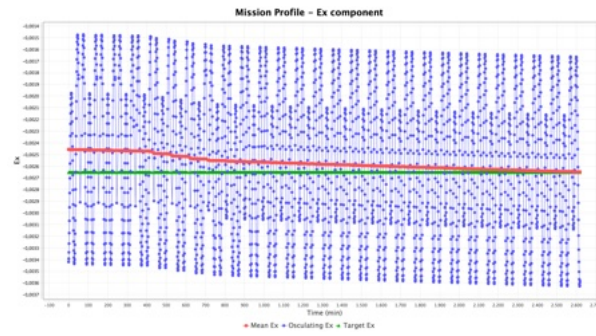


Figure A.37: Evolution of the x-component of the eccentricity vector (e_x) for Window 7.

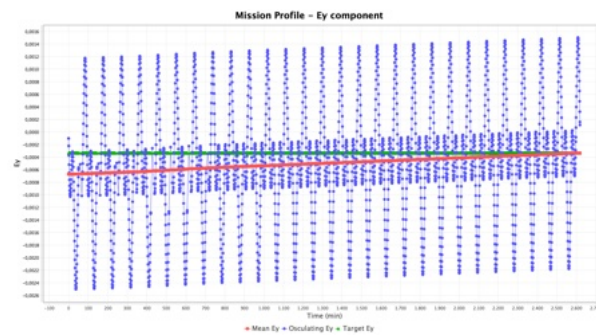


Figure A.38: Evolution of the y-component of the eccentricity vector (e_y) for Window 7.

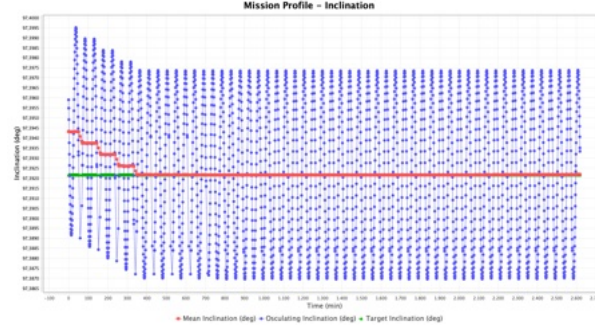


Figure A.39: Evolution of the orbital Inclination (i) in Window 7.

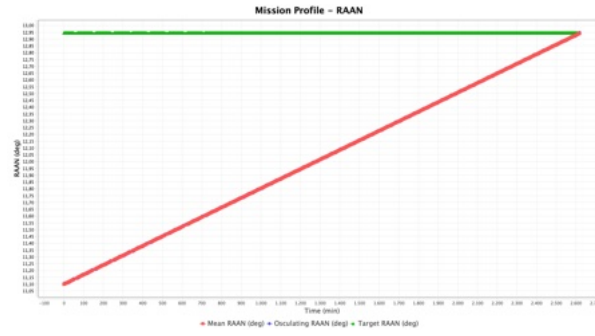


Figure A.40: Evolution of the RAAN (Ω) during Window 7.

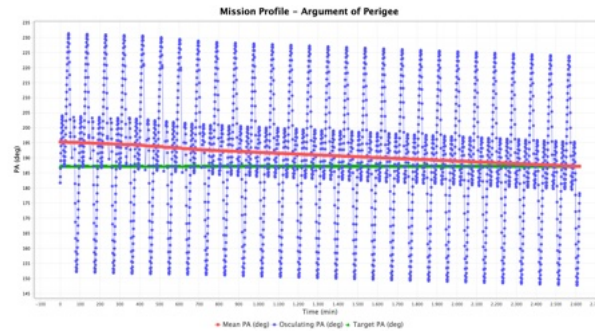


Figure A.41: Evolution of the Argument of Perigee (ω) during Window 7.

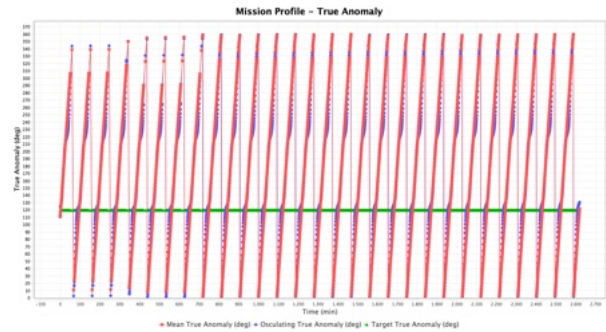


Figure A.42: Evolution of the True Anomaly (ν) throughout Window 7.

A.7 Window 8

Table A.25: Window 8

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-02-13T17:29:36	2026-02-15T13:08:06	2026-02-15T13:08:06
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 818 847.580 m	6 818 798.089 m	6 818 781.353 m
Eccentricity	e	0.002677	0.002750	0.002751
Inclination	i	97.3922°	97.3903°	97.3904°
Arg. of Perigee	ω	187.2085°	180.0375°	180.0095°
RAAN	Ω	12.9440°	14.7886°	14.7872°
True Anomaly	ν	119.3144°	126.4123°	128.8957°

Table A.26: Target State Errors Summary - Window 8

Parameter	Symbol	Error
Semi-Major Axis	Δa	-16.735 m
Inclination	Δi	0.000073°
Eccentricity X	Δe_x	-0.000000
Eccentricity Y	Δe_y	0.000001
RAAN	$\Delta \Omega$	-0.001332°
Arg. of Perigee	$\Delta \omega$	-0.028°
True Anomaly	$\Delta \nu$	2.483°
Arg. of Latitude	Δu	2.455°

Table A.27: Normal Maneuvers Summary - Window 8. SQP ΔV : 0.285298 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL (°)	Thrust Z
2026-02-13 18:19:45	2026-02-13 18:39:45	1200.00	0.081702	0.081702	180.144	1.0
2026-02-13 19:53:16	2026-02-13 20:13:16	1200.00	0.081703	0.163405	180.144	1.0
2026-02-13 21:26:47	2026-02-13 21:46:47	1200.00	0.081704	0.245109	180.144	1.0
2026-02-13 23:08:10	2026-02-13 23:12:26	255.39	0.017388	0.262497	180.144	1.0
2026-02-14 19:24:15	2026-02-14 19:27:48	212.55	0.014472	0.276969	180.144	1.0
2026-02-15 07:52:30	2026-02-15 07:55:51	201.25	0.013703	0.290672	180.143	1.0

RESULTS

Table A.28: Tangential Maneuvers Summary - Window 8. SQP AOL: 162.72° , v_{Tan} SQP: 0.24 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma\Delta V$ [m/s]
2026-02-14 00:37:41	2026-02-14 00:41:04	203.2	RAISING	156.38	169.49	106.77	162.94	0.013838	0.01
2026-02-14 02:11:47	2026-02-14 02:14:00	133.1	RAISING	158.64	167.23	106.44	162.93	0.009061	0.02
2026-02-14 03:45:15	2026-02-14 03:47:34	139.4	RAISING	158.44	167.43	106.33	162.93	0.009492	0.03
2026-02-14 05:18:43	2026-02-14 05:21:07	143.8	RAISING	158.30	167.57	106.22	162.93	0.009788	0.04
2026-02-14 06:52:15	2026-02-14 06:54:38	143.6	RAISING	158.30	167.57	106.09	162.93	0.009779	0.05
2026-02-14 08:25:46	2026-02-14 08:28:09	143.4	RAISING	158.31	167.56	105.97	162.94	0.009762	0.06
2026-02-14 09:59:17	2026-02-14 10:01:40	143.4	RAISING	158.31	167.56	105.84	162.94	0.009762	0.07
2026-02-14 11:32:48	2026-02-14 11:35:11	143.4	RAISING	158.31	167.56	105.71	162.94	0.009763	0.08
2026-02-14 13:06:19	2026-02-14 13:08:42	143.4	RAISING	158.32	167.56	105.58	162.94	0.009763	0.09
2026-02-14 14:39:50	2026-02-14 14:42:14	143.4	RAISING	158.32	167.56	105.45	162.94	0.009762	0.10
2026-02-14 16:13:21	2026-02-14 16:15:45	143.4	RAISING	158.32	167.56	105.32	162.94	0.009761	0.11
2026-02-14 17:46:52	2026-02-14 17:49:16	143.3	RAISING	158.32	167.56	105.18	162.94	0.009759	0.12
2026-02-14 20:52:36	2026-02-14 20:57:37	301.5	RAISING	153.23	172.67	105.88	162.95	0.020526	0.14
2026-02-14 22:27:29	2026-02-14 22:29:46	136.6	RAISING	158.55	167.36	104.72	162.95	0.009303	0.15
2026-02-15 00:01:01	2026-02-15 00:03:16	134.5	RAISING	158.61	167.28	104.55	162.95	0.009159	0.16
2026-02-15 01:34:28	2026-02-15 01:36:51	143.0	RAISING	158.33	167.56	104.45	162.95	0.009740	0.17
2026-02-15 03:07:59	2026-02-15 03:10:22	143.6	RAISING	158.32	167.58	104.29	162.95	0.009780	0.18
2026-02-15 04:41:30	2026-02-15 04:43:53	143.1	RAISING	158.33	167.57	104.09	162.95	0.009746	0.19
2026-02-15 06:15:01	2026-02-15 06:17:24	143.1	RAISING	158.34	167.56	103.88	162.95	0.009741	0.20
2026-02-15 09:20:44	2026-02-15 09:25:46	301.6	RAISING	153.23	172.69	106.68	162.96	0.020535	0.22
2026-02-15 10:55:38	2026-02-15 10:57:54	136.1	RAISING	158.57	167.35	102.53	162.96	0.009267	0.23
2026-02-15 12:29:10	2026-02-15 12:31:24	134.3	RAISING	158.62	167.29	101.03	162.95	0.009145	0.24

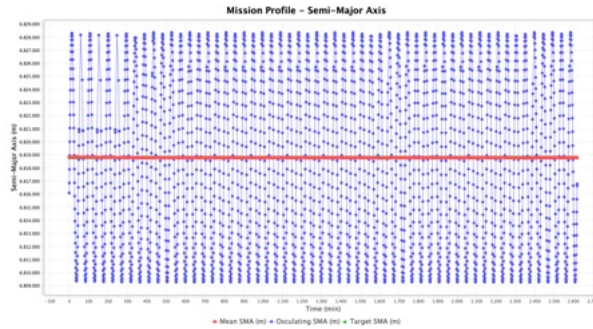


Figure A.43: Evolution of the Semi-Major Axis (a) during Window 8.

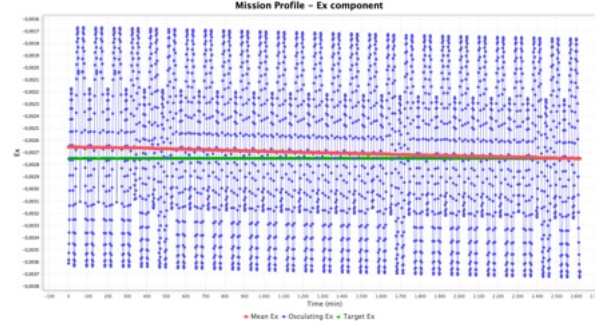


Figure A.44: Evolution of the x-component of the eccentricity vector (e_x) for Window 8.

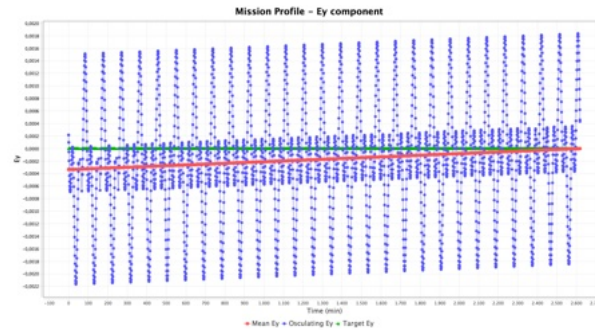


Figure A.45: Evolution of the y-component of the eccentricity vector (e_y) for Window 8.

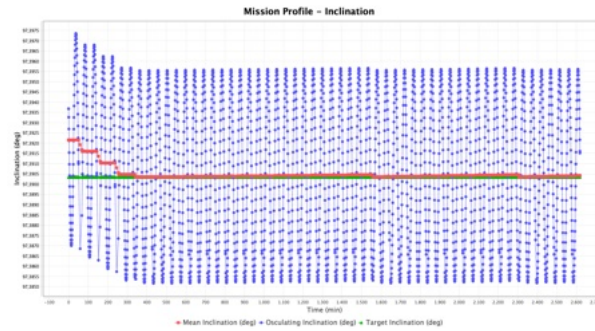


Figure A.46: Evolution of the orbital Inclination (i) in Window 8.

RESULTS

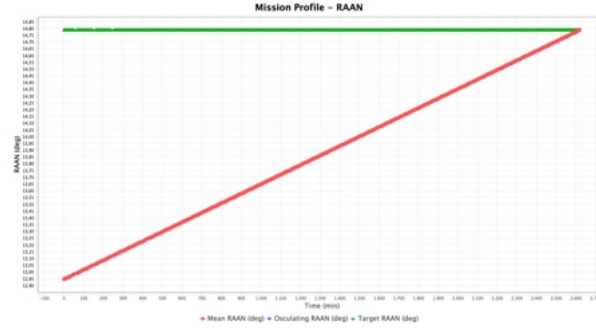


Figure A.47: Evolution of the RAAN (Ω) during Window 8.

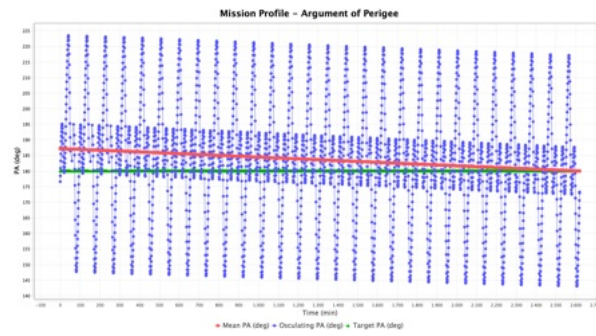


Figure A.48: Evolution of the Argument of Perigee (ω) during Window 8.

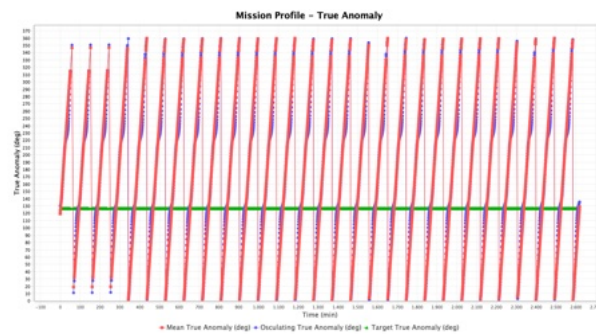


Figure A.49: Evolution of the True Anomaly (ν) throughout Window 8.

A.8 Window 9

Table A.29: Window 9

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-02-15T13:08:06	2026-02-17T08:46:37	2026-02-17T08:46:37
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 818 798.089 m	6 818 504.776 m	6 818 489.380 m
Eccentricity	e	0.002750	0.002792	0.002795
Inclination	i	97.3903°	97.3885°	97.3885°
Arg. of Perigee	ω	180.0375°	173.3146°	173.3084°
RAAN	Ω	14.7886°	16.6329°	16.6317°
True Anomaly	ν	126.4123°	133.4213°	136.0700°

Table A.30: Target State Errors Summary - Window 9

Parameter	Symbol	Error
Semi-Major Axis	Δa	−15.396 m
Inclination	Δi	0.000084°
Eccentricity X	Δe_x	−0.000003
Eccentricity Y	Δe_y	0.000001
RAAN	$\Delta \Omega$	−0.001259°
Arg. of Perigee	$\Delta \omega$	−0.006°
True Anomaly	$\Delta \nu$	2.649°
Arg. of Latitude	Δu	2.642°

RESULTS

Table A.31: Normal Maneuvers Summary - Window 9. SQP ΔV : 0.331632 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL ($^\circ$)	Thrust Z
2026-02-15 13:58:16	2026-02-15 14:18:16	1200.00	0.081702	0.081702	180.143	1.0
2026-02-15 15:31:47	2026-02-15 15:51:47	1200.00	0.081703	0.163405	180.143	1.0
2026-02-15 17:05:18	2026-02-15 17:25:18	1200.00	0.081704	0.245109	180.143	1.0
2026-02-15 18:44:57	2026-02-15 18:52:40	462.98	0.031523	0.276632	180.143	1.0
2026-02-16 04:08:11	2026-02-16 04:11:36	205.92	0.014021	0.290652	180.143	1.0
2026-02-16 13:29:00	2026-02-16 13:32:55	234.79	0.015987	0.306639	180.143	1.0
2026-02-16 21:16:46	2026-02-16 21:20:16	209.48	0.014263	0.320903	180.142	1.0
2026-02-17 05:04:15	2026-02-17 05:07:54	219.24	0.014928	0.335830	180.142	1.0

Table A.32: Tangential Maneuvers Summary - Window 9. SQP AOL: 167.90°, v_{Tan} SQP: 0.10 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]
2026-02-15 20:09:14	2026-02-15 20:29:14	1200.0	BRAKING	129.49	206.88	274.32	168.17	-0.081704	-0.08
2026-02-15 21:48:47	2026-02-15 21:56:42	474.1	BRAKING	152.84	183.43	278.26	168.13	-0.032280	-0.11
2026-02-15 23:24:54	2026-02-15 23:27:38	164.5	RAISING	162.87	173.49	100.27	168.18	0.011201	-0.10
2026-02-16 00:58:38	2026-02-16 01:00:55	137.4	RAISING	163.75	172.61	100.03	168.18	0.009355	-0.09
2026-02-16 02:32:06	2026-02-16 02:34:29	142.4	RAISING	163.59	172.77	99.89	168.18	0.009696	-0.08
2026-02-16 05:37:52	2026-02-16 05:42:46	294.1	RAISING	158.70	177.67	100.22	168.18	0.020022	-0.06
2026-02-16 07:12:39	2026-02-16 07:15:01	142.0	RAISING	163.60	172.77	99.41	168.19	0.009671	-0.05
2026-02-16 08:46:11	2026-02-16 08:48:29	138.3	RAISING	163.72	172.64	99.22	168.18	0.009413	-0.04
2026-02-16 10:19:39	2026-02-16 10:22:03	143.4	RAISING	163.56	172.81	99.07	168.18	0.009761	-0.03
2026-02-16 11:53:10	2026-02-16 11:55:34	143.7	RAISING	163.55	172.82	98.89	168.19	0.009787	-0.03
2026-02-16 14:58:56	2026-02-16 15:03:50	293.2	RAISING	158.73	177.65	99.44	168.19	0.019964	-0.01
2026-02-16 16:33:43	2026-02-16 16:36:05	142.5	RAISING	163.59	172.79	98.26	168.19	0.009704	0.00
2026-02-16 18:07:15	2026-02-16 18:09:34	138.3	RAISING	163.73	172.65	97.98	168.19	0.009416	0.01
2026-02-16 19:40:44	2026-02-16 19:43:07	143.3	RAISING	163.57	172.81	97.75	168.19	0.009755	0.02
2026-02-16 22:46:30	2026-02-16 22:51:23	293.5	RAISING	158.72	177.66	98.70	168.19	0.019986	0.04
2026-02-17 00:21:16	2026-02-17 00:23:38	142.1	RAISING	163.61	172.78	96.64	168.20	0.009675	0.05
2026-02-17 01:54:49	2026-02-17 01:57:07	138.2	RAISING	163.74	172.65	96.02	168.19	0.009409	0.06
2026-02-17 03:28:17	2026-02-17 03:30:40	143.2	RAISING	163.57	172.82	95.34	168.19	0.009749	0.07
2026-02-17 06:34:03	2026-02-17 06:38:57	293.4	RAISING	158.73	177.66	97.32	168.20	0.019979	0.09
2026-02-17 08:08:50	2026-02-17 08:11:12	142.1	RAISING	163.62	172.79	86.98	168.20	0.009676	0.10

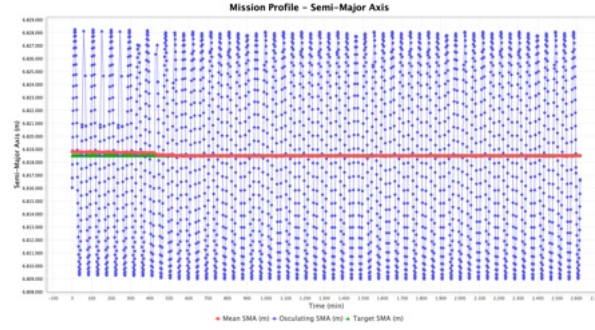


Figure A.50: Evolution of the Semi-Major Axis (a) during Window 9.

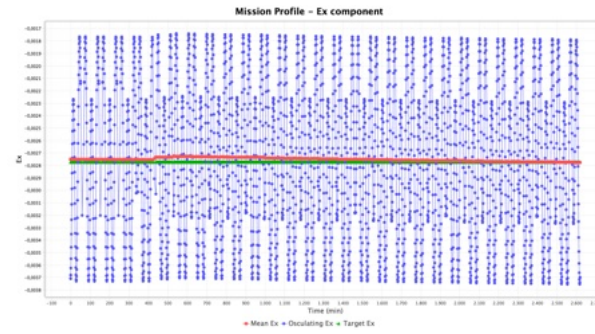


Figure A.51: Evolution of the x-component of the eccentricity vector (e_x) for Window 9.

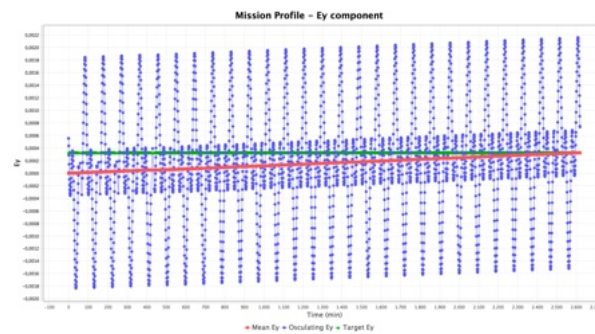


Figure A.52: Evolution of the y-component of the eccentricity vector (e_y) for Window 9.

RESULTS

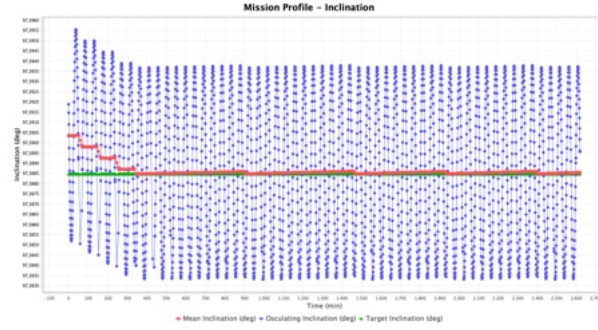


Figure A.53: Evolution of the orbital Inclination (i) in Window 9.

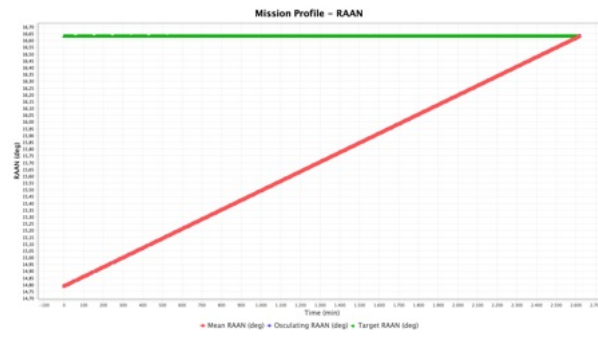


Figure A.54: Evolution of the RAAN (Ω) during Window 9.

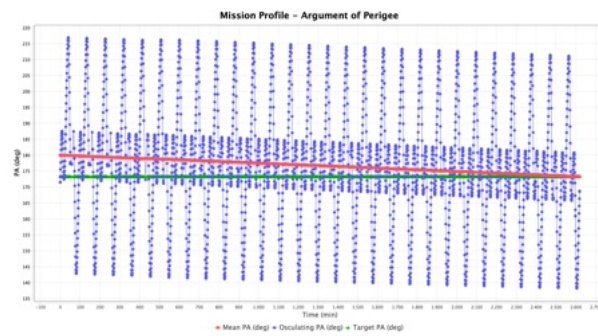


Figure A.55: Evolution of the Argument of Perigee (ω) during Window 9.

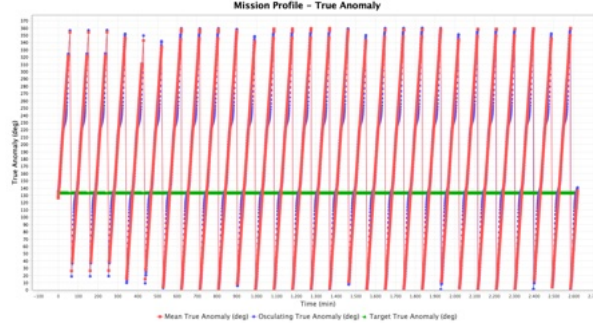


Figure A.56: Evolution of the True Anomaly (ν) throughout Window 9.

A.9 Window 10

Table A.33: Window 10

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-02-17T08:46:37	2026-02-19T04:25:08	2026-02-19T04:25:08
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 818 504.776 m	6 817 820.577 m	6 817 785.663 m
Eccentricity	e	0.002792	0.002778	0.002782
Inclination	i	97.3885°	97.3865°	97.3865°
Arg. of Perigee	ω	173.3146°	166.7479°	166.7754°
RAAN	Ω	16.6329°	18.4774°	18.4763°
True Anomaly	ν	133.4213°	141.3229°	144.1704°

Table A.34: Target State Errors Summary - Window 10

Parameter	Symbol	Error
Semi-Major Axis	Δa	-34.914 m
Inclination	Δi	0.000035°
Eccentricity X	Δe_x	-0.000004
Eccentricity Y	Δe_y	-0.000000
RAAN	$\Delta \Omega$	-0.001170°
Arg. of Perigee	$\Delta \omega$	0.028°
True Anomaly	$\Delta \nu$	2.848°
Arg. of Latitude	Δu	2.875°

Table A.35: Normal Maneuvers Summary - Window 10. SQP ΔV : 0.352431 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL (°)	Thrust Z
2026-02-17 09:36:41	2026-02-17 09:56:41	1200.00	0.081702	0.081702	180.142	1.0
2026-02-17 11:10:12	2026-02-17 11:30:12	1200.00	0.081703	0.163405	180.142	1.0
2026-02-17 12:43:42	2026-02-17 13:03:42	1200.00	0.081704	0.245109	180.142	1.0
2026-02-17 14:21:46	2026-02-17 14:32:40	653.86	0.044519	0.289628	180.142	1.0
2026-02-17 20:39:36	2026-02-17 20:42:53	197.13	0.013423	0.303050	180.142	1.0
2026-02-18 04:26:52	2026-02-18 04:30:35	223.05	0.015187	0.318238	180.142	1.0
2026-02-18 12:14:18	2026-02-18 12:18:09	230.91	0.015722	0.333960	180.141	1.0
2026-02-18 20:01:50	2026-02-18 20:05:35	224.57	0.015291	0.349251	180.141	1.0
2026-02-19 03:49:24	2026-02-19 03:52:59	214.51	0.014606	0.363857	180.141	1.0

Table A.36: Tangential Maneuvers Summary - Window 10. SQP AOL: 169.02° , v_{Tan} SQP: -0.12 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma\Delta V$ [m/s]
2026-02-17 15:47:56	2026-02-17 16:07:56	1200.0	BRAKING	130.60	208.00	256.21	169.29	-0.081704	-0.08
2026-02-17 17:21:26	2026-02-17 17:41:26	1200.0	BRAKING	130.57	207.98	260.06	169.27	-0.081705	-0.16
2026-02-17 18:54:56	2026-02-17 19:14:56	1200.0	BRAKING	130.57	207.98	264.29	169.27	-0.081706	-0.25
2026-02-17 22:05:00	2026-02-17 22:18:53	832.5	BRAKING	142.46	196.18	269.18	169.32	-0.056684	-0.30
2026-02-17 23:44:16	2026-02-17 23:46:36	139.6	RAISING	164.80	173.81	92.94	169.30	0.009505	-0.29
2026-02-18 01:17:42	2026-02-18 01:20:11	148.6	RAISING	164.52	174.12	92.77	169.32	0.010121	-0.28
2026-02-18 02:51:14	2026-02-18 02:53:39	145.2	RAISING	164.64	174.01	92.52	169.32	0.009886	-0.27
2026-02-18 05:56:59	2026-02-18 06:01:53	294.4	RAISING	159.82	178.82	92.83	169.32	0.020048	-0.25
2026-02-18 07:31:44	2026-02-18 07:34:08	144.4	RAISING	164.67	173.98	91.73	169.33	0.009831	-0.24
2026-02-18 09:05:16	2026-02-18 09:07:36	140.4	RAISING	164.79	173.85	91.41	169.32	0.009558	-0.23
2026-02-18 10:38:43	2026-02-18 10:41:08	144.7	RAISING	164.66	173.99	91.10	169.32	0.009851	-0.22
2026-02-18 13:44:28	2026-02-18 13:49:23	294.7	RAISING	159.82	178.83	91.52	169.32	0.020063	-0.20
2026-02-18 15:19:13	2026-02-18 15:21:37	144.5	RAISING	164.67	173.99	89.82	169.33	0.009840	-0.19
2026-02-18 16:52:45	2026-02-18 16:55:05	140.4	RAISING	164.80	173.86	89.21	169.33	0.009560	-0.18
2026-02-18 18:26:13	2026-02-18 18:28:37	144.7	RAISING	164.66	174.00	88.56	169.33	0.009850	-0.17
2026-02-18 21:31:57	2026-02-18 21:36:52	294.5	RAISING	159.83	178.83	88.87	169.33	0.020050	-0.15
2026-02-18 23:06:42	2026-02-18 23:09:07	144.5	RAISING	164.67	174.00	84.87	169.33	0.009837	-0.14
2026-02-19 00:40:14	2026-02-19 00:42:35	140.4	RAISING	164.80	173.86	82.30	169.33	0.009559	-0.13
2026-02-19 02:13:42	2026-02-19 02:16:07	144.6	RAISING	164.67	174.00	77.98	169.33	0.009846	-0.12

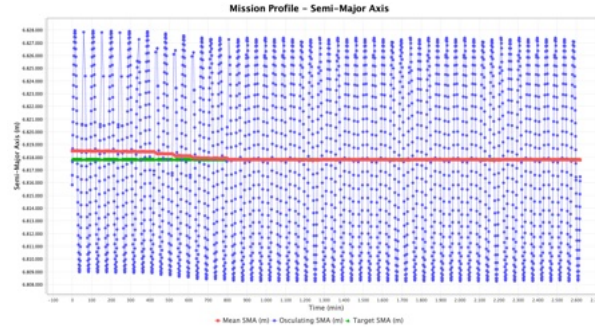


Figure A.57: Evolution of the Semi-Major Axis (a) during Window 10.

RESULTS

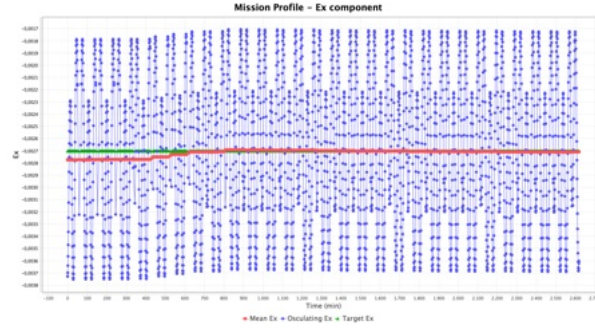


Figure A.58: Evolution of the x-component of the eccentricity vector (e_x) for Window 10.

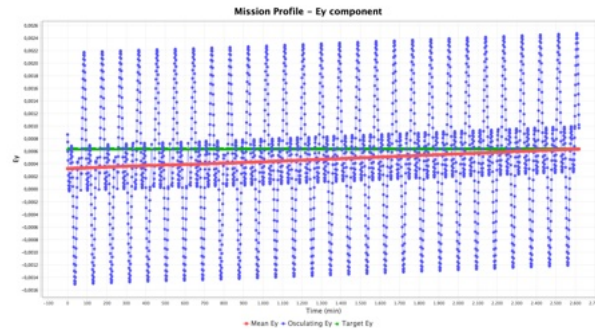


Figure A.59: Evolution of the y-component of the eccentricity vector (e_y) for Window 10.

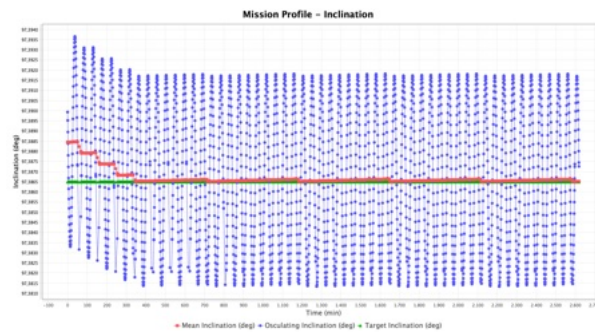


Figure A.60: Evolution of the orbital Inclination (i) in Window 10.

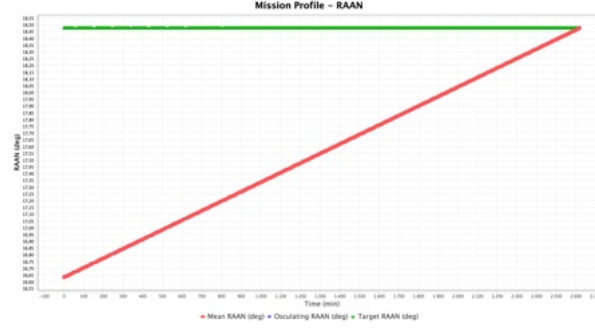


Figure A.61: Evolution of the RAAN (Ω) during Window 10.

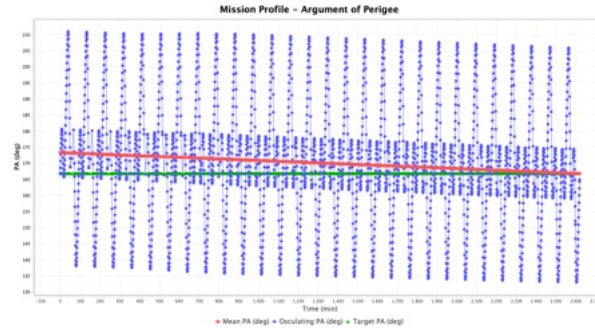


Figure A.62: Evolution of the Argument of Perigee (ω) during Window 10.

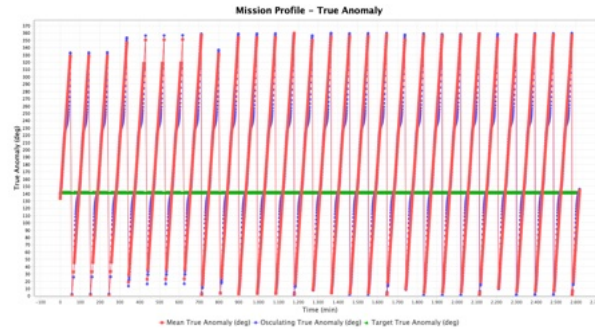


Figure A.63: Evolution of the True Anomaly (ν) throughout Window 10.

