Politecnico di Torino

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Master's Degree in Aerospace Engineering

Master's Degree Thesis

Space Based Air Traffic Management Concepts Mission Analysis & Differential Air Drag Controller Design and Development

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Federico Covitti

Daejeon, November 12, 2019

Summary

The aim of this study is to show and underline the effective capabilities of the Cubesats platform, nowadays even more used over the pure scientific-purpose demonstration. The Air traffic management is actually one among the most studied sector in the aeronautic field, to lead to an even more safe ambience. According to international agencies guidelines, there is the will to standardize protocols to make the flight transportation, the safest way to move around the world.

Consequently, a lot of rules and laws have been made, for instance by International Civil Aviation Organization, ICAO, to provide the maximum of the safety possible. Among the recent standards adopted, the members states of the ICAO proposed the adoption of a new 15 min aircraft tracking gap allowed, this both to reduce the so-called “safety-bubbles” used in the route planning, and then reducing the fuel cost, optimizing the paths, and also to reduce the search-and-rescue bottleneck that a lack of tracking would lead to.

Unfortunately, in some areas of the world, this standard actually cannot be accomplished, due to the impossibility to provide adequate infrastructure. IE, North Alaskan and oceanic zones. On the other hand, some recent mission like as GOMX, operated by GomSpace ApS, demonstrated the feasibility to use the ADS-B Rx/Tx in space, leading to the possibility to use optimized constellation of small satellites in low Earth orbit, to receive signals from aircraft and relay it to ground station.

Under this general objective, the purpose of the thesis has been to study some Orbit Design to optimize design variables like: constellation type, number of

satellites, orbital parameters, according to constraint as Area of interest, simulated air traffic and receiver characteristic.

Not only, to better understand the Cubesat Constellation capabilities, one other concept has been studied in deep: the Differential Air Drag control. The Cubesats platforms are nowadays among the most cheap and reliable options for several kind of purposes. On the other hand, their reduced size lead to some constraint, like a reduced control capabilities, especially regarding the orbit control, while the Attitude is, in general, well granted by several system, especially in Low Earth Orbit.

A new concept to provide orbit control, without the requirement of huge *Delta-V* capability onboard but that rely on the ability of our spacecraft to change its attitude relatively easily, is the Air Differential Drag control, which main idea is quite simple. Indeed, offering different Cross-Area to the velocity direction, we are able to change the orbit degradation time, modifying the relative speed between two units in our constellation without the use of any kind of fuel.

An algorithm in Matlab has been developed, to study at first the effective possibility to use this concept to phase our satellites in a reasonable amount of time without a too excessive orbit degradation and at second to provide the control profile, through the time spent in each drag profile, high or low.

In conclusion, starting from data obtained from several past researches, including ones focused on cubesat capability to receive ADS-B signal, as well as similar researches on the possibility to use nanosatellite constellation to improve the ATM situation, we derived a set of feasible constellation, together with a control concept able to spread our satellites along the orbit chosen, almost consumption-free.

Acknowledgment

And I would like to acknowledge the AGI System Tool Kit team, for the help and the availability they showed me, providing all the licenses and the support needed to achieve the goals of our research.

I would like to dedicate this thesis to my loving parents to thanks them to have believed in me since the beginning..

.. to the ones, friends and not, who I met along the road, to teach me the world is various and never boring..

.. to my professors, Italians and not, whom strongly and passionately transmitted me their love for the subject and for the space, especially Prof.ssa Battipede and 교송님방효충..

.. and to the life, to the fate, to mine determination, to let me be where I am.

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1. Introduction

Cubesat Capabilities are nowadays increasing and increasing, opening to new challenges and possibilities in this sector, behind the pure educational and technology demonstration purposes. With an increasing number of even cheaper launch possibilities and the privatization of the space sector, is becoming easier to enter the space economy with multi satellite missions that are becoming possible thanks to the nanosatellite.

Some examples could be found in *imaging and distributed sensing sector,* like, as an example, *atmospheric sampling and distributed antennas missions* [1]. "*Missions with multiple small satellites can deliver a comparable or greater mission capability [..] with enhanced flexibility and robustness to the fault"* since, by instance, the loss of one satellite in the constellation almost never lead to the mission failure.

Small satellites could be categorized according to their weight, starting from femto satellites, to picosatellites, ending with nanosatellites, among which the most famous and used nowadays are the CubeSats. This thanks to the standardization of their features and, accordingly, of the deployment system, that opens the door to more frequent and cheap launch windows as a secondary payload.

One other classification is more related to the mission and discern between *Formation Flying and Constellation* missions, with or without control for the latter and with or without docking for the first type.

The definition rely upon the possibility, for the FF missions' satellites, to track at least one other satellite in the formation and base its own controller law on the state of the other, while with the constellation, even if indeed each satellite is supposed to be distributed in a specific pattern in respect to the others, them could be easily controlled independently.

1.1 Cubesat Constellation Review

Helping us with the article mentioned in [1], here we would like to present a couple of examples of how nanosatellites possibilities and missions are spreading in different fields, like planetary/earth science, astro and helio physics and finally, technology demonstration.

As for the Earth Science related mission, we could mention three different cases, that put-on light the differences between the missions that could be accomplished. We can indeed find DICE mission (*Dynamic Ionosphere CubeSat Experiment)* able, using two 1.5U cubesats provided with *different probes,* to measure electric field and plasma densities. These Satellites are not able to perform control position.

On the contrary we could find very interesting concepts in the Flock Constellation from PlanetLabs. This consist in more than 100 3U CubeSats, which aim is to provide daily complete earth imaging, while providing position control through an innovative control scheme that use Differential Air Drag between spacecraft to phase them, changing their Cross-Sectional Area modifying attitude or by opening and closing their solar panels, without any consumption of fuel onboard; indeed we will explore this possibility in depth later. A part of these satellites was already put on orbit, through several launches, proving the ADC capabilities.

One other idea we would like to name is the *OLFAR (Orbiting Low Frequency Antennas for Radio Astronomy)* mission concept, led by Delft University of Technology. This aim to deploy a swarm constellation of 50–1000 nanosatellites for radio astronomy in the operational band of 0.3–30 MHz. "*Because of the opaqueness of the ionosphere to low-frequency radio waves, the frequency band below 30 MHz is one of the last unexplored frequency ranges in radio astronomy.*

Each satellite will host an astronomical antenna of 5.0 m size, which will consist of three orthogonal dipoles" [1]

There are, moreover, a very big number of others currently operating missions, or concepts, interesting to understand the variety of objectives nanosatellite could accomplish, but to mention all of them is not among the purpose of this paper.

Here we would like to mention only one more, from the JPL, that is actually studying the possibility to deploy a constellation of Cubesats around Mars in order to study "*the frequency, geographical distribution and severity of electrical activity with a sensors orders of magnitude less sensitive if compared to the Earth-Based ones*" thanks to their proximity to Mars [1]. Not at all, them could be used to help and improve the communication between the ground station on earth and other approaching vehicles to Mars, that are actually losing their real-time connection, during the descent. A similar mission was accomplished by Marco-A and B that proved the capability for small satellites to really reach the Mars atmosphere and help the control and communication of their "bigger brothers" descending on the surface.

1.2 Cubesat Possibilities Review

We already talked about and focused on the huge world of possibilities that nanosatellites are providing. Among these we explored a bit among which ones that could be actually useful but also economically "acceptable" with some sort of return.

With the increasing privatization of this sector is becoming more and more important the "return" of the missions, in terms of saleability to the market, to make the investors choose our concepts and provide what needed to implement them.

We mentioned indeed the *Flock Constellation* which, providing daily and accurate imaging of the whole earth, thanks also to the proximity of the satellites used to image to the earth itself, is able to sell these images to whoever could need them, for earth and meteorological studies, as an example. Moreover, with similar approaches of the flock ones, we could think about the possibility of providing *Disaster Monitoring,* to agencies or nations, by designing orbit which let the satellites focus on particular zones in the world, or just worldwide. Other scientific purposes, like the deep-space wave study, could lead to the possibility of get over the ionosphere in order to better study the phenomena we nowadays could not study properly from the earth surface, due to ionospheric effects and interferences.

Finally, ATM sector is becoming more and more crucial, due to an increasingly growing air traffic scenario. In this, is becoming crucial to track each flight for safety and economic reasons. While regulations are increasing, in order to standardize the aeronautical sector, providing, as an example, maintenance rules or instruction for the proper construction of every single plane. In add, the safety equipment is well regulated as well, with new Eurocontrol, FAA and ICAO regulations that make mandatory the installation of the ADS-B equipment on every high performance aircraft, by instance, or indicating a maximum of 15 minutes of gap, between the reception by the ground stations of the flight status of every single commercial flight.

1.2.1 Future ATM Concepts

In a scenario with an incredibly increasing number of flight every year, is becoming critical to provide real-time tracking and control, not only for safety reason. In fact, in some areas of the world, like Alaska and oceans zones, the flights are scheduled since the beginning, in a non-optimal pathway to avoid collision and safely manage their routes. This is needed since in oceans and Alaska regions there are no possibilities to provide infrastructures capable of monitor continuously the flights, in Alaska especially due to geographical constraints.

Nowadays the Automatic Dependent Surveillance (ADS) is the primary method used to detect airplane states, over the classical radar system. It is a communication system, provided with different protocol, like ADS-B, *Broadcast,* and C, *Contract.* It is intended to provide the most important data, including aircraft position and velocity as determined thanks to the GPS system, that are consequently periodically transmitted, without any human intervention, to others planes in the area or, especially, to the ground stations receivers, able to re-broadcast the data. Unfortunately, this is not possible over "*remote oceans or sparsely populated regions such as Alaska or the Pacific Ocean"*. [6]

This leads to a lack of real-time aircraft information's reception, leading to both the need to use "*safety bubbles"*, larger "safety box" around each aircraft until them reach radar-controlled zones, and, also, to search-and-rescue issues.

At this point the aim of this paper is to study a constellation useful to improve this situation, helping the route management, saving big quantity of money and fuel, and making better the general situation of the Air Traffic Management.

The use of satellite communication could be actually the only way to relay aircraft signals in remote and oceanic areas [6].

