Performance Analysis of the predictive Autonomous Orbit Control (AOC) method

Author: Sara MANGLAVITI

Supervisors: Jérôme THOMASSIN, Michèle LAVAGNA, Thibault GATEAU

September, 2018
Abstract

Because of non-Keplerian forces (i.e., atmospheric drag, gravitational forces of the Sun and the Moon...), Orbit Control (OC) is a vital aspect of every satellite mission. In fact, in order to keep the satellite on a particular reference orbit, some maneuvers have to be executed by the spacecraft. The OC, or the so called station-keeping, guarantees the position accuracy that is required in several space missions. To achieve this precision with minimal ground-based workload, an Autonomous Orbit Control (AOC) has been proposed. In this way, the spacecraft itself will calculate, control and execute the station-keeping maneuvers, without outside intervention. However, the AOC at low altitudes raises the issue of the collision risks management process. The ground segment team, knowing the future action plan of the spacecraft, will be able to estimate the impact risk and deal with it. That’s why a predictive AOC has been implemented. The AOC will calculate, at each passage at the ascending node, a maneuvers horizon for the next 24 hours. In this way the ground segment team will be able to predict the spacecraft dynamics, compare the satellite trajectory with the known near debris ephemeris and, eventually, modify the action plan.

In order to make AOC more predictable for the ground system, the “Centre National d’Eudes Spatiales” (CNES) has studied and developed an algorithmic method based on the presence of a frozen horizon for upcoming maneuvers: all the maneuvers computed by the AOC in this range will be fixed in magnitude and date of achievement. However, due to the variability of the solar activity, the efficiency of this method decreases. A solution has been found adding a second maneuvers horizon in which in-plane and out-of-plane maneuvers are adjustable in amplitude but with a frozen date of achievement. The new method contains several parameters, such as the amplitude of the horizons and control margins. The determination of these parameters for different missions will be the aim of this study.

Keywords: Autonomous Orbit Control, station-keeping, collision risk, solar activity, parameters
# Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>i</td>
</tr>
<tr>
<td>List of Figures</td>
<td>v</td>
</tr>
<tr>
<td>List of Tables</td>
<td>vi</td>
</tr>
<tr>
<td><strong>1 Introduction</strong></td>
<td></td>
</tr>
<tr>
<td>1.1 Autonomous Orbit Control Background</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Subject of the Internship</td>
<td>2</td>
</tr>
<tr>
<td>1.3 Objectives</td>
<td>2</td>
</tr>
<tr>
<td>1.4 Structure of the Document</td>
<td>2</td>
</tr>
<tr>
<td><strong>2 Working Environment</strong></td>
<td></td>
</tr>
<tr>
<td>2.1 About CNES</td>
<td>4</td>
</tr>
<tr>
<td>2.1.1 Mission of the French Space Agency</td>
<td>4</td>
</tr>
<tr>
<td>2.2 CNES Facilities</td>
<td>4</td>
</tr>
<tr>
<td>2.2.1 Headquarters</td>
<td>5</td>
</tr>
<tr>
<td>2.2.2 Toulouse Space Center (CST)</td>
<td>5</td>
</tr>
<tr>
<td>2.2.3 Guiana Space Centre (CSG)</td>
<td>5</td>
</tr>
<tr>
<td>2.2.4 Launcher Directorate (DLA)</td>
<td>6</td>
</tr>
<tr>
<td>2.3 Internship Environment</td>
<td>6</td>
</tr>
<tr>
<td><strong>3 Operating principle of the predictive AOC</strong></td>
<td></td>
</tr>
<tr>
<td>3.1 AOC specifications</td>
<td>7</td>
</tr>
<tr>
<td>3.2 AOC algorithms implementation</td>
<td>8</td>
</tr>
<tr>
<td>3.3 Main steps of the predictive AOC</td>
<td>8</td>
</tr>
<tr>
<td>3.4 In-plane and out-of-plane controllers</td>
<td>10</td>
</tr>
<tr>
<td>3.4.1 Inclination controller</td>
<td>11</td>
</tr>
<tr>
<td>3.4.2 Semi-major axis controller</td>
<td>14</td>
</tr>
<tr>
<td><strong>4 Definition of the AOC parameters</strong></td>
<td>17</td>
</tr>
<tr>
<td>4.1 Control parameters</td>
<td>17</td>
</tr>
<tr>
<td>4.1.1 Horizons parameters</td>
<td>17</td>
</tr>
<tr>
<td>4.1.2 Control margins</td>
<td>17</td>
</tr>
<tr>
<td>4.2 Considerations</td>
<td>19</td>
</tr>
</tbody>
</table>
## Contents

5 Simulation campaign .................................................. 21
   5.1 Simulation Architecture ........................................ 21
   5.2 Selected Missions for simulations .............................. 22
   5.3 Strategy for control parameters choice ....................... 23

6 Control parameters choice .......................................... 24
   6.1 Mission B1 ....................................................... 24
      6.1.1 Choice Validation ......................................... 27
   6.2 Mission B2 ....................................................... 28
      6.2.1 Choice Validation ......................................... 31
   6.3 Mission D1 ....................................................... 31
      6.3.1 Choice Validation ......................................... 34
   6.4 Mission D2 ....................................................... 35
      6.4.1 Choice Validation ......................................... 38
   6.5 Mission F ......................................................... 39
      6.5.1 Choice Validation ......................................... 42
   6.6 Simulations results for other missions .......................... 42