A.10 Window 11

Table A.37: Window 11

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-02-19T04:25:08	2026-02-21T00:03:39	2026-02-21T00:03:39
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 817 820.577 m	6 817 763.650 m	6 817 738.737 m
Eccentricity	e	0.002778	0.002855	0.002857
Inclination	i	97.3865°	97.3842°	97.3843°
Arg. of Perigee	ω	166.7479°	160.3666°	160.3665°
RAAN	Ω	18.4774°	20.3219°	20.3205°
True Anomaly	ν	141.3229°	149.8890°	152.3469°

Table A.38: Target State Errors Summary - Window 11

Parameter	Symbol	Error
Semi-Major Axis	Δa	−24.913 m
Inclination	Δi	0.000096°
Eccentricity X	Δe_x	−0.000001
Eccentricity Y	Δe_y	0.000001
RAAN	$\Delta \Omega$	−0.001390°
Arg. of Perigee	$\Delta \omega$	−0.000°
True Anomaly	$\Delta \nu$	2.458°
Arg. of Latitude	Δu	2.458°

Table A.39: Normal Maneuvers Summary - Window 11. SQP ΔV : 0.360509 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL ($^{\circ}$)	Thrust Z
2026-02-19 05:14:49	2026-02-19 05:34:49	1200.00	0.081702	0.081702	180.141	1.0
2026-02-19 06:48:19	2026-02-19 07:08:19	1200.00	0.081703	0.163405	180.141	1.0
2026-02-19 08:21:49	2026-02-19 08:41:49	1200.00	0.081704	0.245109	180.141	1.0
2026-02-19 09:55:34	2026-02-19 10:15:04	1170.57	0.079701	0.324810	180.141	1.0
2026-02-19 16:17:25	2026-02-19 16:21:11	225.81	0.015375	0.340185	180.140	1.0
2026-02-20 01:38:33	2026-02-20 01:42:00	206.92	0.014088	0.354273	180.140	1.0
2026-02-20 12:33:03	2026-02-20 12:36:27	203.73	0.013871	0.368144	180.140	1.0

Table A.40: Tangential Maneuvers Summary - Window 11. SQP AOL: 169.30 $^{\circ}$, v_{Tan} SQP: 0.24 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^{\circ}$)	End AOL ($^{\circ}$)	Ideal AOL ($^{\circ}$)	Ctr AOL ($^{\circ}$)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]
2026-02-19 11:34:59	2026-02-19 11:37:10	130.5	RAISING	165.32	173.74	88.57	169.53	0.008884	0.01
2026-02-19 13:08:21	2026-02-19 13:10:50	148.2	RAISING	164.83	174.40	88.58	169.62	0.010092	0.02
2026-02-19 14:41:52	2026-02-19 14:44:18	145.7	RAISING	164.91	174.32	88.45	169.62	0.009922	0.03
2026-02-19 17:47:38	2026-02-19 17:52:32	294.1	RAISING	160.12	179.11	88.82	169.62	0.020025	0.05
2026-02-19 19:22:22	2026-02-19 19:24:47	144.7	RAISING	164.95	174.29	88.05	169.62	0.009855	0.06
2026-02-19 20:55:54	2026-02-19 20:58:15	140.7	RAISING	165.08	174.16	87.91	169.62	0.009582	0.07
2026-02-19 22:29:22	2026-02-19 22:31:47	144.7	RAISING	164.95	174.29	87.79	169.62	0.009855	0.08
2026-02-20 00:02:52	2026-02-20 00:05:17	145.0	RAISING	164.94	174.30	87.66	169.62	0.009875	0.09
2026-02-20 03:08:36	2026-02-20 03:13:31	294.5	RAISING	160.12	179.12	88.28	169.62	0.020051	0.11
2026-02-20 04:43:21	2026-02-20 04:45:46	144.4	RAISING	164.96	174.29	87.23	169.62	0.009832	0.12
2026-02-20 06:16:53	2026-02-20 06:19:14	140.6	RAISING	165.08	174.16	87.06	169.62	0.009576	0.13
2026-02-20 07:50:21	2026-02-20 07:52:45	144.7	RAISING	164.95	174.30	86.94	169.62	0.009856	0.14
2026-02-20 09:23:50	2026-02-20 09:26:15	145.1	RAISING	164.94	174.31	86.78	169.62	0.009876	0.15
2026-02-20 10:57:20	2026-02-20 10:59:45	144.9	RAISING	164.95	174.30	86.61	169.63	0.009867	0.16
2026-02-20 14:03:05	2026-02-20 14:08:00	294.7	RAISING	160.11	179.14	88.00	169.62	0.020065	0.18
2026-02-20 15:37:50	2026-02-20 15:40:14	144.3	RAISING	164.97	174.29	86.00	169.63	0.009827	0.19
2026-02-20 17:11:21	2026-02-20 17:13:42	140.7	RAISING	165.09	174.17	85.69	169.63	0.009580	0.20
2026-02-20 18:44:49	2026-02-20 18:47:14	144.8	RAISING	164.95	174.30	85.42	169.63	0.009858	0.21
2026-02-20 20:18:19	2026-02-20 20:20:44	145.1	RAISING	164.95	174.31	84.97	169.63	0.009877	0.22
2026-02-20 21:51:49	2026-02-20 21:54:14	144.9	RAISING	164.95	174.31	84.22	169.63	0.009867	0.23
2026-02-20 23:25:19	2026-02-20 23:27:43	144.9	RAISING	164.95	174.31	82.51	169.63	0.009865	0.24

RESULTS

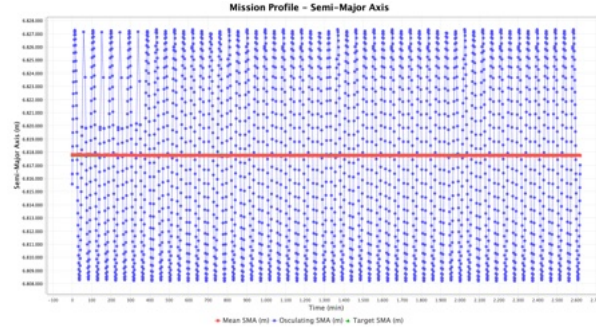


Figure A.64: Evolution of the Semi-Major Axis (a) during Window 11.

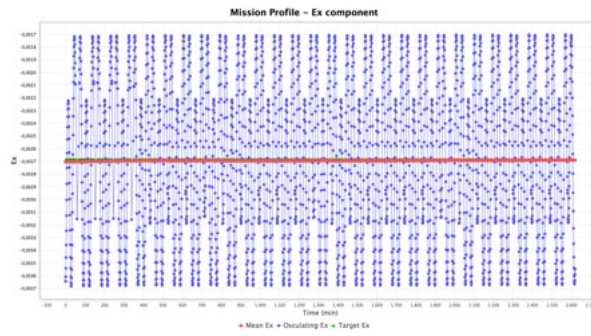


Figure A.65: Evolution of the x-component of the eccentricity vector (e_x) for Window 11.



Figure A.66: Evolution of the y-component of the eccentricity vector (e_y) for Window 11.

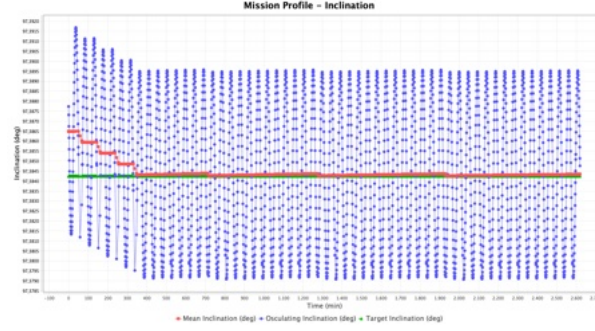


Figure A.67: Evolution of the orbital Inclination (i) in Window 11.

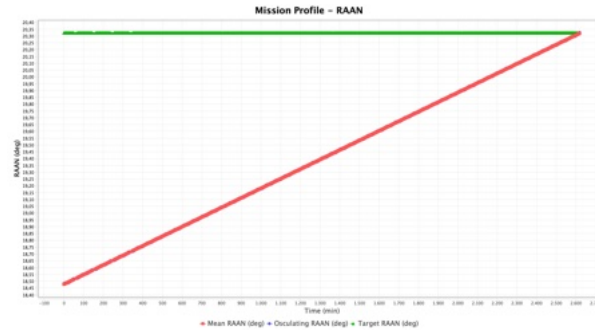


Figure A.68: Evolution of the RAAN (Ω) during Window 11.

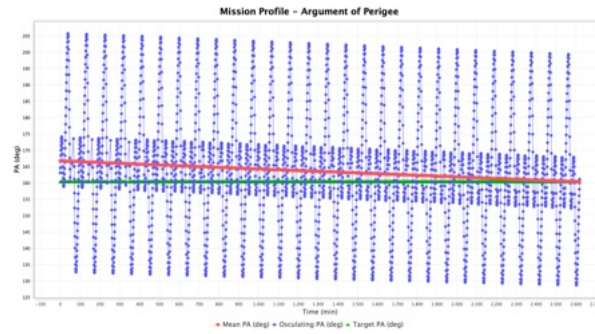


Figure A.69: Evolution of the Argument of Perigee (ω) during Window 11.

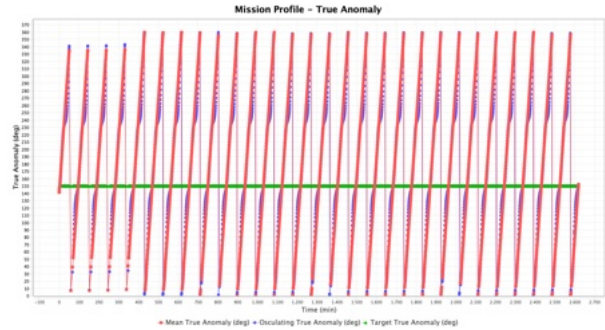


Figure A.70: Evolution of the True Anomaly (ν) throughout Window 11.

A.11 Window 12

Table A.41: Window 12

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-02-21T00:03:39	2026-02-22T19:42:10	2026-02-22T19:42:10
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 817 763.650 m	6 817 664.631 m	6 817 640.611 m
Eccentricity	e	0.002855	0.002925	0.002926
Inclination	i	97.3842°	97.3821°	97.3821°
Arg. of Perigee	ω	160.3666°	154.1402°	154.1492°
RAAN	Ω	20.3219°	22.1658°	22.1644°
True Anomaly	ν	149.8890°	158.4631°	160.9402°

Table A.42: Target State Errors Summary - Window 12

Parameter	Symbol	Error
Semi-Major Axis	Δa	-24.020 m
Inclination	Δi	0.000039°
Eccentricity X	Δe_x	-0.000001
Eccentricity Y	Δe_y	0.000000
RAAN	$\Delta \Omega$	-0.001375°
Arg. of Perigee	$\Delta \omega$	0.009°
True Anomaly	$\Delta \nu$	2.477°
Arg. of Latitude	Δu	2.486°

Table A.43: Normal Maneuvers Summary - Window 12. SQP ΔV : 0.300760 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL (°)	Thrust Z
2026-02-21 00:52:45	2026-02-21 01:12:45	1200.00	0.081702	0.081702	180.139	1.0
2026-02-21 02:26:15	2026-02-21 02:46:15	1200.00	0.081703	0.163405	180.139	1.0
2026-02-21 03:59:45	2026-02-21 04:19:45	1200.00	0.081704	0.245109	180.139	1.0
2026-02-21 05:34:50	2026-02-21 05:51:39	1008.71	0.068680	0.313789	180.139	1.0

RESULTS

Table A.44: Tangential Maneuvers Summary - Window 12. SQP AOL: 169.00° , v_{Tan} SQP: 0.21 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]
2026-02-21 07:11:57	2026-02-21 07:15:54	237.4	BRAKING	160.79	176.93	260.79	169.27	-0.016163	-0.02
2026-02-21 08:46:06	2026-02-21 08:48:47	161.1	RAISING	164.14	174.53	82.15	169.33	0.010966	-0.01
2026-02-21 10:19:45	2026-02-21 10:22:07	142.7	RAISING	164.73	173.94	81.96	169.33	0.009716	0.00
2026-02-21 11:53:13	2026-02-21 11:55:38	144.5	RAISING	164.67	174.00	81.84	169.33	0.009837	0.01
2026-02-21 13:26:43	2026-02-21 13:29:08	145.3	RAISING	164.65	174.02	81.72	169.33	0.009891	0.02
2026-02-21 15:00:12	2026-02-21 15:02:38	145.2	RAISING	164.65	174.02	81.59	169.33	0.009889	0.03
2026-02-21 16:33:42	2026-02-21 16:36:07	145.2	RAISING	164.65	174.02	81.46	169.34	0.009887	0.04
2026-02-21 18:07:12	2026-02-21 18:09:37	145.2	RAISING	164.65	174.02	81.33	169.34	0.009887	0.05
2026-02-21 19:40:41	2026-02-21 19:43:07	145.2	RAISING	164.65	174.02	81.20	169.34	0.009887	0.06
2026-02-21 21:14:11	2026-02-21 21:16:36	145.2	RAISING	164.65	174.02	81.06	169.34	0.009887	0.07
2026-02-21 22:47:41	2026-02-21 22:50:06	145.2	RAISING	164.65	174.02	80.93	169.34	0.009887	0.08
2026-02-22 00:21:10	2026-02-22 00:23:36	145.2	RAISING	164.65	174.02	80.79	169.34	0.009886	0.09
2026-02-22 01:54:40	2026-02-22 01:57:05	145.2	RAISING	164.65	174.02	80.64	169.34	0.009887	0.10
2026-02-22 03:28:10	2026-02-22 03:30:35	145.2	RAISING	164.65	174.02	80.50	169.34	0.009887	0.11
2026-02-22 05:01:39	2026-02-22 05:04:05	145.2	RAISING	164.65	174.03	80.34	169.34	0.009888	0.12
2026-02-22 06:35:09	2026-02-22 06:37:34	145.2	RAISING	164.65	174.03	80.18	169.34	0.009889	0.13
2026-02-22 08:08:39	2026-02-22 08:11:04	145.2	RAISING	164.65	174.03	80.01	169.34	0.009890	0.14
2026-02-22 09:42:08	2026-02-22 09:44:34	145.3	RAISING	164.65	174.03	79.82	169.34	0.009891	0.15
2026-02-22 11:15:38	2026-02-22 11:18:03	145.3	RAISING	164.65	174.03	79.61	169.34	0.009892	0.16
2026-02-22 12:49:08	2026-02-22 12:51:33	145.3	RAISING	164.65	174.03	79.37	169.34	0.009893	0.17
2026-02-22 14:22:37	2026-02-22 14:25:03	145.3	RAISING	164.65	174.03	79.06	169.34	0.009894	0.18
2026-02-22 15:56:07	2026-02-22 15:58:32	145.3	RAISING	164.65	174.03	78.65	169.34	0.009895	0.19
2026-02-22 17:29:37	2026-02-22 17:32:02	145.3	RAISING	164.65	174.03	77.99	169.34	0.009895	0.20
2026-02-22 19:03:07	2026-02-22 19:05:32	145.3	RAISING	164.65	174.03	76.53	169.34	0.009895	0.21

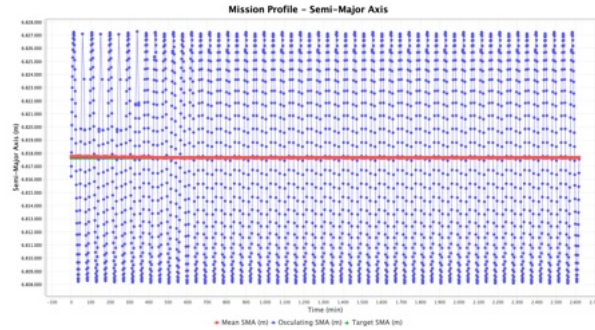


Figure A.71: Evolution of the Semi-Major Axis (a) during Window 12.

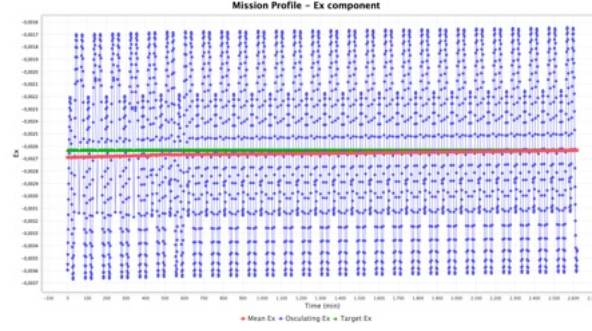


Figure A.72: Evolution of the x-component of the eccentricity vector (e_x) for Window 12.



Figure A.73: Evolution of the y-component of the eccentricity vector (e_y) for Window 12.

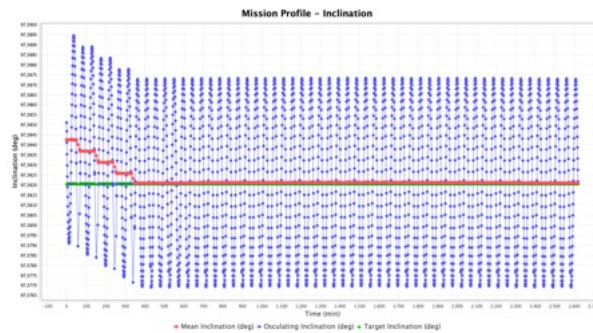


Figure A.74: Evolution of the orbital Inclination (i) in Window 12.

RESULTS

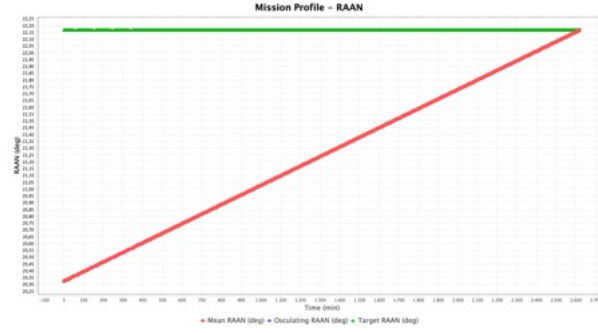


Figure A.75: Evolution of the RAAN (Ω) during Window 12.

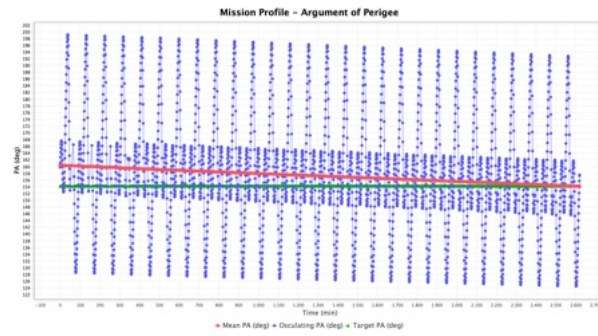


Figure A.76: Evolution of the Argument of Perigee (ω) during Window 12.

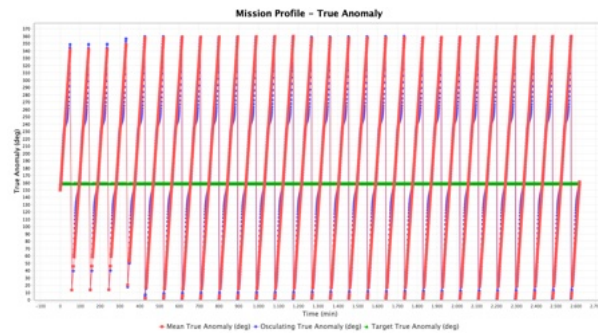


Figure A.77: Evolution of the True Anomaly (ν) throughout Window 12.

A.12 Window 13

Table A.45: Window 13

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-02-22T19:42:10	2026-02-24T15:20:41	2026-02-24T15:20:41
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 817 664.631 m	6 817 336.280 m	6 817 313.673 m
Eccentricity	e	0.002925	0.002960	0.002962
Inclination	i	97.3821°	97.3794°	97.3793°
Arg. of Perigee	ω	154.1402°	147.9240°	147.9663°
RAAN	Ω	22.1658°	24.0091°	24.0077°
True Anomaly	ν	158.4631°	167.4805°	170.0787°

Table A.46: Target State Errors Summary - Window 13

Parameter	Symbol	Error
Semi-Major Axis	Δa	−22.607 m
Inclination	Δi	−0.000039°
Eccentricity X	Δe_x	−0.000003
Eccentricity Y	Δe_y	−0.000001
RAAN	$\Delta \Omega$	−0.001376°
Arg. of Perigee	$\Delta \omega$	0.042°
True Anomaly	$\Delta \nu$	2.598°
Arg. of Latitude	Δu	2.640°

RESULTS

Table A.47: Normal Maneuvers Summary - Window 13. SQP ΔV : 0.325582 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL ($^{\circ}$)	Thrust Z
2026-02-22 20:30:38	2026-02-22 20:50:38	1200.00	0.081702	0.081702	180.138	1.0
2026-02-22 22:04:08	2026-02-22 22:24:08	1200.00	0.081703	0.163405	180.138	1.0
2026-02-22 23:37:37	2026-02-22 23:57:37	1200.00	0.081704	0.245109	180.138	1.0
2026-02-23 01:11:07	2026-02-23 01:31:07	1200.00	0.081704	0.326813	180.138	1.0
2026-02-23 02:47:56	2026-02-23 03:01:17	800.40	0.054497	0.381310	180.137	1.0
2026-02-23 21:34:48	2026-02-23 21:38:08	200.38	-0.013644	0.367666	180.137	-1.0
2026-02-24 11:36:05	2026-02-24 11:39:38	212.97	-0.014501	0.353165	180.136	-1.0

Table A.48: Tangential Maneuvers Summary - Window 13. SQP AOL: 176.37 $^{\circ}$, v_{Tan} SQP: 0.09 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^{\circ}$)	End AOL ($^{\circ}$)	Ideal AOL ($^{\circ}$)	Ctr AOL ($^{\circ}$)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]
2026-02-23 04:17:13	2026-02-23 04:37:13	1200.0	BRAKING	137.98	215.39	247.44	176.71	-0.081705	-0.08
2026-02-23 05:55:22	2026-02-23 06:06:01	638.9	BRAKING	156.05	197.28	251.82	176.67	-0.043502	-0.13
2026-02-23 07:32:56	2026-02-23 07:35:28	152.2	RAISING	171.82	181.65	74.85	176.74	0.010363	-0.11
2026-02-23 09:06:23	2026-02-23 09:09:00	156.7	RAISING	171.70	181.81	74.74	176.76	0.010669	-0.10
2026-02-23 10:39:58	2026-02-23 10:42:24	146.2	RAISING	172.04	181.48	74.55	176.76	0.009956	-0.09
2026-02-23 12:13:27	2026-02-23 12:15:53	146.2	RAISING	172.04	181.48	74.40	176.76	0.009953	-0.08
2026-02-23 13:46:56	2026-02-23 13:49:23	146.2	RAISING	172.04	181.48	74.25	176.76	0.009958	-0.07
2026-02-23 15:20:26	2026-02-23 15:22:52	146.3	RAISING	172.04	181.48	74.09	176.76	0.009958	-0.06
2026-02-23 16:53:55	2026-02-23 16:56:21	146.3	RAISING	172.04	181.48	73.93	176.76	0.009959	-0.05
2026-02-23 18:27:24	2026-02-23 18:29:50	146.3	RAISING	172.04	181.48	73.76	176.76	0.009960	-0.04
2026-02-23 20:00:53	2026-02-23 20:03:20	146.3	RAISING	172.04	181.48	73.58	176.76	0.009960	-0.03
2026-02-23 23:06:39	2026-02-23 23:11:31	292.3	RAISING	167.32	186.19	74.35	176.76	0.019902	-0.01
2026-02-24 00:41:21	2026-02-24 00:43:47	146.0	RAISING	172.05	181.47	72.98	176.76	0.009942	-0.00
2026-02-24 02:14:50	2026-02-24 02:17:17	147.0	RAISING	172.02	181.50	72.77	176.76	0.010008	0.01
2026-02-24 03:48:20	2026-02-24 03:50:46	146.4	RAISING	172.04	181.48	72.51	176.76	0.009967	0.02
2026-02-24 05:21:49	2026-02-24 05:24:15	146.4	RAISING	172.04	181.48	72.21	176.76	0.009968	0.03
2026-02-24 06:55:18	2026-02-24 06:57:45	146.4	RAISING	172.04	181.49	71.85	176.76	0.009969	0.04
2026-02-24 08:28:48	2026-02-24 08:31:14	146.4	RAISING	172.04	181.49	71.41	176.76	0.009970	0.05
2026-02-24 10:02:17	2026-02-24 10:04:43	146.4	RAISING	172.04	181.49	70.83	176.76	0.009971	0.06
2026-02-24 13:08:02	2026-02-24 13:12:55	292.5	RAISING	167.32	186.19	73.82	176.76	0.019915	0.08
2026-02-24 14:42:45	2026-02-24 14:45:11	172.0	RAISING	172.04	181.48	65.21	176.76	0.009963	0.09

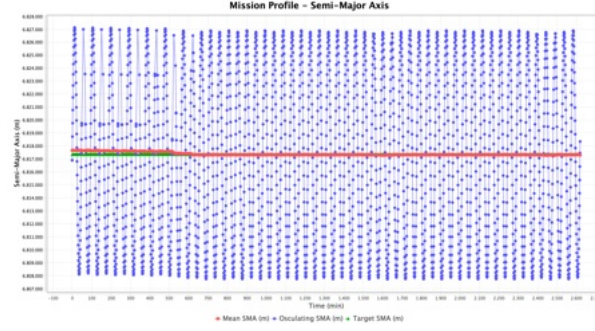


Figure A.78: Evolution of the Semi-Major Axis (a) during Window 13.

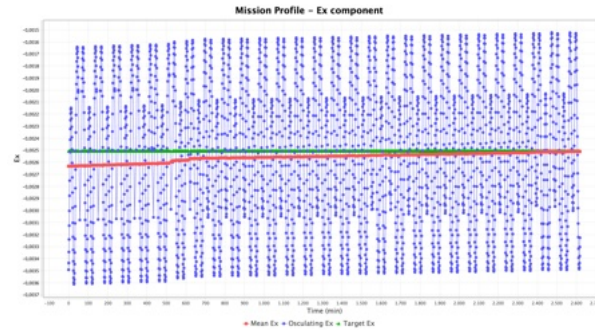


Figure A.79: Evolution of the x-component of the eccentricity vector (e_x) for Window 13.

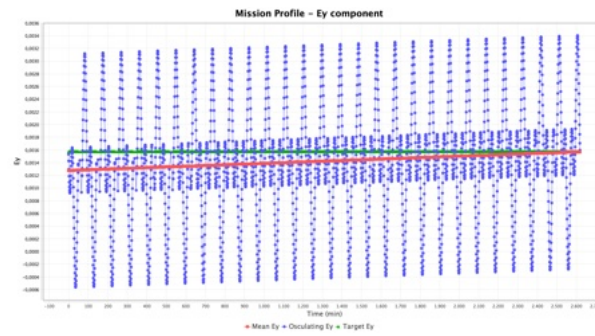


Figure A.80: Evolution of the y-component of the eccentricity vector (e_y) for Window 13.

RESULTS

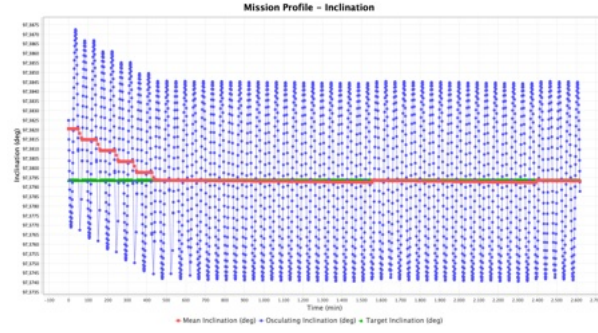


Figure A.81: Evolution of the orbital Inclination (i) in Window 13.

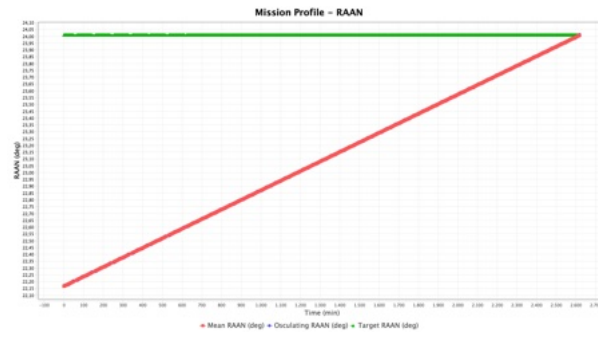


Figure A.82: Evolution of the RAAN (Ω) during Window 13.

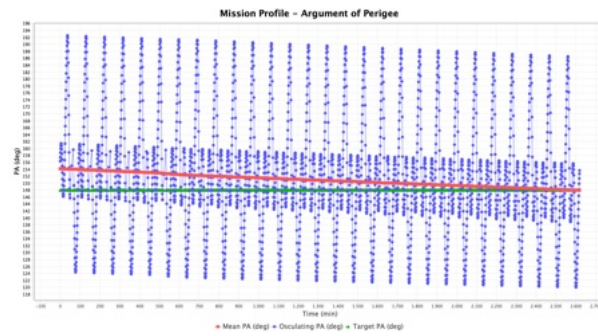


Figure A.83: Evolution of the Argument of Perigee (ω) during Window 13.

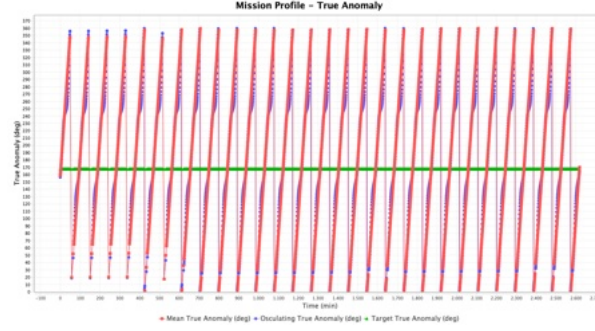


Figure A.84: Evolution of the True Anomaly (ν) throughout Window 13.

A.13 Window 14

Table A.49: Window 14

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-02-24T15:20:41	2026-02-26T10:59:12	2026-02-26T10:59:12
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 817 336.280 m	6 816 865.480 m	6 816 843.494 m
Eccentricity	e	0.002960	0.002975	0.002977
Inclination	i	97.3794°	97.3761°	97.3761°
Arg. of Perigee	ω	147.9240°	141.5981°	141.6633°
RAAN	Ω	24.0091°	25.8519°	25.8505°
True Anomaly	ν	167.4805°	177.4763°	180.1084°

RESULTS

Table A.50: Target State Errors Summary - Window 14

Parameter	Symbol	Error
Semi-Major Axis	Δa	-21.986 m
Inclination	Δi	-0.000014°
Eccentricity X	Δe_x	-0.000004
Eccentricity Y	Δe_y	-0.000001
RAAN	$\Delta \Omega$	-0.001395°
Arg. of Perigee	$\Delta \omega$	0.065°
True Anomaly	$\Delta \nu$	2.632°
Arg. of Latitude	Δu	2.697°

Table A.51: Normal Maneuvers Summary - Window 14. SQP ΔV : 0.401479 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL (°)	Thrust Z
2026-02-24 16:08:24	2026-02-24 16:28:24	1200.00	0.081702	0.081702	180.136	1.0
2026-02-24 17:41:53	2026-02-24 18:01:53	1200.00	0.081703	0.163405	180.136	1.0
2026-02-24 19:15:22	2026-02-24 19:35:22	1200.00	0.081704	0.245109	180.136	1.0
2026-02-24 20:48:51	2026-02-24 21:08:51	1200.00	0.081704	0.326813	180.136	1.0
2026-02-24 22:22:21	2026-02-24 22:42:21	1200.00	0.081705	0.408518	180.136	1.0
2026-02-24 23:59:30	2026-02-25 00:12:10	759.65	0.051723	0.460240	180.136	1.0
2026-02-25 15:38:49	2026-02-25 15:42:26	216.15	-0.014717	0.445523	180.135	-1.0
2026-02-26 08:47:08	2026-02-26 08:50:37	209.01	-0.014231	0.431292	180.134	-1.0

Table A.52: Tangential Maneuvers Summary - Window 14. SQP AOL: 182.93° , v_{Tan}
SQP: 0.01 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma\Delta V$ [m/s]
2026-02-25 01:30:08	2026-02-25 01:50:08	1200.0	BRAKING	144.59	221.96	236.88	183.32	-0.081706	-0.08
2026-02-25 03:03:36	2026-02-25 03:23:36	1200.0	BRAKING	144.51	221.88	240.60	183.24	-0.081706	-0.16
2026-02-25 04:44:31	2026-02-25 04:49:38	306.7	BRAKING	173.34	193.12	245.14	183.24	-0.020883	-0.18
2026-02-25 06:19:24	2026-02-25 06:21:46	141.7	RAISING	178.78	187.91	66.97	183.35	0.009645	-0.17
2026-02-25 07:52:48	2026-02-25 07:55:20	152.3	RAISING	178.44	188.27	66.87	183.36	0.010372	-0.16
2026-02-25 09:26:19	2026-02-25 09:28:46	147.6	RAISING	178.59	188.12	66.69	183.35	0.010053	-0.15
2026-02-25 10:59:47	2026-02-25 11:02:15	148.0	RAISING	178.58	188.13	66.53	183.36	0.010076	-0.14
2026-02-25 12:33:16	2026-02-25 12:35:44	147.9	RAISING	178.59	188.12	66.36	183.36	0.010069	-0.13
2026-02-25 14:06:45	2026-02-25 14:09:13	147.9	RAISING	178.58	188.12	66.18	183.36	0.010071	-0.12
2026-02-25 17:12:28	2026-02-25 17:17:25	296.9	RAISING	173.78	192.93	66.84	183.36	0.020216	-0.10
2026-02-25 18:47:13	2026-02-25 18:49:36	142.7	RAISING	178.74	187.95	65.54	183.35	0.009720	-0.09
2026-02-25 20:20:37	2026-02-25 20:23:10	152.3	RAISING	178.44	188.26	65.40	183.36	0.010367	-0.08
2026-02-25 21:54:08	2026-02-25 21:56:36	147.8	RAISING	178.59	188.12	65.10	183.35	0.010062	-0.07
2026-02-25 23:27:37	2026-02-25 23:30:05	148.1	RAISING	178.58	188.13	64.82	183.35	0.010086	-0.06
2026-02-26 01:01:05	2026-02-26 01:03:34	148.1	RAISING	178.58	188.13	64.49	183.35	0.010081	-0.05
2026-02-26 02:34:34	2026-02-26 02:37:02	148.1	RAISING	178.58	188.13	64.10	183.35	0.010084	-0.04
2026-02-26 04:08:03	2026-02-26 04:10:31	148.1	RAISING	178.58	188.13	63.60	183.35	0.010086	-0.03
2026-02-26 05:41:31	2026-02-26 05:44:00	148.1	RAISING	178.58	188.13	62.95	183.35	0.010087	-0.02
2026-02-26 07:15:00	2026-02-26 07:17:28	148.1	RAISING	178.58	188.13	61.99	183.35	0.010089	-0.01
2026-02-26 10:20:43	2026-02-26 10:25:40	297.6	RAISING	173.76	192.95	65.01	183.36	0.020261	0.01

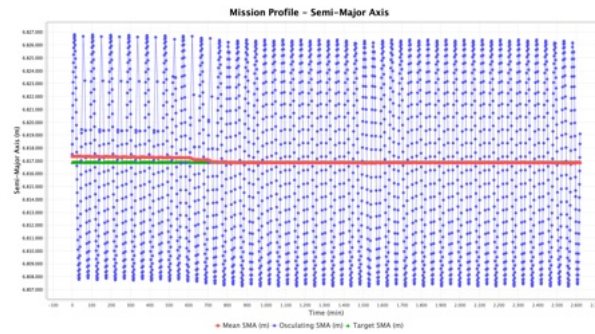


Figure A.85: Evolution of the Semi-Major Axis (a) during Window 14.

RESULTS

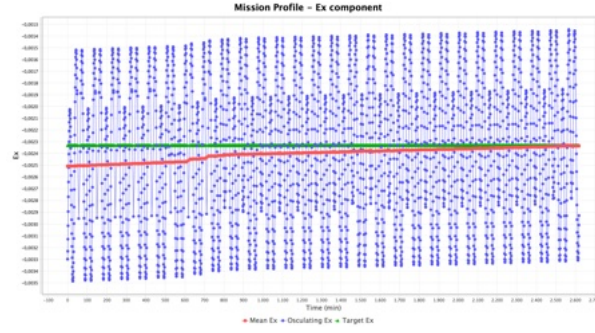


Figure A.86: Evolution of the x-component of the eccentricity vector (e_x) for Window 14.



Figure A.87: Evolution of the y-component of the eccentricity vector (e_y) for Window 14.

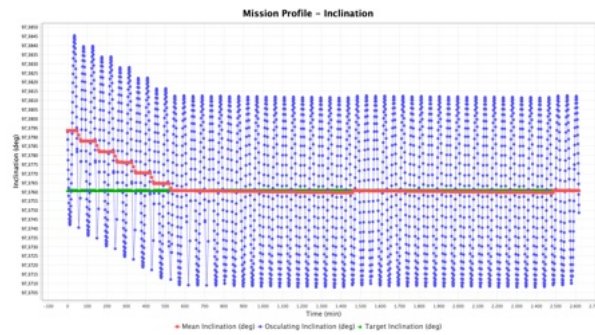


Figure A.88: Evolution of the orbital Inclination (i) in Window 14.

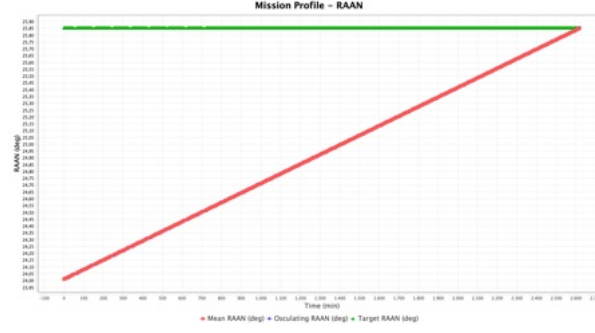


Figure A.89: Evolution of the RAAN (Ω) during Window 14.