At the time of the writing the use of a space ADS-B communication was proved different times by single spacecraft, like *ProbaV,* the first carrying an ADS-B transponder. Most interesting for our purposes would be the GOMX-1, from *Denmark's Gomspace ApS,* a 2U CubeSat which was able to get more than 3.5 million frames before the ADS-B payload stopped to work after 6 months of operational time. Nowadays, approximately 70% of the current commercial aircraft fleet is ADS-B, even if this number means 20% of general aviation; that is why EUROCONTROL and FAA have recently imposed that ADS-B has to be a compulsory equipment on all high performance aircraft before 2020, while ICAO new requirements aim to reduce the maximum gap between every contact with each flights to 15 minutes. These will be the drivers for our constellation design, since is obvious that more than one satellite will be needed to guarantee continuous tracking of every selected areas.

"A fully deployed constellation will allow significant reduction in inter airplane spacing, reduce fuel consumption (and emissions) with informed optimization of routes, reduce flight time, and increase usable airspace leading to a predicted 16-fold increase in transoceanic flights [8]. Nav Canada has reported the reduction of required "safety bubbles" from 60x80 statute miles to 5x5 statute miles over the Hudson Bay, leading to predicted annual fuel savings of $9.8 million/year [8]. ADS-B has been demonstrated (in simulation) to aid collision avoidance planning using dynamic programming [9] and can be used to support Traffic Alert and Collision Avoidance Systems (TCAS)". [6]

1.2.2 Differential Air Drag Controller Concept

The drastic burst of Cubesats into the space scene, open the doors to huge world of new possibilities, improving flexibility and reliability of the space missions, reducing the whole cost, developing, manufacturing and launch costs included. Nevertheless, everything has a price. Indeed, even if is true that the exploit of COTS components and the increasingly miniaturization of parts, hardware and processors, let Cubesat to be capable of accomplish tasks in past only achievable by enormous tons-weighted Satellite, we still have to deal with some restriction that the size bring with it. First of all, the reduced amount of space usable to store a tank, and consequently fuel to allow propulsion.

Indeed, all the first generations of Cubesats were generally lacking of onboard propulsion, aiming just to test components or to accomplish educational purposes. Indeed, "*adding propulsion to these satellites could have been undertaking in terms of engineering, cost and regulations*" [3] To design more sophisticated missions and scenarios it would be surely present the need of control our spacecraft, and in recent days, this problem is becoming more and more studied, in research field, while the Attitude Determination and Control capabilities have already been proved in depth. A lot of micro propulsion devices have been studied and designed recently, as discussed in Chapter 4, but still, unfortunately, due to the reduced amount of fuel a Cubesat could bring with itself, the delta velocity is not enough to allow big orbital maneuver, like inclination changes but only to provide, in lucky cases, constellation keeping. That is why, not only we should focus on the propulsion technology to find new way to provide bigger impulse, with reduced-in-size devices, but, also, we should try to design innovative method to achieve the orbital maneuver we could eventually need.

According to [5], some interesting ideas use some natural effects to achieve the payload distribution we would need to accomplish our mission objectives. As a quick example, especially in LEO, the non-spherical geopotential of the Earth, create a precession motion in every spacecraft with an inclination different from 90°. This effect cannot be escaped, without the use of some sort of engines, but could be used as an advantage since, according to the following formula, the orbital plane will rotate at a certain rate:

$$\dot{\Omega}_{J_2} = -\frac{3}{2}\frac{R_E^2}{\left(a(1-e^2)\right)^2} J_2 \, n \cos i$$

Where Ω is the *Right ascension of the Ascending node,* and consequently this represent its precessing rate.

Indeed, acting on the parameters present in the equation, we could exploit the differential rate of nodal precession to spread in RAAN our orbital planes. This strategy lead to a drifting time required to deploy our constellation, that could be considerable if we would not be able to properly provide considerable differences in altitude, especially at the high inclination we will need to accomplish our mission aims.

In this paper, however, we strongly focused on one other concept to provide orbit control without propulsion, regarding not the out-of-plane maneuver, but the in-plane spreading, between our satellites, the Differential Drag Method.

Using this method to achieve required in-plane separation, we would use active attitude control methods and deployable surfaces to modify the cross sectional area of our satellite, leading to different force acting on the satellite itself and consequently modifying semi-major axis and velocity. This changes, if combined between the satellites within our constellation, could lead to the possibility to separate (or cluster) them, without any fuel requirements.

In fact, actuating changing the Ballistic Coefficient, would lead to drag characteristics changes of our space objects and consequently to differential semimajor axis degradation rates. The lower the satellite, the faster it would be, allowing the spreading with the others satellites in the constellation, left in low-drag profile, then at higher altitude and lower speed. This concept has been studied since is first proposal for station keeping using drag plates in 1989, passing through the introduction of the J2 perturbation and solar radiation pressure effects. As well as several types of controllers have been used to create trajectories or study the collision avoidance problem until recently several missions finally demonstrated the practical use of differential drag on-orbit control, like AeroCube-4 or Flock from PlanetLabs.

2. Mission Planning & Analysis

A crucial phase for every space mission is the so-called Pre-phase A, or phase Zero; in this phase, the feasibility of the mission is studied and the very first concepts design are provided, to properly verify them.

Indeed, is crucial to properly plan the mission, studying the orbital parameters needed to achieve the mission main aims, at least. Moreover, is at the same level crucial to introduce various alternatives to make the decision-maker able to choose between several possibilities according to the investment needed and on the weights of every aspect of the mission itself.

In this section accordingly, we will provide some well-designed mission based on our aims, in order to verify the feasibility, also according to the delta velocity required and in order to compare them.

2.1 STK Simulations

To verify the feasibility of our mission, we decided to use the great capabilities of *Satellite Tool Kit by AGI Technologies,* which provide several useful features, like several propagators and, most important for our purposes, accesses computation between sensors, satellites and airplanes included.

2.1.1 Model Creation

To getting started, we decided to import all among the most important airports in the Alaska region, to starting study the coverage of this particular area. Regarding the aircrafts we tried to use both FACET, a simulation software from NASA, or DAFIF files. Unfortunately, both these files were made inaccessible for the public some years ago. Then we ended up deciding to randomize an overestimated number of flights between the airports we introduced, to be conservative.

About the constellation design drivers, we assumed to use *Walker Constellation,* in other words, constellations composed of several planes, precessing at the same velocity, and with the spacecraft equally spaced along each orbit. This because according to [6], it will provide the *"most uniform continuous coverage of Alaska with the least number of satellites"*. Even if usually multiple launches are required to initiate walker constellation, since plane changes of this entity could require up to 10 *km/s* , we could think about use nodal precession effect to spread in RAAN, while the separation within the same plane can be achieved through both propulsion or by atmospheric drag, using satellite attitude, the way we choose.

Finally, according to our design driver like as area of interest, simulated air traffic and receiver characteristic, we will work on design variables like constellation type, number of satellite and orbital parameter (focusing on altitude and inclination). For the first one, we restricted the range for the altitude between 500 km ad 700 km respectively because under the lower margin, the operational lifetime would be extremely low, without any propulsion to maintain the orbit, while on the other hand, altitude too high will lead to a double issue. The natural degradation orbit time would be more than 25 years, requiring again onboard propulsion according to regulations, while at the same time, it will lower the quality of the signal. We should remember that the ADS-B is still designed to provide an 80NM range of signal, then that already around 500 km of altitude, high sensitive sensors will be required. Of course, the best choice would be to use higher altitude to ensure a full coverage of both aircrafts and ground stations, if it were not for that we have to deal with the signal power and integrity.

To choose the starting orbital parameter we decided the altitude according to the constraints we talked about, while for the inclination we assumed that the 90° one would be the best one to ensure a global coverage. On the other hand, at that inclination, we would not be able to exploit the nodal precession effect to spread our orbital planes in RAAN, saving in multiple launches.

	inclination	*Altitude*	*# Sats*
Walker 90 - 8 - 600	*90°*	*600 km*	*8 - 16*
Walker 90 - 9 - 500	*90°*	*500 km*	*9 - 18*
Walker 70 - 8 - 600	*70°*	*600 km*	*8 - 16*
Walker3 70 - 8 - 600	*70°*	*600 km*	*8 - 24*

2.1.2 Alaskan Coverage

At first, we decided to compute the access of several constellation proposal, between the constellations themselves and the lowest airport in Alaska. This because it will clearly be the most difficult point to contact, as showed in the next two pictures. Here we used a *Coverage Features,* that allowed us to compute the *Time Average Gap* for each Alaska's zones, with each one of the configuration chosen. Here we reported just two of them, since the results are similar: they show an extremely more high Time Average Gap in zones like *Alaska 8, 6, 9,* that represent the lower parts of the Alaska itself, the most low in latitude islands. As long as the "lowest" part of the Alaska will be the most difficult to cover, this will mean that to grant the access with the most southern airport of the country will mean to grant the access to the whole country.

FOM Properties

Time Average Gap FOM
Satisfaction: Less Than 900.000000 sec
FOM value range check is not enabled.

Region Name	Num Accesses	Minimum (sec)	Maximum (sec)	Average (sec)
Alaska_8	187	133.489	133.489	133.489
Alaska_9	184	193.012	193.012	193.012
Alaska_7	188	107.177	107.177	107.177
Alaska_6	196	37.342	65.838	55.723
Alaska_4	199	28.055	37.726	32.891
Alaska_5	0	0.000	0.000	0.000
Alaska_3	203	23.348	28.287	25.499
Alaska_31	202	23.041	23.041	23.041
Alaska_25	210	14.423	25.274	18.703
Alaska	417	0.000	25.436	1.625
Alaska_30	201	21.103	21.103	21.103
Alaska_29	204	21.291	21.291	21.291
Alaska_28	209	15.808	21.681	17.593
Alaska_26	211	13.689	14.910	14.300
Alaska_27	209	14.171	14.171	14.171
Alaska_21	215	10.286	15.810	13.552
Alaska_23	213	10.844	10.844	10.844
Alaska_18	218	9.265	12.316	10.701
Alaska_24	210	14.991	14.991	14.991
Alaska_20	215	12.231	12.940	12.483
Alaska_22	214	11.501	11.501	11.501
Alaska_17	228	6.584	13.295	9.454
Alaska_19	215	10.650	10.650	10.650
Alaska_14	229	5.724	10.274	8.554
Alaska_16	228	6.304	9.142	7.798
Alaska_13	228	7.557	7.893	7.725
Alaska_15	0	0.000	0.000	0.000
Alaska_2	248	3.668	5.075	4.388
Alaska_12	243	4.282	4.282	4.282
Alaska_11	0	0.000	0.000	0.000
Alaska_1	0	0.000	0.000	0.000

Figure 1 - Time Average Gap, Constellation 90 - 9 - 600 _ 2 Planes

We decided to report as results here the access graph for one day, in which the upper and the lower half represent the two different orbital planes. Is obvious then that, removing one of the two planes, we would have a lack of coverage of hours.