7 Conclusions ............................................................ 43
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Control system architecture: from the differences between the measured orbit (simulated) and the guidance orbit, a controller determines the future maneuver needs.</td>
<td>8</td>
</tr>
<tr>
<td>3.2</td>
<td>Overall predictability horizon</td>
<td>9</td>
</tr>
<tr>
<td>3.3</td>
<td>Overall predictability horizon shifted to the right: with respect to Figure 3.2, one can observe that the semi-frozen maneuvers have been updated and the maneuver in the research zone has been recomputed.</td>
<td>10</td>
</tr>
<tr>
<td>3.4</td>
<td>Natural increment trend of inclination and RAAN variation</td>
<td>11</td>
</tr>
<tr>
<td>3.5</td>
<td>Inclination maneuver strategy</td>
<td>11</td>
</tr>
<tr>
<td>3.6</td>
<td>Natural decrement trend of inclination and RAAN variation</td>
<td>12</td>
</tr>
<tr>
<td>3.7</td>
<td>Graphical RAAN command computation: from the subtraction of the actual measured parabola slope and the theoretical parabola slope one can obtain the command value.</td>
<td>13</td>
</tr>
<tr>
<td>3.8</td>
<td>Graphical RAAN command computation: from the subtraction of the actual measured parabola slope and the theoretical parabola slope one can obtain the command value.</td>
<td>13</td>
</tr>
<tr>
<td>3.9</td>
<td>Natural trend of semi-major axis and argument of latitude variation</td>
<td>15</td>
</tr>
<tr>
<td>3.10</td>
<td>Semi-major axis maneuver strategy</td>
<td>15</td>
</tr>
<tr>
<td>4.1</td>
<td>Control margins for the semi-major axis controller</td>
<td>18</td>
</tr>
<tr>
<td>4.2</td>
<td>Control margins for the inclination controller</td>
<td>19</td>
</tr>
<tr>
<td>5.1</td>
<td>Simulation scheme</td>
<td>22</td>
</tr>
<tr>
<td>6.1</td>
<td>Evolution of the semi-major axis variations Mission B1</td>
<td>24</td>
</tr>
<tr>
<td>6.2</td>
<td>Evolution of the argument of latitude variations Mission B1</td>
<td>25</td>
</tr>
<tr>
<td>6.3</td>
<td>Evolution of the inclination variations Mission B1</td>
<td>25</td>
</tr>
<tr>
<td>6.4</td>
<td>Evolution of the RAAN variations Mission B1</td>
<td>25</td>
</tr>
<tr>
<td>6.5</td>
<td>Evolution of the in-plane ground track variations Mission B1</td>
<td>26</td>
</tr>
<tr>
<td>6.6</td>
<td>Evolution of the out-of-plane ground track variations Mission B1</td>
<td>26</td>
</tr>
<tr>
<td>6.7</td>
<td>Solar activity Mission B1</td>
<td>26</td>
</tr>
<tr>
<td>6.8</td>
<td>Evolution of the in-plane and out-of-plane ground tracks variations Mission B1 for two years simulation.</td>
<td>27</td>
</tr>
<tr>
<td>6.9</td>
<td>Solar activity Mission B1 for two years simulation.</td>
<td>28</td>
</tr>
<tr>
<td>6.10</td>
<td>Evolution of the semi-major axis variations Mission B2</td>
<td>28</td>
</tr>
<tr>
<td>6.11</td>
<td>Evolution of the argument of latitude variations Mission B2</td>
<td>29</td>
</tr>
<tr>
<td>6.12</td>
<td>Evolution of the inclination variations Mission B2</td>
<td>29</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>6.13</td>
<td>Evolution of the RAAN variations Mission B2</td>
<td>29</td>
</tr>
<tr>
<td>6.14</td>
<td>Evolution of the in-plane ground track variations Mission B2</td>
<td>30</td>
</tr>
<tr>
<td>6.15</td>
<td>Evolution of the out-of-plane ground track variations Mission B2</td>
<td>30</td>
</tr>
<tr>
<td>6.16</td>
<td>Solar activity Mission B2</td>
<td>30</td>
</tr>
<tr>
<td>6.17</td>
<td>Evolution of the semi-major axis variations Mission D1</td>
<td>31</td>
</tr>
<tr>
<td>6.18</td>
<td>Evolution of the argument of latitude variations Mission D1</td>
<td>32</td>
</tr>
<tr>
<td>6.19</td>
<td>Evolution of the inclination variations Mission D1</td>
<td>32</td>
</tr>
<tr>
<td>6.20</td>
<td>Evolution of the RAAN variations Mission D1</td>
<td>32</td>
</tr>
<tr>
<td>6.21</td>
<td>Evolution of the in-plane ground track variations Mission D1</td>
<td>33</td>
</tr>
<tr>
<td>6.22</td>
<td>Evolution of the out-of-plane ground track variations Mission D1</td>
<td>33</td>
</tr>
<tr>
<td>6.23</td>
<td>Solar activity Mission D1</td>
<td>33</td>
</tr>
<tr>
<td>6.24</td>
<td>Evolution of the in-plane and out-of-plane ground tracks variations Mission D1</td>
<td>34</td>
</tr>
<tr>
<td>6.25</td>
<td>Solar activity Mission D1 for two years simulation</td>
<td>35</td>
</tr>
<tr>
<td>6.26</td>
<td>Evolution of the semi-major axis variations Mission D2</td>
<td>35</td>
</tr>
<tr>
<td>6.27</td>
<td>Evolution of the argument of latitude variations Mission D2</td>
<td>36</td>
</tr>
<tr>
<td>6.28</td>
<td>Evolution of the inclination variations Mission D2</td>
<td>36</td>
</tr>
<tr>
<td>6.29</td>
<td>Evolution of the RAAN variations Mission D2</td>
<td>36</td>
</tr>
<tr>
<td>6.30</td>
<td>Evolution of the in-plane ground track variations Mission D2</td>
<td>37</td>
</tr>
<tr>
<td>6.31</td>
<td>Evolution of the out-of-plane ground track variations Mission D2</td>
<td>37</td>
</tr>
<tr>
<td>6.32</td>
<td>Solar activity Mission D2</td>
<td>37</td>
</tr>
<tr>
<td>6.33</td>
<td>Evolution of the in-plane and out-of-plane ground tracks variations Mission D2</td>
<td>38</td>
</tr>
<tr>
<td>6.34</td>
<td>Solar activity Mission D2 for two years simulation</td>
<td>39</td>
</tr>
<tr>
<td>6.35</td>
<td>Evolution of the semi-major axis variations Mission F</td>
<td>39</td>
</tr>
<tr>
<td>6.36</td>
<td>Evolution of the argument of latitude variations Mission F</td>
<td>40</td>
</tr>
<tr>
<td>6.37</td>
<td>Evolution of the inclination variations Mission F</td>
<td>40</td>
</tr>
<tr>
<td>6.38</td>
<td>Evolution of the RAAN variations Mission F</td>
<td>40</td>
</tr>
<tr>
<td>6.39</td>
<td>Evolution of the in-plane ground track variations Mission F</td>
<td>41</td>
</tr>
<tr>
<td>6.40</td>
<td>Evolution of the out-of-plane ground track variations Mission F</td>
<td>41</td>
</tr>
<tr>
<td>6.41</td>
<td>Solar activity Mission F</td>
<td>41</td>
</tr>
</tbody>
</table>
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Control Margins</td>
<td>18</td>
</tr>
<tr>
<td>5.1</td>
<td>Control Margins</td>
<td>23</td>
</tr>
<tr>
<td>6.1</td>
<td>Control Margins Mission B1</td>
<td>24</td>
</tr>
<tr>
<td>6.2</td>
<td>Control Margins Mission B2</td>
<td>28</td>
</tr>
<tr>
<td>6.3</td>
<td>Control Margins Mission D1</td>
<td>31</td>
</tr>
<tr>
<td>6.4</td>
<td>Control Margins Mission D2</td>
<td>35</td>
</tr>
<tr>
<td>6.5</td>
<td>Control Margins Mission F</td>
<td>39</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

This internship report is written as a requirement for the completion of the Double Degree Program in Space Engineering, imparted by Politecnico di Milano and the Institut Superieur de l’Aeronautique et de l’Espace (ISAE-SUPAERO). The internship has taken place from April to September 2018 in the French Space Agency CNES (Centre National d’Etudes Spatiales).

In this first introductory chapter, the subject of the internship will be presented as well as the topic background knowledge. Furthermore, a brief description of the objectives and structure of the document will be illustrated in the last sections.

1.1 Autonomous Orbit Control Background

The Toulouse Space Centre prepares the technical policy and the innovative orbital systems of the future. The program of Research & Technology (R&T) covers all the necessary techniques for a space system (Earth observation, telecommunications, location/navigation, science, security), as well as the cross-cutting techniques (on-board and in-flight technologies, micro-technologies, platforms, etc.).

An Autonomous Orbit Control method (AOC), that allows both in-plane and out-of-plane maneuvers to be planned and performed autonomously, has been developed by the CNES and successfully experimented on Demeter [2], a Myriade satellite (CNES line of micro-satellites).

The AOC can provide both significant operations cost reductions and increased mission performance. By controlling the orbit to match a chosen reference, ground operations are significantly reduced and scheduling becomes highly predictable. AOC gains in value for very low Earth orbit satellites, when the effects of atmospheric drag must very often be compensated for.

Feedbacks from different projects have confirmed the necessity to develop a predictive AOC that, providing the future spacecraft trajectory, aims at improving the assessment of the debris collision risk.