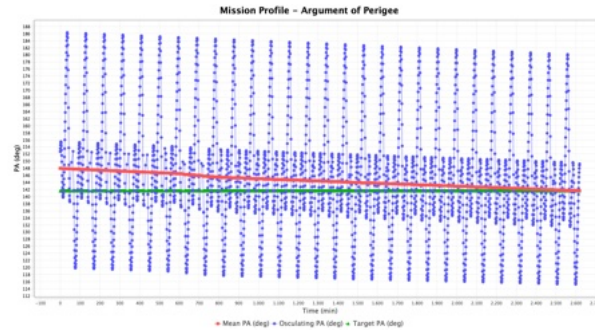


Figure A.90: Evolution of the Argument of Perigee (ω) during Window 14.

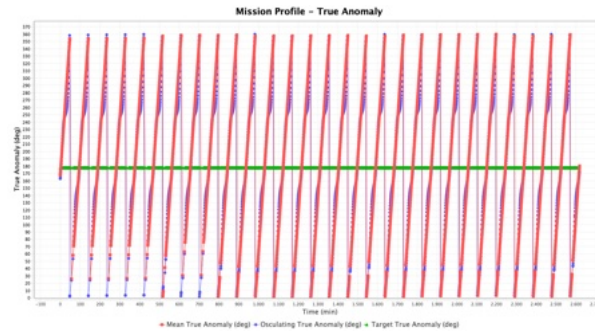


Figure A.91: Evolution of the True Anomaly (ν) throughout Window 14.

A.14 Window 15

Table A.53: Window 15

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-02-26T10:59:12	2026-02-28T06:37:43	2026-02-28T06:37:43
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 816 865.480 m	6 816 378.134 m	6 816 356.288 m
Eccentricity	e	0.002975	0.002987	0.002989
Inclination	i	97.3761°	97.3735°	97.3735°
Arg. of Perigee	ω	141.5981°	135.3087°	135.3798°
RAAN	Ω	25.8519°	27.6944°	27.6931°
True Anomaly	ν	177.4763°	188.4890°	191.1493°

Table A.54: Target State Errors Summary - Window 15

Parameter	Symbol	Error
Semi-Major Axis	Δa	−21.846 m
Inclination	Δi	0.000033°
Eccentricity X	Δe_x	−0.000004
Eccentricity Y	Δe_y	−0.000002
RAAN	$\Delta \Omega$	−0.001307°
Arg. of Perigee	$\Delta \omega$	0.071°
True Anomaly	$\Delta \nu$	2.660°
Arg. of Latitude	Δu	2.731°

Table A.55: Normal Maneuvers Summary - Window 15. SQP ΔV : 0.353315 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL ($^{\circ}$)	Thrust Z
2026-02-26 11:45:56	2026-02-26 12:05:56	1200.00	0.081702	0.081702	180.134	1.0
2026-02-26 13:19:24	2026-02-26 13:39:24	1200.00	0.081703	0.163405	180.134	1.0
2026-02-26 14:52:53	2026-02-26 15:12:53	1200.00	0.081704	0.245109	180.134	1.0
2026-02-26 16:26:22	2026-02-26 16:46:22	1200.00	0.081704	0.326813	180.134	1.0
2026-02-26 18:04:32	2026-02-26 18:15:09	637.25	0.043389	0.370202	180.134	1.0

Table A.56: Tangential Maneuvers Summary - Window 15. SQP AOL: 180.25° , v_{Tan} SQP: 0.00 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^{\circ}$)	End AOL ($^{\circ}$)	Ideal AOL ($^{\circ}$)	Ctr AOL ($^{\circ}$)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]
2026-02-26 19:33:26	2026-02-26 19:53:26	1200.0	BRAKING	141.90	219.26	230.22	180.63	-0.081705	-0.08
2026-02-26 21:06:54	2026-02-26 21:26:54	1200.0	BRAKING	141.82	219.18	233.56	180.55	-0.081706	-0.16
2026-02-26 22:45:19	2026-02-26 22:55:25	605.6	BRAKING	161.01	200.06	237.65	180.55	-0.041232	-0.20
2026-02-27 00:22:39	2026-02-27 00:25:03	144.5	RAISING	175.96	185.28	60.45	180.62	0.009839	-0.19
2026-02-27 01:55:58	2026-02-27 01:58:41	162.9	RAISING	175.40	185.90	60.40	180.65	0.011094	-0.18
2026-02-27 03:29:33	2026-02-27 03:32:02	149.4	RAISING	175.83	185.47	60.19	180.65	0.010174	-0.17
2026-02-27 05:03:01	2026-02-27 05:05:31	149.9	RAISING	175.82	185.48	60.04	180.65	0.010205	-0.16
2026-02-27 06:36:29	2026-02-27 06:38:59	149.7	RAISING	175.82	185.48	59.89	180.65	0.010195	-0.15
2026-02-27 08:09:57	2026-02-27 08:12:27	149.8	RAISING	175.82	185.48	59.73	180.65	0.010197	-0.14
2026-02-27 09:43:25	2026-02-27 09:45:55	149.8	RAISING	175.82	185.48	59.56	180.65	0.010199	-0.13
2026-02-27 11:16:53	2026-02-27 11:19:23	149.8	RAISING	175.82	185.48	59.39	180.65	0.010200	-0.12
2026-02-27 12:50:21	2026-02-27 12:52:51	149.8	RAISING	175.82	185.48	59.21	180.65	0.010201	-0.11
2026-02-27 14:23:49	2026-02-27 14:26:19	149.8	RAISING	175.82	185.48	59.01	180.65	0.010202	-0.10
2026-02-27 15:57:17	2026-02-27 15:59:47	149.8	RAISING	175.82	185.48	58.81	180.65	0.010203	-0.09
2026-02-27 17:30:46	2026-02-27 17:33:15	149.9	RAISING	175.82	185.48	58.58	180.65	0.010204	-0.08
2026-02-27 19:04:14	2026-02-27 19:06:43	149.9	RAISING	175.82	185.48	58.33	180.65	0.010206	-0.07
2026-02-27 20:37:42	2026-02-27 20:40:12	149.9	RAISING	175.81	185.48	58.05	180.65	0.010208	-0.06
2026-02-27 22:11:10	2026-02-27 22:13:40	150.0	RAISING	175.81	185.48	57.72	180.65	0.010210	-0.05
2026-02-27 23:44:38	2026-02-27 23:47:08	150.0	RAISING	175.81	185.48	57.31	180.65	0.010213	-0.04
2026-02-28 01:18:06	2026-02-28 01:20:36	150.0	RAISING	175.81	185.48	56.77	180.65	0.010215	-0.03
2026-02-28 02:51:34	2026-02-28 02:54:04	150.1	RAISING	175.81	185.49	56.01	180.65	0.010218	-0.02
2026-02-28 04:25:02	2026-02-28 04:27:32	150.1	RAISING	175.81	185.49	54.78	180.65	0.010220	-0.01
2026-02-28 05:58:30	2026-02-28 06:01:00	150.1	RAISING	175.81	185.49	52.23	180.65	0.010222	0.00

RESULTS

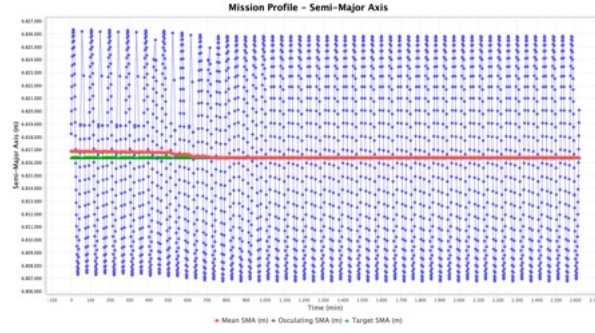


Figure A.92: Evolution of the Semi-Major Axis (a) during Window 15.

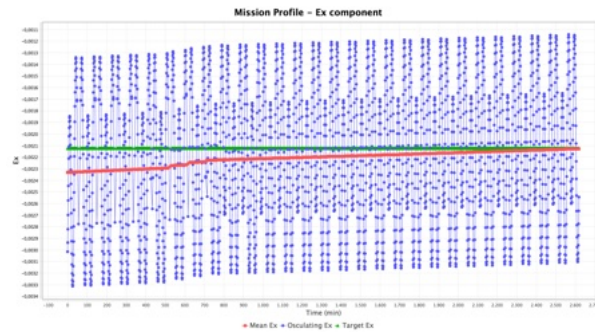


Figure A.93: Evolution of the x-component of the eccentricity vector (e_x) for Window 15.

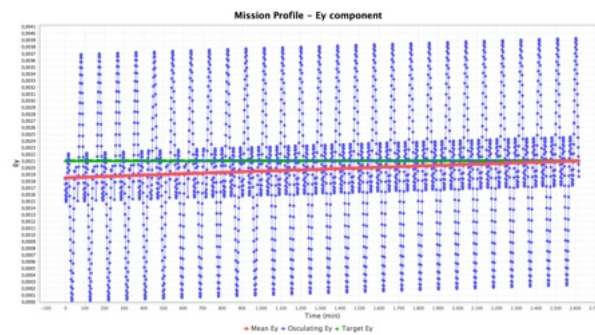


Figure A.94: Evolution of the y-component of the eccentricity vector (e_y) for Window 15.

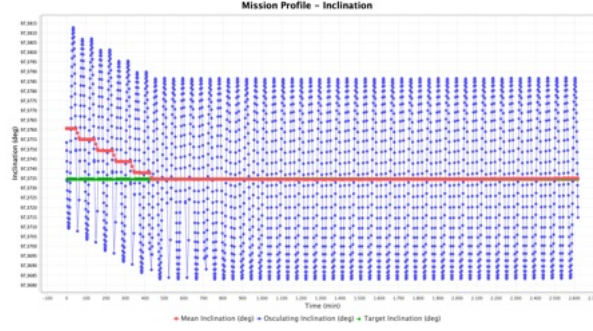


Figure A.95: Evolution of the orbital Inclination (i) in Window 15.

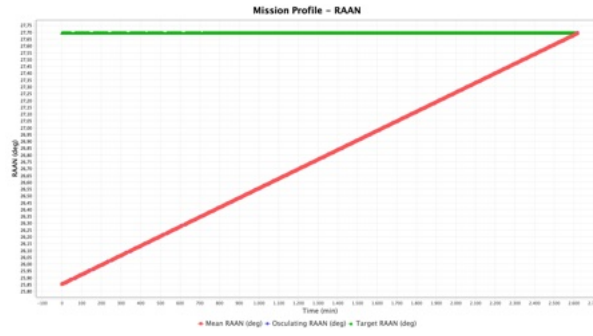


Figure A.96: Evolution of the RAAN (Ω) during Window 15.

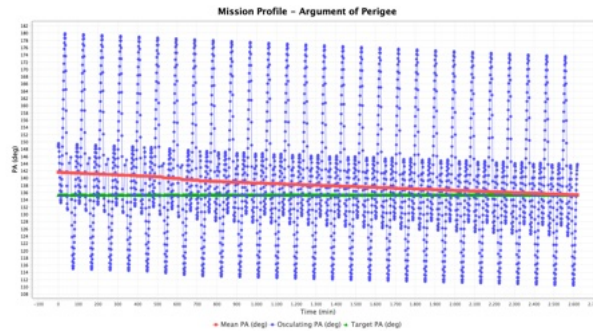


Figure A.97: Evolution of the Argument of Perigee (ω) during Window 15.

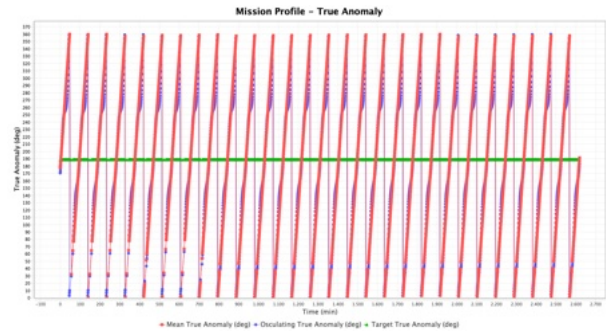


Figure A.98: Evolution of the True Anomaly (ν) throughout Window 15.

A.15 Window 16

Table A.57: Window 16

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-02-28T06:37:43	2026-03-02T02:16:14	2026-03-02T02:16:14
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 816 378.134 m	6 815 909.260 m	6 815 886.687 m
Eccentricity	e	0.002987	0.003000	0.003001
Inclination	i	97.3735°	97.3712°	97.3713°
Arg. of Perigee	ω	135.3087°	129.1251°	129.1944°
RAAN	Ω	27.6944°	29.5369°	29.5357°
True Anomaly	ν	188.4890°	200.4514°	203.1379°

Table A.58: Target State Errors Summary - Window 16

Parameter	Symbol	Error
Semi-Major Axis	Δa	-22.573 m
Inclination	Δi	0.000108°
Eccentricity X	Δe_x	-0.000003
Eccentricity Y	Δe_y	-0.000002
RAAN	$\Delta \Omega$	-0.001246°
Arg. of Perigee	$\Delta \omega$	0.069°
True Anomaly	$\Delta \nu$	2.686°
Arg. of Latitude	Δu	2.756°

Table A.59: Normal Maneuvers Summary - Window 16. SQP ΔV : 0.359138 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL (°)	Thrust Z
2026-02-28 07:23:11	2026-02-28 07:43:11	1200.00	0.081702	0.081702	180.132	1.0
2026-02-28 08:56:39	2026-02-28 09:16:39	1200.00	0.081703	0.163405	180.132	1.0
2026-02-28 10:30:07	2026-02-28 10:50:07	1200.00	0.081704	0.245109	180.132	1.0
2026-02-28 12:04:13	2026-02-28 12:22:57	1124.33	0.076552	0.321661	180.132	1.0
2026-02-28 23:06:00	2026-02-28 23:09:37	216.76	0.014759	0.336419	180.131	1.0
2026-03-01 10:00:22	2026-03-01 10:03:41	199.48	0.013583	0.350002	180.131	1.0
2026-03-01 19:21:04	2026-03-01 19:24:29	205.16	0.013969	0.363971	180.130	1.0

RESULTS

Table A.60: Tangential Maneuvers Summary - Window 16. SQP AOL: 181.06° , v_{Tan} SQP: 0.02 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma\Delta V$ [m/s]
2026-02-28 13:37:22	2026-02-28 13:57:22	1200.0	BRAKING	142.65	219.98	224.28	181.37	-0.081705	-0.08
2026-02-28 15:10:50	2026-02-28 15:30:50	1200.0	BRAKING	142.63	219.96	227.23	181.35	-0.081705	-0.16
2026-02-28 16:49:13	2026-02-28 16:59:22	609.8	BRAKING	161.68	200.99	230.86	181.35	-0.041517	-0.20
2026-02-28 18:26:35	2026-02-28 18:28:58	143.0	RAISING	176.81	186.03	143.00	181.42	0.009739	-0.20
2026-02-28 19:59:52	2026-02-28 20:02:37	165.4	RAISING	176.12	186.78	165.40	181.45	0.011261	-0.18
2026-02-28 21:33:26	2026-02-28 21:35:57	151.2	RAISING	176.58	186.32	151.20	181.45	0.010295	-0.17
2026-03-01 00:39:05	2026-03-01 00:44:09	303.6	RAISING	171.66	191.23	303.60	181.45	0.020673	-0.15
2026-03-01 02:13:50	2026-03-01 02:16:18	148.3	RAISING	176.67	186.22	148.30	181.44	0.010094	-0.14
2026-03-01 03:47:14	2026-03-01 03:49:49	155.2	RAISING	176.45	186.45	155.20	181.45	0.010570	-0.13
2026-03-01 05:20:43	2026-03-01 05:23:15	151.7	RAISING	176.56	186.34	151.70	181.45	0.010327	-0.12
2026-03-01 06:54:11	2026-03-01 06:56:43	151.9	RAISING	176.56	186.34	151.90	181.45	0.010340	-0.11
2026-03-01 08:27:38	2026-03-01 08:30:10	151.8	RAISING	176.56	186.34	151.80	181.45	0.010338	-0.10
2026-03-01 11:33:17	2026-03-01 11:38:21	304.1	RAISING	171.64	191.25	304.10	181.45	0.020709	-0.08
2026-03-01 13:08:03	2026-03-01 13:10:31	148.2	RAISING	176.66	186.22	148.20	181.44	0.010092	-0.07
2026-03-01 14:41:27	2026-03-01 14:44:02	155.4	RAISING	176.44	186.45	155.40	181.45	0.010578	-0.06
2026-03-01 16:14:56	2026-03-01 16:17:28	151.8	RAISING	176.55	186.34	151.80	181.45	0.010338	-0.05
2026-03-01 17:48:23	2026-03-01 17:50:55	152.0	RAISING	176.55	186.35	152.00	181.45	0.010351	-0.04
2026-03-01 20:54:02	2026-03-01 20:59:06	304.3	RAISING	171.63	191.25	304.30	181.45	0.020722	-0.02
2026-03-01 22:28:47	2026-03-01 22:31:16	148.4	RAISING	176.66	186.22	148.40	181.44	0.010105	-0.01
2026-03-02 00:02:11	2026-03-02 00:04:47	155.6	RAISING	176.43	186.46	155.60	181.45	0.010597	0.00

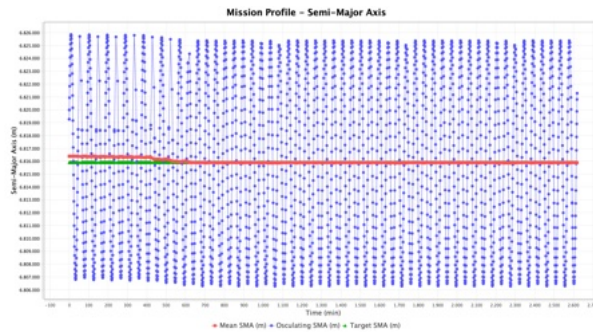


Figure A.99: Evolution of the Semi-Major Axis (a) during Window 16.

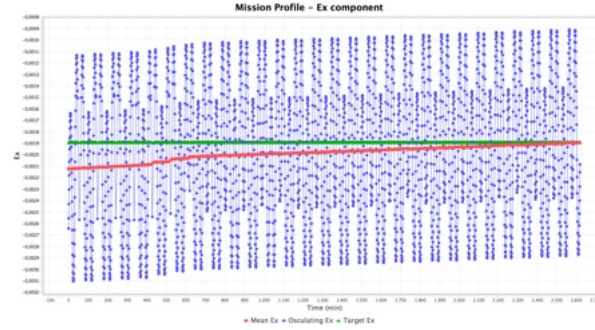


Figure A.100: Evolution of the x-component of the eccentricity vector (e_x) for Window 16.

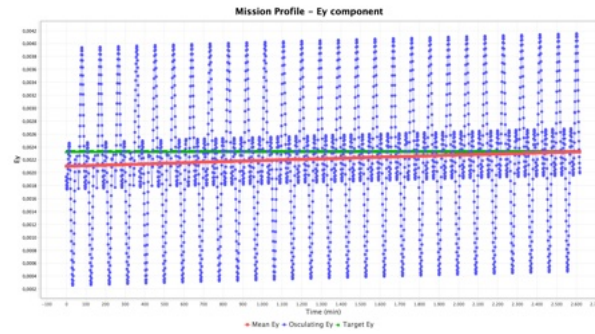


Figure A.101: Evolution of the y-component of the eccentricity vector (e_y) for Window 16.

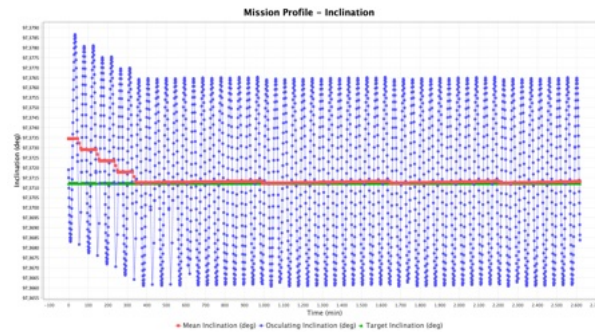


Figure A.102: Evolution of the orbital Inclination (i) in Window 16.

RESULTS

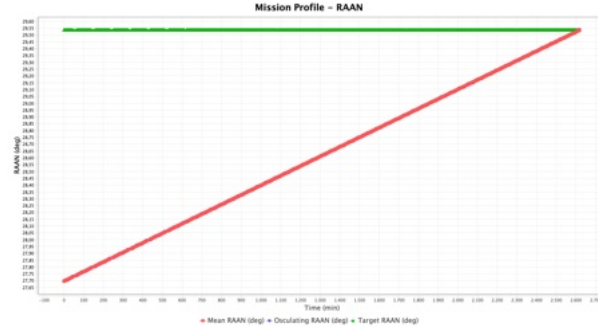


Figure A.103: Evolution of the RAAN (Ω) during Window 16.

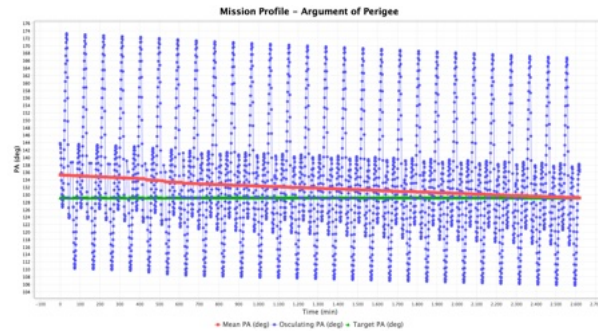


Figure A.104: Evolution of the Argument of Perigee (ω) during Window 16.

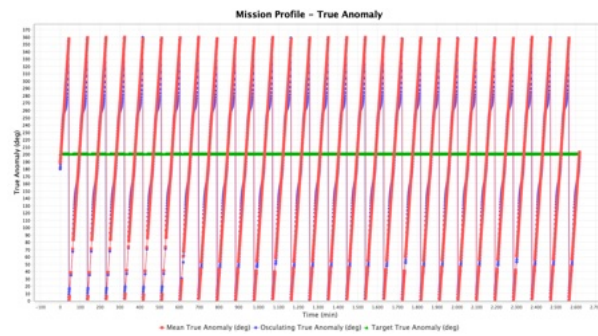


Figure A.105: Evolution of the True Anomaly (ν) throughout Window 16.

A.16 Window 17

Table A.61: Window 17

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-03-02T02:16:14	2026-03-03T21:54:45	2026-03-03T21:54:45
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 815 909.260 m	6 815 434.243 m	6 815 409.324 m
Eccentricity	e	0.003000	0.003010	0.003010
Inclination	i	97.3712°	97.3695°	97.3696°
Arg. of Perigee	ω	129.1251°	122.9947°	123.0572°
RAAN	Ω	29.5369°	31.3795°	31.3783°
True Anomaly	ν	200.4514°	213.4052°	216.1296°

Table A.62: Target State Errors Summary - Window 17

Parameter	Symbol	Error
Semi-Major Axis	Δa	−24.919 m
Inclination	Δi	0.000082°
Eccentricity X	Δe_x	−0.000002
Eccentricity Y	Δe_y	−0.000002
RAAN	$\Delta \Omega$	−0.001183°
Arg. of Perigee	$\Delta \omega$	0.062°
True Anomaly	$\Delta \nu$	2.724°
Arg. of Latitude	Δu	2.787°

RESULTS

Table A.63: Normal Maneuvers Summary - Window 17. SQP ΔV : 0.316784 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL ($^{\circ}$)	Thrust Z
2026-03-02 03:00:10	2026-03-02 03:20:10	1200.00	0.081702	0.081702	180.130	1.0
2026-03-02 04:33:38	2026-03-02 04:53:38	1200.00	0.081703	0.163405	180.130	1.0
2026-03-02 06:07:14	2026-03-02 06:26:56	1182.75	0.080529	0.243935	180.130	1.0
2026-03-02 10:55:40	2026-03-02 10:59:14	213.40	0.014530	0.258464	180.130	1.0
2026-03-02 18:42:58	2026-03-02 18:46:25	207.80	0.014149	0.272613	180.129	1.0
2026-03-03 02:30:03	2026-03-03 02:33:49	226.02	0.015390	0.288003	180.129	1.0
2026-03-03 10:17:15	2026-03-03 10:21:07	232.23	0.015812	0.303815	180.128	1.0
2026-03-03 18:04:29	2026-03-03 18:08:22	233.61	0.015906	0.319721	180.128	1.0

Table A.64: Tangential Maneuvers Summary - Window 17. SQP AOL: 183.64 $^{\circ}$, v_{Tan} SQP: 0.02 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^{\circ}$)	End AOL ($^{\circ}$)	Ideal AOL ($^{\circ}$)	Ctr AOL ($^{\circ}$)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]
2026-03-02 07:41:32	2026-03-02 08:01:32	1200.0	BRAKING	145.22	222.52	217.80	183.93	-0.081704	-0.08
2026-03-02 09:14:58	2026-03-02 09:34:58	1200.0	BRAKING	145.20	222.49	220.12	183.91	-0.081705	-0.16
2026-03-02 12:26:22	2026-03-02 12:37:27	664.8	BRAKING	162.59	205.42	223.26	184.03	-0.045267	-0.21
2026-03-02 14:04:11	2026-03-02 14:06:30	139.2	RAISING	179.49	188.46	139.20	183.98	0.009479	-0.20
2026-03-02 15:37:24	2026-03-02 15:40:13	169.3	RAISING	178.57	189.48	169.30	184.02	0.011526	-0.19
2026-03-02 17:10:59	2026-03-02 17:13:32	153.0	RAISING	179.09	188.95	153.00	184.02	0.010415	-0.18
2026-03-02 20:16:34	2026-03-02 20:21:44	309.7	RAISING	174.04	194.00	309.70	184.02	0.021088	-0.16
2026-03-02 21:51:22	2026-03-02 21:53:49	147.5	RAISING	179.26	188.76	147.50	184.01	0.010046	-0.15
2026-03-02 23:24:43	2026-03-02 23:27:22	158.7	RAISING	178.91	189.13	158.70	184.02	0.010804	-0.14
2026-03-03 00:58:13	2026-03-03 01:00:46	153.7	RAISING	179.07	188.97	153.70	184.02	0.010463	-0.13
2026-03-03 04:03:49	2026-03-03 04:08:58	309.6	RAISING	174.04	193.99	309.60	184.02	0.021079	-0.11
2026-03-03 05:38:36	2026-03-03 05:41:04	148.2	RAISING	179.23	188.78	148.20	184.01	0.010089	-0.10
2026-03-03 07:11:58	2026-03-03 07:14:37	158.8	RAISING	178.90	189.13	158.80	184.02	0.010813	-0.09
2026-03-03 08:45:27	2026-03-03 08:48:01	153.9	RAISING	179.06	188.97	153.90	184.02	0.010477	-0.08
2026-03-03 11:51:03	2026-03-03 11:56:13	309.8	RAISING	174.04	193.99	309.80	184.02	0.021091	-0.06
2026-03-03 13:25:51	2026-03-03 13:28:19	148.4	RAISING	179.22	188.79	148.40	184.01	0.010107	-0.05
2026-03-03 14:59:12	2026-03-03 15:01:51	158.9	RAISING	178.90	189.13	158.90	184.01	0.010821	-0.04
2026-03-03 16:32:42	2026-03-03 16:35:16	154.0	RAISING	179.05	188.97	154.00	184.01	0.010485	-0.03
2026-03-03 19:38:18	2026-03-03 19:43:28	310.0	RAISING	174.03	193.99	310.00	184.01	0.021109	-0.01
2026-03-03 21:13:05	2026-03-03 21:15:34	148.5	RAISING	179.22	188.78	148.50	184.00	0.010114	0.02

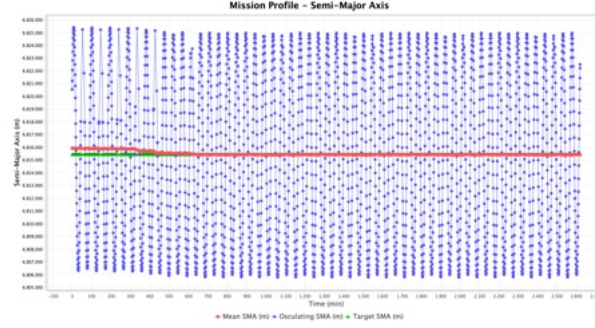


Figure A.106: Evolution of the Semi-Major Axis (a) during Window 17.

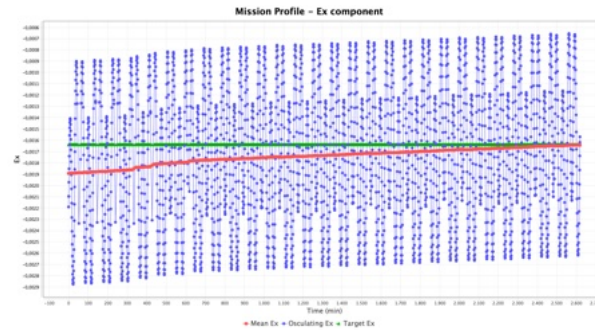


Figure A.107: Evolution of the x-component of the eccentricity vector (e_x) for Window 17.

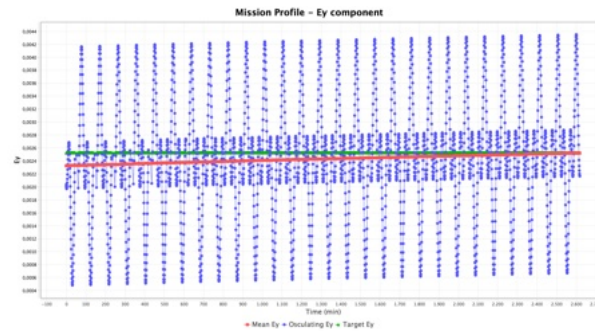


Figure A.108: Evolution of the y-component of the eccentricity vector (e_y) for Window 17.

RESULTS

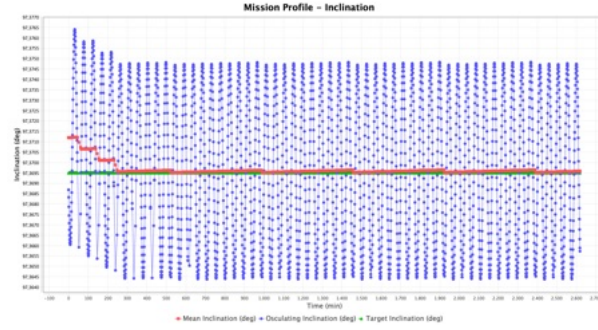


Figure A.109: Evolution of the orbital Inclination (i) in Window 17.

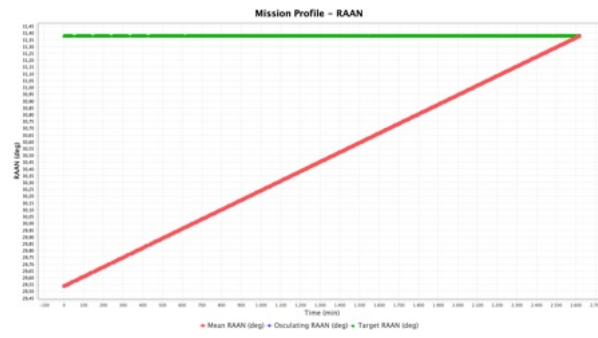


Figure A.110: Evolution of the RAAN (Ω) during Window 17.

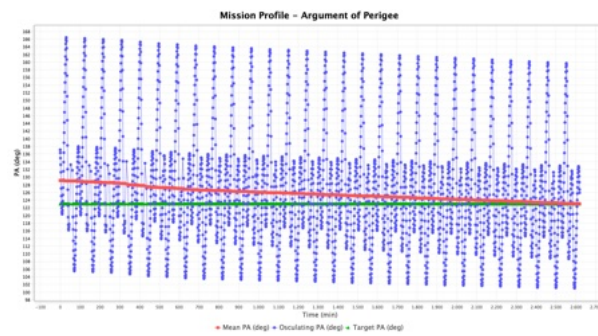


Figure A.111: Evolution of the Argument of Perigee (ω) during Window 17.

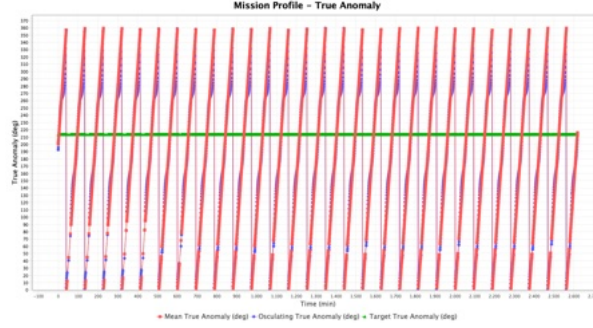


Figure A.112: Evolution of the True Anomaly (ν) throughout Window 17.

A.17 Window 18

Table A.65: Window 18

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-03-03T21:54:45	2026-03-05T17:33:16	2026-03-05T17:33:16
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 815 434.243 m	6 814 923.147 m	6 814 896.725 m
Eccentricity	e	0.003010	0.003016	0.003015
Inclination	i	97.3695°	97.3678°	97.3679°
Arg. of Perigee	ω	122.9947°	116.8361°	116.9019°
RAAN	Ω	31.3795°	33.2223°	33.2211°
True Anomaly	ν	213.4052°	227.4824°	230.2300°

Table A.66: Target State Errors Summary - Window 18

Parameter	Symbol	Error
Semi-Major Axis	Δa	-26.422 m
Inclination	Δi	0.000043°
Eccentricity X	Δe_x	-0.000003
Eccentricity Y	Δe_y	-0.000003
RAAN	$\Delta \Omega$	-0.001176°
Arg. of Perigee	$\Delta \omega$	0.066°
True Anomaly	$\Delta \nu$	2.748°
Arg. of Latitude	Δu	2.814°

Table A.67: Normal Maneuvers Summary - Window 18. SQP ΔV : 0.302632 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL (°)	Thrust Z
2026-03-03 22:36:53	2026-03-03 22:56:53	1200.00	0.081702	0.081702	180.128	1.0
2026-03-04 00:10:20	2026-03-04 00:30:20	1200.00	0.081703	0.163405	180.128	1.0
2026-03-04 01:44:38	2026-03-04 02:02:55	1097.00	0.074691	0.238096	180.127	1.0
2026-03-04 06:32:24	2026-03-04 06:35:50	205.83	0.014014	0.252110	180.127	1.0
2026-03-04 14:19:33	2026-03-04 14:23:04	210.73	0.014348	0.266458	180.127	1.0
2026-03-04 22:06:44	2026-03-04 22:10:15	210.66	0.014343	0.280801	180.126	1.0
2026-03-05 05:54:02	2026-03-05 05:57:20	198.32	0.013503	0.294305	180.126	1.0
2026-03-05 15:14:29	2026-03-05 15:18:09	219.83	0.014968	0.309273	180.125	1.0

Table A.68: Tangential Maneuvers Summary - Window 18. SQP AOL: 182.85° , v_{Tan} SQP: 0.00 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma\Delta V$ [m/s]
2026-03-04 03:18:00	2026-03-04 03:38:00	1200.0	BRAKING	144.43	221.70	210.83	183.13	-0.081704	-0.08
2026-03-04 04:51:26	2026-03-04 05:11:26	1200.0	BRAKING	144.40	221.67	212.74	183.10	-0.081705	-0.16
2026-03-04 08:00:19	2026-03-04 08:16:23	964.6	BRAKING	152.11	214.22	215.29	183.21	-0.065681	-0.23
2026-03-04 09:40:34	2026-03-04 09:42:58	144.9	RAISING	178.46	187.79	37.93	183.13	0.009864	-0.22
2026-03-04 11:13:49	2026-03-04 11:16:38	169.1	RAISING	177.76	188.65	37.91	183.20	0.011515	-0.21
2026-03-04 12:47:22	2026-03-04 12:49:58	155.6	RAISING	178.19	188.21	37.77	183.20	0.010593	-0.20
2026-03-04 15:52:55	2026-03-04 15:58:09	313.8	RAISING	173.09	193.30	38.15	183.20	0.021367	-0.18
2026-03-04 17:27:43	2026-03-04 17:30:14	150.8	RAISING	178.33	188.05	37.45	183.19	0.010269	-0.17
2026-03-04 19:01:05	2026-03-04 19:03:45	160.7	RAISING	178.02	188.37	37.42	183.20	0.010944	-0.16
2026-03-04 20:34:33	2026-03-04 20:37:09	156.1	RAISING	178.17	188.22	37.31	183.20	0.010628	-0.15
2026-03-04 23:40:07	2026-03-04 23:45:21	314.0	RAISING	173.08	193.31	37.95	183.20	0.021383	-0.13
2026-03-05 01:14:54	2026-03-05 01:17:25	151.0	RAISING	178.32	188.05	37.04	183.19	0.010283	-0.12
2026-03-05 02:48:16	2026-03-05 02:50:57	161.0	RAISING	178.01	188.38	37.06	183.20	0.010962	-0.11
2026-03-05 04:21:44	2026-03-05 04:24:21	156.3	RAISING	178.16	188.23	36.98	183.20	0.010645	-0.10
2026-03-05 07:27:18	2026-03-05 07:32:33	314.7	RAISING	173.06	193.32	38.25	183.20	0.021425	-0.08
2026-03-05 09:02:06	2026-03-05 09:04:37	151.1	RAISING	178.32	188.05	36.89	183.18	0.010291	-0.07
2026-03-05 10:35:27	2026-03-05 10:38:08	161.1	RAISING	178.01	188.38	37.09	183.19	0.010970	-0.06
2026-03-05 12:08:56	2026-03-05 12:11:32	156.5	RAISING	178.15	188.23	37.17	183.19	0.010656	-0.05
2026-03-05 13:42:22	2026-03-05 13:44:59	156.8	RAISING	178.14	188.24	37.45	183.19	0.010679	-0.04
2026-03-05 16:47:56	2026-03-05 16:53:10	314.6	RAISING	173.06	193.31	46.09	183.19	0.021420	0.00

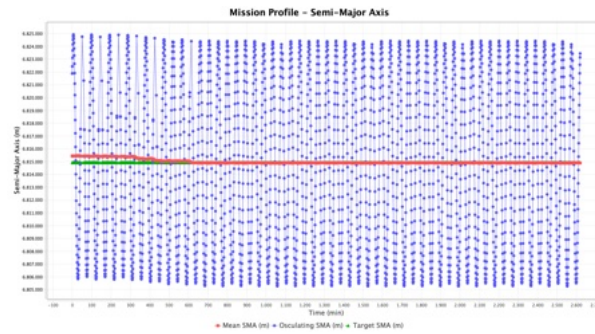


Figure A.113: Evolution of the Semi-Major Axis (a) during Window 18.