Moreover, we utilized the great capabilities of System Tool Kit, to compute some coverage Figures of Merit, like the percentage of Alaska covered by our constellation, and the percentage of the satisfaction of the criteria, *Revisit Time* less than 15 minutes.

To do this, we modeled our system with the 24 most important Alaskan airport, as reported in the figure:

Aniak_Airport_AK
Bethel_Airport_AK
Deadhorse_Airport_AK
Dillingham_Airport_AK
Edward_G_Pitka_Sr_Airport_AK
Fairbanks_International_Airport_AK
Homer_Airport_AK
Juneau_International_Airport_AK
Kenai_Municipal_Airport_AK
Ketchikan_International_Airport_AK
King_Salmon_Airport_AK
Kodiak_Airport_AK
Lake_Hood_Seaplane_Base_Airport_AK
Merle_K_Mudhole_Smith_Airport_AK
Merrill_Field_Dr_Anchorage_AK_99501_United_States
Nome_Airport_AK
Petersburg_James_A_Johnson_Airport_AK
Ralph_Wien_Memorial_Airport_AK
Sitka_Rocky_Gutierrez_Airport_AK
St_Mary_s_Airport_AK
Ted_Stevens_Anchorage_International_Airport_AK
Unalakleet_Airport_AK
Unalaska_Airport_AK
Valdez_Pioneer_Field_Airport_AK
Wiley_Post_Will_Rogers_Memorial_AK
Wrangell_Airport_AK
Yakutat_Airport_AK

Figure 2 - Most Important Alaskan Airports

Later, we defined a Coverage Definition creating a grid which covered every Alaskan dryland, attaching to it a Figure of Merit, through which estimate the quality of the coverage.

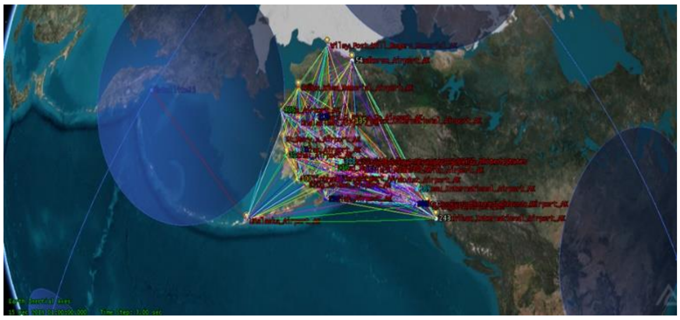


Figure 3 - Alaska Model and Simulated Air Traffic

Finally, utilizing MatLab, we simulated an overestimated Air Traffic, that linked all the airports around the country.

Walker 90 - 8 - 500

At first, we decided to utilize the constellation with the lowest altitude to grant a good Quality Factor for our link, even if this will lead to a reduced operational lifetime. Here the graph for the constellation so-called *Walker90-8-500,* with an inclination of 90°, 500 km of altitude and 8 Satellites per plane. We will be able to appreciate the coverage that lack for just minutes more than the 15 minutes of gap suggested by ICAO. In order, we will report per each configurations, the *Graph Access* between the Constellation and the Southern Alaska's Airport, as mentioned in the introduction of this chapter, the *Simple Coverage* of the interested Area, the *Percentage of Satisfaction* of the ICAO criteria, of a *Time Maximum Gap* inferior to 15 minutes, represented by the Revisit Time of the routes.

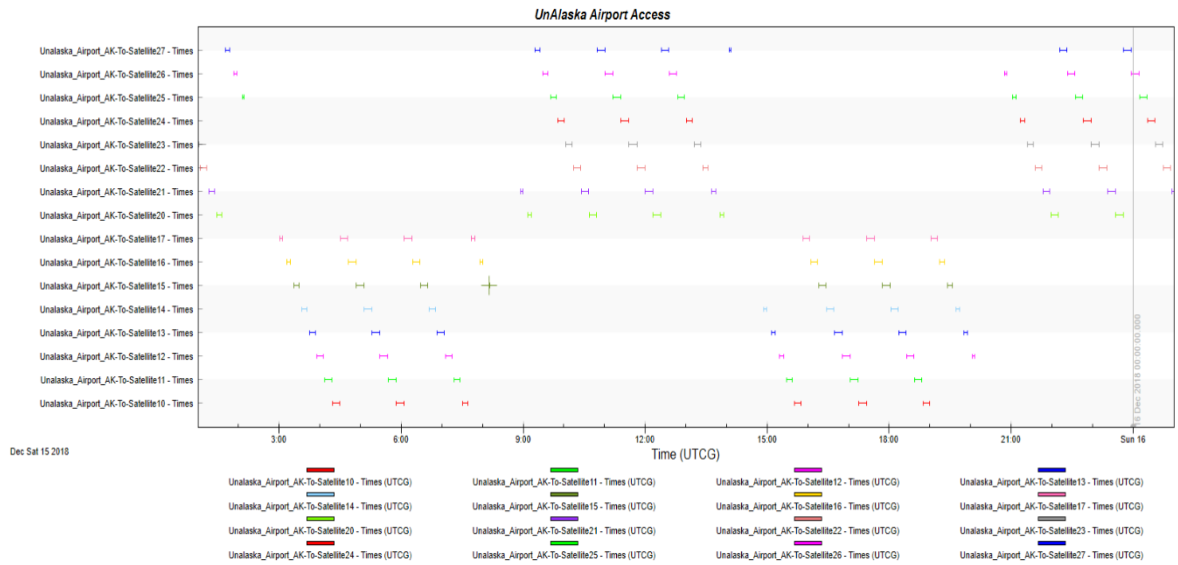


Figure 5 - 90-8-500 Unalaska Airport Accesses

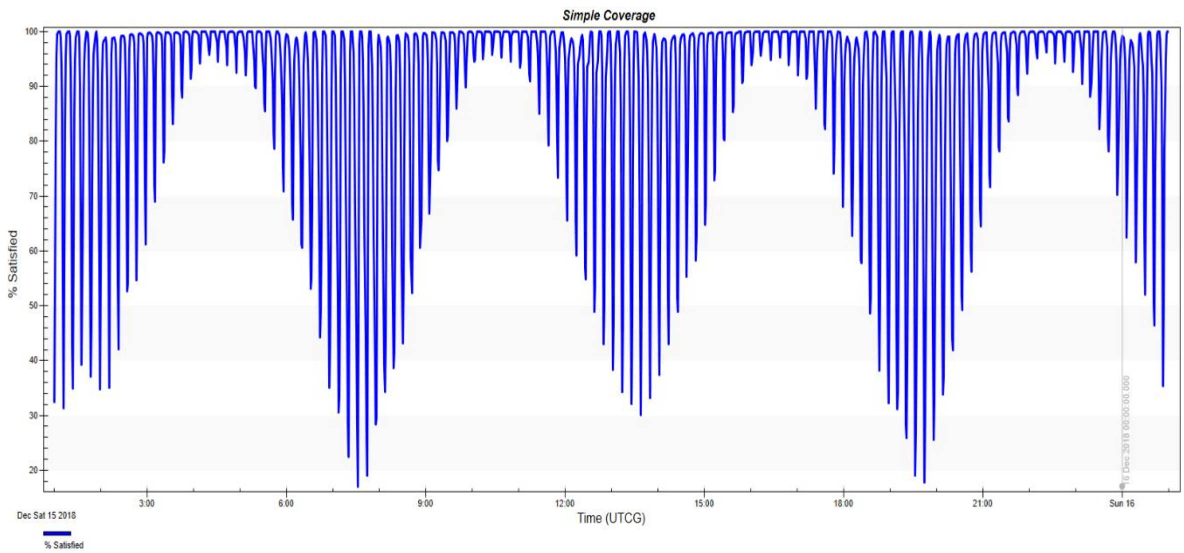


Figure 4 - 90-8-500 Simple Coverage

Even if the quality of the coverage seems to be quite good, we can observe that at certain times, there is a gap in coverage definitely longer than the 15 minutes suggested by the new ICAO regulation, indeed this configuration is not acceptable. This behavior is well represented also by the *Simple Coverage Graph,* that shows how the coverage drop under the 30% periodically.

Walker 90 - 9 - 500

To fill the gap at this altitude we tried to raise the number of satellites per each plane to 9, unfortunately some gap within the passage of the Area of Interest from one plane to one other, are still present and bigger in time than 15 minutes.