If a collision risk is detected, ground segment should offer and define an avoidance strategy. From an operational point of view, these tasks require from 12 to 24 hours. Therefore, it should be very interesting to freeze the maneuvers during this
horizon time \[\text{II}\]. However, considering the variability of the solar activity, one can say that the predictability of a frozen horizon method is not reliable. So in order to compensate this uncertainty, a second maneuvers horizon has been added. The characteristic of this zone is that the maneuvers are adjustable in amplitude but with a frozen date of achievement.

The predictive AOC is characterized by several parameters (i.e. the size of the horizons previously defined) that allow to adapt this kind of control for several missions and respect the constraints on the in-plane and out-of-plane control thresholds.

1.2 Subject of the Internship

Driven by the Space Mechanics department and incorporated within the framework of an R&T study, this internship concerns the analysis of the effects of the AOC parameters on the station-keeping performances, from simulations results, for different satellite missions. In particular, it has been proved how the optimization of these parameters is not completely predictable.

1.3 Objectives

The objectives of the internship were not only technical. This opportunity was also important to have the first contact with the space field and the first experience of a real job.

The objectives can be summarized as follows:

- To define new methods or to improve the existing ones in order to optimize the predictability duration of the control technique taking the station-keeping accuracy into consideration.
- To implement these improvements on the existing simulator (on Java).
- To run numerical simulations for several satellite missions in order to estimate the performance of these new methods.

1.4 Structure of the Document

The document is structured in five chapters, where each chapter has its different sections and subsections.

Chapter 1 corresponds to the introduction. It starts with the general background of the AOC method, followed by a brief introduction to the subject of the internship. Furthermore, it gives a global description of the main objectives of internship.

Chapter 2 describes the organism where the internship has taken place. It explains the main objectives of the company, in this case CNES, as well as its main structure. Additionally, the specific internship environment is detailed (department and
division).

**Chapter 3** provides specific information about the operating principle of the AOC. It explains the orbital parameters utilized in the study, what kind of maneuvers are executed by the controller and how it computes them.

**Chapter 4** explains how the AOC algorithm is parametrized. In particular, in this chapter one can find the identification and interpretation of these parameters and some considerations about them as well as their selection.

**Chapter 5** describes the simulations’ architecture considered for the determination of the control parameters, the missions identified for the simulations and the criteria chosen for the selection of the parameters.

**Chapter 6** contains a resume of the report and some conclusions on the control performances.
Chapter 2

Working Environment

This chapter explains the working environment of the internship in order to get to know the company better, its organization, its mission and activities. Besides, the department concerning the internship and the particular service where it was carried out will be described, including the activities, responsibilities and objectives of the organisms that are appropriate.

2.1 About CNES

CNES stands for Centre National d’Etudes Spatiales, which corresponds to the French space agency for space programs and technical center. It is a public, industrial and commercial, scientific and technical institution, which is financially independent. It is responsible for advising the Government, implementing the French space policy, leading, as project owner, the system architecture for innovation and finally, designing new space systems [3].

2.1.1 Mission of the French Space Agency

The principal mission of CNES is to provide an overall vision of space solutions through its systems skills and to innovate. In addition to this, there are other missions, which are:

- To remain attentive to users and their requirements.
- To remain at the crossroads of scientific/technological laboratories, and industrial & service enterprises.
- To stimulate scientific, technological and industrial research and innovation, for institutional and commercial requirements.

2.2 CNES Facilities

There are four centers for complementary vocations. One in Paris Les Halles, corresponding to the headquarters with 186 people. One in Toulouse, more focused on
satellites control and orbital vehicles design and development, with 1762 employees. Another one in Kourou, where the launch base is placed with 276 employees. Finally, the last one is placed in Paris Daumesnil, where all the study, design and development of Ariane, Soyuz and Vega launch systems is carried out. It has 210 employees.

2.2.1 Headquarters

All CNES administrative operations are directed from the CNES headquarters in Paris. It combines all CNES’s functional structures. Administrators at headquarters, together with the overseeing ministries, establish and promote CNES’s policy. They also define strategic guidelines for the agency’s technical centers and its relations with outside partners.

2.2.2 Toulouse Space Center (CST)

The opening of the CST in 1968 was the result of the decentralization of French high-tech industries from the Paris area to the provinces. The CST replaced the former space center at Brtigny-sur-Orge.

At this key site for space research, the center develops complete space systems with its partners in industry and the scientific community, right up to their entry into operational service. The CST is unique in terms of its size and the diversity of its activities.

The CST participates in scientific and instrumentation projects, and leads research and application programs such as Argos, Helios and InSight. It also leads the orbital system Projects (satellites and on-board payloads, ground segments) and satellite station acquisition & keeping operations. It manages the technical policy and preparation of the future as well.

This center develops and executes scientific balloon-borne experiments and ensures the use of data as well as development of innovative applications.

2.2.3 Guiana Space Centre (CSG)

The CSG is dedicated to Europe’s launcher program. It is responsible for the safety of people, property and the environment by delegation of the State. It coordinates all resources needed for launch infrastructures, launcher and payload preparation, control of launch operations and the equipment required for launch. As well, it participates in the construction of new launch units (Ariane 6). The site was chosen in 1967 for its ideal location 5° north of the equator, which is ideal for launching geostationary satellites. It also offers the advantage of its proximity to the Atlantic Ocean and a favorable climate.
2.2.4 Launcher Directorate (DLA)

The Launcher Directorate (DLA), in Paris-Daumesnil, leads all developments of new European launch systems (both launch and ground segments), under contract to the European Space Agency (ESA). The DLA maintains constant supervision of the launcher from production to marketing and launch, through Arianespace. It develops technological demonstrators in order to prepare for future launchers. It also leads the research on new concepts for launchers and advanced propulsion systems.

2.3 Internship Environment

The Toulouse Space center is where the internship has taken place, in particular, into a division of Flight Dynamics Department, that is Space Mechanics. To be more precise, hierarchically one can find:

- The Orbital Systems and Flight Dynamics Department (DSO/DV) that develops and carries out the studies on the space mechanics aspects, such as orbit restitution and resources localization and on the Attitude and Orbit Control System (AOCS). All the phases R&T, phases 0 and A, development phases and operation monitoring are realized in this department.

  - In this department one can find several divisions. One of them is the space Mechanics Systems (MS) division. Its goals are to coordinate the support for space mechanics aspects in a project, to optimize satellite positioning and maintenance strategies for isolated or in-formation satellites, collision avoidance, in-orbit services, interplanetary transfers and guided atmospheric flights.
Chapter 3

Operating principle of the predictive AOC

3.1 AOC specifications

In order to have a predictive AOC that takes orbital perturbation variability (such as the solar activity variation) into account, a second maneuvers horizon has been introduced. In this second horizon the maneuvers can be adjusted in amplitude. To do that, a maneuver plan update is realized at each ascending node crossing. The updating is based on the determination of the needed correction on orbital parameters, in order to keep the ground tracks in a specified window (ΔT is the in-track relative position and ΔW is the out-of-plane relative position).

One of the highlights of the predictive AOC is its generic nature. In fact, in order to have an algorithm that is easily adaptable to different satellites, missions and orbits (the algorithm developed can consider only the Low Earth Orbits), it has been decided to base the AOC on the orbital mechanics physics rather than on the use of a classical controller (i.e. PID controllers). Following, it is shown the set of orbital parameters 3.10 used to describe the satellite dynamics:

\[
\begin{pmatrix}
a \\
e_x = e \cdot \cos(\omega) \\
e_y = e \cdot \sin(\omega) \\
i \\
\Omega \\
\alpha = \omega + \theta
\end{pmatrix}
\] (3.1)

where \( a \) is the semi-major axis, \( e \) is the eccentricity, \( \omega \) is the argument of the periapsis, \( i \) is the inclination, \( \Omega \) is the right ascension of the ascending node, \( \theta \) is the true anomaly and \( \alpha \) is the argument of latitude.