RESULTS

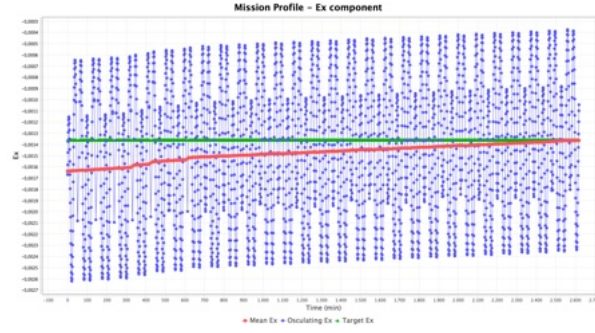


Figure A.114: Evolution of the x-component of the eccentricity vector (e_x) for Window 18.

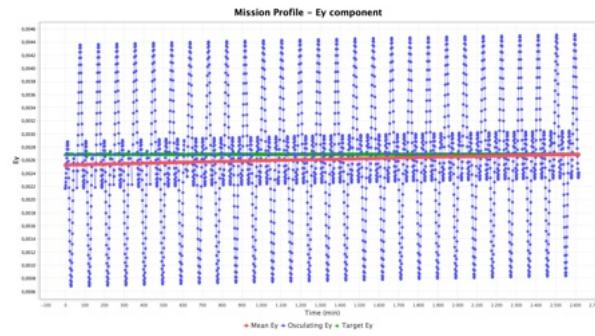


Figure A.115: Evolution of the y-component of the eccentricity vector (e_y) for Window 18.

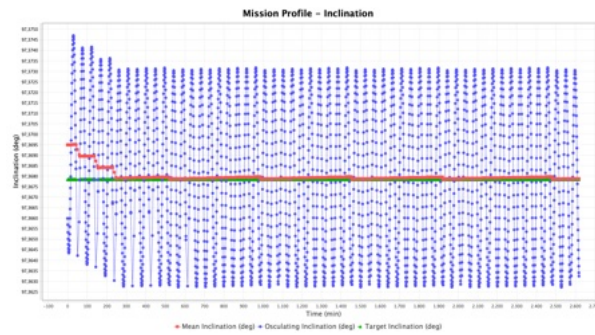


Figure A.116: Evolution of the orbital Inclination (i) in Window 18.

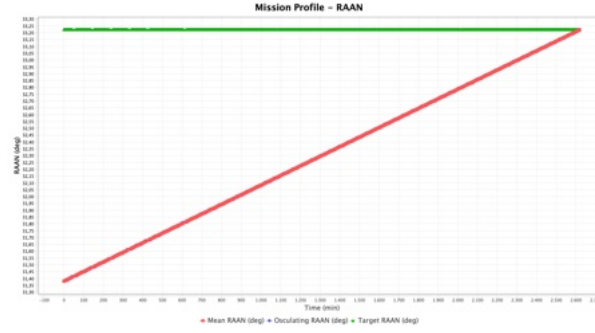


Figure A.117: Evolution of the RAAN (Ω) during Window 18.

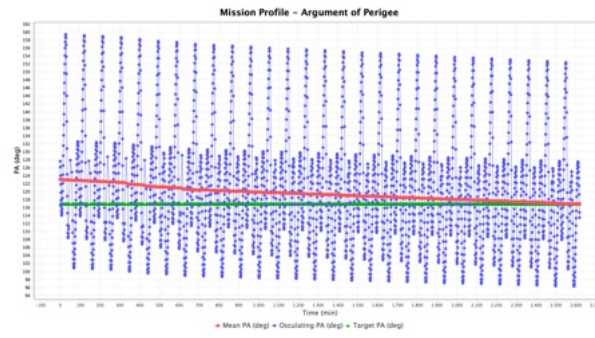


Figure A.118: Evolution of the Argument of Perigee (ω) during Window 18.

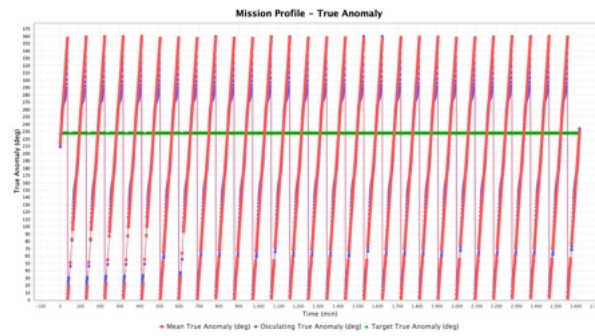


Figure A.119: Evolution of the True Anomaly (ν) throughout Window 18.

A.18 Window 19

Table A.69: Window 19

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-03-05T17:33:16	2026-03-07T13:11:46	2026-03-07T13:11:46
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 814 923.147 m	6 814 423.156 m	6 814 394.237 m
Eccentricity	e	0.003016	0.003020	0.003018
Inclination	i	97.3678°	97.3661°	97.3661°
Arg. of Perigee	ω	116.8361°	110.7656°	110.8120°
RAAN	Ω	33.2223°	35.0652°	35.0640°
True Anomaly	ν	227.4824°	242.6042°	245.3555°

Table A.70: Target State Errors Summary - Window 19

Parameter	Symbol	Error
Semi-Major Axis	Δa	−28.919 m
Inclination	Δi	0.000046°
Eccentricity X	Δe_x	−0.000002
Eccentricity Y	Δe_y	−0.000003
RAAN	$\Delta \Omega$	−0.001200°
Arg. of Perigee	$\Delta \omega$	0.046°
True Anomaly	$\Delta \nu$	2.751°
Arg. of Latitude	Δu	2.798°

Table A.71: Normal Maneuvers Summary - Window 19. SQP ΔV : 0.281360 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL ($^{\circ}$)	Thrust Z
2026-03-05 18:13:19	2026-03-05 18:33:19	1200.00	0.081702	0.081702	180.125	1.0
2026-03-05 19:46:45	2026-03-05 20:06:45	1200.00	0.081703	0.163405	180.125	1.0
2026-03-05 21:20:11	2026-03-05 21:40:11	1200.00	0.081704	0.245109	180.125	1.0
2026-03-06 00:35:12	2026-03-06 00:38:55	222.65	0.015159	0.260268	180.125	1.0
2026-03-06 13:02:44	2026-03-06 13:06:15	210.66	0.014343	0.274612	180.124	1.0
2026-03-07 04:37:05	2026-03-07 04:40:28	203.57	0.013861	0.288472	180.123	1.0

Table A.72: Tangential Maneuvers Summary - Window 19. SQP AOL: 186.08 $^{\circ}$, v_{Tan} SQP: 0.01 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^{\circ}$)	End AOL ($^{\circ}$)	Ideal AOL ($^{\circ}$)	Ctr AOL ($^{\circ}$)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]
2026-03-05 22:55:14	2026-03-05 23:15:14	1200.0	BRAKING	147.65	224.86	204.46	186.33	-0.081704	-0.08
2026-03-06 02:02:07	2026-03-06 02:22:07	1200.0	BRAKING	147.75	224.96	205.71	186.42	-0.081705	-0.16
2026-03-06 03:38:24	2026-03-06 03:52:39	855.1	BRAKING	158.74	213.76	207.43	186.29	-0.058225	-0.22
2026-03-06 05:17:52	2026-03-06 05:20:03	131.3	RAISING	182.11	190.56	131.30	186.34	0.008939	-0.21
2026-03-06 06:50:59	2026-03-06 06:53:50	170.2	RAISING	180.94	191.89	170.20	186.41	0.011587	-0.20
2026-03-06 08:24:31	2026-03-06 08:27:09	157.5	RAISING	181.34	191.48	157.50	186.41	0.010726	-0.19
2026-03-06 09:57:56	2026-03-06 10:00:35	159.1	RAISING	181.29	191.53	159.10	186.41	0.010834	-0.18
2026-03-06 11:31:22	2026-03-06 11:34:01	158.7	RAISING	181.30	191.51	158.70	186.41	0.010807	-0.17
2026-03-06 14:36:52	2026-03-06 14:42:14	321.3	RAISING	176.07	196.74	321.30	186.41	0.021874	-0.15
2026-03-06 16:11:43	2026-03-06 16:14:13	149.9	RAISING	181.57	191.22	149.90	186.39	0.010209	-0.14
2026-03-06 17:45:02	2026-03-06 17:47:46	164.5	RAISING	181.11	191.70	164.50	186.41	0.011204	-0.13
2026-03-06 19:18:31	2026-03-06 19:21:09	158.5	RAISING	181.30	191.50	158.50	186.40	0.010791	-0.12
2026-03-06 20:51:56	2026-03-06 20:54:35	159.2	RAISING	181.28	191.52	159.20	186.40	0.010837	-0.11
2026-03-06 22:25:22	2026-03-06 22:28:01	159.0	RAISING	181.29	191.52	159.00	186.40	0.010827	-0.10
2026-03-06 23:58:47	2026-03-07 00:01:26	159.1	RAISING	181.28	191.52	159.10	186.40	0.010833	-0.09
2026-03-07 01:32:13	2026-03-07 01:34:52	159.1	RAISING	181.28	191.52	159.10	186.40	0.010836	-0.08
2026-03-07 03:05:39	2026-03-07 03:08:18	159.2	RAISING	181.28	191.52	159.20	186.40	0.010840	-0.07
2026-03-07 06:11:08	2026-03-07 06:16:31	322.3	RAISING	176.03	196.77	322.30	186.40	0.021944	-0.05
2026-03-07 07:46:00	2026-03-07 07:48:30	181.55	RAISING	181.55	191.22	150.40	186.38	0.010239	-0.04
2026-03-07 09:19:18	2026-03-07 09:22:03	165.0	RAISING	181.09	191.70	165.00	186.40	0.011234	-0.03
2026-03-07 10:52:47	2026-03-07 10:55:26	159.0	RAISING	181.28	191.51	159.00	186.39	0.010823	-0.02
2026-03-07 12:26:12	2026-03-07 12:28:52	159.6	RAISING	181.26	191.53	159.60	186.39	0.010866	0.01

RESULTS

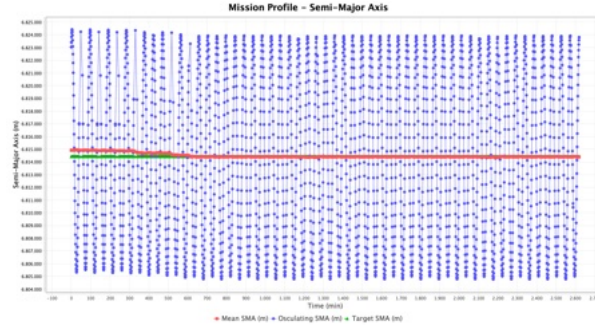


Figure A.120: Evolution of the Semi-Major Axis (a) during Window 19.



Figure A.121: Evolution of the x-component of the eccentricity vector (e_x) for Window 19.

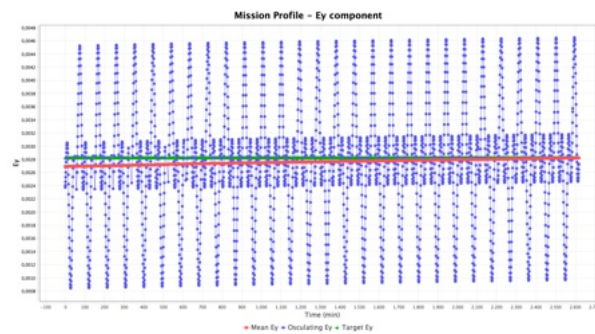


Figure A.122: Evolution of the y-component of the eccentricity vector (e_y) for Window 19.

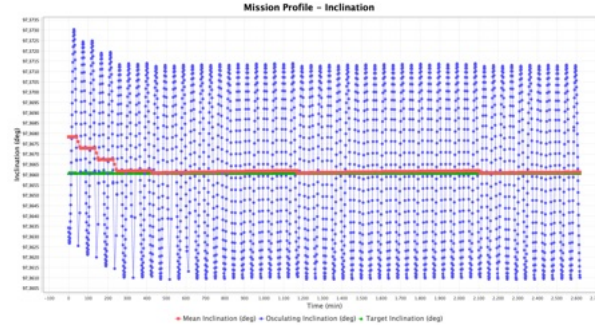


Figure A.123: Evolution of the orbital Inclination (i) in Window 19.

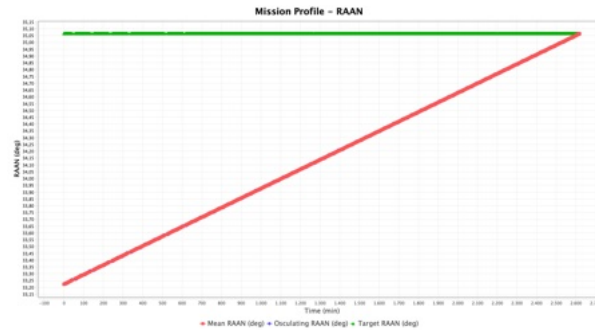


Figure A.124: Evolution of the RAAN (Ω) during Window 19.

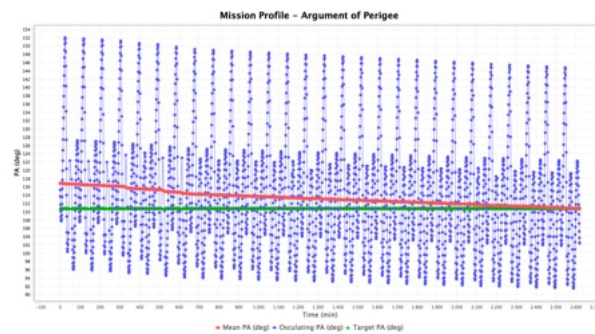


Figure A.125: Evolution of the Argument of Perigee (ω) during Window 19.

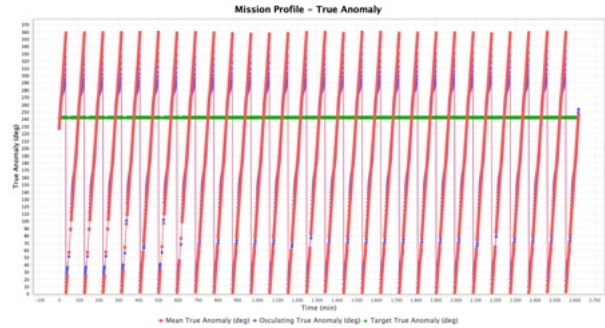


Figure A.126: Evolution of the True Anomaly (ν) throughout Window 19.

A.19 Window 20

Table A.73: Window 20

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-03-07T13:11:46	2026-03-09T08:50:17	2026-03-09T08:50:17
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 814 423.156 m	6 814 103.833 m	6 814 074.350 m
Eccentricity	e	0.003020	0.003028	0.003026
Inclination	i	97.3661°	97.3636°	97.3636°
Arg. of Perigee	ω	110.7656°	105.2341°	105.2268°
RAAN	Ω	35.0652°	36.9078°	36.9064°
True Anomaly	ν	242.6042°	258.1229°	260.7815°

Table A.74: Target State Errors Summary - Window 20

Parameter	Symbol	Error
Semi-Major Axis	Δa	-29.483 m
Inclination	Δi	0.000002°
Eccentricity X	Δe_x	0.000001
Eccentricity Y	Δe_y	-0.000001
RAAN	$\Delta \Omega$	-0.001342°
Arg. of Perigee	$\Delta \omega$	-0.007°
True Anomaly	$\Delta \nu$	2.659°
Arg. of Latitude	Δu	2.651°

Table A.75: Normal Maneuvers Summary - Window 20. SQP ΔV : 0.340609 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL (°)	Thrust Z
2026-03-07 13:49:27	2026-03-07 14:09:27	1200.00	0.081702	0.081702	180.123	1.0
2026-03-07 15:22:53	2026-03-07 15:42:53	1200.00	0.081703	0.163405	180.122	1.0
2026-03-07 16:56:19	2026-03-07 17:16:19	1200.00	0.081704	0.245109	180.122	1.0
2026-03-07 18:29:44	2026-03-07 18:49:44	1200.00	0.081704	0.326813	180.122	1.0
2026-03-07 20:09:09	2026-03-07 20:17:11	481.78	0.032803	0.359616	180.122	1.0

RESULTS

Table A.76: Tangential Maneuvers Summary - Window 20. SQP AOL: 183.38° , v_{Tan} SQP: 0.12 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]
2026-03-07 21:37:31	2026-03-07 21:57:31	1200.0	BRAKING	145.00	222.20	199.55	183.67	-0.081705	-0.08
2026-03-07 23:16:09	2026-03-07 23:25:40	570.6	BRAKING	165.20	201.91	201.08	183.57	-0.038852	-0.12
2026-03-08 00:53:09	2026-03-08 00:55:32	143.1	RAISING	179.04	188.25	22.05	183.65	0.009746	-0.11
2026-03-08 02:26:20	2026-03-08 02:29:14	173.8	RAISING	178.08	189.27	22.03	183.68	0.011836	-0.10
2026-03-08 03:59:52	2026-03-08 04:02:32	160.1	RAISING	178.53	188.82	21.91	183.68	0.010900	-0.09
2026-03-08 05:33:17	2026-03-08 05:35:58	161.2	RAISING	178.49	188.86	21.83	183.68	0.010973	-0.08
2026-03-08 07:06:42	2026-03-08 07:09:23	160.9	RAISING	178.50	188.85	21.75	183.68	0.010953	-0.07
2026-03-08 08:40:07	2026-03-08 08:42:48	160.9	RAISING	178.50	188.85	21.67	183.67	0.010958	-0.06
2026-03-08 10:13:33	2026-03-08 10:16:14	161.0	RAISING	178.49	188.85	21.60	183.67	0.010959	-0.05
2026-03-08 11:46:58	2026-03-08 11:49:39	161.0	RAISING	178.49	188.85	21.53	183.67	0.010961	-0.04
2026-03-08 13:20:23	2026-03-08 13:23:04	161.0	RAISING	178.49	188.85	21.48	183.67	0.010963	-0.03
2026-03-08 14:53:48	2026-03-08 14:56:29	161.0	RAISING	178.49	188.85	21.43	183.67	0.010965	-0.02
2026-03-08 16:27:14	2026-03-08 16:29:55	161.1	RAISING	178.49	188.85	21.39	183.67	0.010968	-0.01
2026-03-08 18:00:39	2026-03-08 18:03:20	161.1	RAISING	178.49	188.85	21.37	183.67	0.010971	0.00
2026-03-08 19:34:04	2026-03-08 19:36:45	161.2	RAISING	178.48	188.85	21.37	183.67	0.010974	0.01
2026-03-08 21:07:29	2026-03-08 21:10:11	161.2	RAISING	178.48	188.85	21.40	183.67	0.010977	0.02
2026-03-08 22:40:55	2026-03-08 22:43:36	161.3	RAISING	178.48	188.85	21.47	183.67	0.010981	0.03
2026-03-09 00:14:20	2026-03-09 00:17:01	161.3	RAISING	178.47	188.85	21.60	183.66	0.010985	0.04
2026-03-09 01:47:45	2026-03-09 01:50:27	161.4	RAISING	178.47	188.85	21.82	183.66	0.010989	0.05
2026-03-09 03:21:10	2026-03-09 03:23:52	161.4	RAISING	178.47	188.85	22.20	183.66	0.010993	0.06
2026-03-09 04:54:36	2026-03-09 04:57:17	161.5	RAISING	178.47	188.85	22.86	183.66	0.010996	0.08
2026-03-09 06:28:01	2026-03-09 06:30:42	161.5	RAISING	178.46	188.85	24.18	183.66	0.010999	0.09
2026-03-09 08:01:26	2026-03-09 08:04:08	161.6	RAISING	178.46	188.86	27.55	183.66	0.011002	0.11

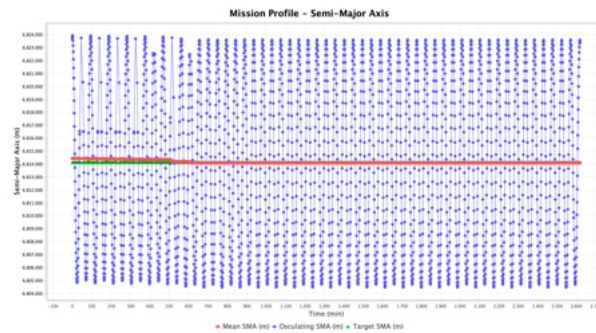


Figure A.127: Evolution of the Semi-Major Axis (a) during Window 20.

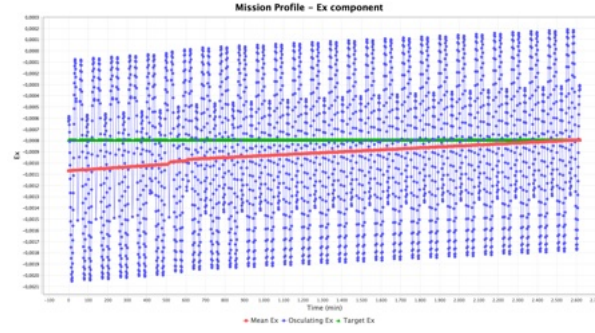


Figure A.128: Evolution of the x-component of the eccentricity vector (e_x) for Window 20.

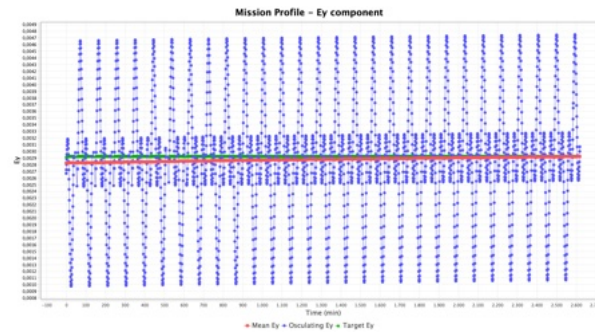


Figure A.129: Evolution of the y-component of the eccentricity vector (e_y) for Window 20.

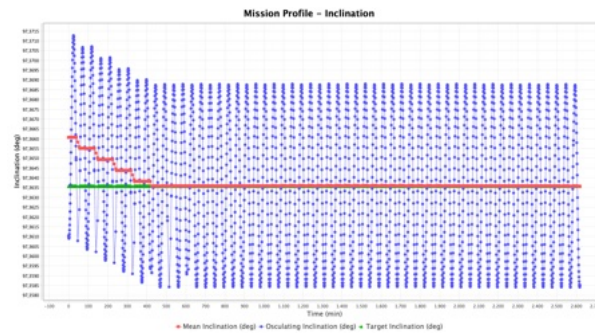


Figure A.130: Evolution of the orbital Inclination (i) in Window 20.

RESULTS

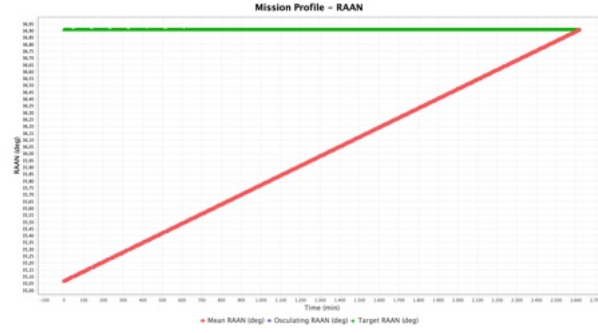


Figure A.131: Evolution of the RAAN (Ω) during Window 20.

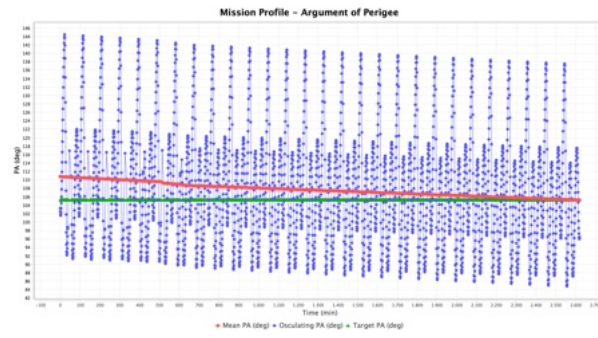


Figure A.132: Evolution of the Argument of Perigee (ω) during Window 20.

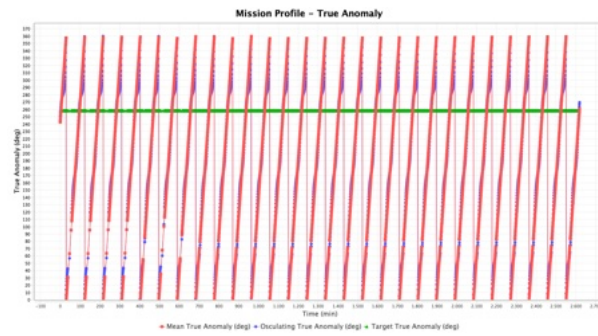


Figure A.133: Evolution of the True Anomaly (ν) throughout Window 20.

A.20 Window 21

Table A.77: Window 21

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-03-09T08:50:17	2026-03-11T04:28:48	2026-03-11T04:28:48
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 814 103.833 m	6 813 729.487 m	6 813 700.710 m
Eccentricity	e	0.003028	0.003026	0.003024
Inclination	i	97.3636°	97.3618°	97.3618°
Arg. of Perigee	ω	105.2341°	99.6143°	99.6182°
RAAN	Ω	36.9078°	38.7501°	38.7488°
True Anomaly	ν	258.1229°	274.5228°	277.2614°

Table A.78: Target State Errors Summary - Window 21

Parameter	Symbol	Error
Semi-Major Axis	Δa	−28.776 m
Inclination	Δi	−0.000021°
Eccentricity X	Δe_x	0.000000
Eccentricity Y	Δe_y	−0.000002
RAAN	$\Delta \Omega$	−0.001238°
Arg. of Perigee	$\Delta \omega$	0.004°
True Anomaly	$\Delta \nu$	2.739°
Arg. of Latitude	Δu	2.743°

RESULTS

Table A.79: Normal Maneuvers Summary - Window 21. SQP ΔV : 0.214970 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL ($^\circ$)	Thrust Z
2026-03-09 09:25:22	2026-03-09 09:45:22	1200.00	0.081702	0.081702	180.120	1.0
2026-03-09 10:58:47	2026-03-09 11:18:47	1200.00	0.081703	0.163405	180.120	1.0
2026-03-09 12:32:12	2026-03-09 12:52:12	1200.00	0.081704	0.245109	180.120	1.0
2026-03-11 02:02:23	2026-03-11 02:05:54	211.03	0.014369	0.259478	180.117	-1.0

Table A.80: Tangential Maneuvers Summary - Window 21. SQP AOL: 189.41° , v_{Tan} SQP: 0.09 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]
2026-03-09 14:08:05	2026-03-09 14:28:05	1200.0	BRAKING	150.95	228.07	191.90	189.59	-0.081704	-0.08
2026-03-09 15:41:29	2026-03-09 16:01:29	1200.0	BRAKING	150.91	228.02	191.86	189.54	-0.081705	-0.16
2026-03-09 18:57:35	2026-03-09 18:59:00	85.2	RAISING	186.75	192.23	12.08	189.49	0.005799	-0.16
2026-03-09 20:29:39	2026-03-09 20:33:53	253.8	RAISING	181.52	197.83	11.94	189.68	0.017283	-0.14
2026-03-09 22:03:52	2026-03-09 22:06:29	157.2	RAISING	184.61	194.71	11.82	189.66	0.010703	-0.13
2026-03-09 23:37:12	2026-03-09 23:39:58	166.5	RAISING	184.32	195.02	11.74	189.67	0.011337	-0.12
2026-03-10 01:10:39	2026-03-10 01:13:21	162.9	RAISING	184.43	194.90	11.65	189.67	0.011092	-0.11
2026-03-10 02:44:03	2026-03-10 02:46:47	163.4	RAISING	184.41	194.92	11.56	189.67	0.011126	-0.10
2026-03-10 04:17:28	2026-03-10 04:20:11	163.3	RAISING	184.42	194.91	11.49	189.67	0.011121	-0.08
2026-03-10 05:50:53	2026-03-10 05:53:36	163.4	RAISING	184.41	194.91	11.41	189.66	0.011125	-0.07
2026-03-10 07:24:18	2026-03-10 07:27:01	163.4	RAISING	184.41	194.91	11.35	189.66	0.011128	-0.06
2026-03-10 08:57:42	2026-03-10 09:00:26	163.5	RAISING	184.41	194.91	11.29	189.66	0.011130	-0.05
2026-03-10 10:31:07	2026-03-10 10:33:51	163.5	RAISING	184.41	194.91	11.24	189.66	0.011132	-0.04
2026-03-10 12:04:32	2026-03-10 12:07:15	163.5	RAISING	184.40	194.91	11.20	189.66	0.011133	-0.03
2026-03-10 13:37:57	2026-03-10 13:40:40	163.5	RAISING	184.40	194.91	11.18	189.66	0.011135	-0.02
2026-03-10 15:11:22	2026-03-10 15:14:05	163.6	RAISING	184.40	194.91	11.17	189.66	0.011137	-0.01
2026-03-10 16:44:46	2026-03-10 16:47:30	163.6	RAISING	184.40	194.91	11.20	189.66	0.011139	0.00
2026-03-10 18:18:11	2026-03-10 18:20:55	163.6	RAISING	184.40	194.91	11.26	189.66	0.011143	0.02
2026-03-10 19:51:36	2026-03-10 19:54:20	163.7	RAISING	184.39	194.91	11.39	189.65	0.011146	0.03
2026-03-10 21:25:01	2026-03-10 21:27:45	163.8	RAISING	184.39	194.91	11.60	189.65	0.011151	0.04
2026-03-10 22:58:26	2026-03-10 23:01:09	163.8	RAISING	184.39	194.91	11.95	189.65	0.011155	0.05
2026-03-11 00:31:50	2026-03-11 00:34:34	163.9	RAISING	184.38	194.91	12.58	189.65	0.011160	0.06
2026-03-11 03:37:15	2026-03-11 03:42:49	334.7	RAISING	178.90	200.41	19.45	189.66	0.022790	0.08

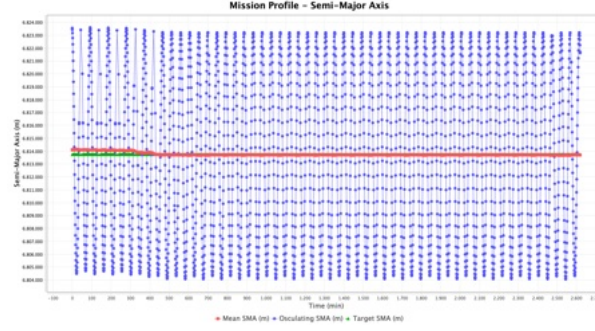


Figure A.134: Evolution of the Semi-Major Axis (a) during Window 21.

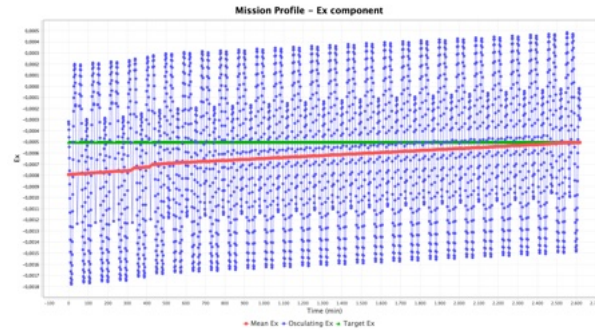


Figure A.135: Evolution of the x-component of the eccentricity vector (e_x) for Window 21.

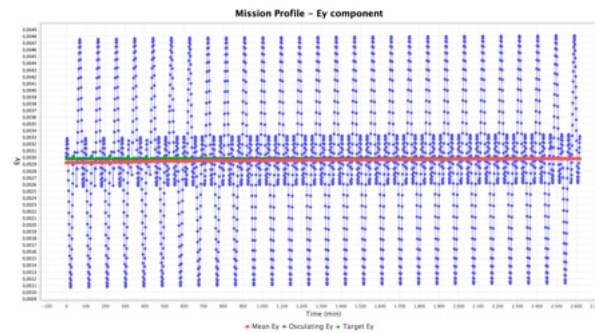


Figure A.136: Evolution of the y-component of the eccentricity vector (e_y) for Window 21.

RESULTS

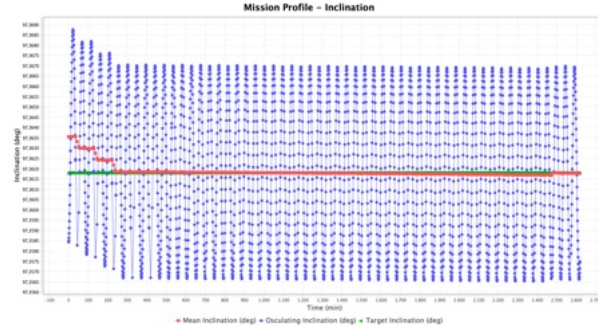


Figure A.137: Evolution of the orbital Inclination (i) in Window 21.

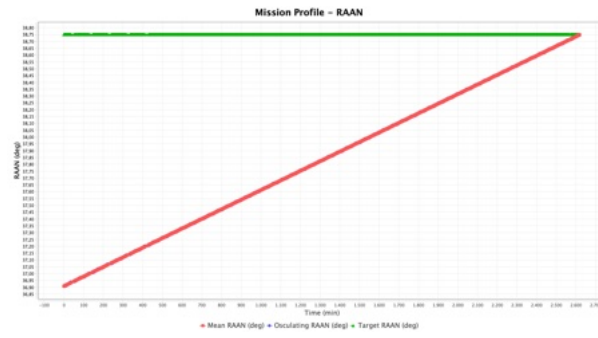


Figure A.138: Evolution of the RAAN (Ω) during Window 21.

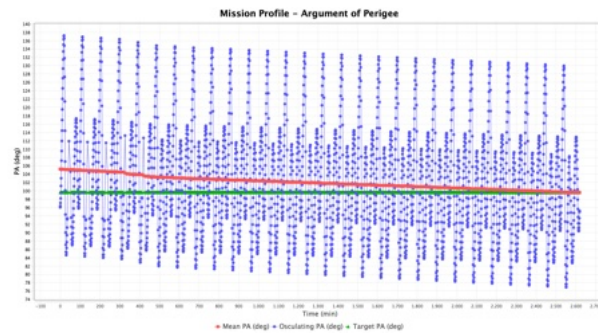


Figure A.139: Evolution of the Argument of Perigee (ω) during Window 21.

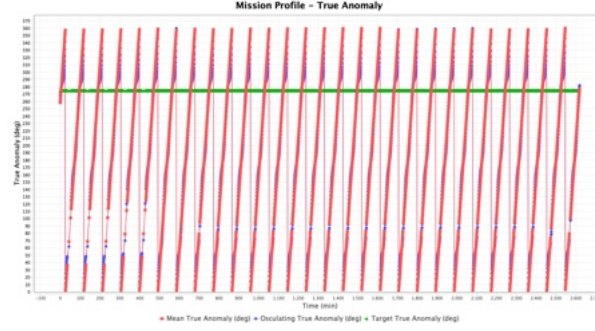


Figure A.140: Evolution of the True Anomaly (ν) throughout Window 21.