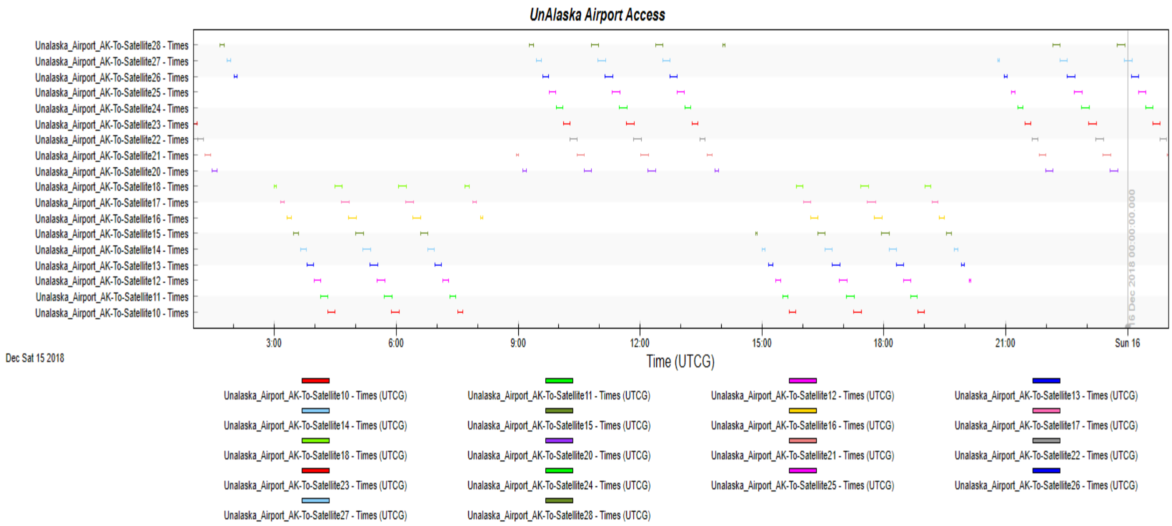


Figure 6 - 90-9-500 Unalaska Airport Accesses

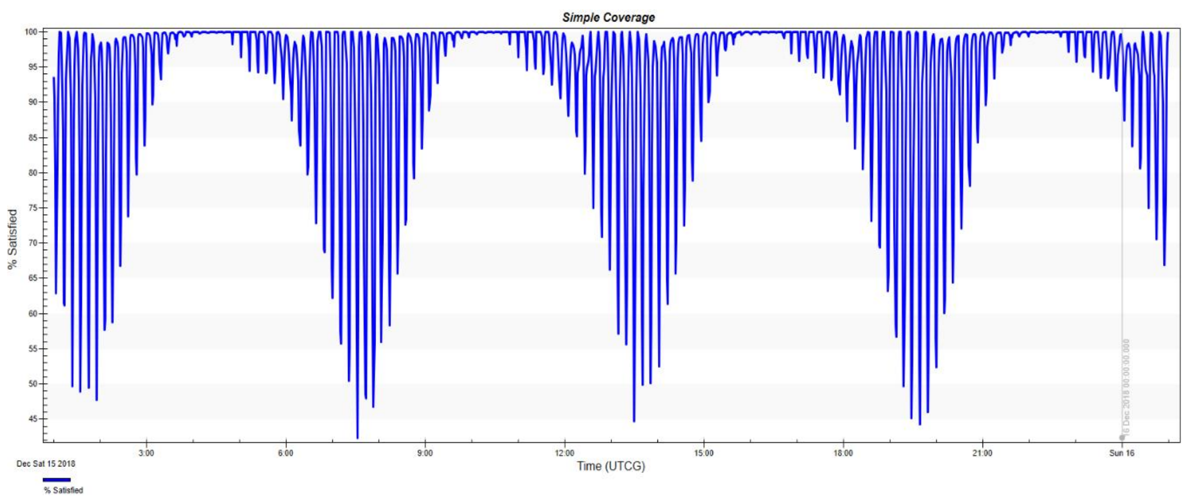


Figure 7 - 90-9-500 Simple Coverage

Even if the coverage seems to be improved, and the gaps between every access with the southern airport are reduced, we are still far from the ICAO suggestion. Moreover the Simple Coverage Graph, has a similar behavior to the previous, but we should notice that now the lowest point is 40 % and not 20 % anymore, but still unacceptable. One other useful graph could be the number of accesses between the Constellation and the Fleet. Even if is decreasing behavior is justified by the progressive arrival of flights to their destination, the drops in the graph show the missing of connection at certain times.

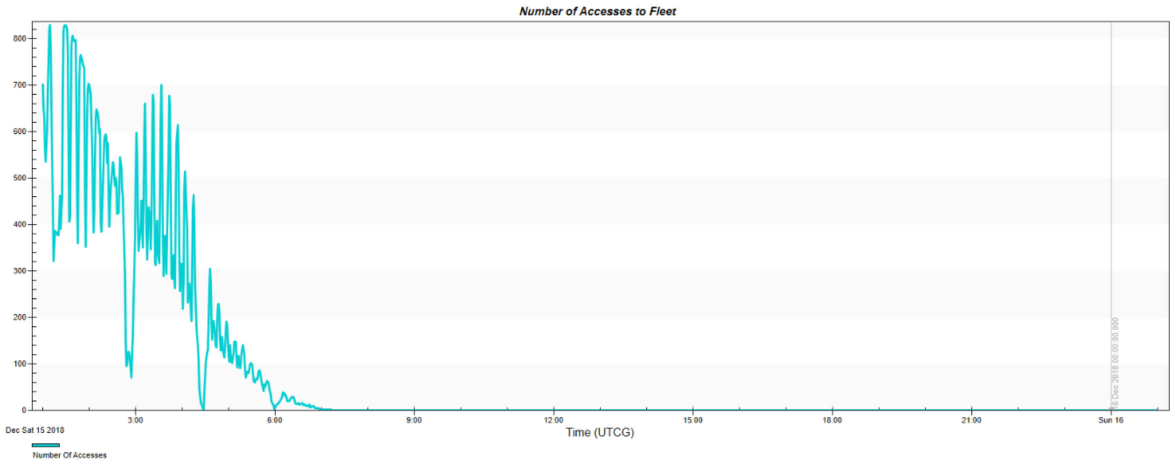


Figure 8 – 90-9-500 Constellation Number of Accesses

Walker 90 - 8 - 600

Here the graph for the constellation so-called *Walker90-8-600,* with an inclination of 90°, 600 km of altitude and 8 Satellites per plane. We will be able to appreciate the almost continuous coverage that lack very rarely for just some minutes more than the 15 minutes of gap suggested by ICAO. Again we will report the *Graph Access* between the Constellation and the Southern Alaska's Airport, the *Simple Coverage* of the interested Area, the *Percentage of Satisfaction* of the ICAO criteria, of a *Time Maximum Gap* inferior to 15 minutes, represented by the Revisit Time of the routes.

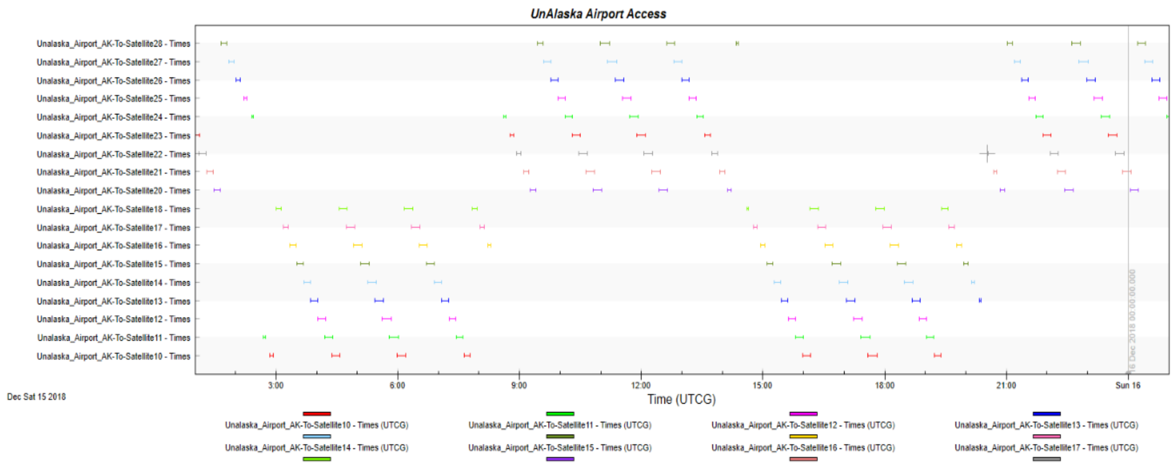


Figure 9 - 90-8-600 Unalaska Airport Accesses

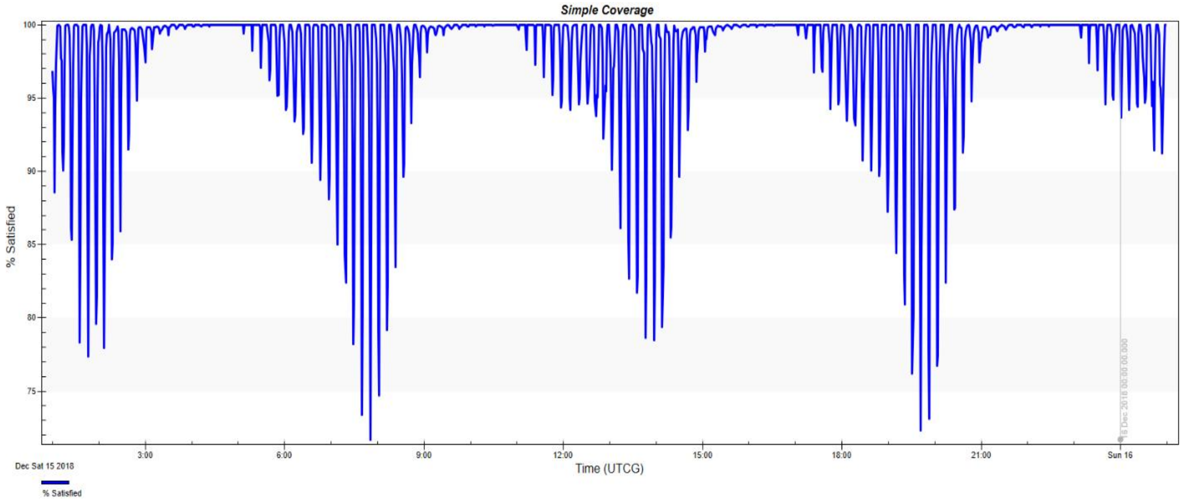


Figure 10 - 90-8-600 Simple Coverage

The simple coverage, together with the reduced amount and length of gaps in the previous graph, shows clearly how 100 km of altitude, improved the quality a lot. Now, the lowest peak, is around 70 %, even if still with the same trend of the previous constellation, since type and inclination have not been changed. In the next report we will appreciate the percentage of satisfaction of the ICAO criteria, around the 100 %.

```
                FOM Properties
-----------------------------------------------
Maximum Revisit Time
Minimum number of assets required: 1
Gaps at ends of analysis interval are considered
Satisfaction: Less Than 900.000000 sec
FOM value range check is not enabled.


% Satisfied    Area Satisfied (km^2)
-----------    ---------------------
      99.73               1481384.95
```

Figure 11 – 90-8-600 Criteria Satisfaction

Walker 90 - 9 - 600

Here we tried to improve the coverage of the previous design adding a satellite per each plane*,* with an inclination of 90°, 600 km of altitude. Also, in this case, there are few lack longer than 15 minutes, very remotely. A way to improve this would surely be to add an additional plane, but the less of 1% improvement could be not worth the cost.