Several constraints have been taken into account, such as the space environment limitations, the mission requirements and some system specifications (such as propulsion system limitations). Moreover, maneuvers are located only within specific time slots that are useless for the mission; this last requirement is related to the incom-
patibility of the mission and the orbital control, and the priority given to the mission.

To realize an efficient orbital control it is necessary to take the orbital perturbations into account such as the effects of solar and lunar gravitation, solar radiation pressure, terrestrial tides and atmospheric drag. Note that the geopotential effects are included inside the reference and guidance orbits models.

3.2 AOC algorithms implementation

To evaluate the performances of the controller, AOC algorithms have been implemented in a particular simulator that simulates the orbital dynamics of the satellite and the on-board navigator (e.g. GPS receiver). The AOC is activated once per orbital period (at each detection of ascending node crossing). The simulator is implemented under the class-based and object-oriented Java language, using the Eclipse IDE (Integrated Development Environment) and the software versioning system SVN. Space dynamics and mathematics libraries are commonly used to code both the AOC algorithms and the orbital dynamics simulator (Figure 3.1).

The spacecraft trajectory is simulated integrating differential equations derived from the orbital perturbation forces modeling. The numerical integration is performed by a multi-step integrator Dormand-Prince (based on the 8th-order Runge-Kutta method).

3.3 Main steps of the predictive AOC

As it has been stated previously, two horizons can be defined for the computation and update of the station-keeping maneuvers: the frozen and semi-frozen horizon. In order to respect the constraints related to the ground tracks windows (tangential and transversal window), another region has been identified, that is the search time zone. The latter one is important because it defines the area, after the two horizons, in which the constraints on the tracks windows are still respected. When one of
them is no longer satisfied, the search time zone ends.

Figure 3.2: Overall predictability horizon [1].

This time line (Figure 3.2), equally spaced, represents the sequence of ascending nodes that the satellite is going to cross (or in other words the number of orbits that the spacecraft is going to travel on). To describe the satellite dynamics, an orbital state vector has to be defined. In order to do that, the first step is to compute the differences ($\Delta e_x$, $\Delta e_y$, $\Delta \Omega$, $\Delta \alpha$) between the guidance parameters (which correspond to the reference orbit parameters) and the measured orbit. These differences together with the computed previous one (stored on-board) allow to compute the derivatives of the differences exploiting the polynomial curve fitting and assuming linear or quadratic trend. One can now identify the orbital state as the state vector composed by the orbital parameters’ differences and their derivatives.

A preliminary initialization step for the AOC is to calculate, at its first activation, the sequence of maneuvers along the whole horizon. To do that it considers just one simple horizon, whose duration is obtained by merging the frozen and semi-frozen horizons. Then, it computes the positions and magnitude of the needed maneuvers (in order to respect the thresholds constraints).

Starting from its second activation, the AOC considers an horizon composed by the previous defined three zones: frozen, semi-frozen and research areas. At each activation it performs an on-board analytical propagation, starting from the current node state, in order to compute the future theoretical state at the realization date of the first semi-frozen maneuver. Using the new state so obtained, the AOC updates the maneuver. The propagation continues for each maneuver that is located in the semi-frozen horizon, and that is going to be, eventually, updated. The velocity updated in this way can be restricted or canceled according to the propulsion system limitations.

Concerning the research zone, the AOC recalculates completely the maneuvers at each AOC activation. In particular, it estimates the date before which a maneuver is needed (in order to respect the thresholds constraints) and, browses through the list of the available maneuvers slots to calculate the optimal maneuver. If the latter one is not located in the first orbit following the semi-frozen horizon, it is discarded and recalculated at the next AOC activation. Moreover, this region is marked out by the end of the semi-frozen horizon and the date of the last feasible maneuver after which the ground tracks windows constraints are no longer respected. Once the AOC have computed this last maneuver, it stops the operating process and it
waits for the next activation.

The AOC is activated at each ascending node crossing and it updates each time the semi-frozen maneuvers and computes a new sequence of maneuvers in the search time zone. Besides, each time that the satellite crosses the ascending node, the two horizons are shifted by one to the right. This means that the semi-frozen maneuvers, so the ones that have frozen data of achievement, will, eventually, pass from the semi-frozen horizon to the frozen one. In the same way, a maneuver that is located in the first orbit of the research zone will have, at the next AOC activation, a frozen date of achievement.

The updating allows to take unexpected orbital parameters variations into account and so it leads to a better station-keeping performance. However, it adds as well an uncertainty for the collision risk computation. That’s why a good compromise between predictability (obtainable with a full frozen horizon) and control performances (realizable with a full semi-frozen horizon) has to be achieved.

3.4 In-plane and out-of-plane controllers

The in-plane and out-of-plane station-keeping are realized by two different controllers. This implies that two kinds of maneuvers, which are semi-major axis and inclination maneuvers, are computed almost independently by the two controllers. The in-plane controller takes the semi-major axis, the argument of latitude and the eccentricity variations into account. In particular, it tries to compensate a semi-major axis decrement by commanding a velocity variation. The out-of-plane controller considers the variations of both the inclination and the right ascension of the ascending node (RAAN). As previously, a modification of the inclination leads the controller to perform a velocity variation command. Since the controller is able to perform one maneuver at the time, the first predicted crossing of the control thresholds ($\Delta\Omega$ or $\Delta\alpha$), determines the maneuver type (semi-major axis or inclination). Depending on the kind of the selected maneuver, the controller will have a different behavior.
3.4.1 Inclination controller

If an inclination control has been chosen, for its computation the AOC will browse through, in reverse chronological order, the list of available slots for inclination maneuver. As soon as a slot including a node is found (ascending or descending), an analytical propagation from the current node state to the maneuver realization date (at the node) is performed. Then, the velocity command is computed to determine the velocity increment or decrement.

The inclination controller analyzes the variations of both inclination and RAAN. In particular, exploiting the natural trend of these two parameters variations (Figure 3.4), it computes and executes a maneuver just before a threshold ($\Delta \Omega_{\text{max}}$ in Figure 3.5) is crossed. As shown in Figure 3.4, the variation of RAAN evolves parabolically at the same time as the secular variation of inclination increases. The slope of the inclination variation is globally determined by geopotential effects and it is locally affected by seasonal events due to the Sun gravitational attraction. The oscillations, instead, are caused by the Moon gravitational attraction.

![Figure 3.4: Natural increment trend of inclination and RAAN variation](image)

![Figure 3.5: Inclination maneuver strategy](image)

It's possible to have the case of decreasing inclination, depending on the orbit.
parametrization; in this case the trend of the RAAN variation will be parabolically concave Figure 3.6).