A.21 Window 22

Table A.81: Window 22

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-03-11T04:28:48	2026-03-13T00:07:19	2026-03-13T00:07:19
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 813 729.487 m	6 812 893.562 m	6 812 864.336 m
Eccentricity	e	0.003026	0.003021	0.003018
Inclination	i	97.3618°	97.3599°	97.3598°
Arg. of Perigee	ω	99.6143°	92.7633°	92.8330°
RAAN	Ω	38.7501°	40.5924°	40.5912°
True Anomaly	ν	274.5228°	293.5118°	296.4293°

RESULTS

Table A.82: Target State Errors Summary - Window 22

Parameter	Symbol	Error
Semi-Major Axis	Δa	-29.226 m
Inclination	Δi	-0.000107°
Eccentricity X	Δe_x	-0.000004
Eccentricity Y	Δe_y	-0.000003
RAAN	$\Delta \Omega$	-0.001152°
Arg. of Perigee	$\Delta \omega$	0.070°
True Anomaly	$\Delta \nu$	2.917°
Arg. of Latitude	Δu	2.987°

Table A.83: Normal Maneuvers Summary - Window 22. SQP ΔV : 0.228037 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL ($^\circ$)	Thrust Z
2026-03-11 05:01:04	2026-03-11 05:21:04	1200.00	0.081702	0.081702	180.117	1.0
2026-03-11 06:34:29	2026-03-11 06:54:29	1200.00	0.081703	0.163405	180.117	1.0
2026-03-11 08:07:54	2026-03-11 08:27:54	1200.00	0.081704	0.245109	180.117	1.0
2026-03-11 09:48:15	2026-03-11 09:54:22	366.63	0.024963	0.270072	180.117	1.0
2026-03-12 04:30:23	2026-03-12 04:33:52	208.89	0.014223	0.284295	180.115	-1.0

Table A.84: Tangential Maneuvers Summary - Window 22. SQP AOL: 188.24° , v_{Tan} SQP: -0.16 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma\Delta V$ [m/s]
2026-03-11 11:16:53	2026-03-11 11:36:53	1200.0	BRAKING	149.85	226.94	184.94	188.48	-0.081704	-0.08
2026-03-11 12:50:16	2026-03-11 13:10:16	1200.0	BRAKING	149.72	226.81	184.65	188.34	-0.081705	-0.16
2026-03-11 14:23:40	2026-03-11 14:43:40	1200.0	BRAKING	149.72	226.81	184.25	188.34	-0.081705	-0.25
2026-03-11 15:57:04	2026-03-11 16:17:04	1200.0	BRAKING	149.72	226.80	183.78	188.34	-0.081706	-0.33
2026-03-11 17:33:18	2026-03-11 17:47:38	860.2	BRAKING	160.66	215.92	183.20	188.33	-0.058569	-0.39
2026-03-11 19:12:46	2026-03-11 19:14:59	133.2	RAISING	184.10	192.66	2.54	188.38	0.009070	-0.38
2026-03-11 20:45:51	2026-03-11 20:48:44	173.0	RAISING	182.90	194.01	2.39	188.46	0.011781	-0.37
2026-03-11 22:19:19	2026-03-11 22:22:04	165.7	RAISING	183.13	193.77	2.34	188.45	0.011285	-0.36
2026-03-11 23:52:42	2026-03-11 23:55:29	167.4	RAISING	183.07	193.83	2.29	188.45	0.011398	-0.35
2026-03-12 01:26:06	2026-03-12 01:28:53	167.2	RAISING	183.08	193.82	2.25	188.45	0.011382	-0.33
2026-03-12 02:59:29	2026-03-12 03:02:17	167.3	RAISING	183.08	193.82	2.22	188.45	0.011391	-0.32
2026-03-12 06:04:51	2026-03-12 06:10:31	340.2	RAISING	177.53	199.38	340.20	188.46	0.023164	-0.30
2026-03-12 07:39:46	2026-03-12 07:42:22	156.3	RAISING	183.41	193.45	156.30	188.43	0.010642	-0.29
2026-03-12 09:13:01	2026-03-12 09:15:55	173.5	RAISING	182.87	194.02	173.50	188.45	0.011816	-0.28
2026-03-12 10:46:28	2026-03-12 10:49:15	166.9	RAISING	183.08	193.80	166.90	188.44	0.011366	-0.27
2026-03-12 12:19:52	2026-03-12 12:22:40	167.7	RAISING	183.05	193.83	167.70	188.44	0.011420	-0.25
2026-03-12 13:53:16	2026-03-12 13:56:03	167.5	RAISING	183.06	193.82	167.50	188.44	0.011406	-0.24
2026-03-12 15:26:39	2026-03-12 15:29:27	167.6	RAISING	183.06	193.82	167.60	188.44	0.011410	-0.23
2026-03-12 17:00:03	2026-03-12 17:02:51	167.6	RAISING	183.06	193.82	167.60	188.44	0.011412	-0.22
2026-03-12 18:33:27	2026-03-12 18:36:15	167.6	RAISING	183.05	193.82	167.60	188.44	0.011415	-0.21
2026-03-12 20:06:51	2026-03-12 20:09:38	167.7	RAISING	183.05	193.82	167.70	188.44	0.011419	-0.20
2026-03-12 21:40:15	2026-03-12 21:43:02	167.8	RAISING	183.05	193.82	167.80	188.44	0.011423	-0.18
2026-03-12 23:13:38	2026-03-12 23:16:26	167.8	RAISING	183.04	193.82	167.80	188.43	0.011428	-0.16

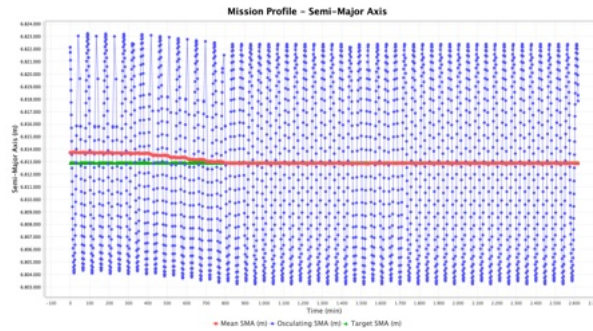


Figure A.141: Evolution of the Semi-Major Axis (a) during Window 22.

RESULTS

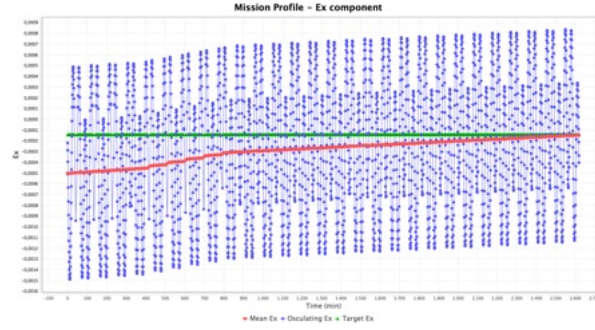


Figure A.142: Evolution of the x-component of the eccentricity vector (e_x) for Window 22.

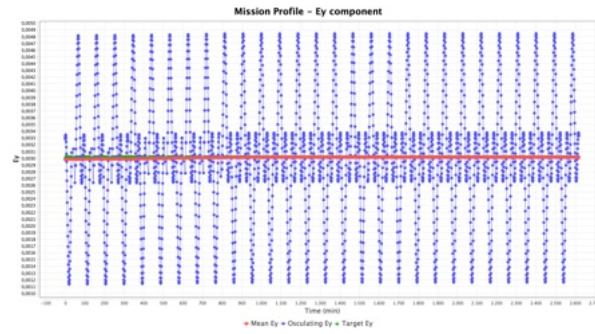


Figure A.143: Evolution of the y-component of the eccentricity vector (e_y) for Window 22.

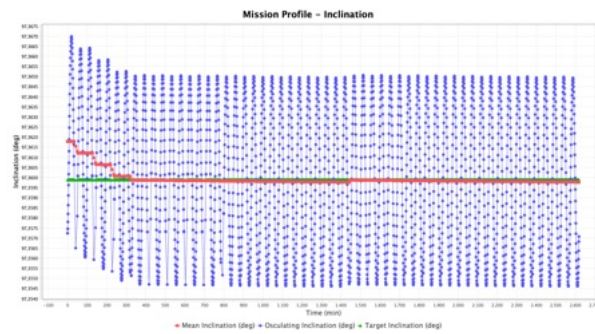


Figure A.144: Evolution of the orbital Inclination (i) in Window 22.

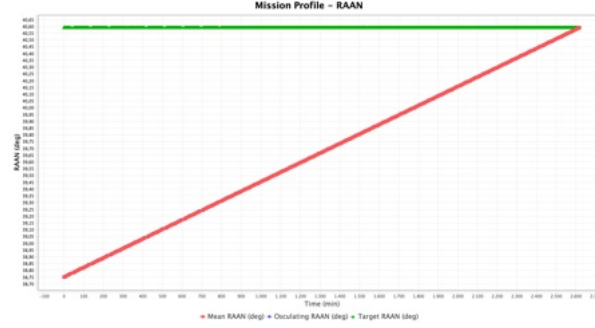


Figure A.145: Evolution of the RAAN (Ω) during Window 22.

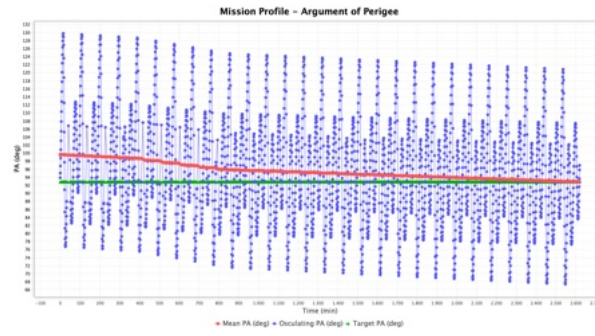


Figure A.146: Evolution of the Argument of Perigee (ω) during Window 22.

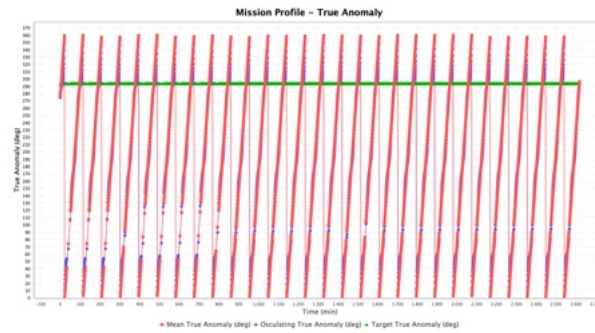


Figure A.147: Evolution of the True Anomaly (ν) throughout Window 22.

A.22 Window 23

Table A.85: Window 23

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-03-13T00:07:19	2026-03-14T19:45:50	2026-03-14T19:45:50
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 812 893.562 m	6 812 401.440 m	6 812 368.387 m
Eccentricity	e	0.003021	0.003009	0.003008
Inclination	i	97.3599°	97.3576°	97.3576°
Arg. of Perigee	ω	92.7633°	86.9130°	86.9171°
RAAN	Ω	40.5924°	42.4348°	42.4335°
True Anomaly	ν	293.5118°	313.0240°	315.8292°

Table A.86: Target State Errors Summary - Window 23

Parameter	Symbol	Error
Semi-Major Axis	Δa	−33.052 m
Inclination	Δi	−0.000056°
Eccentricity X	Δe_x	−0.000000
Eccentricity Y	Δe_y	−0.000001
RAAN	$\Delta \Omega$	−0.001253°
Arg. of Perigee	$\Delta \omega$	0.004°
True Anomaly	$\Delta \nu$	2.805°
Arg. of Latitude	Δu	2.809°

Table A.87: Normal Maneuvers Summary - Window 23. SQP ΔV : 0.289792 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL ($^\circ$)	Thrust Z
2026-03-13 00:36:26	2026-03-13 00:56:26	1200.00	0.081702	0.081702	180.114	1.0
2026-03-13 02:09:50	2026-03-13 02:29:50	1200.00	0.081703	0.163405	180.114	1.0
2026-03-13 03:43:14	2026-03-13 04:03:14	1200.00	0.081704	0.245109	180.114	1.0
2026-03-13 05:18:03	2026-03-13 05:35:11	1028.16	0.070004	0.315113	180.114	1.0

Table A.88: Tangential Maneuvers Summary - Window 23. SQP AOL: 191.77° , v_{Tan} SQP: 0.04 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]
2026-03-13 06:53:04	2026-03-13 07:13:04	1200.0	BRAKING	153.30	230.33	176.89	191.89	-0.081705	-0.08
2026-03-13 08:26:27	2026-03-13 08:46:27	1200.0	BRAKING	153.22	230.24	175.48	191.81	-0.081705	-0.16
2026-03-13 10:03:07	2026-03-13 10:16:33	806.3	BRAKING	165.89	217.65	173.71	191.80	-0.054900	-0.22
2026-03-13 11:41:29	2026-03-13 11:44:59	209.4	RAISING	185.14	198.58	352.06	191.86	0.014255	-0.20
2026-03-13 13:15:15	2026-03-13 13:18:01	166.0	RAISING	186.60	197.26	351.95	191.93	0.011305	-0.19
2026-03-13 14:48:36	2026-03-13 14:51:27	171.2	RAISING	186.44	197.43	351.85	191.94	0.011660	-0.18
2026-03-13 16:22:00	2026-03-13 16:24:50	169.7	RAISING	186.49	197.38	351.76	191.94	0.011558	-0.17
2026-03-13 17:55:23	2026-03-13 17:58:13	170.0	RAISING	186.48	197.39	351.67	191.93	0.011577	-0.16
2026-03-13 19:28:46	2026-03-13 19:31:36	170.0	RAISING	186.48	197.39	351.59	191.93	0.011576	-0.15
2026-03-13 21:02:09	2026-03-13 21:04:59	170.1	RAISING	186.47	197.39	351.52	191.93	0.011582	-0.13
2026-03-13 22:35:32	2026-03-13 22:38:23	170.2	RAISING	186.47	197.39	351.44	191.93	0.011586	-0.12
2026-03-14 00:08:56	2026-03-14 00:11:46	170.2	RAISING	186.46	197.39	351.38	191.93	0.011591	-0.11
2026-03-14 01:42:19	2026-03-14 01:45:09	170.3	RAISING	186.46	197.39	351.33	191.93	0.011596	-0.10
2026-03-14 03:15:42	2026-03-14 03:18:32	170.4	RAISING	186.46	197.39	351.28	191.93	0.011601	-0.09
2026-03-14 04:49:05	2026-03-14 04:51:56	170.4	RAISING	186.46	197.39	351.25	191.93	0.011605	-0.08
2026-03-14 06:22:28	2026-03-14 06:25:19	170.5	RAISING	186.45	197.39	351.25	191.92	0.011608	-0.07
2026-03-14 07:55:51	2026-03-14 07:58:42	170.5	RAISING	186.45	197.39	351.26	191.92	0.011610	-0.05
2026-03-14 09:29:15	2026-03-14 09:32:05	170.5	RAISING	186.45	197.39	351.31	191.92	0.011612	-0.04
2026-03-14 11:02:38	2026-03-14 11:05:28	170.6	RAISING	186.45	197.39	351.42	191.92	0.011614	-0.03
2026-03-14 12:36:01	2026-03-14 12:38:52	170.6	RAISING	186.44	197.39	351.60	191.92	0.011615	-0.02
2026-03-14 14:09:24	2026-03-14 14:12:15	170.6	RAISING	186.44	197.39	351.91	191.92	0.011616	-0.01
2026-03-14 15:42:47	2026-03-14 15:45:38	170.6	RAISING	186.44	197.39	352.46	191.92	0.011618	0.00
2026-03-14 17:16:10	2026-03-14 17:19:01	170.7	RAISING	186.44	197.39	353.52	191.92	0.011621	0.01
2026-03-14 18:49:34	2026-03-14 18:52:24	170.7	RAISING	186.44	197.39	356.00	191.91	0.011624	0.03

RESULTS

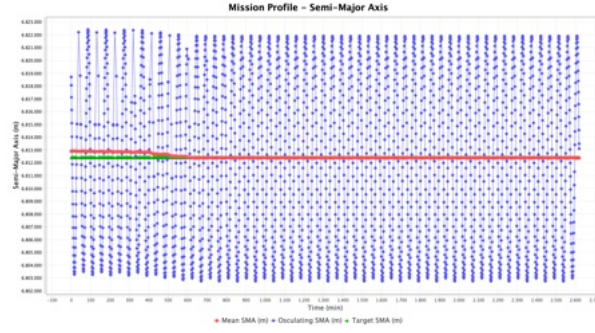


Figure A.148: Evolution of the Semi-Major Axis (a) during Window 23.

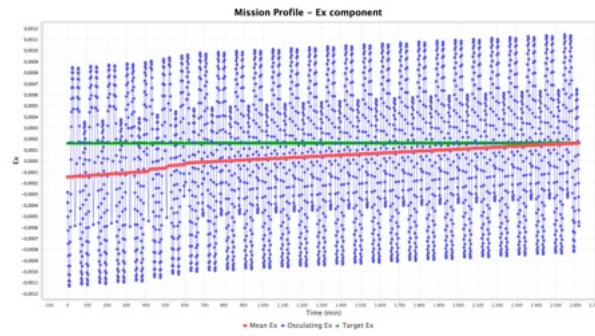


Figure A.149: Evolution of the x-component of the eccentricity vector (e_x) for Window 23.

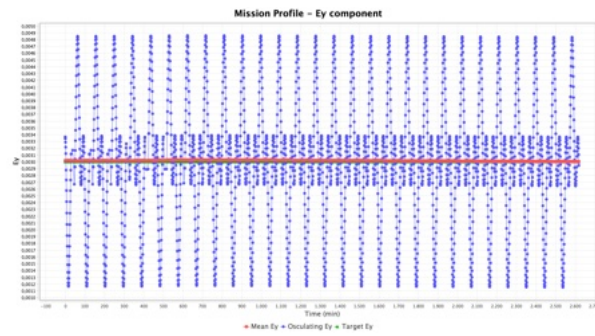


Figure A.150: Evolution of the y-component of the eccentricity vector (e_y) for Window 23.

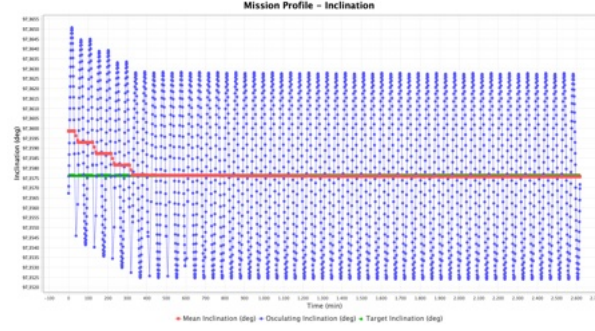


Figure A.151: Evolution of the orbital Inclination (i) in Window 23.

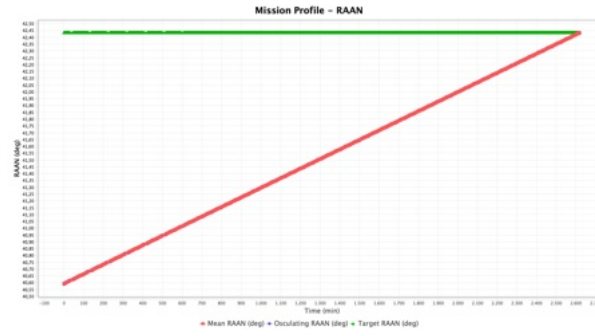


Figure A.152: Evolution of the RAAN (Ω) during Window 23.

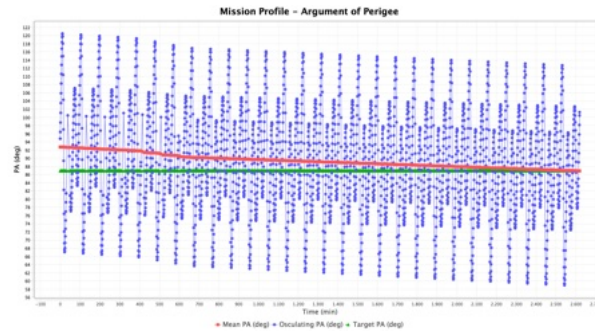


Figure A.153: Evolution of the Argument of Perigee (ω) during Window 23.

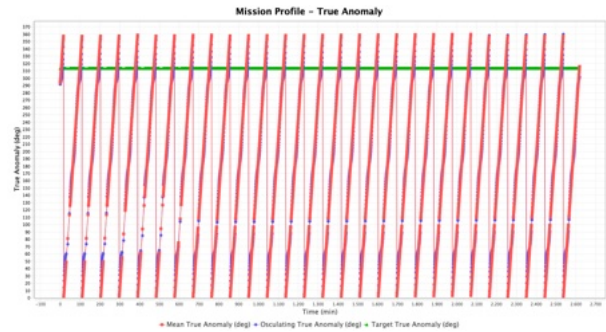


Figure A.154: Evolution of the True Anomaly (ν) throughout Window 23.

A.23 Window 24

Table A.89: Window 24

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-03-14T19:45:50	2026-03-16T15:24:21	2026-03-16T15:24:21
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 812 401.440 m	6 811 986.374 m	6 811 964.559 m
Eccentricity	e	0.003009	0.002989	0.002988
Inclination	i	97.3576°	97.3562°	97.3563°
Arg. of Perigee	ω	86.9130°	81.2986°	81.2941°
RAAN	Ω	42.4348°	44.2772°	44.2761°
True Anomaly	ν	313.0240°	333.3422°	336.1427°

Table A.90: Target State Errors Summary - Window 24

Parameter	Symbol	Error
Semi-Major Axis	Δa	-21.815 m
Inclination	Δi	0.000090°
Eccentricity X	Δe_x	0.000000
Eccentricity Y	Δe_y	-0.000001
RAAN	$\Delta \Omega$	-0.001170°
Arg. of Perigee	$\Delta \omega$	-0.005°
True Anomaly	$\Delta \nu$	2.800°
Arg. of Latitude	Δu	2.796°

Table A.91: Normal Maneuvers Summary - Window 24. SQP ΔV : 0.222372 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL (°)	Thrust Z
2026-03-14 20:11:25	2026-03-14 20:31:25	1200.00	0.081702	0.081702	180.111	1.0
2026-03-14 21:44:48	2026-03-14 22:04:48	1200.00	0.081703	0.163405	180.111	1.0
2026-03-14 23:22:58	2026-03-14 23:33:24	626.17	0.042634	0.206039	180.111	1.0
2026-03-16 05:00:41	2026-03-16 05:04:06	204.97	0.013956	0.219995	180.109	1.0

RESULTS

Table A.92: Tangential Maneuvers Summary - Window 24. SQP AOL: 192.20° , v_{Tan} SQP: 0.09 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma\Delta V$ [m/s]
2026-03-15 00:54:45	2026-03-15 01:14:45	1200.0	BRAKING	169.48	230.75	192.20	192.33	-0.081704	-0.08
2026-03-15 02:28:06	2026-03-15 02:48:06	1200.0	BRAKING	167.49	230.62	192.20	192.20	-0.081704	-0.16
2026-03-15 04:08:59	2026-03-15 04:13:58	298.6	BRAKING	164.89	201.77	192.20	192.19	-0.020329	-0.18
2026-03-15 05:43:10	2026-03-15 05:46:36	206.7	RAISING	185.68	198.95	343.59	192.32	0.014076	-0.17
2026-03-15 07:16:48	2026-03-15 07:19:43	175.2	RAISING	186.71	197.94	343.58	192.33	0.011926	-0.16
2026-03-15 08:50:12	2026-03-15 08:53:05	173.6	RAISING	186.76	197.89	343.50	192.33	0.011820	-0.15
2026-03-15 10:23:35	2026-03-15 10:26:28	172.6	RAISING	186.79	197.86	343.41	192.33	0.011755	-0.13
2026-03-15 11:56:58	2026-03-15 11:59:50	172.6	RAISING	186.79	197.86	343.33	192.32	0.011755	-0.12
2026-03-15 13:30:20	2026-03-15 13:33:13	172.6	RAISING	186.79	197.86	343.25	192.32	0.011754	-0.11
2026-03-15 15:03:43	2026-03-15 15:06:36	172.7	RAISING	186.78	197.86	343.18	192.32	0.011756	-0.10
2026-03-15 16:37:06	2026-03-15 16:39:58	172.7	RAISING	186.78	197.86	343.11	192.32	0.011758	-0.09
2026-03-15 18:10:28	2026-03-15 18:13:21	172.7	RAISING	186.78	197.86	343.05	192.32	0.011761	-0.08
2026-03-15 19:43:51	2026-03-15 19:46:44	172.8	RAISING	186.78	197.86	343.00	192.32	0.011764	-0.06
2026-03-15 21:17:14	2026-03-15 21:20:06	172.8	RAISING	186.77	197.86	342.96	192.32	0.011769	-0.05
2026-03-15 22:50:36	2026-03-15 22:53:29	172.9	RAISING	186.77	197.86	342.93	192.32	0.011773	-0.04
2026-03-16 00:23:59	2026-03-16 00:26:52	173.0	RAISING	186.77	197.86	342.92	192.31	0.011778	-0.03
2026-03-16 01:57:21	2026-03-16 02:00:14	173.1	RAISING	186.76	197.86	342.93	192.31	0.011783	-0.02
2026-03-16 03:30:44	2026-03-16 03:33:37	173.1	RAISING	186.76	197.86	342.97	192.31	0.011788	-0.01
2026-03-16 06:35:58	2026-03-16 06:41:54	355.8	RAISING	180.92	203.73	355.80	192.33	0.024225	0.02
2026-03-16 08:10:59	2026-03-16 08:13:38	159.0	RAISING	187.19	197.39	159.00	192.29	0.010824	0.03
2026-03-16 09:44:12	2026-03-16 09:47:11	178.8	RAISING	186.58	198.04	178.80	192.31	0.012171	0.04
2026-03-16 11:17:38	2026-03-16 11:20:30	172.6	RAISING	186.77	197.84	172.60	192.31	0.011754	0.05
2026-03-16 12:51:00	2026-03-16 12:53:53	173.5	RAISING	186.74	197.87	173.50	192.31	0.011814	0.07
2026-03-16 14:24:23	2026-03-16 14:27:16	173.3	RAISING	186.75	197.86	173.30	192.30	0.011799	0.08

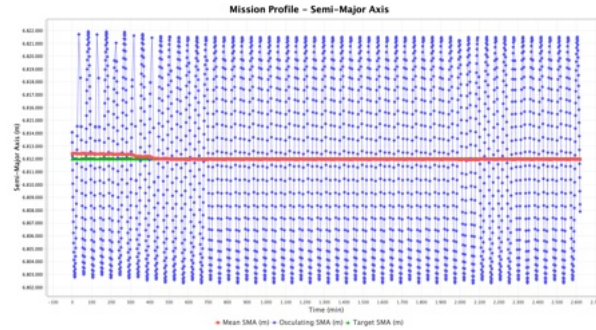


Figure A.155: Evolution of the Semi-Major Axis (a) during Window 24.

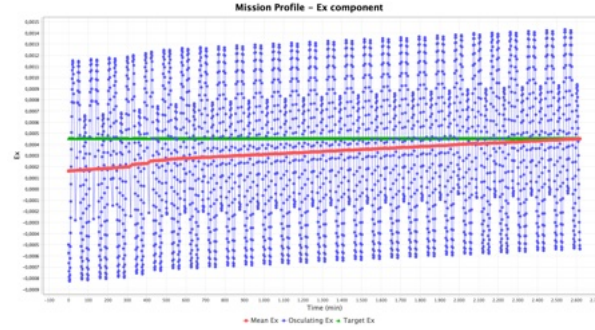


Figure A.156: Evolution of the x-component of the eccentricity vector (e_x) for Window 24.

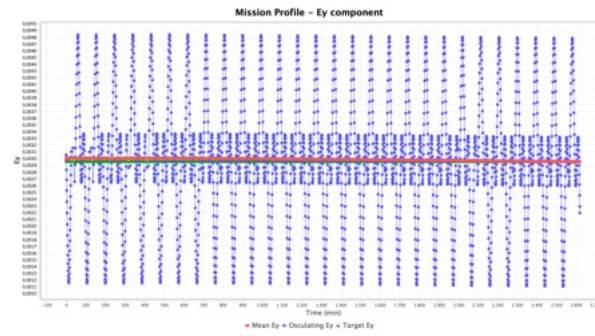


Figure A.157: Evolution of the y-component of the eccentricity vector (e_y) for Window 24.

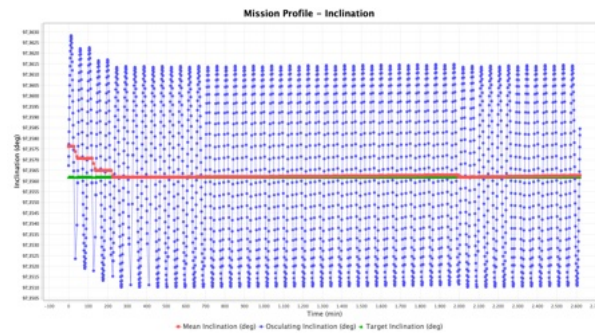


Figure A.158: Evolution of the orbital Inclination (i) in Window 24.

RESULTS

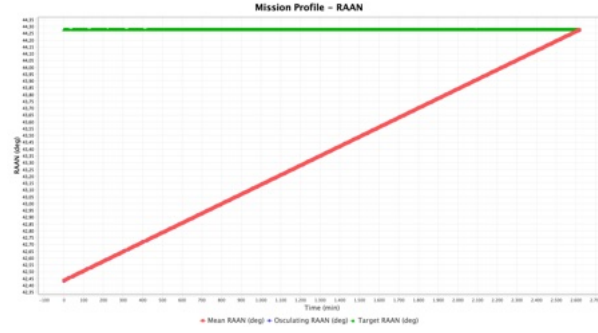


Figure A.159: Evolution of the RAAN (Ω) during Window 24.

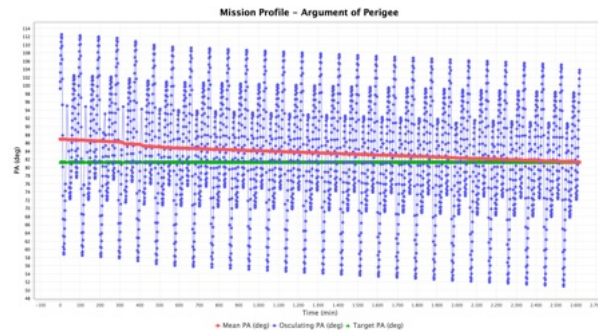


Figure A.160: Evolution of the Argument of Perigee (ω) during Window 24.

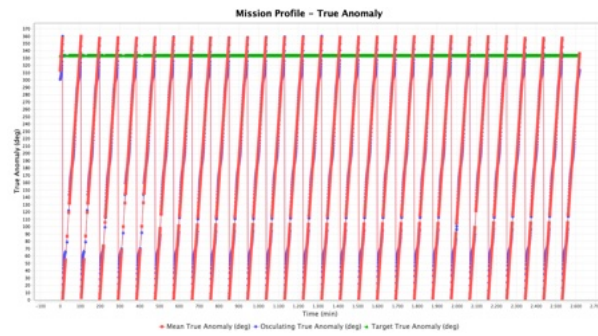


Figure A.161: Evolution of the True Anomaly (ν) throughout Window 24.

A.24 Window 25

Table A.93: Orbit Comparison - Window 25

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-03-16T15:24:21	2026-03-18T11:02:52	2026-03-18T11:02:52
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 811 986.374 m	6 811 934.055 m	6 811 923.675 m
Eccentricity	e	0.002989	0.002939	0.002941
Inclination	i	97.3562°	97.3547°	97.3548°
Arg. of Perigee	ω	81.2986°	76.6251°	76.6100°
RAAN	Ω	44.2772°	46.1197°	46.1184°
True Anomaly	ν	333.3422°	353.2645°	355.7911°

Table A.94: Target State Errors Summary - Window 25

Parameter	Symbol	Error
Semi-Major Axis	Δa	−10.380 m
Inclination	Δi	0.000066°
Eccentricity X	Δe_x	0.000001
Eccentricity Y	Δe_y	0.000002
RAAN	$\Delta \Omega$	−0.001285°
Arg. of Perigee	$\Delta \omega$	−0.015°
True Anomaly	$\Delta \nu$	2.527°
Arg. of Latitude	Δu	2.511°

RESULTS

Table A.95: Normal Maneuvers Summary - Window 25. SQP ΔV : 0.266738 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL ($^{\circ}$)	Thrust Z
2026-03-16 15:46:08	2026-03-16 16:06:08	1200.00	0.081702	0.081702	180.108	1.0
2026-03-16 17:19:31	2026-03-16 17:39:31	1200.00	0.081703	0.163405	180.108	1.0
2026-03-16 18:57:17	2026-03-16 19:08:30	672.80	0.045809	0.209214	180.108	1.0
2026-03-17 05:54:45	2026-03-17 05:58:19	214.67	0.014616	0.223830	180.107	1.0
2026-03-17 15:15:03	2026-03-17 15:18:32	209.02	0.014232	0.238062	180.106	1.0
2026-03-18 00:35:07	2026-03-18 00:39:00	233.07	0.015869	0.253931	180.105	1.0
2026-03-18 08:22:11	2026-03-18 08:25:43	211.86	0.014425	0.268356	180.105	1.0

Table A.96: Tangential Maneuvers Summary - Window 25. SQP AOL: 194.28 $^{\circ}$, v_{Tan} SQP: 0.29 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^{\circ}$)	End AOL ($^{\circ}$)	Ideal AOL ($^{\circ}$)	Ctr AOL ($^{\circ}$)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]
2026-03-16 22:12:11	2026-03-16 22:14:25	133.7	RAISING	189.90	198.47	335.80	194.18	0.009106	0.01
2026-03-16 23:44:24	2026-03-16 23:49:04	279.3	RAISING	185.41	203.32	335.22	194.37	0.019018	0.03
2026-03-17 01:18:41	2026-03-17 01:21:31	169.8	RAISING	188.91	199.80	335.45	194.36	0.011561	0.04
2026-03-17 02:52:01	2026-03-17 02:54:57	176.9	RAISING	188.69	200.03	335.30	194.37	0.012044	0.05
2026-03-17 04:25:25	2026-03-17 04:28:19	173.8	RAISING	188.79	199.93	335.19	194.36	0.011835	0.06
2026-03-17 07:30:37	2026-03-17 07:36:37	359.5	RAISING	182.86	205.91	334.24	194.39	0.024477	0.09
2026-03-17 09:05:40	2026-03-17 09:08:19	159.1	RAISING	189.24	199.44	334.91	194.34	0.010831	0.10
2026-03-17 10:38:53	2026-03-17 10:41:51	178.6	RAISING	188.63	200.08	334.69	194.36	0.012161	0.11
2026-03-17 12:12:18	2026-03-17 12:15:11	173.6	RAISING	188.79	199.92	334.59	194.36	0.011817	0.12
2026-03-17 13:45:40	2026-03-17 13:48:34	174.3	RAISING	188.77	199.94	334.46	194.36	0.011870	0.13
2026-03-17 16:50:53	2026-03-17 16:56:53	359.8	RAISING	182.84	205.91	333.15	194.38	0.024496	0.16
2026-03-17 18:25:55	2026-03-17 18:28:34	159.0	RAISING	189.24	199.43	334.22	194.33	0.010824	0.17
2026-03-17 19:59:08	2026-03-17 20:02:07	178.9	RAISING	188.62	200.08	333.94	194.35	0.012177	0.18
2026-03-17 21:32:33	2026-03-17 21:35:27	173.8	RAISING	188.78	199.92	333.85	194.35	0.011832	0.19
2026-03-17 23:05:56	2026-03-17 23:08:50	174.6	RAISING	188.75	199.94	333.72	194.35	0.011889	0.21
2026-03-18 02:11:08	2026-03-18 02:17:09	360.1	RAISING	182.83	205.91	331.36	194.37	0.024519	0.23
2026-03-18 03:46:11	2026-03-18 03:48:50	159.7	RAISING	189.20	199.44	333.59	194.33	0.010877	0.24
2026-03-18 05:19:24	2026-03-18 05:22:23	179.2	RAISING	188.60	200.09	333.13	194.35	0.012199	0.25
2026-03-18 06:52:49	2026-03-18 06:55:43	174.1	RAISING	188.76	199.92	333.08	194.34	0.011857	0.27
2026-03-18 09:58:01	2026-03-18 10:04:02	360.8	RAISING	182.80	205.92	360.80	194.37	0.024566	0.29

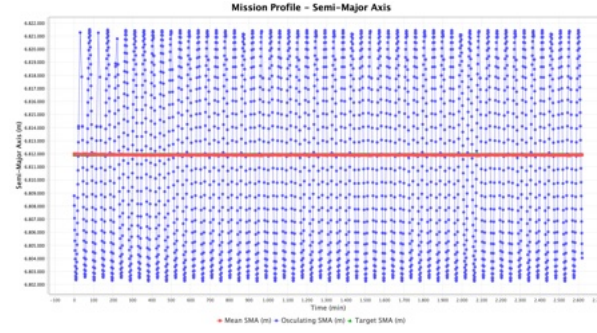


Figure A.162: Evolution of the Semi-Major Axis (a) during Window 25.