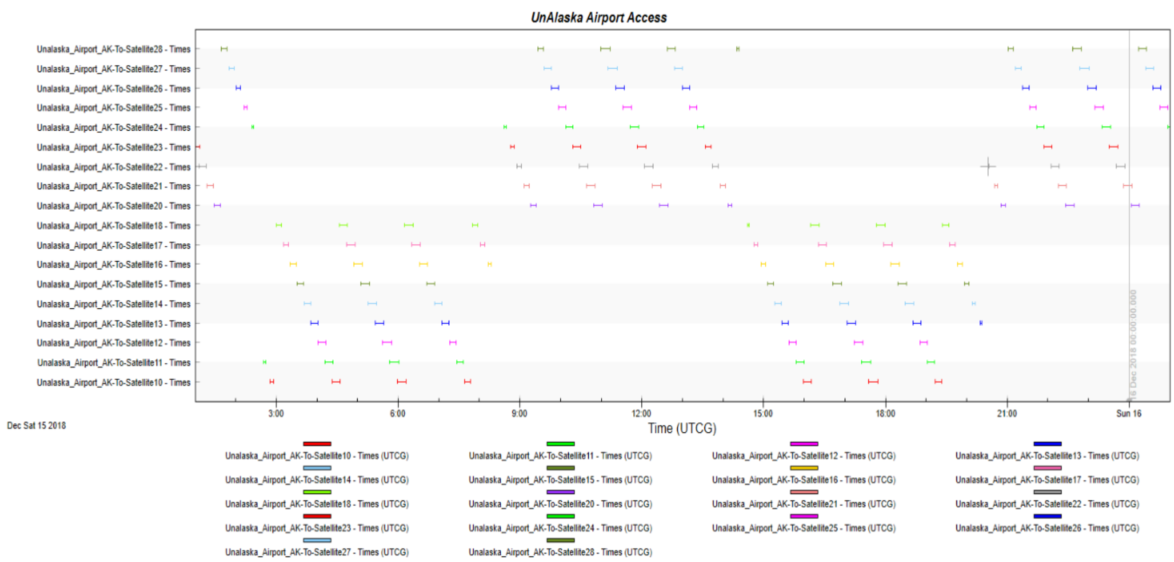


Figure 12 – 90-9-600 UnAlaska Airport Access

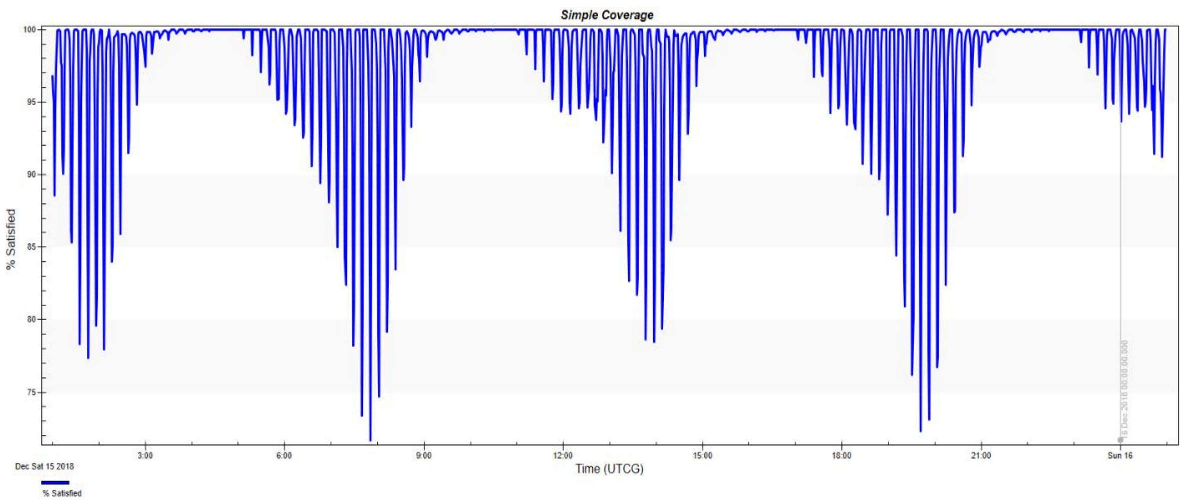


Figure 13 - 90-9-600 Simple Coverage

```
                 FOM Properties
------------------------------------------------
Maximum Revisit Time
Minimum number of assets required: 1
Gaps at ends of analysis interval are considered
Satisfaction: Less Than 900.000000 sec
FOM value range check is not enabled.

% Satisfied    Area Satisfied (km^2)
-----------    ---------------------
      99.73               1481384.95
```

Figure 14 – 90-9-600 Criteria Satisfaction

Walker 70 - 8 - 600

At this point we decide to take care about the mission initialization. Then to better utilize the nodal precession effect to spread our spacecraft in RAAN, we could think about reduce the inclination, still keeping it relatively high, to guarantee the coverage of such northern zones like Alaska. Using an inclination of 70°, an altitude difference of just around 300 km could allow a 90° RAAN spread in less than 6 months. Nevertheless, think about increase the inclination during the mission is out of our possibilities, since none of the onboard propulsion available for nanosatellite would be able to guarantee the delta-v required for an inclination change.

Here the coverage in time, of the new inclined constellation:

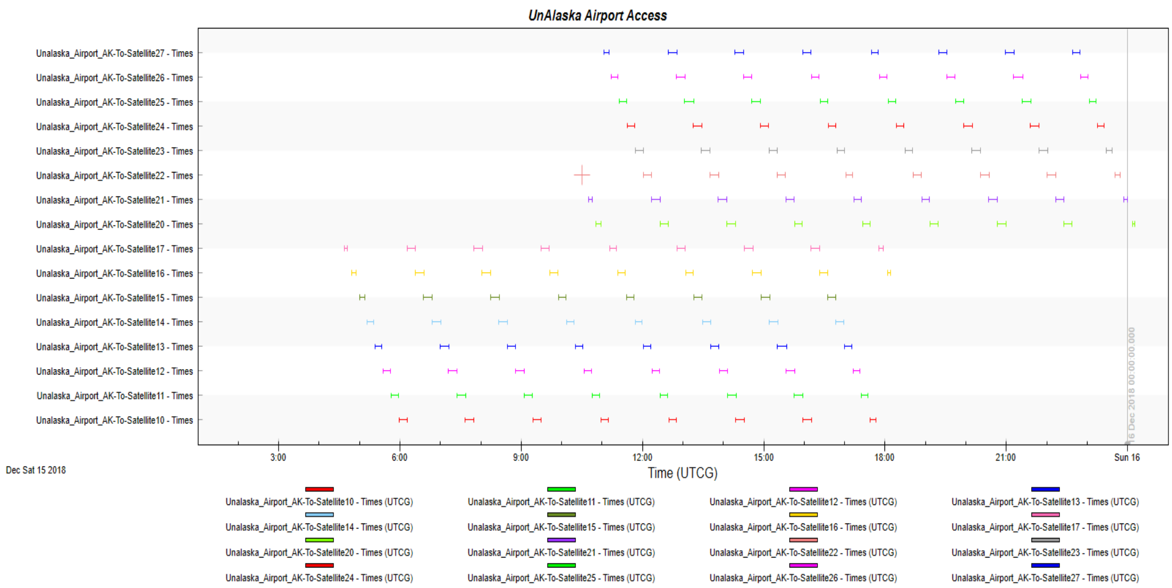


Figure 15 - 70-8-600 Unalaska Airport Accesses

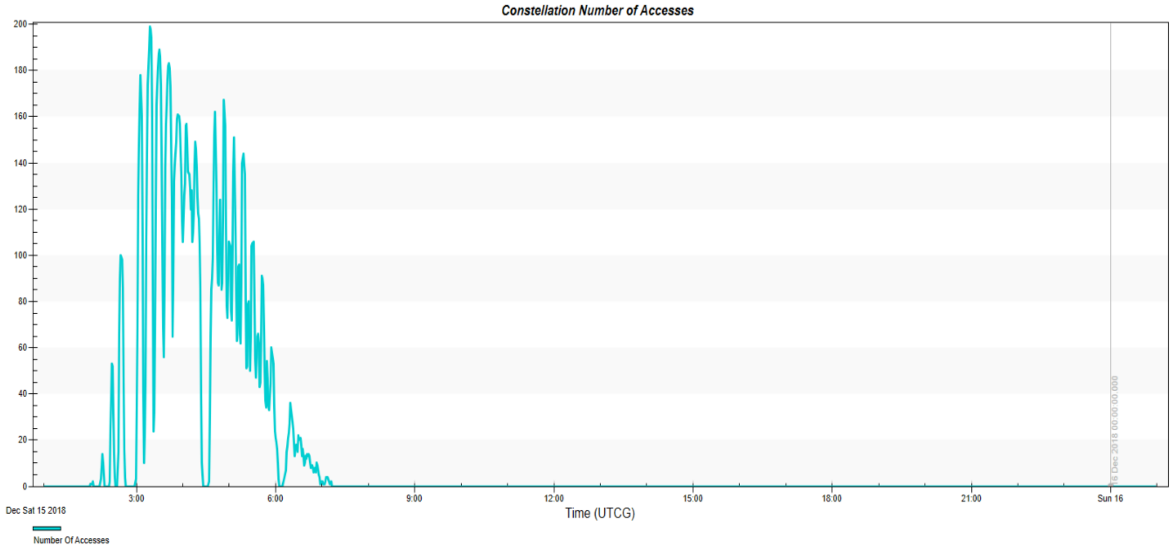


Figure 16 - 70-8-600 Number of Accesses to Fleet

Even if it looks like the coverage now is perfect, with no gaps at all, the very beginning of the graph shows how in certain periods there is no coverage at all. This is due to change in the inclination: indeed this lead to a better coverage in that time of the day while the Alaska lies under the crossing zone between the orbit plane, while on the opposite side, the coverage is not guaranteed due to the enlargement of the space between the two orbits.