Once the state at the theoretical maneuver date has been computed it is possible to get the information about $\Delta \Omega_{\text{mes}}$ and $\dot{\Delta} \Omega_{\text{mes}}$. Moreover, selecting a target parabola tangent to $\Delta \Omega_{\text{max}}$, it is possible to compute $\dot{\Delta} \Omega_{\text{COM,INC}}$ as :

$$\dot{\Delta} \Omega_{\text{COM,INC}} = \dot{\Delta} \Omega_{\text{th}} - \dot{\Delta} \Omega_{\text{mes}}$$  \hspace{1cm} (3.2)

Considering now the case of increasing inclination variation, it is possible to distinguish 2 cases:

- if $\dot{\Delta} \Omega_{\text{mes}} > 0$ and $\Delta \Omega_{\text{mes}} > -\Delta \Omega_{\text{max}}$, so in the case presented in Figure 3.5 and Figure 3.7 the command is obtainable by exploiting simple quadratic equations :

$$\dot{\Delta} \Omega_{\text{COM,INC}} = -\sqrt{2\Delta \dot{\Omega}_{\text{th}}} \sqrt{\Delta \Omega_{\text{max}} + \Delta \Omega_{\text{mes}}} - \Delta \Omega_{\text{mes}}$$  \hspace{1cm} (3.3)

where

$$\Delta \dot{\Omega}_{\text{th}} = -\dot{\Omega} \tan(i) \frac{di}{dt_{\text{th}}} \hspace{0.5cm} \text{with} \hspace{0.5cm} \frac{di}{dt_{\text{th}}} = f(\text{perturbations})$$  \hspace{1cm} (3.4)

- if $\dot{\Delta} \Omega_{\text{mes}} < 0$ and $\Delta \Omega_{\text{mes}} < -\Delta \Omega_{\text{max}}$, as shown in Figure 3.8 the following command is obtained:

$$\Delta \Omega_{\text{COM,INC}} = -\Delta \Omega_{\text{mes}}$$  \hspace{1cm} (3.5)

It is possible to find exactly the same cases for both the scenarios of increasing and decreasing inclination variation. Note that the behavior analyzed previously is
Figure 3.7: Graphical RAAN command computation: from the subtraction of the actual measured parabola slope and the theoretical parabola slope one can obtain the command value.

Figure 3.8: Graphical RAAN command computation: from the subtraction of the actual measured parabola slope and the theoretical parabola slope one can obtain the command value.

inverted in case of decreasing inclination.

In order to estimate $\frac{d\dot{\Omega}}{dt_{th}}$, one should understand what is causing this inclination variation. Three sources of perturbations have been identified:

- The third body perturbation, with secular and long-period effects, that is computed using the following equations [4]:

\[
\frac{di}{dt} = \frac{3}{2} \frac{\mu}{n^3} \frac{Z}{\sqrt{1 - e^2}} (\cos \omega (1 + 4e^2)X - \sin \omega (1 - e^2)Y)
\] (3.6)

Where:
- \(X, Y, Z\) are the components of the unit vector directed from the centre of the Earth to the 3rd body in the (P,Q,W) perifocal coordinate system;
- \(d\) is the distance between the centre of the Earth and the 3rd body;
- \(\mu\) is the gravitational constant of the 3rd body;
- \(n\) is the orbit mean motion.

• The atmospheric drag perturbation.

• The terrestrial tides.

The effects of the last two mentioned perturbations is computed by measuring the past of the inclination variation (for this study, the simulator utilizes a backwards numerical propagation to compute the past satellite dynamics) and removing the known third-body effect. The averaged inclination variation so obtained is considered constant for the next half-parabola. Further studies have shown that this assumption has a minimum impact on the AOC method performances.

Once the command has been computed, the variation of velocity necessary to correct the inclination drift is obtained exploiting the standards flight dynamics equations [5] and converting an orbital variation into a velocity variation.

\[
\Delta i = \Delta \Omega_{COM,INC} / k_{\Omega_i}
\] (3.7)

\[
\Delta v = \Delta i \ast v
\] (3.8)

The out-of-plane relative position (\(\Delta W\)) depends on the argument of latitude, semi-major axis, inclination and RAAN variations. However, just the last one of the mentioned variations has an important impact on the \(\Delta W\). In particular one can say that they are almost proportional:

\[
\Delta \Omega \propto \Delta W
\] (3.9)

So, in order to respect the constraint on \(\Delta W\), it is necessary to limit the value of \(\Delta \Omega\) to a constant value \(\Delta \Omega_{max}\).

### 3.4.2 Semi-major axis controller

In case of semi-major axis maneuver need, the AOC will, first of all, decide if the maneuver has to decrease or increase the semi-major axis value. Then, according to an optimal selection criterion that depends on the value of the current eccentricity, it will choose to maximize the correction of eccentricity or to maximize the velocity increment. Therefore, as in the case of inclination controller, it will browse through the list of available slots for semi-major axis maneuvers. For each available slot
within the search period, the AOC will compute a feasible maneuver and it will rate the maneuvers so obtained. The one with the highest score will be finally chosen and executed.

The semi-major axis controller analyzes the variations of both semi-major axis and argument of latitude. In particular, considering the natural trend of the variation of these two parameters (Figure 3.9), it commands a maneuver execution just before a threshold ($\Delta \alpha_{\text{max}}$ in Figure 3.10) is crossed.

Once the state at the maneuver date has been computed it is possible to get the information about $\Delta \alpha_{\text{mes}}$ and $\dot{\Delta} \alpha_{\text{mes}}$. In order to calculate the command
Δα_COM,SMA needed to target a theoretical parabola tangential to the lowest threshold (-Δα_max), it is necessary to distinguish 2 cases:

- if the drift is to the right, as shown in Figure 3.10, ˙Δα mes > 0 and Δα mes > -Δα_max and so the command is obtainable by exploiting simple quadratic equations:

\[
\Delta \Omega_{COM,SMA,UP} = -\sqrt{2\Delta\alpha_{estim}} \sqrt{\Delta\alpha_{max} + \Delta\alpha_{mes}} - \Delta\alpha_{mes}
\]  

where

\[
\Delta\alpha_{estim} = f(\text{perturbations})
\]

represents the accelerations in terms of argument of latitude caused by the perturbations (mainly the atmospheric drag). Since the perturbations effects on Δα are not really predictable, a constant value is chosen.

- if the drift is to the left, so close to the vertex of the parabola, ˙Δα mes < 0 and the following command is obtained:

\[
\Delta \Omega_{COM,SMA,DOWN} = -\Delta\alpha_{mes}
\]  

With this command it is possible to avoid to cross the lowest threshold but it produces an overconsumption (naturally, the semi-major axis decreases, so a command that reduces the semi-major axis could be avoided).

Once the command has been computed, the velocity variation ΔV needed to correct the semi-major axis drift is obtained from exploiting the standards flight dynamics equations [5] and converting an orbital variation into a velocity increment/decrement.

\[
\Delta a = \Delta\alpha_{COM,SMA} / k_{\alpha,a} - k_{\alpha,i} \Delta i / k_{\alpha,a}
\]

\[
\Delta v = \Delta a / 2a \times v
\]

The variation of the semi-major axis, and consequently of the argument of latitude, has a direct impact on the control box thresholds:

\[
\frac{\Delta T}{a} = 2 (\Delta ex \times \sin(\alpha) - \Delta ey \times \cos(\alpha)) + \Delta \Omega \times \cos(i) + \Delta \alpha
\]

The value of ΔT, that represents the in-plane track difference expressed in local orbital frame (TNW frame), is fixed and has to be respected for a good station-keeping.

From the equation 3.15 it is possible to compute the max value of Δα achievable, after which the control box constraints are no longer respected. Since the values of eccentricity, inclination and semi-major axis vary, the Δα_{max} is dynamic. Moreover, as shown in equation [3.15], the in-track relative position ΔT depends also on the RAAN variation and as explained in the previous subsection, the value of ΔΩ is fixed and equal to ΔW.
Chapter 4

Definition of the AOC parameters

The AOC algorithm utilizes several parameters that need to be set. Some of them are related to the control box thresholds ($\Delta T$ and $\Delta W$) and depend on the satellite mission. Others are related to the control configuration. Once the satellite mission has been selected, the thresholds parameters will be set and it will be necessary to find the optimal values for the control ones.