Figure A.163: Evolution of the x-component of the eccentricity vector (e_x) for Window 25.

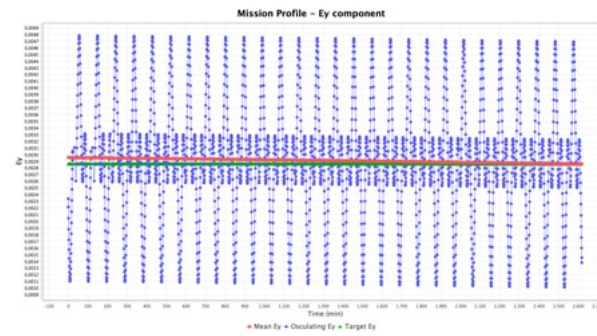


Figure A.164: Evolution of the y-component of the eccentricity vector (e_y) for Window 25.

RESULTS

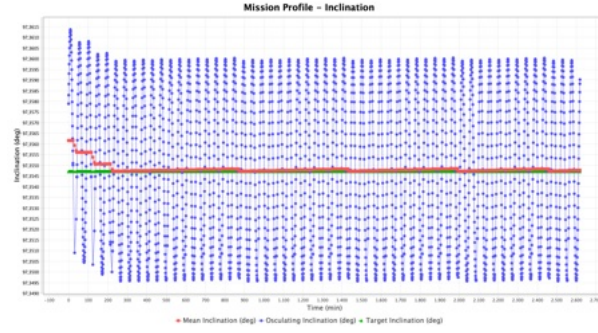


Figure A.165: Evolution of the orbital Inclination (i) in Window 25.

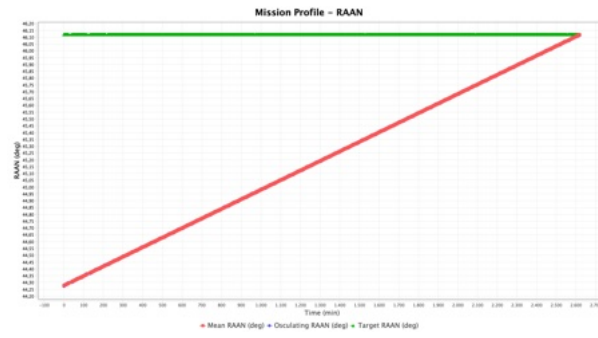


Figure A.166: Evolution of the RAAN (Ω) during Window 25.

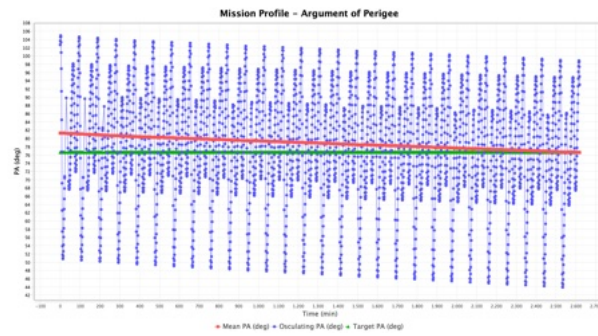


Figure A.167: Evolution of the Argument of Perigee (ω) during Window 25.

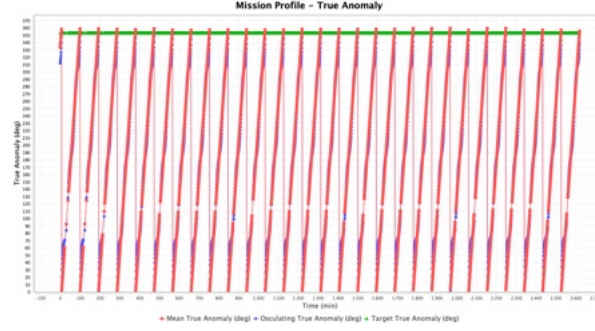


Figure A.168: Evolution of the True Anomaly (ν) throughout Window 25.

A.25 Window 26

Table A.97: Orbit Comparison - Window 26

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-03-18T11:02:52	2026-03-20T06:41:22	2026-03-20T06:41:22
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 811 934.055 m	6 812 446.871 m	6 812 418.951 m
Eccentricity	e	0.002939	0.002835	0.002844
Inclination	i	97.3547°	97.3527°	97.3527°
Arg. of Perigee	ω	76.6251°	73.3004°	73.1663°
RAAN	Ω	46.1197°	47.9617°	47.9602°
True Anomaly	ν	353.2645°	11.3306°	13.6372°

RESULTS

Table A.98: Target State Errors Summary - Window 26

Parameter	Symbol	Error
Semi-Major Axis	Δa	-27.920 m
Inclination	Δi	0.000045°
Eccentricity X	Δe_x	0.000009
Eccentricity Y	Δe_y	0.000007
RAAN	$\Delta \Omega$	-0.001484°
Arg. of Perigee	$\Delta \omega$	-0.134°
True Anomaly	$\Delta \nu$	2.307°
Arg. of Latitude	Δu	2.173°

Table A.99: Normal Maneuvers Summary - Window 26. SQP ΔV : 0.361508 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL ($^\circ$)	Thrust Z
2026-03-18 11:20:44	2026-03-18 11:40:44	1200.00	0.081702	0.081702	180.105	1.0
2026-03-18 12:54:06	2026-03-18 13:14:06	1200.00	0.081703	0.163405	180.105	1.0
2026-03-18 14:27:29	2026-03-18 14:47:29	1200.00	0.081704	0.245109	180.104	1.0
2026-03-18 16:04:48	2026-03-18 16:16:54	725.93	0.049426	0.294535	180.104	1.0
2026-03-18 22:22:38	2026-03-18 22:26:07	209.51	0.014265	0.308800	180.104	1.0
2026-03-19 06:09:26	2026-03-19 06:13:11	225.50	0.015354	0.324154	180.103	1.0
2026-03-19 13:56:15	2026-03-19 14:00:15	239.82	0.016329	0.340484	180.103	1.0
2026-03-19 21:43:13	2026-03-19 21:47:09	236.68	0.016116	0.356600	180.102	1.0
2026-03-20 05:30:12	2026-03-20 05:34:02	229.93	0.015656	0.372256	180.101	1.0

Table A.100: Tangential Maneuvers Summary - Window 26. SQP AOL: 197.38° , v_{Tan} SQP: 0.61 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]
2026-03-18 17:38:44	2026-03-18 17:58:44	1200.0	RAISING	158.90	235.80	306.83	197.42	0.081704	0.08
2026-03-18 19:12:04	2026-03-18 19:32:04	1200.0	RAISING	158.75	235.65	311.40	197.27	0.081705	0.16
2026-03-18 20:45:27	2026-03-18 21:05:27	1200.0	RAISING	158.76	235.65	315.75	197.27	0.081706	0.25
2026-03-18 23:52:16	2026-03-19 00:12:16	1200.0	RAISING	158.95	235.84	318.21	197.46	0.081706	0.33
2026-03-19 01:27:14	2026-03-19 01:43:58	1003.8	RAISING	165.06	229.38	323.19	197.27	0.068347	0.40
2026-03-19 03:07:15	2026-03-19 03:10:45	209.9	RAISING	190.57	204.02	326.79	197.30	0.014289	0.41
2026-03-19 04:40:45	2026-03-19 04:44:05	199.5	RAISING	191.02	203.80	326.55	197.41	0.013583	0.42
2026-03-19 07:46:12	2026-03-19 07:52:13	361.4	RAISING	185.87	209.03	325.08	197.45	0.024610	0.45
2026-03-19 09:21:15	2026-03-19 09:23:54	158.6	RAISING	192.31	202.47	326.03	197.39	0.010799	0.46
2026-03-19 10:54:30	2026-03-19 10:57:26	175.8	RAISING	191.78	203.04	325.57	197.41	0.011971	0.47
2026-03-19 12:27:55	2026-03-19 12:30:48	173.3	RAISING	191.86	202.96	325.25	197.41	0.011797	0.48
2026-03-19 15:33:08	2026-03-19 15:39:09	360.7	RAISING	185.89	209.00	322.78	197.45	0.024563	0.51
2026-03-19 17:08:11	2026-03-19 17:10:50	158.7	RAISING	192.30	202.47	324.16	197.39	0.010809	0.52
2026-03-19 18:41:26	2026-03-19 18:44:22	176.0	RAISING	191.77	203.04	323.35	197.41	0.011981	0.53
2026-03-19 20:14:51	2026-03-19 20:17:44	173.4	RAISING	191.85	202.96	322.69	197.41	0.011807	0.54
2026-03-19 23:20:04	2026-03-19 23:26:05	361.4	RAISING	185.86	209.01	317.28	197.44	0.024606	0.57
2026-03-20 00:55:08	2026-03-20 00:57:46	158.9	RAISING	192.29	202.47	319.52	197.38	0.010818	0.58
2026-03-20 02:28:22	2026-03-20 02:31:19	176.3	RAISING	191.76	203.05	316.57	197.40	0.012003	0.59
2026-03-20 04:01:47	2026-03-20 04:04:41	173.7	RAISING	191.83	202.96	312.46	197.40	0.011829	0.60

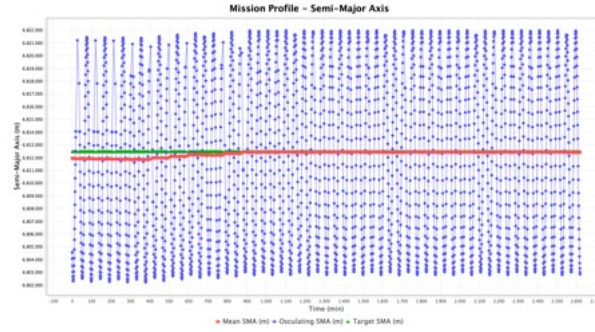


Figure A.169: Evolution of the Semi-Major Axis (a) during Window 26.

RESULTS

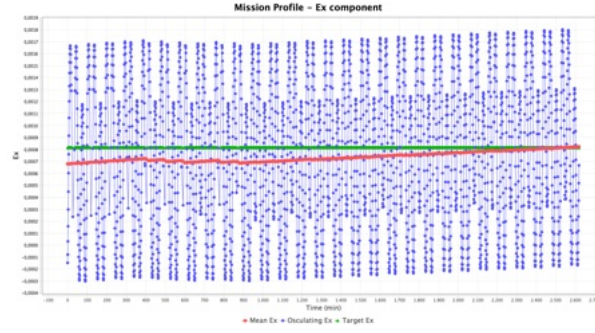


Figure A.170: Evolution of the x-component of the eccentricity vector (e_x) for Window 26.

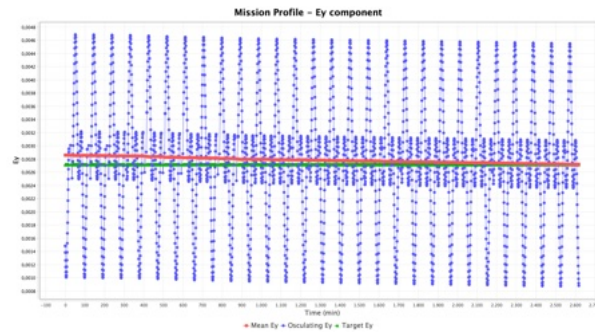


Figure A.171: Evolution of the y-component of the eccentricity vector (e_y) for Window 26.

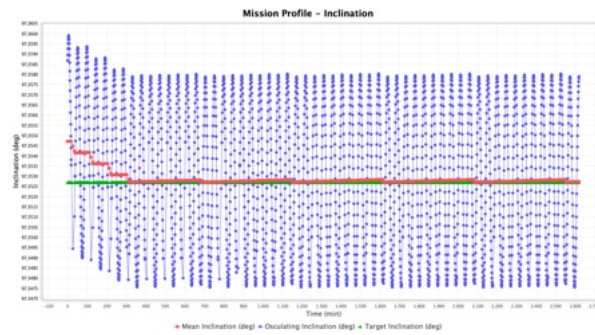


Figure A.172: Evolution of the orbital Inclination (i) in Window 26.

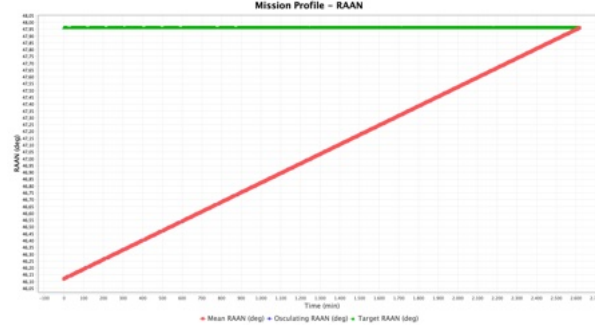


Figure A.173: Evolution of the RAAN (Ω) during Window 26.

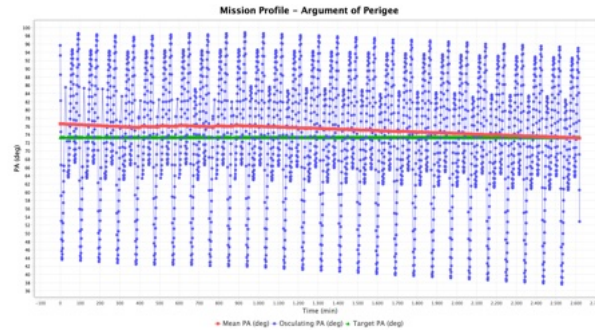


Figure A.174: Evolution of the Argument of Perigee (ω) during Window 26.



Figure A.175: Evolution of the True Anomaly (ν) throughout Window 26.

A.26 Window 27

Table A.101: Window 27 - Orbit Comparison

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-03-20T06:41:22	2026-03-22T02:19:53	2026-03-22T02:19:53
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 812 446.871 m	6 813 513.575 m	6 813 504.689 m
Eccentricity	e	0.002835	0.002677	0.002688
Inclination	i	97.3527°	97.3508°	97.3509°
Arg. of Perigee	ω	73.3004°	71.4151°	71.2297°
RAAN	Ω	47.9617°	49.8025°	49.8009°
True Anomaly	ν	11.3306°	26.1834°	28.4285°

Table A.102: Target State Errors Summary - Window 27

Parameter	Symbol	Error
Semi-Major Axis	Δa	−8.886 m
Inclination	Δi	0.000101°
Eccentricity X	Δe_x	0.000012
Eccentricity Y	Δe_y	0.000007
RAAN	$\Delta \Omega$	−0.001523°
Arg. of Perigee	$\Delta \omega$	−0.185°
True Anomaly	$\Delta \nu$	2.245°
Arg. of Latitude	Δu	2.060°

Table A.103: Normal Maneuvers Summary - Window 27. SQP ΔV : 0.317198 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL ($^{\circ}$)	Thrust Z
2026-03-20 06:55:27	2026-03-20 07:15:27	1200.00	0.081702	0.081702	180.101	1.0
2026-03-20 08:28:50	2026-03-20 08:48:50	1200.00	0.081703	0.163405	180.101	1.0
2026-03-20 10:02:14	2026-03-20 10:22:14	1200.00	0.081704	0.245109	180.101	1.0
2026-03-20 11:42:01	2026-03-20 11:49:12	431.45	0.029376	0.274485	180.101	1.0
2026-03-20 19:30:46	2026-03-20 19:34:22	216.62	0.014750	0.289235	180.100	1.0
2026-03-21 04:51:07	2026-03-21 04:54:51	223.99	0.015252	0.304487	180.099	1.0
2026-03-21 15:45:04	2026-03-21 15:48:38	213.95	0.014568	0.319055	180.099	1.0

Table A.104: Tangential Maneuvers Summary - Window 27. SQP AOL: 197.19° , v_{Tan} SQP: 0.92 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^{\circ}$)	End AOL ($^{\circ}$)	Ideal AOL ($^{\circ}$)	Ctr AOL ($^{\circ}$)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]
2026-03-20 13:13:27	2026-03-20 13:33:27	1200.0	RAISING	158.72	235.60	271.87	197.22	0.081704	0.08
2026-03-20 14:46:48	2026-03-20 15:06:48	1200.0	RAISING	158.55	235.43	275.58	197.05	0.081705	0.16
2026-03-20 16:20:11	2026-03-20 16:40:11	1200.0	RAISING	158.55	235.43	279.51	197.05	0.081705	0.25
2026-03-20 17:53:35	2026-03-20 18:13:35	1200.0	RAISING	158.55	235.43	283.90	197.05	0.081706	0.33
2026-03-20 21:00:25	2026-03-20 21:20:25	1200.0	RAISING	158.74	235.62	284.78	197.24	0.081707	0.41
2026-03-20 22:33:46	2026-03-20 22:53:46	1200.0	RAISING	158.56	235.43	290.60	197.05	0.081707	0.49
2026-03-21 00:07:10	2026-03-21 00:27:10	1200.0	RAISING	158.56	235.43	296.63	197.06	0.081708	0.57
2026-03-21 01:40:35	2026-03-21 02:00:35	1200.0	RAISING	158.56	235.43	303.14	197.06	0.081708	0.65
2026-03-21 03:13:59	2026-03-21 03:33:59	1200.0	RAISING	158.56	235.44	309.98	197.06	0.081709	0.74
2026-03-21 06:24:47	2026-03-21 06:36:54	727.2	RAISING	173.93	220.51	314.14	197.24	0.049515	0.78
2026-03-21 08:02:47	2026-03-21 08:05:40	173.2	RAISING	191.58	202.67	318.45	197.13	0.011797	0.80
2026-03-21 09:36:21	2026-03-21 09:38:57	156.2	RAISING	192.20	202.20	317.61	197.20	0.010634	0.81
2026-03-21 11:09:38	2026-03-21 11:12:30	171.5	RAISING	191.71	202.69	316.64	197.20	0.011679	0.82
2026-03-21 12:43:03	2026-03-21 12:45:54	170.8	RAISING	191.73	202.67	315.68	197.20	0.011631	0.83
2026-03-21 14:16:28	2026-03-21 14:19:19	171.2	RAISING	191.71	202.68	314.51	197.20	0.011657	0.84
2026-03-21 17:21:45	2026-03-21 17:27:41	356.0	RAISING	185.83	208.63	356.00	197.23	0.024240	0.87
2026-03-21 18:56:49	2026-03-21 18:59:24	155.6	RAISING	192.19	202.15	309.05	197.17	0.010597	0.88
2026-03-21 20:30:04	2026-03-21 20:32:58	173.8	RAISING	191.63	202.76	304.92	197.19	0.011835	0.89
2026-03-21 22:03:30	2026-03-21 22:06:21	170.9	RAISING	191.72	202.66	299.38	197.19	0.011638	0.90
2026-03-21 23:36:55	2026-03-21 23:39:46	171.5	RAISING	191.70	202.68	289.64	197.19	0.011677	0.91
2026-03-22 01:10:19	2026-03-22 01:13:11	171.5	RAISING	191.70	202.68	270.64	197.19	0.011676	0.92

RESULTS

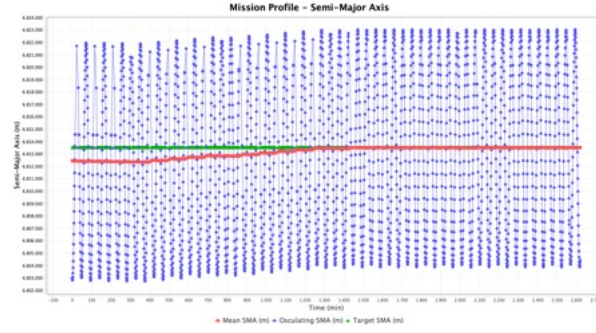


Figure A.176: Evolution of the Semi-Major Axis (a) during Window 27.

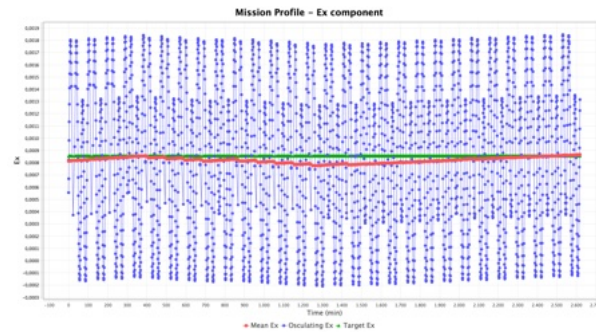


Figure A.177: Evolution of the x-component of the eccentricity vector (e_x) for Window 27.

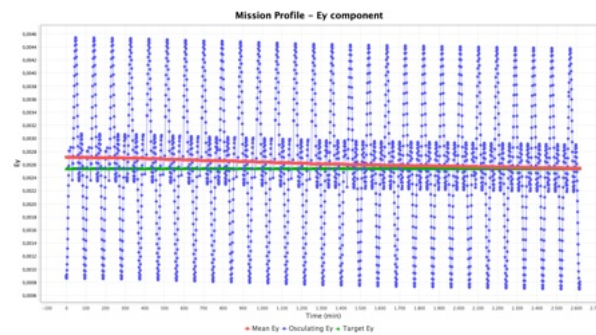


Figure A.178: Evolution of the y-component of the eccentricity vector (e_y) for Window 27.

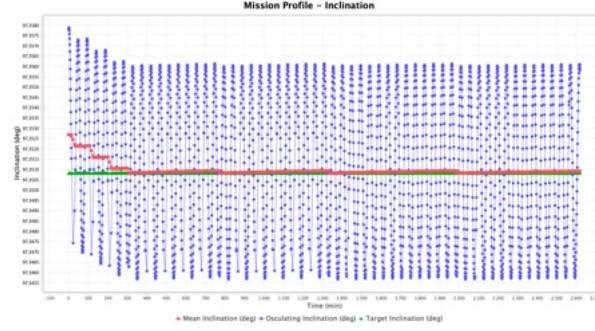


Figure A.179: Evolution of the orbital Inclination (i) in Window 27.

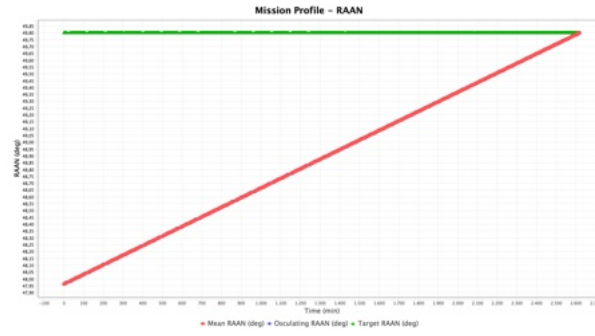


Figure A.180: Evolution of the RAAN (Ω) during Window 27.

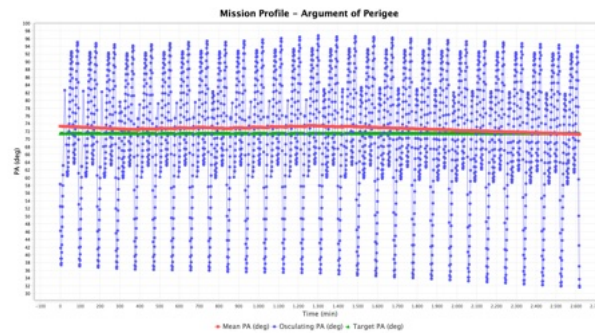


Figure A.181: Evolution of the Argument of Perigee (ω) during Window 27.



Figure A.182: Evolution of the True Anomaly (ν) throughout Window 27.

A.27 Window 28

Table A.105: Orbit Comparison - Window 28

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-03-22T02:19:53	2026-03-23T21:58:24	2026-03-23T21:58:24
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 813 513.575 m	6 814 976.298 m	6 814 961.694 m
Eccentricity	e	0.002677	0.002479	0.002492
Inclination	i	97.3508°	97.3483°	97.3483°
Arg. of Perigee	ω	71.4151°	70.7395°	70.4459°
RAAN	Ω	49.8025°	51.6414°	51.6398°
True Anomaly	ν	26.1834°	36.9904°	39.4217°

Table A.106: Target State Errors Summary - Window 28

Parameter	Symbol	Error
Semi-Major Axis	Δa	-14.605 m
Inclination	Δi	0.000035°
Eccentricity X	Δe_x	0.000016
Eccentricity Y	Δe_y	0.000008
RAAN	$\Delta \Omega$	-0.001559°
Arg. of Perigee	$\Delta \omega$	-0.294°
True Anomaly	$\Delta \nu$	2.431°
Arg. of Latitude	Δu	2.138°

Table A.107: Normal Maneuvers Summary - Window 28. SQP ΔV : 0.349165 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL (°)	Thrust Z
2026-03-22 02:30:38	2026-03-22 02:50:38	1200.00	0.081702	0.081702	180.098	1.0
2026-03-22 04:04:02	2026-03-22 04:24:02	1200.00	0.081703	0.163405	180.098	1.0
2026-03-22 05:37:27	2026-03-22 05:57:27	1200.00	0.081704	0.245109	180.097	1.0
2026-03-22 07:10:51	2026-03-22 07:30:51	1200.00	0.081704	0.326813	180.097	1.0
2026-03-22 08:49:30	2026-03-22 08:59:02	572.76	0.038997	0.365810	180.097	1.0

RESULTS

Table A.108: Tangential Maneuvers Summary - Window 28. SQP AOL: 197.87° , v_{Tan} SQP: 1.14 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma\Delta V$ [m/s]
2026-03-22 10:22:18	2026-03-22 10:42:18	1200.0	RAISING	159.39	236.25	247.05	197.88	0.081705	0.08
2026-03-22 11:55:40	2026-03-22 12:15:40	1200.0	RAISING	159.23	236.09	248.72	197.71	0.081706	0.16
2026-03-22 13:29:05	2026-03-22 13:49:05	1200.0	RAISING	159.23	236.09	250.60	197.72	0.081706	0.25
2026-03-22 15:02:30	2026-03-22 15:22:30	1200.0	RAISING	159.23	236.09	252.80	197.72	0.081707	0.33
2026-03-22 16:35:55	2026-03-22 16:55:55	1200.0	RAISING	159.23	236.09	255.40	197.72	0.081707	0.41
2026-03-22 18:09:20	2026-03-22 18:29:20	1200.0	RAISING	159.23	236.09	258.50	197.72	0.081708	0.49
2026-03-22 19:42:45	2026-03-22 20:02:45	1200.0	RAISING	159.24	236.09	262.21	197.72	0.081708	0.57
2026-03-22 21:16:11	2026-03-22 21:36:11	1200.0	RAISING	159.24	236.10	266.69	197.72	0.081709	0.65
2026-03-22 22:49:37	2026-03-22 23:09:37	1200.0	RAISING	159.24	236.10	272.12	197.72	0.081709	0.74
2026-03-23 00:23:02	2026-03-23 00:43:02	1200.0	RAISING	159.24	236.10	278.69	197.72	0.081710	0.82
2026-03-23 01:56:28	2026-03-23 02:16:28	1200.0	RAISING	159.24	236.10	286.52	197.72	0.081711	0.90
2026-03-23 03:29:55	2026-03-23 03:49:55	1200.0	RAISING	159.24	236.10	295.64	197.72	0.081711	0.98
2026-03-23 05:08:21	2026-03-23 05:18:21	599.3	RAISING	178.52	216.90	305.78	197.72	0.040805	1.02
2026-03-23 06:44:50	2026-03-23 06:48:48	237.8	RAISING	190.20	205.43	309.17	197.81	0.016194	1.04
2026-03-23 08:18:56	2026-03-23 08:21:36	159.8	RAISING	192.74	202.98	308.50	197.86	0.010881	1.05
2026-03-23 09:52:18	2026-03-23 09:55:07	168.7	RAISING	192.47	203.27	306.55	197.87	0.011487	1.06
2026-03-23 11:25:45	2026-03-23 11:28:32	167.1	RAISING	192.52	203.22	304.31	197.87	0.011378	1.07
2026-03-23 12:59:11	2026-03-23 13:01:59	167.3	RAISING	192.51	203.22	301.36	197.87	0.011393	1.08
2026-03-23 14:32:38	2026-03-23 14:35:25	167.3	RAISING	192.51	203.22	297.36	197.87	0.011391	1.09
2026-03-23 16:06:04	2026-03-23 16:08:51	167.3	RAISING	192.51	203.22	291.65	197.86	0.011391	1.11
2026-03-23 17:39:31	2026-03-23 17:42:18	167.3	RAISING	192.51	203.22	283.05	197.86	0.011393	1.12
2026-03-23 19:12:57	2026-03-23 19:15:44	167.3	RAISING	192.50	203.22	269.37	197.86	0.011395	1.13
2026-03-23 20:46:23	2026-03-23 20:49:11	167.4	RAISING	192.50	203.22	247.92	197.86	0.011399	1.14

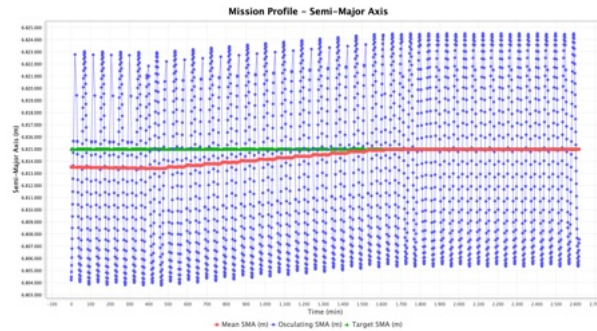


Figure A.183: Evolution of the Semi-Major Axis (a) during Window 28.

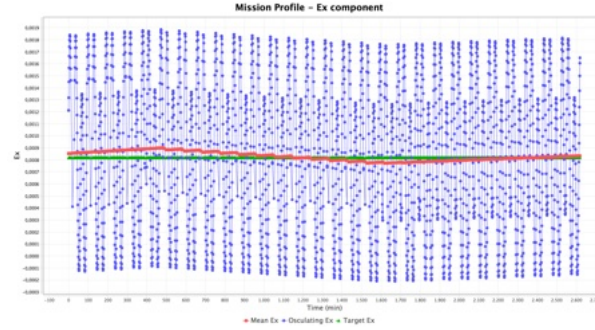


Figure A.184: Evolution of the x-component of the eccentricity vector (e_x) for Window 28.

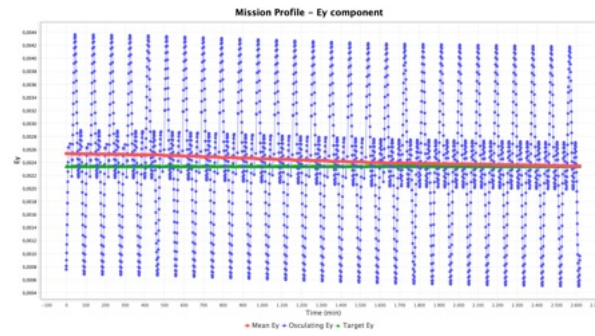


Figure A.185: Evolution of the y-component of the eccentricity vector (e_y) for Window 28.

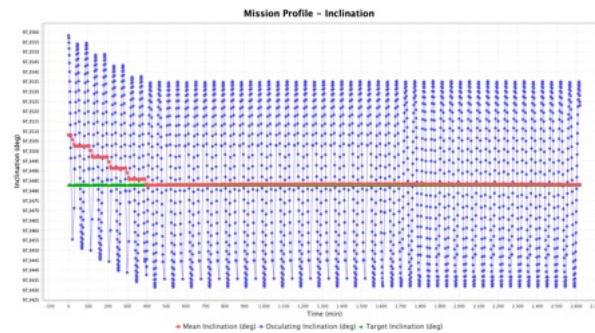


Figure A.186: Evolution of the orbital Inclination (i) in Window 28.

RESULTS

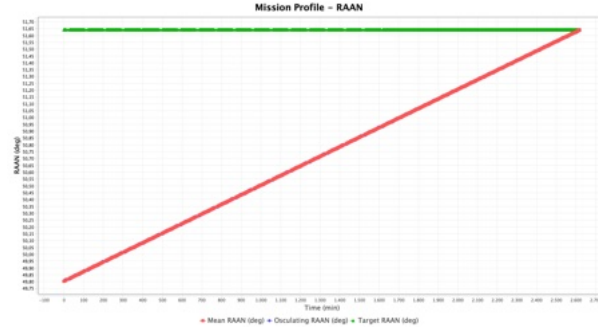


Figure A.187: Evolution of the RAAN (Ω) during Window 28.

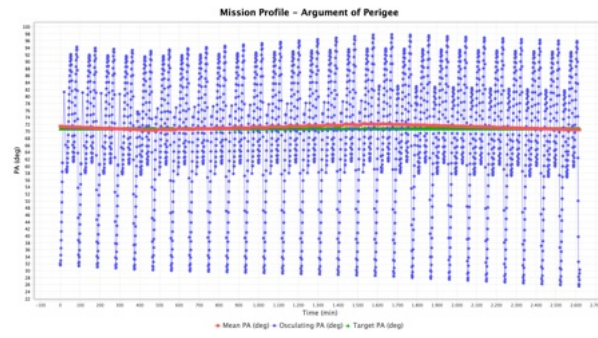


Figure A.188: Evolution of the Argument of Perigee (ω) during Window 28.

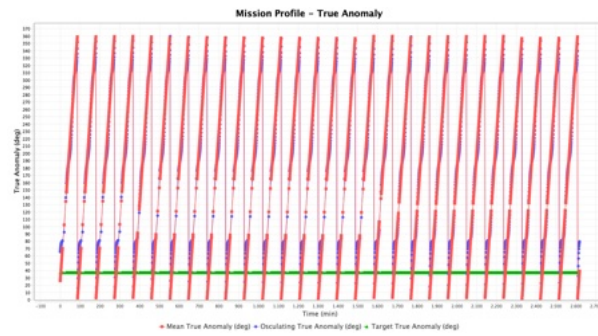


Figure A.189: Evolution of the True Anomaly (ν) throughout Window 28.