This problem could be easily solved using three orbital planes instead, while adding further spacecraft does not help at all. The inability for this Constellation to fulfill the aims of our mission is further proved by the Simple Coverage graph and by the satisfaction Criteria that follow:

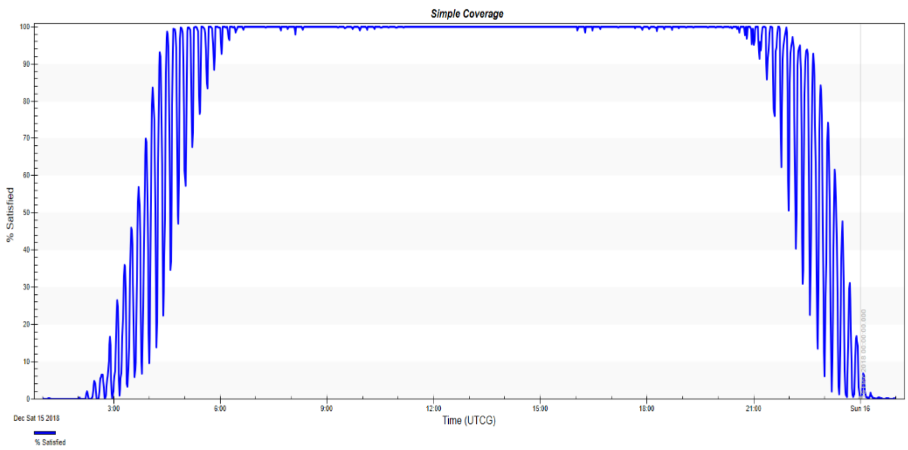


Figure 17 - 70-8-600 Simple Coverage

```
                FOM Properties
-------------------------------------------------
Maximum Revisit Time
Minimum number of assets required: 1
Gaps at ends of analysis interval are considered
Satisfaction: Less Than 900.000000 sec
FOM value range check is not enabled.

% Satisfied    Area Satisfied (km^2)
-----------    ---------------------
       0.00                     0.00
```

Figure 18 - 70-8-600 Criteria Satisfaction

Walker3 70 - 8 - 600

In this case we fixed the problem that came up in the last example, adding an additional plane. Of course, now the coverage is complete with no gap at all, for no time. On the other hand, this costed us the deployment of 8 additional satellites in one additional plane. What we should think about is that we made this inclination change to save on propulsion / multiple launches to deploy our 2 planes constellation. If launcher dispositive like Sherpa, will be concretely able to deploy 8 additional satellites at an altitude of 300 km more than the main orbit deployment, it should be worthy to save on the cost of a second launch. Otherwise, deciding to use multiple launches, two as an example, we could come back to 90° inclination possibility, that guarantee an optimal coverage, utilizing 8 satellite less.

Moreover, a 3 planes constellation, should be able to guarantee the full coverage on oceanic zones as well, providing, essentially a world-wide coverage. We will focus on this later.

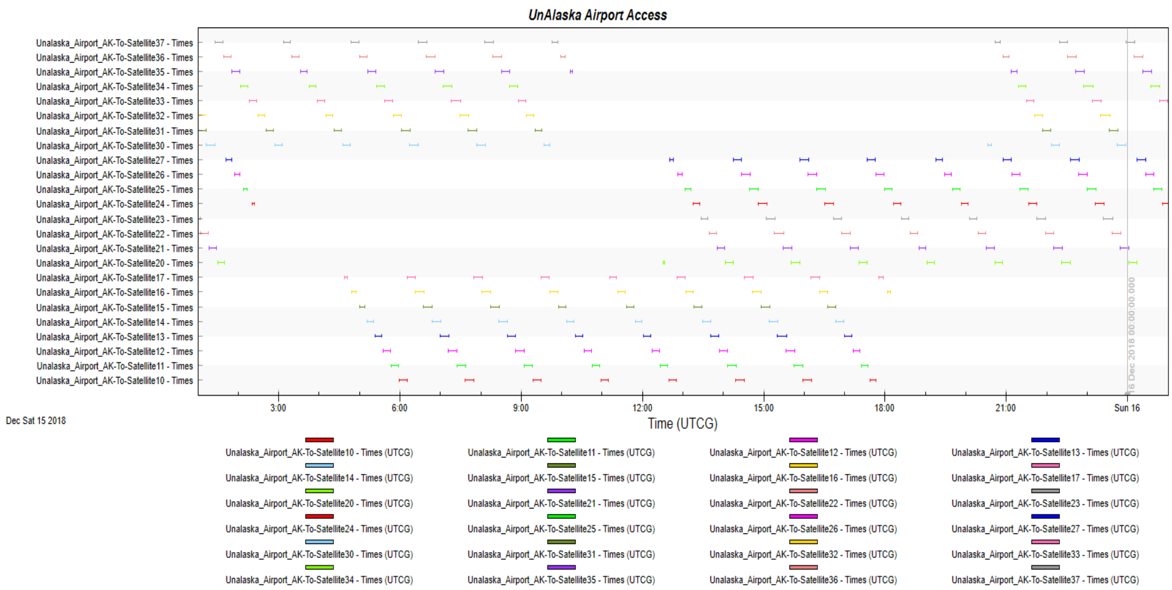


Figure 19 - 70-8-600 Unalaska Airport Accesses

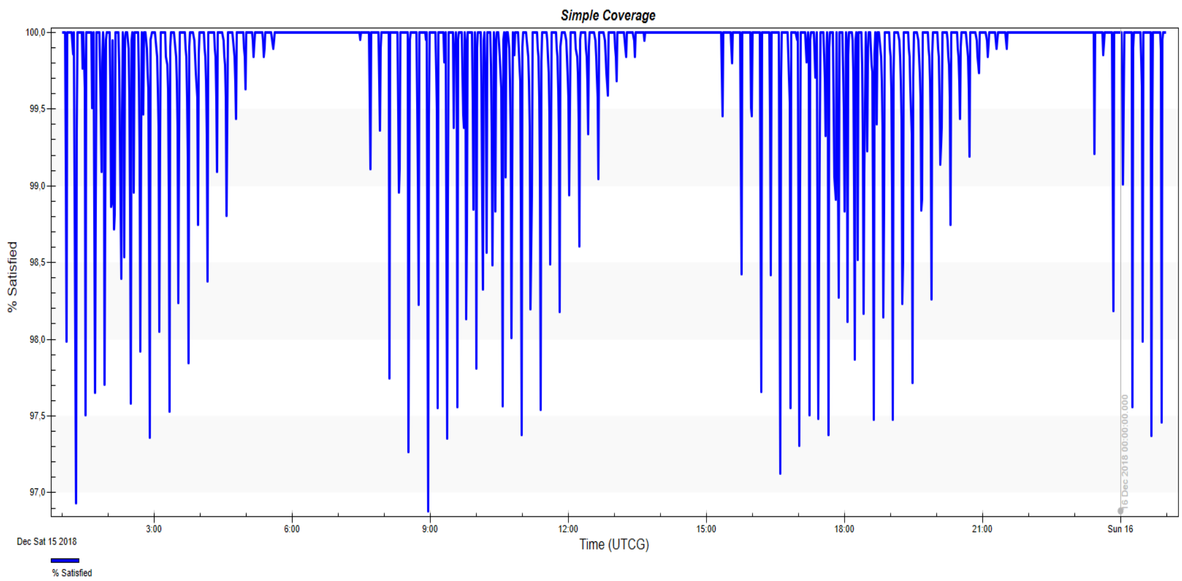


Figure 20 - 70-8-600 3P Simple Coverage

We can now appreciate the almost perfect coverage provided by this constellation of our Interest Ares. The lowest peak in time of coverage is around 97 %, while the Criteria of Gaps under 900 s , is 100 % satisfied. Moreover this constellation, will allow us to exploit the Nodal Precession effect to initialize the mission itself.

```
                    FOM Properties
------------------------------------------------
Maximum Revisit Time
Minimum number of assets required: 1
Gaps at ends of analysis interval are considered
Satisfaction: Less Than 900.000000 sec
FOM value range check is not enabled.


% Satisfied    Area Satisfied (km^2)
-----------    ---------------------
     100.00               1485264.58
```

Figure 21 - 70-8-600 3P Criteria Satisfaction

This leads to the conclusion that the best option among the ones proved, is this last one, able to let us deploy the constellation utilizing only Nodal Precession effect and Differential Air Drag controller as we will see in the next chapter.

2.1.3 Ocean Coverage

In this paragraph we would like to briefly evaluate the quality of a possible worldwide coverage, by our constellation. In order to do this, we introduced and simulated two additional flights between three airports around the world: *Paris, Beijing and Brasilia International Airports.* We simulated two flights, one over the Atlantic Ocean and one over the Pacific one. This because, of course, for our polar constellation, the most difficult area to cover would be exactly the equatorial zone.