4.1 Control parameters

As previously stated, a collection of control parameters has to be set. Among them, it is possible to distinguish two types: the horizons parameters and the control margins.

4.1.1 Horizons parameters

The AOC computes and executes maneuvers all along the horizon. In this horizon it is possible to identify three zones: frozen and semi-frozen horizon and the research zone. The length of the latter one depends on the date of the last feasible maneuver after which the ground tracks windows constraints are no longer respected. Concerning the frozen and semi-frozen horizon, there is no definition for their length (it is possible to talk about length or corresponding number of frozen and semi-frozen orbits). To achieve good AOC performances, a compromise for the couple of horizons lengths has to be identified. From now on, these parameters will be called:

- $n_{\text{orb}, \text{fr}}$
- $n_{\text{orb}, \text{semi-fr}}$

4.1.2 Control margins

It is possible to distinguish two kinds of control margins:

- the ones related to the command computation and therefore to the theoretical parabola;
• the other ones that trigger a maneuver need (associated to the real parabola).

In the first group, one can find $\Delta \alpha_{tg_{parab}}$ and $\Delta \Omega_{tg_{parab}}$.

As previously explained, the commands $\Delta \Omega$ and $\Delta \alpha$ are computed by the controllers in order to match a target parabola. This parabola is tangent to an horizontal line that can be identified thanks to these two parameters (Figure 4.1 and Figure 4.2). Estimated from equations 3.15 and 3.9 these parameters are actually margins since they represent a percentage of $\Delta T$ and $\Delta W$. As result, they identify a parabola whose size is always smaller than the one that it is possible to get utilizing $\Delta \alpha_{max}$ and $\Delta \Omega_{max}$. In this way, if a solar activity variation changes the satellite dynamics, the AOC will still be able to respect the control thresholds. Therefore, these parameters have been introduced in order to avoid maneuvering.

In the second group, it is possible to define other three parameters: $\Delta \alpha_{up\_limit}$, $\Delta \alpha_{down\_limit}$ and $\Delta \Omega_{limit}$.

They trigger a maneuver need and represent a percentage of the $\Delta T$ or $\Delta W$ thresholds. Estimated from equations 3.15 and 3.9 they identify a "maneuver need line": if the real (or measured) parabola crosses it, a maneuver is executed (Figure 4.1 and Figure 4.2).

Resuming, 5 control margins have to be set:

<table>
<thead>
<tr>
<th>Physical Interpretation</th>
<th>$\Delta \alpha_{tg_{parab}}$</th>
<th>$\Delta \Omega_{tg_{parab}}$</th>
<th>$\Delta \alpha_{up_limit}$</th>
<th>$\Delta \alpha_{down_limit}$</th>
<th>$\Delta \Omega_{limit}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>%$\Delta T$</td>
<td>%$\Delta W$</td>
<td>1 - %$\Delta T$</td>
<td>1 - %$\Delta T$</td>
<td>1 - %$\Delta W$</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.1: Control margins for the semi-major axis controller
4.2 Considerations

Some considerations about these parameters:

- An optimal compromise for the horizons lengths has to be achieved. However, if the control box thresholds are respected without taking into considerations the semi-frozen horizon, its size will be considered zero. In this way a better predictability can be achieved.

- If the satellite orbit has an altitude up to 800 km (therefore a Low Earth Orbit (LEO) with an high altitude orbit), the $\Delta \alpha_{tg\_parab}$ will have an high value ($\approx 1$), due to the lower atmospheric drag that induces lower semi-major axis variation. This means that this margin will not have a great importance for the control.

- Since the maneuver that decreases the semi-major axis ($\Delta a_{down}$) corresponds to an overconsumption, it will be important, in order to optimize the control, to avoid, as much as possible, its computation and execution. The best way to avoid these kinds of maneuvers is to reduce the value of $\Delta \alpha_{tg\_parab}$, in order to decrease the probability to have a crossing of the limit line margin $\Delta \alpha_{down\_limit}$ that trigger a maneuver need.

- Considering the definition of $\Delta \alpha_{tg\_parab}$ and $\Delta \alpha_{down\_limit}$, the following condition can easily be deduced: $\Delta \alpha_{tg\_parab} < (1 - \Delta \alpha_{down\_limit})$

- A low value of $\Delta \alpha_{up\_limit}$, $\Delta \alpha_{down\_limit}$ and $\Delta \Omega_{down\_limit}$ will reduce the frequency of maneuvers by increasing the time between the maneuver needs.
• Considering the LEO with a high altitude orbit, it is possible to notice that the maneuvers to decrement the semi-major axis cannot be avoided due to the propulsion system limitations.

• All these parameters have been introduced in the AOC algorithm in order to take the uncertainty of the solar activity variation and the errors caused by some approximations and hypotheses into consideration.
Chapter 5

Simulation campaign

A simulation campaign has been realized in order to identify the optimal values for the control parameters. Since the parameters strongly depend on the mission altitude, a collection of missions will be considered. The simulation campaign has been performed by exploiting the CNES computer cluster, that represents a group of independent servers interconnected through a dedicated network to work as one centralized data processing resource. Clusters are capable of performing multiple complex instructions by distributing workload across all connected servers. That’s why its utilization has been indispensable to reduce the computational time and to run simultaneous simulations. Several Shell scripts have been created for the realization of the simulation campaign with the computer cluster.

5.1 Simulation Architecture

First of all, the choice of the horizons duration has to be made. In fact for each couple of \((\text{nb}_{\text{orb, fr}}, \text{nb}_{\text{orb, semi, fr}})\) it is possible to determine several sequences of control margins values that lead to different dynamic behavior. The steps identified for the simulations are shown in Figure 5.1.

From the scheme in Figure 5.1 one can easily understand that the number of simulations grows exponentially. This could cause data storage problems, but most of all, a time computation problem. That’s why, a simulation strategy is necessary. First of all, it has been decided to focus the attention on a total horizon duration of about 24 hours; that are all the couples \((\text{nb}_{\text{orb, fr}}, \text{nb}_{\text{orb, semi, fr}})\), with a total orbits number corresponding to a 24 hours duration. Then, an initialization sequence of simulations is running with the specific following sizes couple:

\[
\text{nb}_{\text{orb, fr}} = \text{nb}_{\text{max, orb, 24h}} \quad \text{and} \quad \text{nb}_{\text{orb, semi, fr}} = 0 \quad (5.1)
\]

That is to say, the semi-frozen horizon is not considered. If a solution that respects the thresholds constraints can be achieved with this setting, the others couples are not going to be tested since the solution without semi-frozen horizon allows to have a better predictability.
Another step to reduce the simulations number consists in considering the independence of the control margins. In this way, it is possible to fix four of five parameters and so to run a sequence of simulations in which the only changing value is one control margin. Once an "optimal" value for this margin has been found, it will be fixed and stocked and another sequence of simulations will be ran, with the variation of just one control margin. In this way, it will be possible to have, after five sequences of simulations, an array of "optimal" values for the control margins. The number of simulations for each sequence of simulations it depends on the range of values that one wants to test.