A.28 Window 29

Table A.109: Orbit Comparison - Window 29

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-03-23T21:58:24	2026-03-25T17:36:55	2026-03-25T17:36:55
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 814 976.298 m	6 816 792.107 m	6 816 753.445 m
Eccentricity	e	0.002479	0.002235	0.002254
Inclination	i	97.3483°	97.3460°	97.3460°
Arg. of Perigee	ω	70.7395°	71.2541°	70.7839°
RAAN	Ω	51.6414°	53.4779°	53.4763°
True Anomaly	ν	36.9904°	42.9472°	45.4981°

Table A.110: Target State Errors Summary - Window 29

Parameter	Symbol	Error
Semi-Major Axis	Δa	−38.661 m
Inclination	Δi	−0.000019°
Eccentricity X	Δe_x	0.000024
Eccentricity Y	Δe_y	0.000012
RAAN	$\Delta \Omega$	−0.001579°
Arg. of Perigee	$\Delta \omega$	−0.470°
True Anomaly	$\Delta \nu$	2.551°
Arg. of Latitude	Δu	2.081°

RESULTS

Table A.111: Normal Maneuvers Summary - Window 29. SQP ΔV : 0.269716 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL ($^{\circ}$)	Thrust Z
2026-03-23 22:06:32	2026-03-23 22:26:32	1200.00	0.081702	0.081702	180.094	1.0
2026-03-23 23:39:59	2026-03-23 23:59:59	1200.00	0.081703	0.163405	180.094	1.0
2026-03-24 01:13:25	2026-03-24 01:33:25	1200.00	0.081704	0.245109	180.094	1.0
2026-03-24 02:47:37	2026-03-24 03:06:05	1108.09	0.075446	0.320555	180.094	1.0
2026-03-25 02:17:00	2026-03-25 02:20:24	204.22	0.013906	0.334461	180.092	-1.0
2026-03-25 16:18:09	2026-03-25 16:21:49	220.42	0.015009	0.349470	180.091	-1.0

Table A.112: Tangential Maneuvers Summary - Window 29. SQP AOL: 201.29 $^{\circ}$, v_{Tan} SQP: 1.33 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^{\circ}$)	End AOL ($^{\circ}$)	Ideal AOL ($^{\circ}$)	Ctr AOL ($^{\circ}$)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]
2026-03-24 04:25:47	2026-03-24 04:45:47	1200.0	RAISING	162.75	239.58	238.61	201.21	0.081705	0.08
2026-03-24 05:59:12	2026-03-24 06:19:12	1200.0	RAISING	162.63	239.47	239.40	201.10	0.081705	0.16
2026-03-24 07:32:38	2026-03-24 07:52:38	1200.0	RAISING	162.63	239.47	240.26	201.10	0.081706	0.25
2026-03-24 09:06:05	2026-03-24 09:26:05	1200.0	RAISING	162.64	239.47	241.25	201.10	0.081706	0.33
2026-03-24 10:39:32	2026-03-24 10:59:32	1200.0	RAISING	162.64	239.47	242.42	201.10	0.081707	0.41
2026-03-24 12:12:59	2026-03-24 12:32:59	1200.0	RAISING	162.64	239.47	243.80	201.10	0.081707	0.49
2026-03-24 13:46:26	2026-03-24 14:06:26	1200.0	RAISING	162.64	239.47	245.44	201.10	0.081708	0.57
2026-03-24 15:19:54	2026-03-24 15:39:54	1200.0	RAISING	162.64	239.47	247.42	201.10	0.081709	0.65
2026-03-24 16:53:21	2026-03-24 17:13:21	1200.0	RAISING	162.64	239.47	249.84	201.11	0.081709	0.74
2026-03-24 18:26:49	2026-03-24 18:46:49	1200.0	RAISING	162.64	239.47	252.83	201.11	0.081710	0.82
2026-03-24 20:00:17	2026-03-24 20:20:17	1200.0	RAISING	162.64	239.47	256.61	201.11	0.081710	0.90
2026-03-24 21:33:45	2026-03-24 21:53:45	1200.0	RAISING	162.65	239.48	261.43	201.11	0.081711	0.98
2026-03-24 23:07:13	2026-03-24 23:27:13	1200.0	RAISING	162.65	239.48	267.69	201.11	0.081711	1.06
2026-03-25 00:40:41	2026-03-25 01:00:41	1200.0	RAISING	162.65	239.48	275.87	201.11	0.081712	1.14
2026-03-25 03:47:42	2026-03-25 04:07:42	1200.0	RAISING	162.85	239.68	279.11	201.32	0.081713	1.23
2026-03-25 05:29:01	2026-03-25 05:33:13	252.7	RAISING	193.02	209.20	293.76	201.11	0.017210	1.24
2026-03-25 07:02:35	2026-03-25 07:06:41	246.2	RAISING	193.37	209.13	290.92	201.25	0.016766	1.26
2026-03-25 08:36:45	2026-03-25 08:39:28	162.4	RAISING	196.05	206.45	288.52	201.25	0.011056	1.27
2026-03-25 10:10:14	2026-03-25 10:12:56	162.5	RAISING	196.06	206.46	282.97	201.26	0.011062	1.28
2026-03-25 11:43:43	2026-03-25 11:46:25	162.3	RAISING	196.07	206.45	275.62	201.26	0.011052	1.29
2026-03-25 13:17:11	2026-03-25 13:19:54	162.3	RAISING	196.07	206.45	265.65	201.26	0.011051	1.30
2026-03-25 14:50:40	2026-03-25 14:53:22	162.3	RAISING	196.06	206.45	252.36	201.26	0.011051	1.31

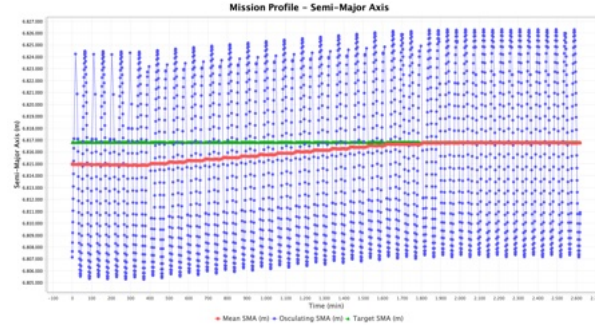


Figure A.190: Evolution of the Semi-Major Axis (a) during Window 29.

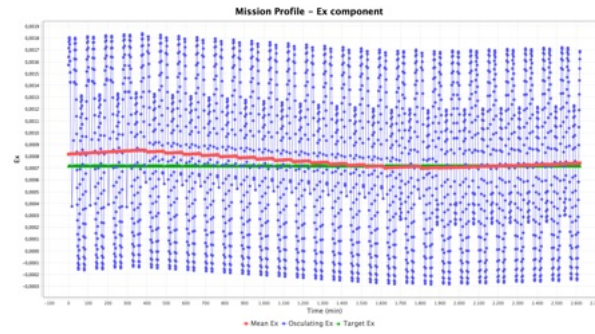


Figure A.191: Evolution of the x-component of the eccentricity vector (e_x) for Window 29.

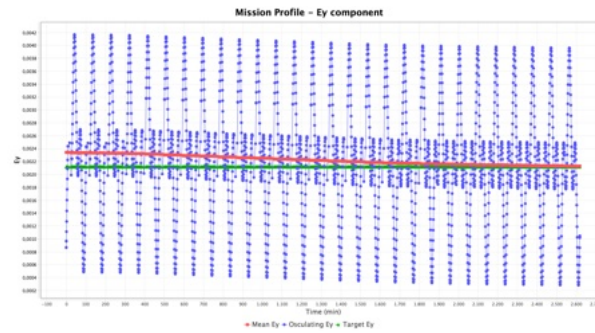


Figure A.192: Evolution of the y-component of the eccentricity vector (e_y) for Window 29.

RESULTS

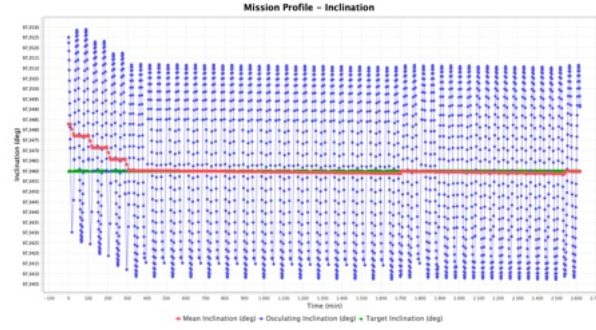


Figure A.193: Evolution of the orbital Inclination (i) in Window 29.

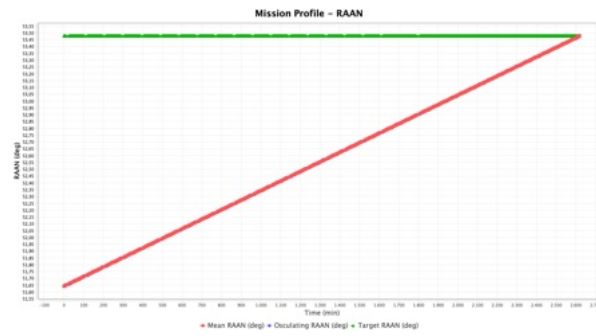


Figure A.194: Evolution of the RAAN (Ω) during Window 29.

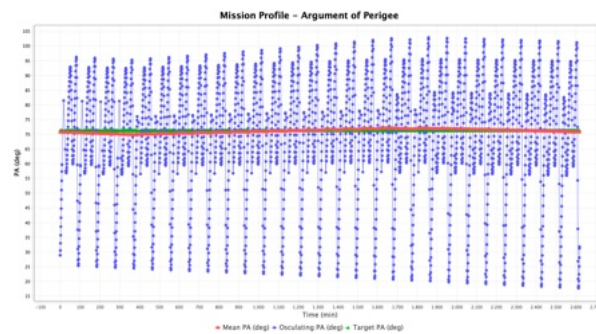


Figure A.195: Evolution of the Argument of Perigee (ω) during Window 29.

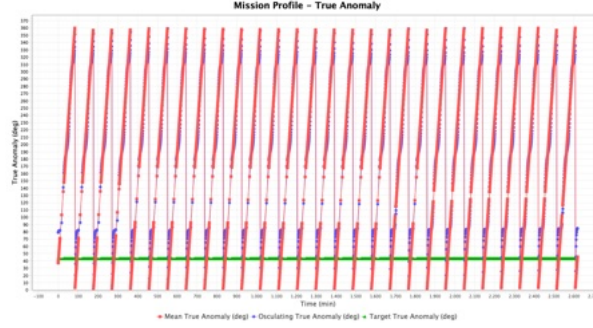


Figure A.196: Evolution of the True Anomaly (ν) throughout Window 29.

A.29 Window 30

Table A.113: Orbit Comparison - Window 30

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-03-25T17:36:55	2026-03-27T13:15:26	2026-03-27T13:15:26
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 816 792.107 m	6 819 063.725 m	6 819 046.013 m
Eccentricity	e	0.002235	0.001946	0.001965
Inclination	i	97.3460°	97.3431°	97.3430°
Arg. of Perigee	ω	71.2541°	73.8862°	73.2341°
RAAN	Ω	53.4779°	55.3118°	55.3104°
True Anomaly	ν	42.9472°	42.2404°	45.4699°

RESULTS

Table A.114: Target State Errors Summary - Window 30

Parameter	Symbol	Error
Semi-Major Axis	Δa	-17.712 m
Inclination	Δi	-0.000020°
Eccentricity X	Δe_x	0.000027
Eccentricity Y	Δe_y	0.000011
RAAN	$\Delta \Omega$	-0.001420°
Arg. of Perigee	$\Delta \omega$	-0.652°
True Anomaly	$\Delta \nu$	3.230°
Arg. of Latitude	Δu	2.577°

Table A.115: Normal Maneuvers Summary - Window 30. SQP ΔV : 0.350153 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL ($^\circ$)	Thrust Z
2026-03-25 17:43:23	2026-03-25 18:03:23	1200.00	0.081702	0.081702	180.090	1.0
2026-03-25 19:16:52	2026-03-25 19:36:52	1200.00	0.081703	0.163405	180.090	1.0
2026-03-25 20:50:20	2026-03-25 21:10:20	1200.00	0.081704	0.245109	180.090	1.0
2026-03-25 22:23:49	2026-03-25 22:43:49	1200.00	0.081704	0.326813	180.090	1.0
2026-03-25 23:57:24	2026-03-26 00:17:11	1186.60	0.080792	0.407605	180.090	1.0
2026-03-26 18:47:26	2026-03-26 18:50:54	208.03	0.014165	0.421770	180.088	-1.0
2026-03-27 10:22:34	2026-03-27 10:26:03	209.41	0.014260	0.436030	180.087	-1.0

Table A.116: Tangential Maneuvers Summary - Window 30. SQP AOL: 203.80° , v_{Tan} SQP: 1.57 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]
2026-03-26 01:36:55	2026-03-26 01:56:55	1200.0	RAISING	165.26	242.07	227.60	203.71	0.081705	0.08
2026-03-26 03:10:22	2026-03-26 03:30:22	1200.0	RAISING	165.14	241.96	227.66	203.59	0.081706	0.16
2026-03-26 04:43:50	2026-03-26 05:03:50	1200.0	RAISING	165.14	241.96	227.74	203.60	0.081706	0.25
2026-03-26 06:17:19	2026-03-26 06:37:19	1200.0	RAISING	165.15	241.96	227.84	203.60	0.081707	0.33
2026-03-26 07:50:49	2026-03-26 08:10:49	1200.0	RAISING	165.15	241.96	227.97	203.60	0.081708	0.41
2026-03-26 09:24:18	2026-03-26 09:44:18	1200.0	RAISING	165.15	241.96	228.13	203.60	0.081708	0.49
2026-03-26 10:57:47	2026-03-26 11:17:47	1200.0	RAISING	165.15	241.97	228.33	203.60	0.081709	0.57
2026-03-26 12:31:17	2026-03-26 12:51:17	1200.0	RAISING	165.15	241.97	228.57	203.60	0.081709	0.65
2026-03-26 14:04:47	2026-03-26 14:24:47	1200.0	RAISING	165.15	241.97	228.87	203.60	0.081710	0.74
2026-03-26 15:38:17	2026-03-26 15:58:17	1200.0	RAISING	165.15	241.97	229.25	203.60	0.081710	0.82
2026-03-26 17:11:47	2026-03-26 17:31:47	1200.0	RAISING	165.16	241.97	229.73	203.61	0.081711	0.90
2026-03-26 20:18:51	2026-03-26 20:38:51	1200.0	RAISING	165.38	242.19	227.54	203.83	0.081712	0.98
2026-03-26 21:52:18	2026-03-26 22:12:18	1200.0	RAISING	165.16	241.97	227.86	203.61	0.081712	1.06
2026-03-26 23:25:48	2026-03-26 23:45:48	1200.0	RAISING	165.16	241.97	228.42	203.61	0.081713	1.14
2026-03-27 00:59:19	2026-03-27 01:19:19	1200.0	RAISING	165.16	241.97	229.19	203.61	0.081713	1.23
2026-03-27 02:32:50	2026-03-27 02:52:50	1200.0	RAISING	165.16	241.98	230.30	203.61	0.081714	1.31
2026-03-27 04:06:21	2026-03-27 04:26:21	1200.0	RAISING	165.16	241.98	231.96	203.61	0.081714	1.39
2026-03-27 05:39:52	2026-03-27 05:59:52	1200.0	RAISING	165.16	241.98	234.66	203.61	0.081715	1.47
2026-03-27 07:16:03	2026-03-27 07:30:43	880.7	RAISING	175.41	231.78	239.67	203.61	0.059973	1.53
2026-03-27 08:55:07	2026-03-27 08:58:43	216.3	RAISING	196.74	210.58	244.24	203.66	0.014729	1.55
2026-03-27 12:00:57	2026-03-27 12:07:04	366.7	RAISING	192.09	215.56	218.85	203.83	0.024972	1.57

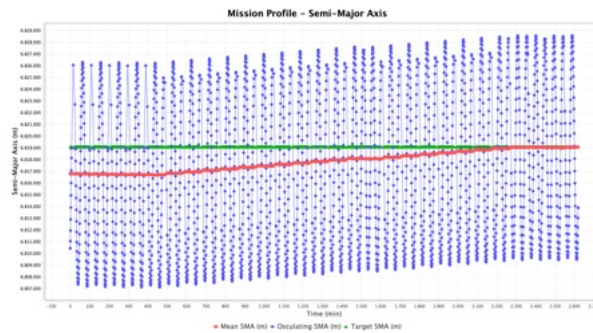


Figure A.197: Evolution of the Semi-Major Axis (a) during Window 30.

RESULTS

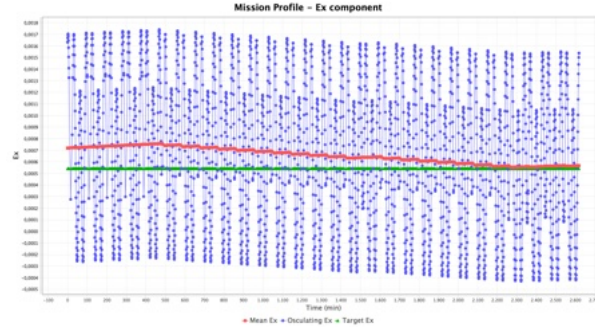


Figure A.198: Evolution of the x-component of the eccentricity vector (e_x) for Window 30.

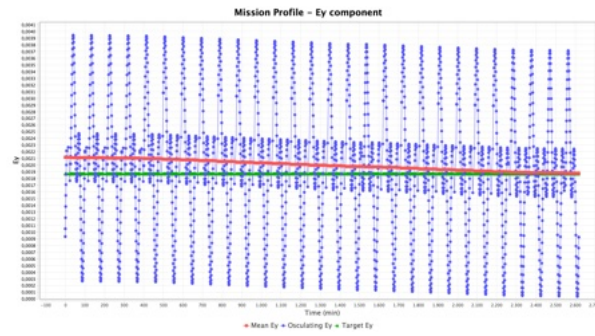


Figure A.199: Evolution of the y-component of the eccentricity vector (e_y) for Window 30.

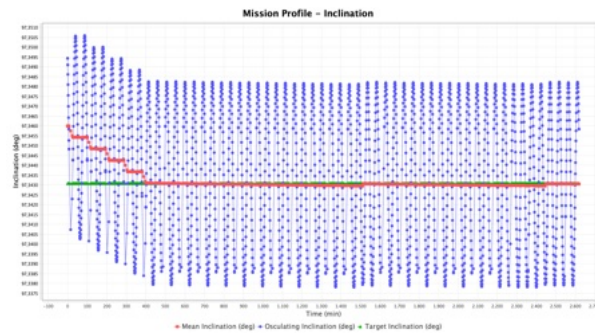


Figure A.200: Evolution of the orbital Inclination (i) in Window 30.

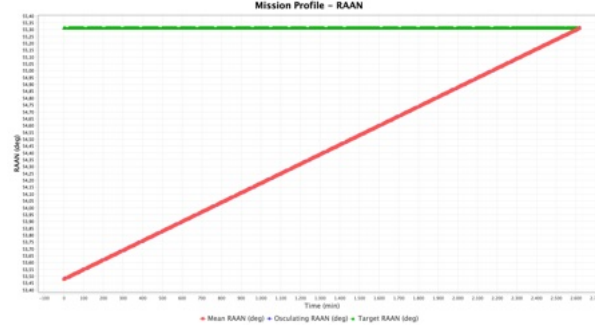


Figure A.201: Evolution of the RAAN (Ω) during Window 30.

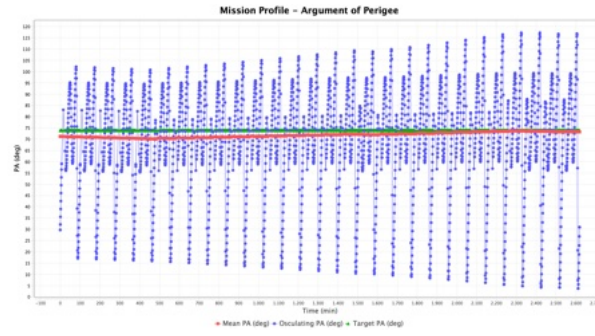


Figure A.202: Evolution of the Argument of Perigee (ω) during Window 30.

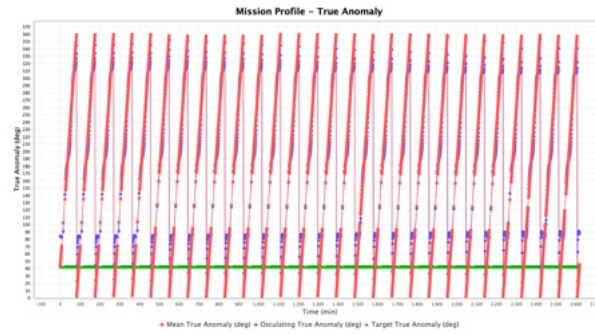


Figure A.203: Evolution of the True Anomaly (ν) throughout Window 30.

A.30 Window 31

Table A.117: Orbit Comparison - Window 31

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-03-27T13:15:26	2026-03-29T08:53:57	2026-03-29T08:53:57
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 819 063.725 m	6 821 882.952 m	6 821 872.855 m
Eccentricity	e	0.001946	0.001631	0.001650
Inclination	i	97.3431°	97.3410°	97.3410°
Arg. of Perigee	ω	73.8862°	80.5018°	79.5020°
RAAN	Ω	55.3118°	57.1427°	57.1415°
True Anomaly	ν	42.2404°	31.9030°	35.5855°

Table A.118: Target State Errors Summary - Window 31

Parameter	Symbol	Error
Semi-Major Axis	Δa	−10.097 m
Inclination	Δi	−0.000034°
Eccentricity X	Δe_x	0.000031
Eccentricity Y	Δe_y	0.000014
RAAN	$\Delta \Omega$	−0.001283°
Arg. of Perigee	$\Delta \omega$	−1.000°
True Anomaly	$\Delta \nu$	3.682°
Arg. of Latitude	Δu	2.683°

Table A.119: Normal Maneuvers Summary - Window 31. SQP ΔV : 0.265434 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL ($^{\circ}$)	Thrust Z
2026-03-27 13:21:24	2026-03-27 13:41:24	1200.00	0.081702	0.081702	180.087	1.0
2026-03-27 14:54:56	2026-03-27 15:14:56	1200.00	0.081703	0.163405	180.086	1.0
2026-03-27 16:28:27	2026-03-27 16:48:27	1200.00	0.081704	0.245109	180.086	1.0
2026-03-27 18:07:03	2026-03-27 18:16:54	591.55	0.040277	0.285386	180.086	1.0

Table A.120: Tangential Maneuvers Summary - Window 31. SQP AOL: 205.14 $^{\circ}$, v_{Tan} SQP: 1.86 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^{\circ}$)	End AOL ($^{\circ}$)	Ideal AOL ($^{\circ}$)	Ctr AOL ($^{\circ}$)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]
2026-03-27 19:42:01	2026-03-27 20:02:01	1200.0	RAISING	166.70	243.51	220.71	205.14	0.081704	0.08
2026-03-27 21:15:30	2026-03-27 21:35:30	1200.0	RAISING	166.50	243.31	220.52	204.94	0.081705	0.16
2026-03-27 22:49:01	2026-03-27 23:09:01	1200.0	RAISING	166.50	243.31	220.40	204.94	0.081706	0.25
2026-03-28 00:22:33	2026-03-28 00:42:33	1200.0	RAISING	166.50	243.31	220.27	204.94	0.081706	0.33
2026-03-28 01:56:05	2026-03-28 02:16:05	1200.0	RAISING	166.50	243.31	220.14	204.95	0.081707	0.41
2026-03-28 03:29:37	2026-03-28 03:49:37	1200.0	RAISING	166.50	243.31	220.01	204.95	0.081707	0.49
2026-03-28 05:03:09	2026-03-28 05:23:09	1200.0	RAISING	166.50	243.31	219.88	204.95	0.081708	0.57
2026-03-28 06:36:42	2026-03-28 06:56:42	1200.0	RAISING	166.51	243.32	219.75	204.95	0.081708	0.65
2026-03-28 08:10:15	2026-03-28 08:30:15	1200.0	RAISING	166.51	243.32	219.61	204.95	0.081709	0.74
2026-03-28 09:43:47	2026-03-28 10:03:47	1200.0	RAISING	166.51	243.32	219.48	204.95	0.081709	0.82
2026-03-28 11:17:20	2026-03-28 11:37:20	1200.0	RAISING	166.51	243.32	219.33	204.95	0.081710	0.90
2026-03-28 12:50:53	2026-03-28 13:10:53	1200.0	RAISING	166.51	243.32	219.19	204.96	0.081711	0.98
2026-03-28 14:24:27	2026-03-28 14:44:27	1200.0	RAISING	166.51	243.32	219.04	204.96	0.081711	1.06
2026-03-28 15:58:00	2026-03-28 16:18:00	1200.0	RAISING	166.51	243.32	218.88	204.96	0.081712	1.14
2026-03-28 17:31:34	2026-03-28 17:51:34	1200.0	RAISING	166.52	243.33	218.72	204.96	0.081712	1.23
2026-03-28 19:05:07	2026-03-28 19:25:07	1200.0	RAISING	166.52	243.33	218.54	204.96	0.081713	1.31
2026-03-28 20:38:41	2026-03-28 20:58:41	1200.0	RAISING	166.52	243.33	218.35	204.96	0.081713	1.39
2026-03-28 22:12:15	2026-03-28 22:32:15	1200.0	RAISING	166.52	243.33	218.14	204.96	0.081714	1.47
2026-03-28 23:45:49	2026-03-29 00:05:49	1200.0	RAISING	166.52	243.33	217.90	204.96	0.081715	1.55
2026-03-29 01:19:24	2026-03-29 01:39:24	1200.0	RAISING	166.52	243.33	217.62	204.97	0.081715	1.63
2026-03-29 02:52:58	2026-03-29 03:12:58	1200.0	RAISING	166.52	243.33	217.27	204.97	0.081716	1.72
2026-03-29 04:26:33	2026-03-29 04:46:33	1200.0	RAISING	166.53	243.34	216.77	204.97	0.081716	1.80
2026-03-29 06:04:22	2026-03-29 06:15:53	691.2	RAISING	182.84	227.08	215.98	204.97	0.047071	1.84
2026-03-29 07:41:16	2026-03-29 07:46:12	296.4	RAISING	195.56	214.53	211.81	205.05	0.020185	1.86

RESULTS

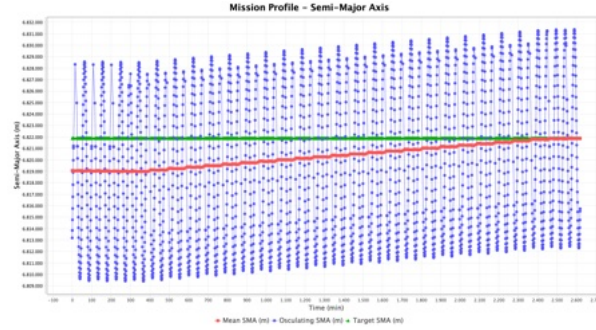


Figure A.204: Evolution of the Semi-Major Axis (a) during Window 31.

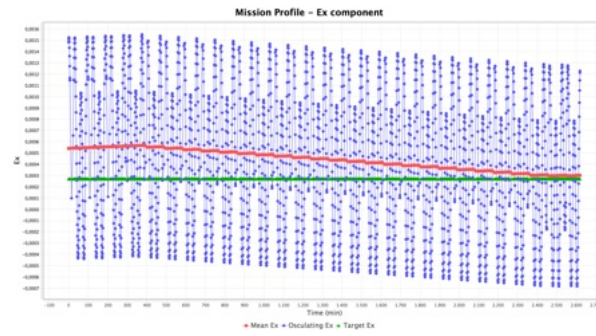


Figure A.205: Evolution of the x-component of the eccentricity vector (e_x) for Window 31.

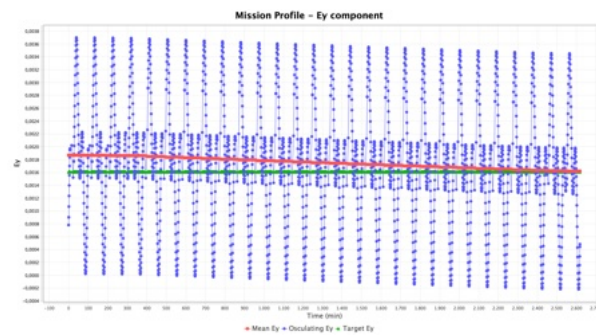


Figure A.206: Evolution of the y-component of the eccentricity vector (e_y) for Window 31.

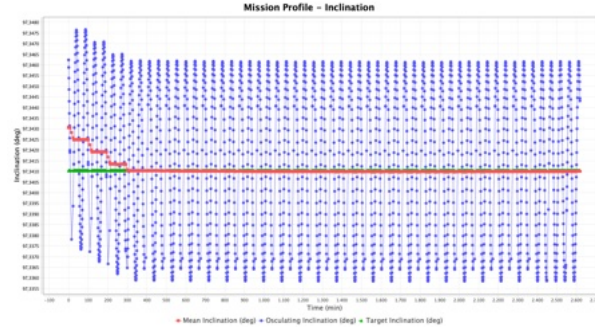


Figure A.207: Evolution of the orbital Inclination (i) in Window 31.

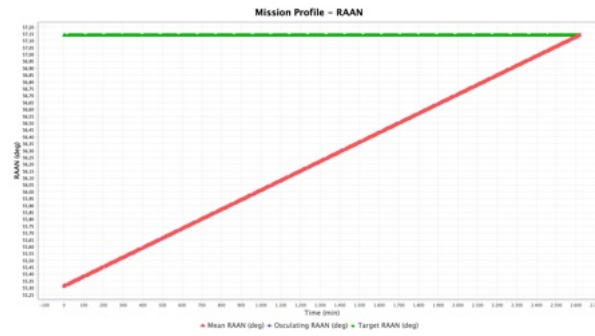


Figure A.208: Evolution of the RAAN (Ω) during Window 31.

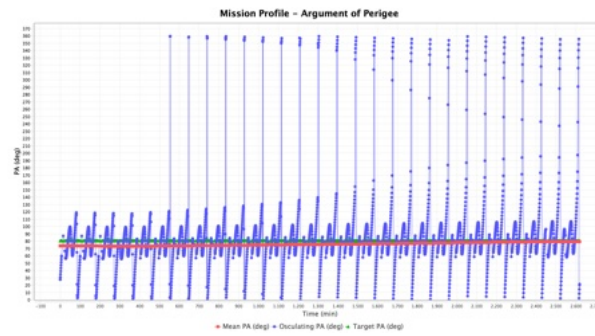


Figure A.209: Evolution of the Argument of Perigee (ω) during Window 31.

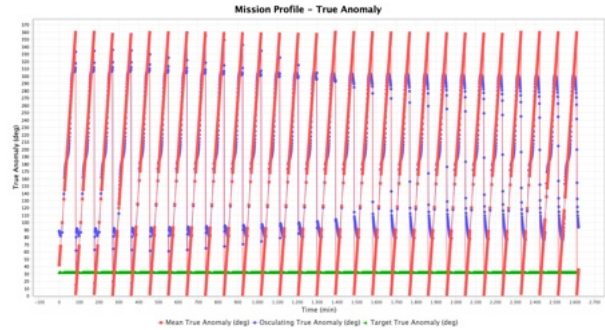


Figure A.210: Evolution of the True Anomaly (ν) throughout Window 31.

A.31 Window 32

Table A.121: Orbit Comparison - Window 32

Parameter	Symbol	Initial State	Target State	Simulation Results
<i>Time Data</i>				
Epoch (UTC)	t_0, t_f	2026-03-29T08:53:57	2026-03-31T04:32:28	2026-03-31T04:32:28
<i>Keplerian Elements</i>				
Semi-Major Axis	a	6 821 882.952 m	6 824 954.795 m	6 824 898.133 m
Eccentricity	e	0.001631	0.001356	0.001375
Inclination	i	97.3410°	97.3400°	97.3401°
Arg. of Perigee	ω	80.5018°	92.2416°	90.5231°
RAAN	Ω	57.1427°	58.9707°	58.9696°
True Anomaly	ν	31.9030°	9.9192°	14.2292°

Table A.122: Target State Errors Summary - Window 32

Parameter	Symbol	Error
Semi-Major Axis	Δa	−56.663 m
Inclination	Δi	0.000115°
Eccentricity X	Δe_x	0.000040
Eccentricity Y	Δe_y	0.000020
RAAN	$\Delta \Omega$	−0.001193°
Arg. of Perigee	$\Delta \omega$	−1.718°
True Anomaly	$\Delta \nu$	4.310°
Arg. of Latitude	Δu	2.592°

Table A.123: Normal Maneuvers Summary - Window 32. SQP ΔV : 0.185678 m/s.

Start Time (UTC)	End Time (UTC)	Duration (s)	ΔV [m/s]	$\Sigma \Delta V$ [m/s]	AOL (°)	Thrust Z
2026-03-29 09:00:54	2026-03-29 09:20:54	1200.00	0.081702	0.081702	180.083	1.0
2026-03-29 10:36:20	2026-03-29 10:52:37	977.41	0.066548	0.148250	180.083	1.0
2026-03-30 03:52:17	2026-03-30 03:55:45	208.11	0.014170	0.162420	180.081	1.0
2026-03-30 17:54:50	2026-03-30 17:58:18	208.68	0.014210	0.176630	180.080	1.0

RESULTS

Table A.124: Tangential Maneuvers Summary - Window 32. SQP AOL: 206.69° , v_{Tan} SQP: 1.99 m/s.

Start Time (UTC)	End Time (UTC)	Dur. (s)	Type	Start AOL ($^\circ$)	End AOL ($^\circ$)	Ideal AOL ($^\circ$)	Ctr AOL ($^\circ$)	ΔV [m/s]	$\Sigma\Delta V$ [m/s]
2026-03-29 12:14:58	2026-03-29 12:34:58	1200.0	RAISING	168.23	245.04	217.22	206.67	0.081703	0.08
2026-03-29 13:48:31	2026-03-29 14:08:31	1200.0	RAISING	168.07	244.88	217.06	206.51	0.081704	0.16
2026-03-29 15:22:06	2026-03-29 15:42:06	1200.0	RAISING	168.08	244.88	216.96	206.52	0.081705	0.25
2026-03-29 16:55:42	2026-03-29 17:15:42	1200.0	RAISING	168.08	244.89	216.85	206.52	0.081705	0.33
2026-03-29 18:29:17	2026-03-29 18:49:17	1200.0	RAISING	168.08	244.89	216.74	206.52	0.081706	0.41
2026-03-29 20:02:53	2026-03-29 20:22:53	1200.0	RAISING	168.08	244.89	216.63	206.52	0.081706	0.49
2026-03-29 21:36:29	2026-03-29 21:56:29	1200.0	RAISING	168.08	244.89	216.53	206.52	0.081707	0.57
2026-03-29 23:10:05	2026-03-29 23:30:05	1200.0	RAISING	168.08	244.89	216.42	206.52	0.081707	0.65
2026-03-30 00:43:41	2026-03-30 01:03:41	1200.0	RAISING	168.08	244.89	216.32	206.52	0.081708	0.74
2026-03-30 02:17:17	2026-03-30 02:37:17	1200.0	RAISING	168.09	244.89	216.21	206.53	0.081709	0.82
2026-03-30 05:24:34	2026-03-30 05:44:34	1200.0	RAISING	168.32	245.13	215.33	206.76	0.081709	0.90
2026-03-30 06:58:06	2026-03-30 07:18:06	1200.0	RAISING	168.09	244.90	215.11	206.53	0.081710	0.98
2026-03-30 08:31:43	2026-03-30 08:51:43	1200.0	RAISING	168.09	244.90	214.95	206.53	0.081710	1.06
2026-03-30 10:05:20	2026-03-30 10:25:20	1200.0	RAISING	168.09	244.90	214.78	206.53	0.081711	1.14
2026-03-30 11:38:57	2026-03-30 11:58:57	1200.0	RAISING	168.09	244.90	214.59	206.53	0.081711	1.23
2026-03-30 13:12:34	2026-03-30 13:32:34	1200.0	RAISING	168.10	244.90	214.40	206.53	0.081712	1.31
2026-03-30 14:46:12	2026-03-30 15:06:12	1200.0	RAISING	168.10	244.91	214.20	206.54	0.081713	1.39
2026-03-30 16:19:49	2026-03-30 16:39:49	1200.0	RAISING	168.10	244.91	213.97	206.54	0.081713	1.47
2026-03-30 19:27:08	2026-03-30 19:47:08	1200.0	RAISING	168.33	245.14	212.51	206.77	0.081714	1.55
2026-03-30 21:00:43	2026-03-30 21:20:43	1200.0	RAISING	168.10	244.91	211.91	206.54	0.081714	1.63
2026-03-30 22:34:21	2026-03-30 22:54:21	1200.0	RAISING	168.10	244.91	211.35	206.54	0.081715	1.72
2026-03-31 00:07:59	2026-03-31 00:27:59	1200.0	RAISING	168.10	244.91	210.61	206.54	0.081716	1.80
2026-03-31 01:41:37	2026-03-31 02:01:37	1200.0	RAISING	168.11	244.91	209.61	206.54	0.081716	1.88
2026-03-31 03:15:16	2026-03-31 03:35:16	1200.0	RAISING	168.11	244.92	208.12	206.55	0.081717	1.96

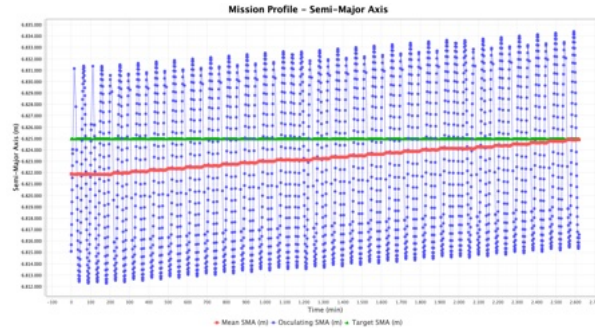


Figure A.211: Evolution of the Semi-Major Axis (a) during Window 32.

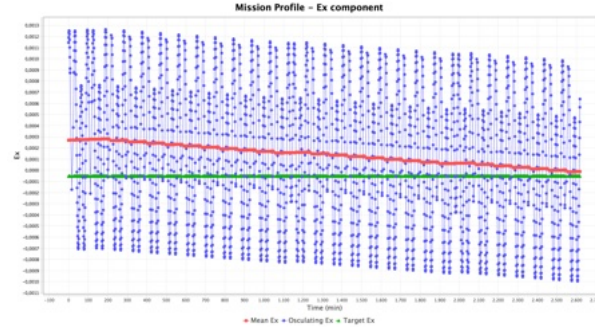


Figure A.212: Evolution of the x-component of the eccentricity vector (e_x) for Window 32.

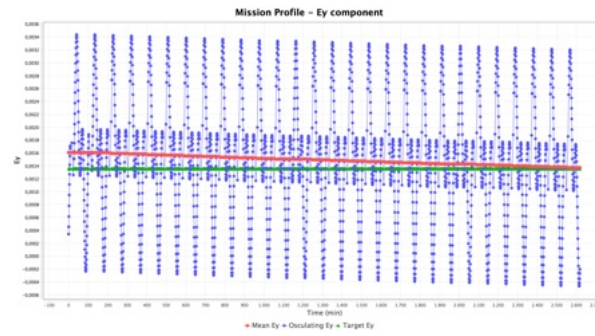


Figure A.213: Evolution of the y-component of the eccentricity vector (e_y) for Window 32.

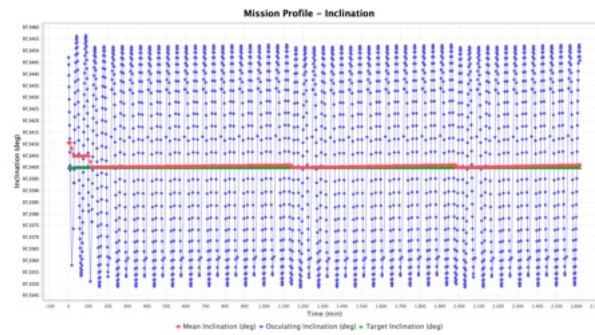


Figure A.214: Evolution of the orbital Inclination (i) in Window 32.

RESULTS

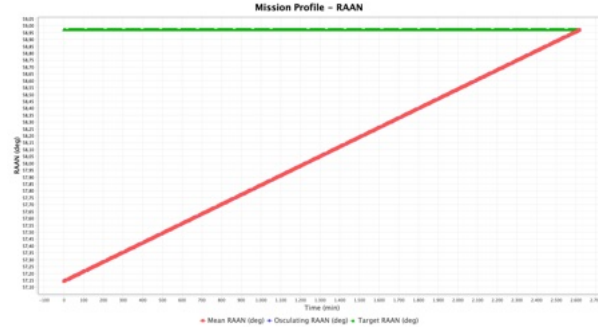


Figure A.215: Evolution of the RAAN (Ω) during Window 32.

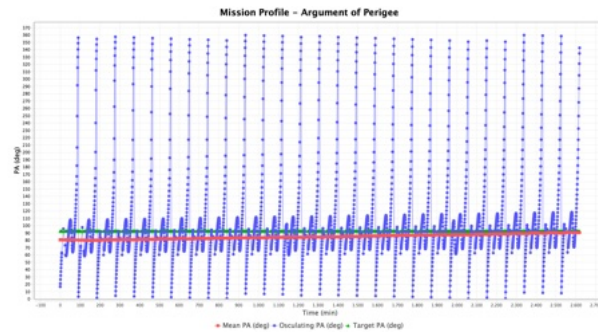


Figure A.216: Evolution of the Argument of Perigee (ω) during Window 32.

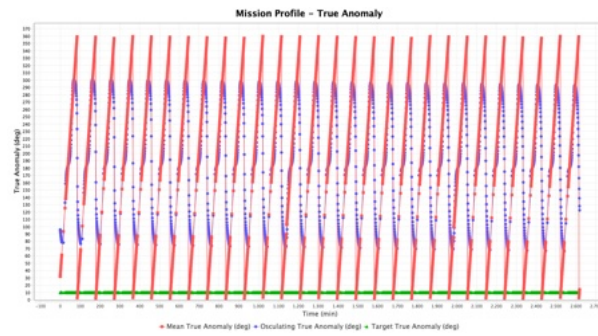


Figure A.217: Evolution of the True Anomaly (ν) throughout Window 32.

Bibliography

- [1] Telespazio, *Fucino Space Centre*, <https://www.telespazio.com/en/business/space-centres-teleports/fucino-space-centre>
- [2] MarketsandMarkets, *LEO Satellite Market Report*, <https://www.marketsandmarkets.com/Market-Reports/leo-satellite-market-252330251.html>
- [3] Representation of LEO satellite constellation, <https://www.alessiobrandimarti.it/costellazioni-satellitari-internet-futuro/>
- [4] IRIDE, *Iride Space Programme Brochure*, <https://indd.adobe.com/view/ec6c1320-2357-4d75-889f-e29baf505c3c>
- [5] Online Star Register (OSR), *Legge di gravitazione universale*, <https://osr.org/it/blog/osr-it/legge-di-gravitazione-universale/>
- [6] Manuela Battipede, *Mechanics of Space Flight – Lecture Slides*, Politecnico di Torino, 2024.
- [7] David A. Vallado, *Fundamentals of Astrodynamics and Applications*, 4th ed., Microcosm Press, 2013.
- [8] European Space Agency (ESA), *The Earth's gravity field (geoid) as it will be seen by GOCE*, https://www.esa.int/ESA_Multimedia/Images/2004/10/The_Earth_s_gravity_field_geoid_as_it_will_be_seen_by_GOCE
- [9] Nicolò Stronati, *Ottimizzazione di traiettorie orbitali per satelliti in LEO sotto l'influenza di J_2* , M.Sc. Thesis, Politecnico di Torino, 2020.

BIBLIOGRAPHY

- [10] O. Montenbruck, E. Gill, *Satellite Orbits*, Springer, 2005
- [11] Phys.org, *Don't leave to chance the sight of distant orbital objects*, <https://phys.org/news/2021-03-dont-chance-sight-distant-orbital.html>
- [12] Giovanni Mengali, Alessandro A. Quarta, *Fondamenti di meccanica del volo spaziale*, Nuova ed., Pisa University Press, 2013.
- [13] Wccftech, *SpaceX's Stunning Rocket Engine Is Complex, Yet Simple & 51% More Powerful*, <https://wccftech.com/spacexs-stunning-rocket-engine-is-complex-yet-simple-51-more-powerful/>
- [14] Astrospace.it, *Testato l'AEPS, il sistema propulsivo elettrico del Lunar Gateway*, <https://www.astrospace.it/2023/11/03/testato-laeps-il-sistema-propulsivo-elettrico-del-lunar-gateway/>
- [15] Howard D. Curtis, *Orbital Mechanics for Engineering Students*, Elsevier Butterworth-Heinemann, 2005.
- [16] Lorenzo Casalino, *Space Propulsion – Lecture Slides*, Politecnico di Torino, 2025.
- [17] T.N. Edelbaum, *Propulsion Requirements for Controllable Satellites*, *ARS Journal*, Vol. 31, 1961.
- [18] Roger R. Bate, Donald D. Mueller, Jerry E. White, *Fundamentals of Astrodynamics*, Dover Publications, Inc. New York, 1971.
- [19] Orekit Documentation, <https://www.orekit.org/doc-maven.html>
- [20] Paul Boggs, *Sequential Quadratic Programming*, Acta Numerica, 1995.
- [21] IERS Conventions (2010), <https://www.iers.org/IERS/EN/Publications/TechnicalNotes/tn36>.
- [22] S. A. Holmes , W. E. Featherstone, *A unified approach to the Clenshaw summation and the recursive computation of very high degree and order fully normalised associated Legendre functions*, *Journal of Geodesy*, 2002.

- [23] I. Cavallari. *Predictive Autonomous Orbit Control: Integration of a New Maneuver Type*, Politecnico di Milano, 2019.

List of Figures

1.1	Conceptual representation of a Low Earth Orbit (LEO) satellite constellation for telecommunication services [3]	2
2.1	Solar System [5]	8
2.2	Representation of the 2BP in a generic inertial RF [6]	9
2.3	Conic sections [6]	11
2.4	Elliptical Orbits [7]	12
2.5	Keplerian Orbital Elements [7]	13
2.6	Geocentric Equatorial System (IJK) [7]	18
2.7	Satellite Coordinate Systems, RSW and NTW [7]	20
2.8	Geoid and Earth's gravity field model derived from U.S. GRACE satellite data [8]	22
2.9	Harmonics' effects [9]	23
2.10	Orbit Classification [11]	34
2.11	Conical shadow model (not to scale) [12]	37
3.1	Raptor 3, an example of chemical propulsion [13]	41
3.2	Hall Thruster [14]	43
3.3	Thrust Component Directions [16]	47
3.4	Normalized Variations of Semimajor Axis and Inclination [16]	50
3.5	Optimal Maneuvers for Inclination and Semimajor Axis Changes [16]	51
3.6	Main orbit (0) and two phasing orbits, faster (1) and slower (2). T_0 is the period of the main orbit. [15]	53
3.7	Phasing maneuver. [15]	53
4.1	Evolution of the Semi-Major Axis (a) during Window 1.	62

LIST OF FIGURES

4.2	Evolution of the Semi-Major Axis (a) during Window 1.	64
4.3	Evolution of the Semi-Major Axis (a) during Window 1.	67
5.1	Evolution of the Semi-Major Axis (a) during Window 1.	91
5.2	Evolution of the x-component of the eccentricity vector (e_x) for Window 1.	91
5.3	Evolution of the y-component of the eccentricity vector (e_y) for Window 1.	92
5.4	Evolution of the orbital Inclination (i) in Window 1.	92
5.5	Evolution of the RAAN (Ω) during Window 1.	93
5.6	Evolution of the Argument of Perigee (ω) during Window 1. . .	93
5.7	Evolution of the True Anomaly (ν) throughout Window 1. . .	94
5.8	Analysis of the Semi-Major Axis error (Δa) across all 32 simulated maneuver windows.	94
5.9	Progression of the eccentricity vector errors ($\Delta e_x, \Delta e_y$) throughout the operational windows.	95
5.10	Distribution of the orbital Inclination error (Δi) over the mission timeline.	95
5.11	Trend of the Argument of Latitude error (Δu) recorded at the target maneuver points across the sequential simulation windows.	96
A.1	Evolution profile of the Semi-Major Axis (a) during Window 2.	103
A.2	Evolution of the x-component of the eccentricity vector (e_x) for Window 2.	104
A.3	Evolution of the y-component of the eccentricity vector (e_y) for Window 2.	104
A.4	Evolution of the orbital Inclination (i) in Window 2.	104
A.5	Evolution of the RAAN (Ω) during Window 2.	105
A.6	Evolution of the Argument of Perigee (ω) during Window 2. . .	105
A.7	Evolution of the True Anomaly (ν) throughout Window 2. . .	105
A.8	Evolution of the Semi-Major Axis (a) during Window 3.	108
A.9	Evolution of the x-component of the eccentricity vector (e_x) for Window 3.	108

A.10	Evolution of the y-component of the eccentricity vector (e_y) for Window 3.	108
A.11	Evolution of the orbital Inclination (i) in Window 3.	109
A.12	Evolution of the RAAN (Ω) during Window 3.	109
A.13	Evolution of the Argument of Perigee (ω) during Window 3. . .	109
A.14	Evolution of the True Anomaly (ν) throughout Window 3. . .	110
A.15	Evolution of the Semi-Major Axis (a) during Window 4.	112
A.16	Evolution of the x-component of the eccentricity vector (e_x) for Window 4.	113
A.17	Evolution of the y-component of the eccentricity vector (e_y) for Window 4.	113
A.18	Evolution of the orbital Inclination (i) in Window 4.	113
A.19	Evolution of the RAAN (Ω) during Window 4.	114
A.20	Evolution of the Argument of Perigee (ω) during Window 4. . .	114
A.21	Evolution of the True Anomaly (ν) throughout Window 4. . .	114
A.22	Evolution of the Semi-Major Axis (a) during Window 5.	117
A.23	Evolution of the x-component of the eccentricity vector (e_x) for Window 5.	117
A.24	Evolution of the y-component of the eccentricity vector (e_y) for Window 5.	117
A.25	Evolution of the orbital Inclination (i) in Window 5.	118
A.26	Evolution of the RAAN (Ω) during Window 5.	118
A.27	Evolution of the Argument of Perigee (ω) during Window 5. . .	118
A.28	Evolution of the True Anomaly (ν) throughout Window 5. . .	119
A.29	Evolution of the Semi-Major Axis (a) during Window 6.	121
A.30	Evolution of the x-component of the eccentricity vector (e_x) for Window 6.	122
A.31	Evolution of the y-component of the eccentricity vector (e_y) for Window 6.	122
A.32	Evolution of the orbital Inclination (i) in Window 6.	122
A.33	Evolution of the RAAN (Ω) during Window 6.	123
A.34	Evolution of the Argument of Perigee (ω) during Window 6. . .	123
A.35	Evolution of the True Anomaly (ν) throughout Window 6. . .	123
A.36	Evolution of the Semi-Major Axis (a) during Window 7.	126

LIST OF FIGURES

A.37	Evolution of the x-component of the eccentricity vector (e_x) for Window 7.	126
A.38	Evolution of the y-component of the eccentricity vector (e_y) for Window 7.	126
A.39	Evolution of the orbital Inclination (i) in Window 7.	127
A.40	Evolution of the RAAN (Ω) during Window 7.	127
A.41	Evolution of the Argument of Perigee (ω) during Window 7.	127
A.42	Evolution of the True Anomaly (ν) throughout Window 7.	128
A.43	Evolution of the Semi-Major Axis (a) during Window 8.	130
A.44	Evolution of the x-component of the eccentricity vector (e_x) for Window 8.	131
A.45	Evolution of the y-component of the eccentricity vector (e_y) for Window 8.	131
A.46	Evolution of the orbital Inclination (i) in Window 8.	131
A.47	Evolution of the RAAN (Ω) during Window 8.	132
A.48	Evolution of the Argument of Perigee (ω) during Window 8.	132
A.49	Evolution of the True Anomaly (ν) throughout Window 8.	132
A.50	Evolution of the Semi-Major Axis (a) during Window 9.	135
A.51	Evolution of the x-component of the eccentricity vector (e_x) for Window 9.	135
A.52	Evolution of the y-component of the eccentricity vector (e_y) for Window 9.	135
A.53	Evolution of the orbital Inclination (i) in Window 9.	136
A.54	Evolution of the RAAN (Ω) during Window 9.	136
A.55	Evolution of the Argument of Perigee (ω) during Window 9.	136
A.56	Evolution of the True Anomaly (ν) throughout Window 9.	137
A.57	Evolution of the Semi-Major Axis (a) during Window 10.	139
A.58	Evolution of the x-component of the eccentricity vector (e_x) for Window 10.	140
A.59	Evolution of the y-component of the eccentricity vector (e_y) for Window 10.	140
A.60	Evolution of the orbital Inclination (i) in Window 10.	140
A.61	Evolution of the RAAN (Ω) during Window 10.	141
A.62	Evolution of the Argument of Perigee (ω) during Window 10.	141

A.63	Evolution of the True Anomaly (ν) throughout Window 10. . .	141
A.64	Evolution of the Semi-Major Axis (a) during Window 11. . . .	144
A.65	Evolution of the x-component of the eccentricity vector (e_x) for Window 11.	144
A.66	Evolution of the y-component of the eccentricity vector (e_y) for Window 11.	144
A.67	Evolution of the orbital Inclination (i) in Window 11.	145
A.68	Evolution of the RAAN (Ω) during Window 11.	145
A.69	Evolution of the Argument of Perigee (ω) during Window 11. .	145
A.70	Evolution of the True Anomaly (ν) throughout Window 11. . .	146
A.71	Evolution of the Semi-Major Axis (a) during Window 12. . . .	148
A.72	Evolution of the x-component of the eccentricity vector (e_x) for Window 12.	149
A.73	Evolution of the y-component of the eccentricity vector (e_y) for Window 12.	149
A.74	Evolution of the orbital Inclination (i) in Window 12.	149
A.75	Evolution of the RAAN (Ω) during Window 12.	150
A.76	Evolution of the Argument of Perigee (ω) during Window 12. .	150
A.77	Evolution of the True Anomaly (ν) throughout Window 12. . .	150
A.78	Evolution of the Semi-Major Axis (a) during Window 13. . . .	153
A.79	Evolution of the x-component of the eccentricity vector (e_x) for Window 13.	153
A.80	Evolution of the y-component of the eccentricity vector (e_y) for Window 13.	153
A.81	Evolution of the orbital Inclination (i) in Window 13.	154
A.82	Evolution of the RAAN (Ω) during Window 13.	154
A.83	Evolution of the Argument of Perigee (ω) during Window 13. .	154
A.84	Evolution of the True Anomaly (ν) throughout Window 13. . .	155
A.85	Evolution of the Semi-Major Axis (a) during Window 14. . . .	157
A.86	Evolution of the x-component of the eccentricity vector (e_x) for Window 14.	158
A.87	Evolution of the y-component of the eccentricity vector (e_y) for Window 14.	158
A.88	Evolution of the orbital Inclination (i) in Window 14.	158

LIST OF FIGURES

A.89	Evolution of the RAAN (Ω) during Window 14.	159
A.90	Evolution of the Argument of Perigee (ω) during Window 14. . .	159
A.91	Evolution of the True Anomaly (ν) throughout Window 14. . .	159
A.92	Evolution of the Semi-Major Axis (a) during Window 15. . . .	162
A.93	Evolution of the x-component of the eccentricity vector (e_x) for Window 15.	162
A.94	Evolution of the y-component of the eccentricity vector (e_y) for Window 15.	162
A.95	Evolution of the orbital Inclination (i) in Window 15.	163
A.96	Evolution of the RAAN (Ω) during Window 15.	163
A.97	Evolution of the Argument of Perigee (ω) during Window 15. .	163
A.98	Evolution of the True Anomaly (ν) throughout Window 15. . .	164
A.99	Evolution of the Semi-Major Axis (a) during Window 16. . . .	166
A.100	Evolution of the x-component of the eccentricity vector (e_x) for Window 16.	167
A.101	Evolution of the y-component of the eccentricity vector (e_y) for Window 16.	167
A.102	Evolution of the orbital Inclination (i) in Window 16.	167
A.103	Evolution of the RAAN (Ω) during Window 16.	168
A.104	Evolution of the Argument of Perigee (ω) during Window 16. .	168
A.105	Evolution of the True Anomaly (ν) throughout Window 16. . .	168
A.106	Evolution of the Semi-Major Axis (a) during Window 17. . . .	171
A.107	Evolution of the x-component of the eccentricity vector (e_x) for Window 17.	171
A.108	Evolution of the y-component of the eccentricity vector (e_y) for Window 17.	171
A.109	Evolution of the orbital Inclination (i) in Window 17.	172
A.110	Evolution of the RAAN (Ω) during Window 17.	172
A.111	Evolution of the Argument of Perigee (ω) during Window 17. .	172
A.112	Evolution of the True Anomaly (ν) throughout Window 17. . .	173
A.113	Evolution of the Semi-Major Axis (a) during Window 18. . . .	175
A.114	Evolution of the x-component of the eccentricity vector (e_x) for Window 18.	176

A.115	Evolution of the y-component of the eccentricity vector (e_y) for Window 18.	176
A.116	Evolution of the orbital Inclination (i) in Window 18.	176
A.117	Evolution of the RAAN (Ω) during Window 18.	177
A.118	Evolution of the Argument of Perigee (ω) during Window 18. . .	177
A.119	Evolution of the True Anomaly (ν) throughout Window 18. . .	177
A.120	Evolution of the Semi-Major Axis (a) during Window 19. . . .	180
A.121	Evolution of the x-component of the eccentricity vector (e_x) for Window 19.	180
A.122	Evolution of the y-component of the eccentricity vector (e_y) for Window 19.	180
A.123	Evolution of the orbital Inclination (i) in Window 19.	181
A.124	Evolution of the RAAN (Ω) during Window 19.	181
A.125	Evolution of the Argument of Perigee (ω) during Window 19. .	181
A.126	Evolution of the True Anomaly (ν) throughout Window 19. . .	182
A.127	Evolution of the Semi-Major Axis (a) during Window 20. . . .	184
A.128	Evolution of the x-component of the eccentricity vector (e_x) for Window 20.	185
A.129	Evolution of the y-component of the eccentricity vector (e_y) for Window 20.	185
A.130	Evolution of the orbital Inclination (i) in Window 20.	185
A.131	Evolution of the RAAN (Ω) during Window 20.	186
A.132	Evolution of the Argument of Perigee (ω) during Window 20. .	186
A.133	Evolution of the True Anomaly (ν) throughout Window 20. . .	186
A.134	Evolution of the Semi-Major Axis (a) during Window 21. . . .	189
A.135	Evolution of the x-component of the eccentricity vector (e_x) for Window 21.	189
A.136	Evolution of the y-component of the eccentricity vector (e_y) for Window 21.	189
A.137	Evolution of the orbital Inclination (i) in Window 21.	190
A.138	Evolution of the RAAN (Ω) during Window 21.	190
A.139	Evolution of the Argument of Perigee (ω) during Window 21. .	190
A.140	Evolution of the True Anomaly (ν) throughout Window 21. . .	191
A.141	Evolution of the Semi-Major Axis (a) during Window 22. . . .	193

LIST OF FIGURES

A.142	Evolution of the x-component of the eccentricity vector (e_x) for Window 22.	194
A.143	Evolution of the y-component of the eccentricity vector (e_y) for Window 22.	194
A.144	Evolution of the orbital Inclination (i) in Window 22.	194
A.145	Evolution of the RAAN (Ω) during Window 22.	195
A.146	Evolution of the Argument of Perigee (ω) during Window 22.	195
A.147	Evolution of the True Anomaly (ν) throughout Window 22.	195
A.148	Evolution of the Semi-Major Axis (a) during Window 23.	198
A.149	Evolution of the x-component of the eccentricity vector (e_x) for Window 23.	198
A.150	Evolution of the y-component of the eccentricity vector (e_y) for Window 23.	198
A.151	Evolution of the orbital Inclination (i) in Window 23.	199
A.152	Evolution of the RAAN (Ω) during Window 23.	199
A.153	Evolution of the Argument of Perigee (ω) during Window 23.	199
A.154	Evolution of the True Anomaly (ν) throughout Window 23.	200
A.155	Evolution of the Semi-Major Axis (a) during Window 24.	202
A.156	Evolution of the x-component of the eccentricity vector (e_x) for Window 24.	203
A.157	Evolution of the y-component of the eccentricity vector (e_y) for Window 24.	203
A.158	Evolution of the orbital Inclination (i) in Window 24.	203
A.159	Evolution of the RAAN (Ω) during Window 24.	204
A.160	Evolution of the Argument of Perigee (ω) during Window 24.	204
A.161	Evolution of the True Anomaly (ν) throughout Window 24.	204
A.162	Evolution of the Semi-Major Axis (a) during Window 25.	207
A.163	Evolution of the x-component of the eccentricity vector (e_x) for Window 25.	207
A.164	Evolution of the y-component of the eccentricity vector (e_y) for Window 25.	207
A.165	Evolution of the orbital Inclination (i) in Window 25.	208
A.166	Evolution of the RAAN (Ω) during Window 25.	208
A.167	Evolution of the Argument of Perigee (ω) during Window 25.	208

A.168	Evolution of the True Anomaly (ν) throughout Window 25. . .	209
A.169	Evolution of the Semi-Major Axis (a) during Window 26. . . .	211
A.170	Evolution of the x-component of the eccentricity vector (e_x) for Window 26.	212
A.171	Evolution of the y-component of the eccentricity vector (e_y) for Window 26.	212
A.172	Evolution of the orbital Inclination (i) in Window 26.	212
A.173	Evolution of the RAAN (Ω) during Window 26.	213
A.174	Evolution of the Argument of Perigee (ω) during Window 26. .	213
A.175	Evolution of the True Anomaly (ν) throughout Window 26. . .	213
A.176	Evolution of the Semi-Major Axis (a) during Window 27. . . .	216
A.177	Evolution of the x-component of the eccentricity vector (e_x) for Window 27.	216
A.178	Evolution of the y-component of the eccentricity vector (e_y) for Window 27.	216
A.179	Evolution of the orbital Inclination (i) in Window 27.	217
A.180	Evolution of the RAAN (Ω) during Window 27.	217
A.181	Evolution of the Argument of Perigee (ω) during Window 27. .	217
A.182	Evolution of the True Anomaly (ν) throughout Window 27. . .	218
A.183	Evolution of the Semi-Major Axis (a) during Window 28. . . .	220
A.184	Evolution of the x-component of the eccentricity vector (e_x) for Window 28.	221
A.185	Evolution of the y-component of the eccentricity vector (e_y) for Window 28.	221
A.186	Evolution of the orbital Inclination (i) in Window 28.	221
A.187	Evolution of the RAAN (Ω) during Window 28.	222
A.188	Evolution of the Argument of Perigee (ω) during Window 28. .	222
A.189	Evolution of the True Anomaly (ν) throughout Window 28. . .	222
A.190	Evolution of the Semi-Major Axis (a) during Window 29. . . .	225
A.191	Evolution of the x-component of the eccentricity vector (e_x) for Window 29.	225
A.192	Evolution of the y-component of the eccentricity vector (e_y) for Window 29.	225
A.193	Evolution of the orbital Inclination (i) in Window 29.	226

LIST OF FIGURES

A.194	Evolution of the RAAN (Ω) during Window 29.	226
A.195	Evolution of the Argument of Perigee (ω) during Window 29. .	226
A.196	Evolution of the True Anomaly (ν) throughout Window 29. . .	227
A.197	Evolution of the Semi-Major Axis (a) during Window 30. . . .	229
A.198	Evolution of the x-component of the eccentricity vector (e_x) for Window 30.	230
A.199	Evolution of the y-component of the eccentricity vector (e_y) for Window 30.	230
A.200	Evolution of the orbital Inclination (i) in Window 30.	230
A.201	Evolution of the RAAN (Ω) during Window 30.	231
A.202	Evolution of the Argument of Perigee (ω) during Window 30. .	231
A.203	Evolution of the True Anomaly (ν) throughout Window 30. . .	231
A.204	Evolution of the Semi-Major Axis (a) during Window 31. . . .	234
A.205	Evolution of the x-component of the eccentricity vector (e_x) for Window 31.	234
A.206	Evolution of the y-component of the eccentricity vector (e_y) for Window 31.	234
A.207	Evolution of the orbital Inclination (i) in Window 31.	235
A.208	Evolution of the RAAN (Ω) during Window 31.	235
A.209	Evolution of the Argument of Perigee (ω) during Window 31. .	235
A.210	Evolution of the True Anomaly (ν) throughout Window 31. . .	236
A.211	Evolution of the Semi-Major Axis (a) during Window 32. . . .	238
A.212	Evolution of the x-component of the eccentricity vector (e_x) for Window 32.	239
A.213	Evolution of the y-component of the eccentricity vector (e_y) for Window 32.	239
A.214	Evolution of the orbital Inclination (i) in Window 32.	239
A.215	Evolution of the RAAN (Ω) during Window 32.	240
A.216	Evolution of the Argument of Perigee (ω) during Window 32. .	240
A.217	Evolution of the True Anomaly (ν) throughout Window 32. . .	240

List of Tables

2.1	Classification of orbital trajectories based on conic sections. . .	14
2.2	Coordinate Systems Summary	20
5.1	Numerical Integrator Configuration.	84
5.2	Operational Constraints on Maneuver Duration.	84
5.3	Force Model and Spacecraft Physical Parameters.	85
5.4	Maneuver Waiting Time Constraints configured in the planner.	85
5.5	Window 1	89
5.6	Target State Errors Summary - Window 1	89
5.7	Normal Maneuvers Summary - Window 1. SQP ΔV : 0.288677 m/s.	90
5.8	Tangential Maneuvers Summary - Window 1. SQP AOL: 159.57°, v_{Tan} SQP: 1.21 m/s.	90
A.1	Window 2	101
A.2	Target State Errors Summary - Window 2	102
A.3	Normal Maneuvers Summary - Window 2. SQP ΔV : 0.304232 m/s.	102
A.4	Tangential Maneuvers Summary - Window 2. SQP AOL: 156.50°, v_{Tan} SQP: 1.08 m/s.	103
A.5	Window 3	106
A.6	Target State Errors Summary - Window 3	106
A.7	Normal Maneuvers Summary - Window 3. SQP ΔV : 0.170272 m/s.	107
A.8	Tangential Maneuvers Summary - Window 3. SQP AOL: 160.87°, v_{Tan} SQP: 0.99 m/s.	107

LIST OF TABLES

A.9	Window 4	110
A.10	Target State Errors Summary - Window 4	111
A.11	Normal Maneuvers Summary - Window 4. SQP ΔV : 0.292595 m/s.	111
A.12	Tangential Maneuvers Summary - Window 4. SQP AOL: 157.81°, v_{Tan} SQP: 0.89 m/s.	112
A.13	Window 5	115
A.14	Target State Errors Summary - Window 5	115
A.15	Normal Maneuvers Summary - Window 5. SQP ΔV : 0.349184 m/s.	116
A.16	Tangential Maneuvers Summary - Window 5. SQP AOL: 160.22°, v_{Tan} SQP: 0.56 m/s.	116
A.17	Window 6	119
A.18	Target State Errors Summary - Window 6	120
A.19	Normal Maneuvers Summary - Window 6. SQP ΔV : 0.335830 m/s.	120
A.20	Tangential Maneuvers Summary - Window 6. SQP AOL: 162.44°, v_{Tan} SQP: 0.46 m/s.	121
A.21	Window 7	124
A.22	Target State Errors Summary - Window 7	124
A.23	Normal Maneuvers Summary - Window 7. SQP ΔV : 0.291318 m/s.	125
A.24	Tangential Maneuvers Summary - Window 7. SQP AOL: 162.88°, v_{Tan} SQP: 0.49 m/s.	125
A.25	Window 8	128
A.26	Target State Errors Summary - Window 8	129
A.27	Normal Maneuvers Summary - Window 8. SQP ΔV : 0.285298 m/s.	129
A.28	Tangential Maneuvers Summary - Window 8. SQP AOL: 162.72°, v_{Tan} SQP: 0.24 m/s.	130
A.29	Window 9	133
A.30	Target State Errors Summary - Window 9	133
A.31	Normal Maneuvers Summary - Window 9. SQP ΔV : 0.331632 m/s.	134

A.32	Tangential Maneuvers Summary - Window 9. SQP AOL: 167.90° , v_{Tan} SQP: 0.10 m/s.	134
A.33	Window 10	137
A.34	Target State Errors Summary - Window 10	138
A.35	Normal Maneuvers Summary - Window 10. SQP ΔV : 0.352431 m/s.	138
A.36	Tangential Maneuvers Summary - Window 10. SQP AOL: 169.02° , v_{Tan} SQP: -0.12 m/s.	139
A.37	Window 11	142
A.38	Target State Errors Summary - Window 11	142
A.39	Normal Maneuvers Summary - Window 11. SQP ΔV : 0.360509 m/s.	143
A.40	Tangential Maneuvers Summary - Window 11. SQP AOL: 169.30° , v_{Tan} SQP: 0.24 m/s.	143
A.41	Window 12	146
A.42	Target State Errors Summary - Window 12	147
A.43	Normal Maneuvers Summary - Window 12. SQP ΔV : 0.300760 m/s.	147
A.44	Tangential Maneuvers Summary - Window 12. SQP AOL: 169.00° , v_{Tan} SQP: 0.21 m/s.	148
A.45	Window 13	151
A.46	Target State Errors Summary - Window 13	151
A.47	Normal Maneuvers Summary - Window 13. SQP ΔV : 0.325582 m/s.	152
A.48	Tangential Maneuvers Summary - Window 13. SQP AOL: 176.37° , v_{Tan} SQP: 0.09 m/s.	152
A.49	Window 14	155
A.50	Target State Errors Summary - Window 14	156
A.51	Normal Maneuvers Summary - Window 14. SQP ΔV : 0.401479 m/s.	156
A.52	Tangential Maneuvers Summary - Window 14. SQP AOL: 182.93° , v_{Tan} SQP: 0.01 m/s.	157
A.53	Window 15	160
A.54	Target State Errors Summary - Window 15	160

LIST OF TABLES

A.55	Normal Maneuvers Summary - Window 15. SQP ΔV : 0.353315 m/s.	161
A.56	Tangential Maneuvers Summary - Window 15. SQP AOL: 180.25°, v_{Tan} SQP: 0.00 m/s.	161
A.57	Window 16	164
A.58	Target State Errors Summary - Window 16	165
A.59	Normal Maneuvers Summary - Window 16. SQP ΔV : 0.359138 m/s.	165
A.60	Tangential Maneuvers Summary - Window 16. SQP AOL: 181.06°, v_{Tan} SQP: 0.02 m/s.	166
A.61	Window 17	169
A.62	Target State Errors Summary - Window 17	169
A.63	Normal Maneuvers Summary - Window 17. SQP ΔV : 0.316784 m/s.	170
A.64	Tangential Maneuvers Summary - Window 17. SQP AOL: 183.64°, v_{Tan} SQP: 0.02 m/s.	170
A.65	Window 18	173
A.66	Target State Errors Summary - Window 18	174
A.67	Normal Maneuvers Summary - Window 18. SQP ΔV : 0.302632 m/s.	174
A.68	Tangential Maneuvers Summary - Window 18. SQP AOL: 182.85°, v_{Tan} SQP: 0.00 m/s.	175
A.69	Window 19	178
A.70	Target State Errors Summary - Window 19	178
A.71	Normal Maneuvers Summary - Window 19. SQP ΔV : 0.281360 m/s.	179
A.72	Tangential Maneuvers Summary - Window 19. SQP AOL: 186.08°, v_{Tan} SQP: 0.01 m/s.	179
A.73	Window 20	182
A.74	Target State Errors Summary - Window 20	183
A.75	Normal Maneuvers Summary - Window 20. SQP ΔV : 0.340609 m/s.	183
A.76	Tangential Maneuvers Summary - Window 20. SQP AOL: 183.38°, v_{Tan} SQP: 0.12 m/s.	184

A.77	Window 21	187
A.78	Target State Errors Summary - Window 21	187
A.79	Normal Maneuvers Summary - Window 21. SQP ΔV : 0.214970 m/s.	188
A.80	Tangential Maneuvers Summary - Window 21. SQP AOL: 189.41°, v_{Tan} SQP: 0.09 m/s.	188
A.81	Window 22	191
A.82	Target State Errors Summary - Window 22	192
A.83	Normal Maneuvers Summary - Window 22. SQP ΔV : 0.228037 m/s.	192
A.84	Tangential Maneuvers Summary - Window 22. SQP AOL: 188.24°, v_{Tan} SQP: -0.16 m/s.	193
A.85	Window 23	196
A.86	Target State Errors Summary - Window 23	196
A.87	Normal Maneuvers Summary - Window 23. SQP ΔV : 0.289792 m/s.	197
A.88	Tangential Maneuvers Summary - Window 23. SQP AOL: 191.77°, v_{Tan} SQP: 0.04 m/s.	197
A.89	Window 24	200
A.90	Target State Errors Summary - Window 24	201
A.91	Normal Maneuvers Summary - Window 24. SQP ΔV : 0.222372 m/s.	201
A.92	Tangential Maneuvers Summary - Window 24. SQP AOL: 192.20°, v_{Tan} SQP: 0.09 m/s.	202
A.93	Orbit Comparison - Window 25	205
A.94	Target State Errors Summary - Window 25	205
A.95	Normal Maneuvers Summary - Window 25. SQP ΔV : 0.266738 m/s.	206
A.96	Tangential Maneuvers Summary - Window 25. SQP AOL: 194.28°, v_{Tan} SQP: 0.29 m/s.	206
A.97	Orbit Comparison - Window 26	209
A.98	Target State Errors Summary - Window 26	210
A.99	Normal Maneuvers Summary - Window 26. SQP ΔV : 0.361508 m/s.	210

LIST OF TABLES

A.100	Tangential Maneuvers Summary - Window 26. SQP AOL: 197.38°, v_{Tan} SQP: 0.61 m/s.	211
A.101	Window 27 - Orbit Comparison	214
A.102	Target State Errors Summary - Window 27	214
A.103	Normal Maneuvers Summary - Window 27. SQP ΔV : 0.317198 m/s.	215
A.104	Tangential Maneuvers Summary - Window 27. SQP AOL: 197.19°, v_{Tan} SQP: 0.92 m/s.	215
A.105	Orbit Comparison - Window 28	218
A.106	Target State Errors Summary - Window 28	219
A.107	Normal Maneuvers Summary - Window 28. SQP ΔV : 0.349165 m/s.	219
A.108	Tangential Maneuvers Summary - Window 28. SQP AOL: 197.87°, v_{Tan} SQP: 1.14 m/s.	220
A.109	Orbit Comparison - Window 29	223
A.110	Target State Errors Summary - Window 29	223
A.111	Normal Maneuvers Summary - Window 29. SQP ΔV : 0.269716 m/s.	224
A.112	Tangential Maneuvers Summary - Window 29. SQP AOL: 201.29°, v_{Tan} SQP: 1.33 m/s.	224
A.113	Orbit Comparison - Window 30	227
A.114	Target State Errors Summary - Window 30	228
A.115	Normal Maneuvers Summary - Window 30. SQP ΔV : 0.350153 m/s.	228
A.116	Tangential Maneuvers Summary - Window 30. SQP AOL: 203.80°, v_{Tan} SQP: 1.57 m/s.	229
A.117	Orbit Comparison - Window 31	232
A.118	Target State Errors Summary - Window 31	232
A.119	Normal Maneuvers Summary - Window 31. SQP ΔV : 0.265434 m/s.	233
A.120	Tangential Maneuvers Summary - Window 31. SQP AOL: 205.14°, v_{Tan} SQP: 1.86 m/s.	233
A.121	Orbit Comparison - Window 32	236
A.122	Target State Errors Summary - Window 32	237

A.123	Normal Maneuvers Summary - Window 32. SQP ΔV : 0.185678 m/s.	237
A.124	Tangential Maneuvers Summary - Window 32. SQP AOL: 206.69°, v_{Tan} SQP: 1.99 m/s.	238