The values obtained in this way are not literally optimal. In fact, it is important to understand that each value has a physical interpretation that has to be considered (Table 4.1 and Figure 4.1, Figure 4.2). For example, the value $\Delta \alpha_{\text{up limit}}$ should not be large since it represents the limit maneuver line, so large value corresponds to large number of maneuver (overconsumption). The same applies to the other $\Delta \alpha_{\text{down limit}}$ and $\Delta \Omega_{\text{lim}}$ values. It will be the opposite for the $\Delta \alpha_{\text{tg parab}}$ and $\Delta \Omega_{\text{tg parab}}$ since they represent a percentage of the thresholds $\Delta T$ and $\Delta W$.

### 5.2 Selected Missions for simulations

In order to consider different scenarios and so different environments and satellite behaviors, a collection of space missions has been selected for the simulations (the values of altitude and inclination are approximated):
Table 5.1: Control Margins

<table>
<thead>
<tr>
<th>Name</th>
<th>Scientific Aim</th>
<th>Altit.</th>
<th>Inclin.</th>
<th>LT</th>
<th>Sol. activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission A1</td>
<td>Constellation Obs.</td>
<td>470 km</td>
<td>SSO</td>
<td>10:30</td>
<td>High</td>
</tr>
<tr>
<td>Mission A2</td>
<td>Constellation Obs.</td>
<td>470 km</td>
<td>SSO</td>
<td>10:30</td>
<td>Medium</td>
</tr>
<tr>
<td>Mission B1</td>
<td>Optical/Radar Imaging</td>
<td>700 km</td>
<td>SSO</td>
<td>10:30</td>
<td>High</td>
</tr>
<tr>
<td>Mission B2</td>
<td>Radar Imaging</td>
<td>700 km</td>
<td>SSO</td>
<td>06:00</td>
<td>High</td>
</tr>
<tr>
<td>Mission C</td>
<td>Earth Observation</td>
<td>700 km</td>
<td>10°</td>
<td>-</td>
<td>High</td>
</tr>
<tr>
<td>Mission D1</td>
<td>Scientific environment</td>
<td>800 km</td>
<td>SSO</td>
<td>22:00</td>
<td>Low</td>
</tr>
<tr>
<td>Mission D2</td>
<td>Scientific environment</td>
<td>800 km</td>
<td>SSO</td>
<td>22:00</td>
<td>High</td>
</tr>
<tr>
<td>Mission E</td>
<td>Telecom</td>
<td>1200 km</td>
<td>90°</td>
<td>-</td>
<td>High</td>
</tr>
<tr>
<td>Mission F</td>
<td>Altimetry</td>
<td>1300 km</td>
<td>65°</td>
<td>-</td>
<td>High</td>
</tr>
</tbody>
</table>

where SSO means Sun synchronous Orbit and LT is the local time. For each mission, an available maneuver slots set is defined taking into account the mission specificity.

5.3 Strategy for control parameters choice

For each control margin, a collection of values is tested. Therefore, with a sequence of simulations (number of simulations equal to the number of values tested) it is possible to determine the optimal value for one control margin.

In order to decide which value is the optimal one, a set of criteria has been considered, based on the minimization of the maneuvers consumptions and the number of thrusts. In particular, a focus is given on the maneuvers that decrease the semi-major axis ($\Delta a_{down}$). In this way, rating the different tested values according to these criteria, it has been possible to select the optimal one.

It is important to remember that these values have, first of all, to respect the thresholds requirements and also to minimize the maneuvers consumption. Furthermore, the station-keeping windows requirement expresses an availability for the mission realization. The constraints are defined as a proportion of the satellite presence inside the thresholds windows.

For each mission, the satellite dynamics has been simulated for a period of 365 days in order to take into account seasonal effects and statistics analysis. In addition to these simulations, complementary runs over a two years period has been performed in order to confirm and validate the parameters choice. In this way the solar activity variation is going to be more diverse allowing to have enough data to analyze the AOC behavior.
Chapter 6
Control parameters choice

In this chapter the results of the simulation campaign are discussed. For each mission, the variation of the semi-major axis, inclination, argument of latitude, RAAN and the trend of the ground track relative positions, along a period of 365 days, are analyzed. Moreover, the solar activity flux is shown in order to explain some variation peaks in the previously mentioned trends.

In the following figures, one can note in red the real variation trend along the orbits, in blue the value of the variation at the ascending node and in green the maneuver point.

6.1 Mission B1

The first analyzed mission is B1. The control parameters values, obtained as simulations results, are shown in table 6.1 (horizon total duration of about 24 hours):

<table>
<thead>
<tr>
<th>nb_{orb,fr}</th>
<th>nb_{orb,semi,fr}</th>
<th>\Delta T_{up,margin}</th>
<th>\Delta T_{down,margin}</th>
<th>\Delta W_{margin}</th>
<th>\Delta \alpha_{margin}</th>
<th>\Delta \Omega_{margin}</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0</td>
<td>0.1</td>
<td>0.15</td>
<td>0.05</td>
<td>0.5</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Figure 6.1: Evolution of the semi-major axis variations Mission B1
One can easily compare the trends of Figures 6.1, 6.3, 6.2, 6.4 with the ones analyzed before in Figure 3.9 and Figure 3.6. As shown in Figure 6.5 and Figure 6.6, the AOC allows to respect quite well the thresholds constraints $\Delta T_{\text{max}}$ and $\Delta W_{\text{max}}$. Observing the solar activity variation
Figure 6.5: Evolution of the in-plane ground track variations Mission B1

Figure 6.6: Evolution of the out-of-plane ground track variations Mission B1

Figure 6.7: Solar activity Mission B1
in Figure 6.7, from days (180 to 200) one can see that the solar activity varies continuously and this leads to a not optimal control. In fact, one can note in Figure 6.2 that the parabolas targeted by the controller are limited in size; this causes an increment of the number of maneuvers.

### 6.1.1 Choice Validation

As stated in the previous chapter, to validate the parameters choice, a two years simulation has to be analyzed.

![Evolution of the in-plane and out-of-plane ground track variations](image)

As shown in Figure 6.8, the constraints are still respected and so the parameters choice is validated.
6.2 Mission B2

The second analyzed mission is B2. The control parameters values, obtained as simulations results, are shown in table 6.2 (horizon total duration of about 24 hours):

### Table 6.2: Control Margins Mission B2

<table>
<thead>
<tr>
<th>nb_{orb,fr}</th>
<th>nb_{orb,semi,fr}</th>
<th>∆T_{up,margin}</th>
<th>∆T_{down,margin}</th>
<th>∆W_{margin}</th>
<th>∆α_{margin}</th>
<th>∆Ω_{margin}</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0</td>
<td>0.05</td>
<td>0.1</td>
<td>0.15</td>
<td>0.5</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Figure 6.9: Solar activity Mission B1 for two years simulation.

Figure 6.10: Evolution of the semi-major axis variations Mission B2
Figure 6.11: Evolution of the argument of latitude variations Mission B2

Figure 6.12: Evolution of the inclination variations Mission B2

Figure 6.13: Evolution of the RAAN variations Mission B2
Figure 6.14: Evolution of the in-plane ground track variations Mission B2

Figure 6.15: Evolution of the out-of-plane ground track variations Mission B2

Figure 6.16: Solar activity Mission B2
For this mission, it is possible to observe the irregular behavior of the inclination variation in Figure 6.12. In fact, the inclination variation slope is very low and some variations are induced by phenomena not completely analyzed. The low slope does not allow the control of RAAN drift by inclination correction and requires to had direct RAAN correction. This specific case has been analyzed at the end of the internship, therefore its resolution has not been achieved.

6.2.1 Choice Validation

No choice validation has been realized for this mission since the results obtained with one year simulation show a satellite dynamics that is not reliable.

6.3 Mission D1

The analyzed mission is now D1. The control parameters values, obtained as simulations results, are shown in table 6.3 (horizon total duration of about 24 hours):

<table>
<thead>
<tr>
<th>nb_{orb,fr}</th>
<th>nb_{orb,semi fray}</th>
<th>\Delta T_{up margin}</th>
<th>\Delta T_{down margin}</th>
<th>\Delta W_{margin}</th>
<th>\Delta \alpha_{margin}</th>
<th>\Delta \Omega_{margin}</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>0</td>
<td>0.15</td>
<td>0.1</td>
<td>0.2</td>
<td>0.8</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Figure 6.17: Evolution of the semi-major axis variations Mission D1

The mission D1 has an high altitude orbit (it is still a LEO). This means that the effects of the atmospheric drag are really low. Consequently, the variation of the solar activity does not impact the control as for the previous missions. It is so possible to relax some control margins and still obtain an optimal behavior.
Figure 6.18: Evolution of the argument of latitude variations Mission D1

Figure 6.19: Evolution of the inclination variations Mission D1

Figure 6.20: Evolution of the RAAN variations Mission D1
Figure 6.21: Evolution of the in-plane ground track variations Mission D1

Figure 6.22: Evolution of the out-of-plane ground track variations Mission D1

Figure 6.23: Solar activity Mission D1
6.3.1 Choice Validation

In order to validate the collection of parameters selected, a two years simulation is analyzed.

![Evolution of the in-plane and out-of-plane ground track variations](image)

Figure 6.24: Evolution of the in-plane and out-of-plane ground tracks variations Mission D1 for two years simulation.

The trends obtained are completely acceptable as well as the number and the magnitude of the $\Delta a_{\text{down}}$ maneuvers.
6.4 Mission D2

The analyzed mission is now D2. The control parameters values, obtained as simulations results, are shown in table 6.4 (horizon total duration of about 24 hours):

Table 6.4: Control Margins Mission D2

<table>
<thead>
<tr>
<th>nb_{orb,fr}</th>
<th>nb_{orb,semi,fr}</th>
<th>( \Delta T_{up,margin} )</th>
<th>( \Delta T_{down,margin} )</th>
<th>( \Delta W_{margin} )</th>
<th>( \Delta \alpha_{margin} )</th>
<th>( \Delta \Omega_{margin} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>0</td>
<td>0.1</td>
<td>0.15</td>
<td>0.2</td>
<td>0.8</td>
<td>0.8</td>
</tr>
</tbody>
</table>

One can observe in Figure 6.30 a peak between days (100 - 120). Looking at Figure 6.28 and 6.29, it is possible to notice that an inclination maneuver is executed.
Figure 6.27: Evolution of the argument of latitude variations Mission D2

Figure 6.28: Evolution of the inclination variations Mission D2

Figure 6.29: Evolution of the RAAN variations Mission D2
Figure 6.30: Evolution of the in-plane ground track variations Mission D2

Figure 6.31: Evolution of the out-of-plane ground track variations Mission D2

Figure 6.32: Solar activity Mission D2
The AOC cannot, until now, perform several maneuvers on the same orbit. This means that, if a need of semi-major axis and inclination maneuver is detected, just one of them will be performed. In this case, the need of an out-of-plane maneuver excludes the possibility of a semi-major axis correction and so it causes the cross of the in-plane threshold.

### 6.4.1 Choice Validation

A validation simulation is now performed in order to verify the sequence of parameters selected previously.

![Evolution of the in-plane ground track variations](image1)

![Evolution of the out-of-plane ground track variations](image2)

Figure 6.33: Evolution of the in-plane and out-of-plane ground tracks variations Mission D2 for two years simulation.

The simulation results show that the parameters chosen previously allow to respect the constraints thresholds with a minimum maneuver consumption.
6.5 Mission F

The last analyzed mission is now F. The control parameters values, obtained as simulations results, are shown in table 6.5 (horizon total duration of about 24 hours):

Table 6.5: Control Margins Mission F

<table>
<thead>
<tr>
<th>nb_{orb,fr}</th>
<th>nb_{orb,semi,fr}</th>
<th>ΔT_{up,margin}</th>
<th>ΔT_{down,margin}</th>
<th>ΔW_{margin}</th>
<th>Δα_{margin}</th>
<th>ΔΩ_{margin}</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>0</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.4</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Figure 6.35: Evolution of the semi-major axis variations Mission F
Figure 6.36: Evolution of the argument of latitude variations Mission F

Figure 6.37: Evolution of the inclination variations Mission F

Figure 6.38: Evolution of the RAAN variations Mission F
Figure 6.39: Evolution of the in-plane ground track variations Mission F

Figure 6.40: Evolution of the out-of-plane ground track variations Mission F

Figure 6.41: Solar activity Mission F
The behavior obtained in this case is similar to the one analyzed for the mission B2. Therefore an inclination controller improvement has been identified. As previously, the trend observed in Figure 6.37 is not comparable to the one analyzed in Figure 3.6, where a constant decreasing behavior can be easily described. Since no physical explanation has been achieved for this phenomena, a more deeply analysis of the controller inclination in the AOC algorithm has to be realized.

6.5.1 Choice Validation

No choice validation has been realized for this mission since the results obtained with one year simulation show a satellite dynamics that is not reliable.

6.6 Simulations results for other missions

The missions A1, A2, C and E are not analyzed in this report. In fact, no optimal solution has been found for them. In particular, for an horizon duration of about 24 hours, none of the couple \((n_{\text{orb},fr}, n_{\text{orb},\text{semi},fr})\) satisfies the thresholds constraints. The problem for the missions A1 and A2 is related to the low value of the altitude orbit. In this case, in fact, the variation of the solar activity (or the atmospheric drag) is large and does not allow the AOC to predict very well the maneuvers need. Instead, concerning the mission C and E, the problem is related to the inclination value. In fact, the inclination variation is caused mostly by the effects of the geopotential perturbation. The mission C and E are respectively almost equatorial and polar; the orbits so described are not subjected to an high geopotential perturbation and this provokes, in some way, a problem for the inclination controller.
Chapter 7

Conclusions

This report has described and analyzed the possibility of using a predictive Autonomous Control Orbit, in the future, for limiting the ground-based workload and guaranteeing a perfect and optimal station-keeping.

The predictive behavior of the AOC allows taking collision risks into account. For that, a frozen horizon has been considered. Moreover, in order to improve the AOC performances, a semi-frozen horizon has been introduced, allowing to take into account the strong and unpredictable perturbations variations such as the solar activity variability.

Two types of controllers have been described: the inclination and semi-major axis controllers that are based on an orbital state vector.

In order to compute the command to target a $\Delta\alpha$ and $\Delta\Omega$ parabola, control margins have been introduced.

In the AOC algorithm it is possible to find several parameters whose values are not fixed. In order to select the values for all the control parameters, several simulations have been performed.

According to maneuver minimization criteria, the parameters values have been chosen for several representative missions, and the obtained satellite behaviors have been analyzed.

To validate the choices for the control margins values, a two years simulation has been considered and evaluated. The simulations’ results have shown and confirmed a good control performance. However, this conclusion is not general. In fact, depending on the kind of orbit considered for the mission, it is possible to describe different control behaviors. Further work is then necessary in order to improve the inclination controller. Moreover, a solution with an electrical propulsion system has been considered and almost implemented. Therefore, the realization of another sequence of simulations for this different propulsion system should be completed and analyzed.
Bibliography