We used the same approach and features utilized in the previous paragraph, computing the accesses between each airplane with the satellites and computing the time gap between each connections, obtaining the following results, for the 90° inclination cases:

Walker 90-8-600

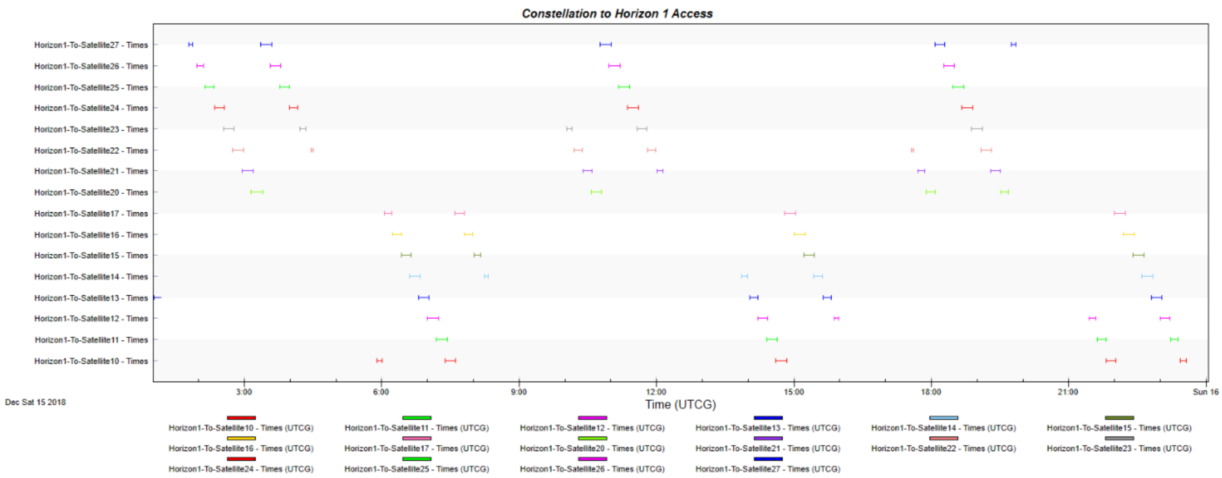


Figure 23 - 90-8-600 Horizon Accesses

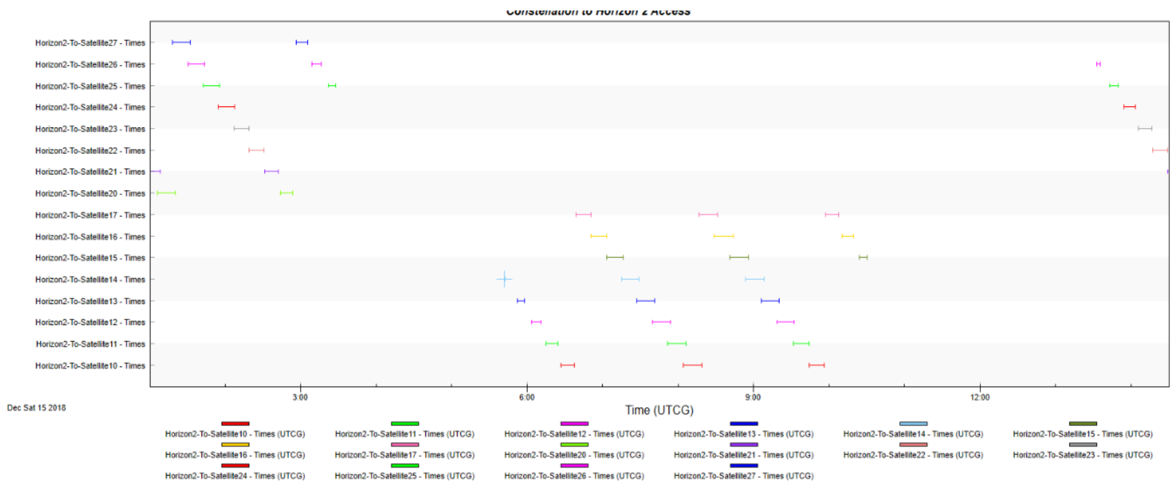


Figure 22 - 90-8-600 Horizon II Accesses

Walker 90-9-600

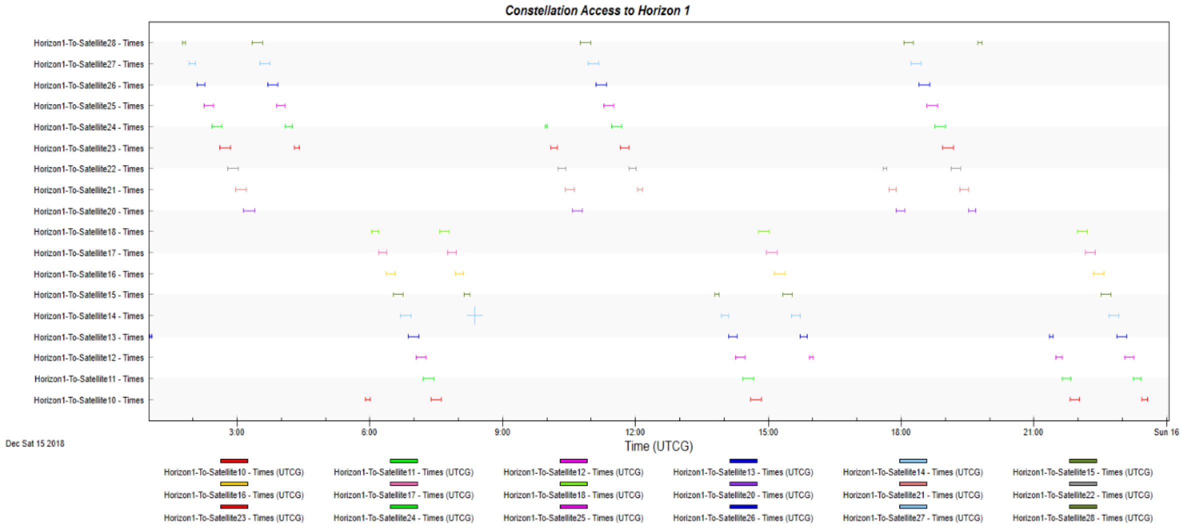


Figure 24 - 90-9-600 Horizon Accesses

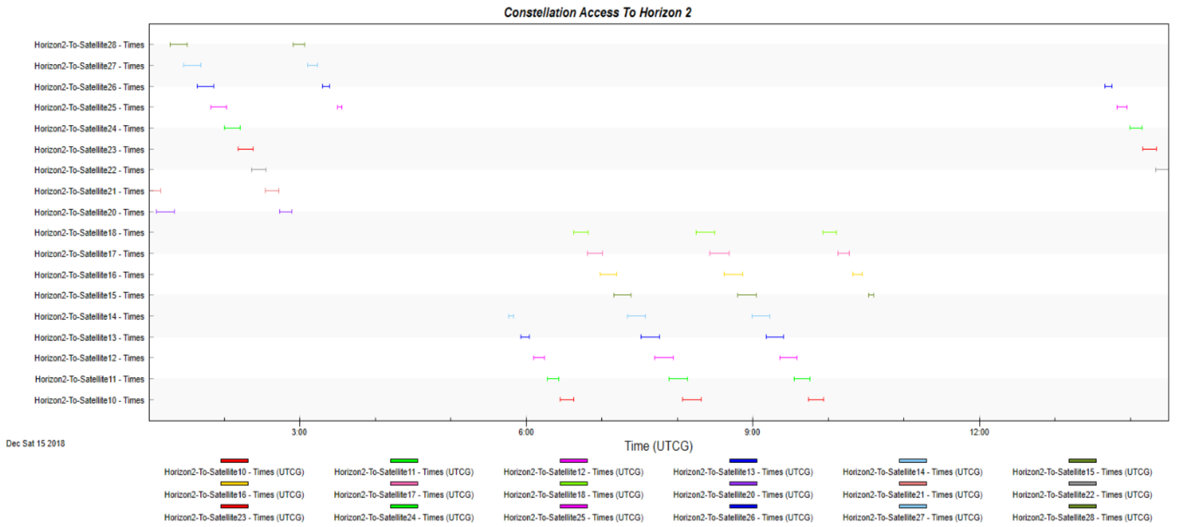


Figure 25 - 90-9-600 Horizon II Accesses

Is clear that not even with 9 satellites we would be able to grant an equatorial coverage for our planes' routes. This because, unless we would strongly raise the altitudes of our satellites, them would be never able to access moving vehicles flying in between the two orbital planes. That is why we also did not computed the same *accesses' graphs* for the 500km altitude constellation, because the result could just be worse. On the other hand, a 3 planes constellation seems to grant better results.

Here we would like to report the same graphs for the 70° inclined, 3 planes, case:

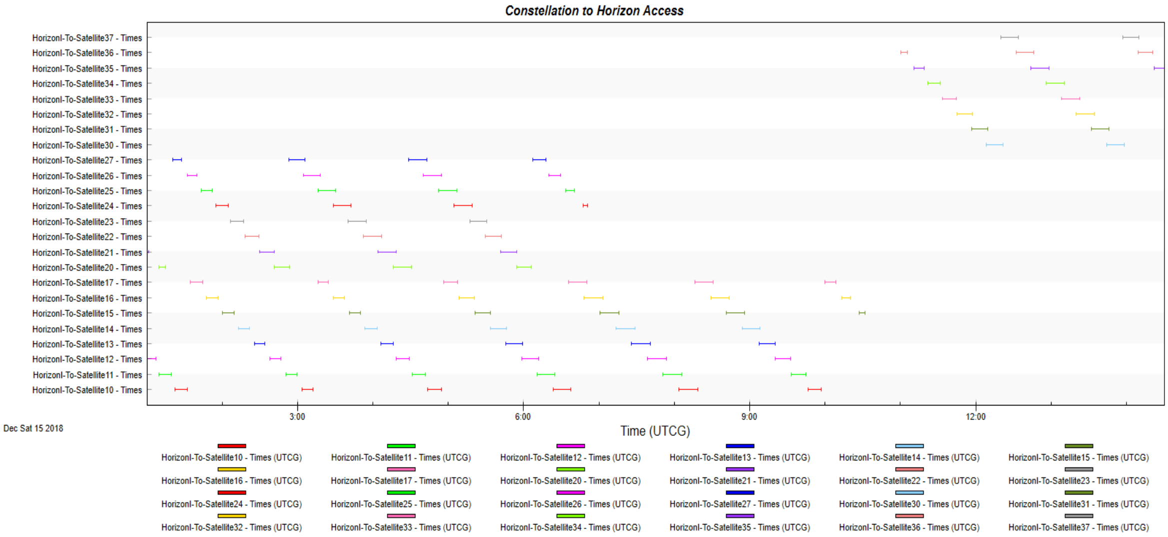


Figure 26 - 70-8-600 3P Horizon Accesses

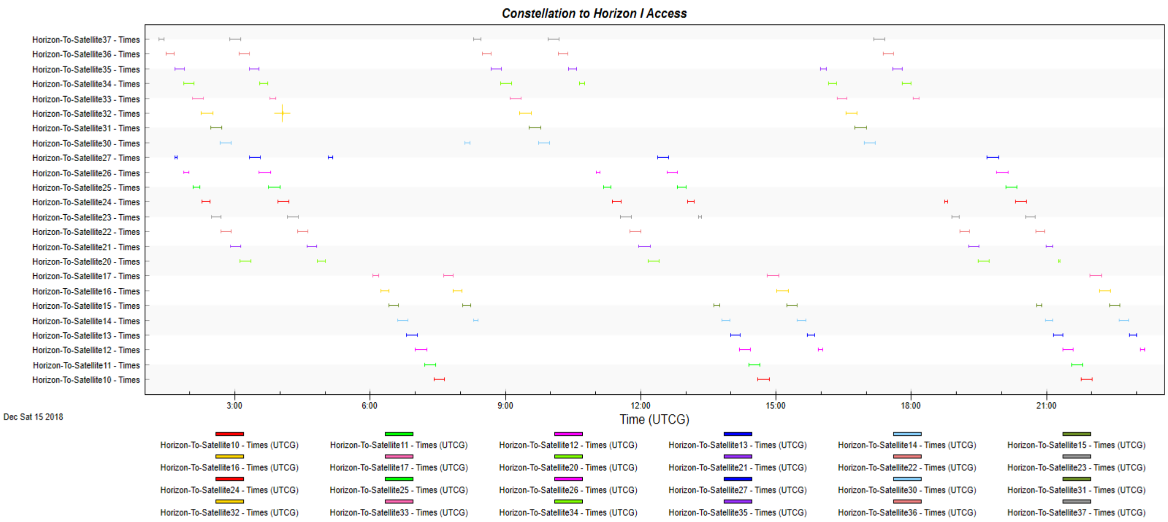


Figure 27 - 70-8-600 3P Horizon II Accesses

We are able to appreciate now the capacity for our 3 planes constellation to grant almost a continuous coverage also for the equatorial zones, with the Pacific Ocean flight, completely tracked for the whole flight-time. Nevertheless, still some over 15 minutes gaps are possible, as proved by the Atlantic Ocean flight. To improve this situation we could both think about to raise the altitude or the inclination a bit, or alternatively add a final fourth plane, that will grant with no doubts a worldwide-coverage.

2.1.4 Connection Quality

Finally, we decided to study the Connection Quality, through a Link Budget analysis, utilizing the powerful features offered by STK software. According to [6],[7] and [12] we modeled our receiver and transmitter, basing on the real systems nowadays used on the aircrafts and on the GOMX demonstration mission, which we will talk about in depth in the apposite Chapter 4. We used the equatorial flights to verify the quality of the connection, since these represent the worst case in terms of Range and the final constellation that show the best result in terms of realization and coverage. (*NDR, Walker3 70-8-600)*

We provided only two of the satellites of our constellation, since we expect the results to be similar with every other satellite, with an antenna modeled on the Specifications mentioned in the article in references. These are essentially:

- Helical Shaped Antenna
- 40 cm length – deployed
- 10 dB of Gain
- 1090 MHz Tuning Frequency
- 9 cm of Diameter

For the aircraft we utilized a general antenna with the following specifications:

- 960 – 1220 MHz Frequency, tuned on 1090 MHz
- Around 103 cm length
- Omni Directional
- 34 dBW Power

Following we will be able to appreciate the Report which put the light on the connection characteristic. Assuming an acceptable BER value of 10^{-9}, we could say the connection is still not perfect. This because the Nominal Range of the ADS-B signal transmission is normally of 80NM, thus high sensitive receiver are needed.

For this reason, we can conclude that the connection quality is enough high for the analysis we produced so far. Indeed, some improvement to the antenna specs could be done, as well as increasing in the power of signal transmitted.

Aircraft-Horizon-Sensor-Sensor25-Transmitter-Transmitter1-To-Satellite-Satellite10-Sensor-Sensor2-Receiver-Receiver1, Receiver-Receiver2

Time (UTCG)	Transmitter1-To-Receiver1 - EIRP (dBW)	Transmitter1-To-Receiver1 - Eb/No (dB)	Transmitter1-To-Receiver1 - BER
15 Dec 2018 07:24:48.991	35.000	9.8248	5.856871E-06
15 Dec 2018 07:25:48.000	35.000	11.1391	1.709065E-07
15 Dec 2018 07:26:48.000	35.000	12.1637	4.813383E-09
15 Dec 2018 07:27:48.000	35.000	12.3572	2.226152E-09
15 Dec 2018 07:28:48.000	35.000	8.6001	7.048460E-05
15 Dec 2018 07:29:48.000	35.000	11.5332	4.763915E-08
15 Dec 2018 07:30:48.000	35.000	25.3578	1.000000E-30
15 Dec 2018 07:31:48.000	35.000	29.4485	1.000000E-30
15 Dec 2018 07:32:48.000	35.000	27.2919	1.000000E-30
15 Dec 2018 07:33:48.000	35.000	17.3252	1.323324E-25
15 Dec 2018 07:34:48.000	35.000	3.6733	1.543875E-02
15 Dec 2018 07:35:48.000	35.000	11.9815	9.653259E-09
15 Dec 2018 07:36:48.000	35.000	12.3656	2.151166E-09
15 Dec 2018 07:37:48.000	35.000	11.5073	5.198716E-08
15 Dec 2018 07:38:48.000	35.000	10.2654	2.004616E-06
15 Dec 2018 07:39:10.136	35.000	9.7431	7.066214E-06

Time (UTCG)	Transmitter1-To-Receiver1 - EIRP (dBW)	Transmitter1-To-Receiver1 - Eb/No (dB)	Transmitter1-To-Receiver1 - BER
15 Dec 2018 14:35:54.405	35.000	9.8326	5.752313E-06
15 Dec 2018 14:36:54.000	35.000	11.1708	1.548169E-07
15 Dec 2018 14:37:54.000	35.000	12.2197	3.864160E-09
15 Dec 2018 14:38:54.000	35.000	12.3566	2.231201E-09
15 Dec 2018 14:39:54.000	35.000	6.4147	1.539693E-03
15 Dec 2018 14:40:54.000	35.000	19.5807	1.000000E-30
15 Dec 2018 14:41:54.000	35.000	32.1813	1.000000E-30
15 Dec 2018 14:42:54.000	35.000	39.4302	1.000000E-30
15 Dec 2018 14:43:54.000	35.000	44.9999	1.000000E-30
15 Dec 2018 14:44:54.000	35.000	31.9099	1.000000E-30
15 Dec 2018 14:45:54.000	35.000	24.4547	1.000000E-30
15 Dec 2018 14:46:54.000	35.000	-7.2351	2.693315E-01
15 Dec 2018 14:47:54.000	35.000	11.9087	1.264911E-08
15 Dec 2018 14:48:54.000	35.000	12.4025	1.849468E-09
15 Dec 2018 14:49:54.000	35.000	11.4940	5.436329E-08
15 Dec 2018 14:50:54.000	35.000	10.2127	2.291749E-06
15 Dec 2018 14:51:11.035	35.000	9.8047	6.136365E-06

Time (UTCG)	Transmitter1-To-Receiver1 - EIRP (dBW)	Transmitter1-To-Receiver1 - Eb/No (dB)	Transmitter1-To-Receiver1 - BER
15 Dec 2018 21:45:39.283	35.000	9.7408	7.103290E-06
15 Dec 2018 21:46:39.000	35.000	11.0958	1.952886E-07
15 Dec 2018 21:47:39.000	35.000	12.1555	4.969486E-09
15 Dec 2018 21:48:39.000	35.000	12.3290	2.495971E-09
15 Dec 2018 21:49:39.000	35.000	6.9006	8.740363E-04
15 Dec 2018 21:50:39.000	35.000	18.6149	1.000000E-30
15 Dec 2018 21:51:39.000	35.000	31.7068	1.000000E-30
15 Dec 2018 21:52:39.000	35.000	28.2251	1.000000E-30
15 Dec 2018 21:53:39.000	35.000	34.8734	1.000000E-30
15 Dec 2018 21:54:39.000	35.000	32.3937	1.000000E-30
15 Dec 2018 21:55:39.000	35.000	21.9482	1.000000E-30
15 Dec 2018 21:56:39.000	35.000	2.3660	3.165476E-02
15 Dec 2018 21:57:39.000	35.000	12.1102	5.922042E-09
15 Dec 2018 21:58:39.000	35.000	12.2773	3.073296E-09
15 Dec 2018 21:59:39.000	35.000	11.2921	1.054528E-07
15 Dec 2018 22:00:39.000	35.000	9.9636	4.225554E-06
15 Dec 2018 22:00:44.628	35.000	9.8260	5.840894E-06

Time (UTCG)	Transmitter1-To-Receiver2 - EIRP (dBW)	Transmitter1-To-Receiver2 - Eb/No (dB)	Transmitter1-To-Receiver2 - BER
15 Dec 2018 03:06:27.985	35.000	9.5586	1.066153E-05
15 Dec 2018 03:07:27.000	35.000	10.7940	4.786401E-07
15 Dec 2018 03:08:27.000	35.000	11.7892	1.952324E-08
15 Dec 2018 03:09:27.000	35.000	12.2747	3.104844E-09
15 Dec 2018 03:10:27.000	35.000	11.2006	1.410398E-07
15 Dec 2018 03:11:27.000	35.000	1.7147	4.245649E-02
15 Dec 2018 03:12:27.000	35.000	13.1144	7.729374E-11
15 Dec 2018 03:13:27.000	35.000	20.8842	1.000000E-30
15 Dec 2018 03:14:27.000	35.000	20.9933	1.000000E-30
15 Dec 2018 03:15:27.000	35.000	13.5303	9.419096E-12
15 Dec 2018 03:16:27.000	35.000	0.9044	5.827688E-02
15 Dec 2018 03:17:27.000	35.000	11.1418	1.694791E-07
15 Dec 2018 03:18:27.000	35.000	12.2781	3.063492E-09
15 Dec 2018 03:19:27.000	35.000	11.7975	1.894959E-08
15 Dec 2018 03:20:27.000	35.000	10.7927	4.804894E-07
15 Dec 2018 03:21:18.701	35.000	9.7088	7.637388E-06

Time (UTCG)	Transmitter1-To-Receiver2 - EIRP (dBW)	Transmitter1-To-Receiver2 - Eb/No (dB)	Transmitter1-To-Receiver2 - BER
15 Dec 2018 04:50:02.619	35.000	9.6588	8.544537E-06
15 Dec 2018 04:51:02.000	35.000	10.4887	1.117362E-06
15 Dec 2018 04:52:02.000	35.000	11.1237	1.792433E-07
15 Dec 2018 04:53:02.000	35.000	11.5595	4.356796E-08
15 Dec 2018 04:54:02.000	35.000	11.8065	1.834710E-08
15 Dec 2018 04:55:02.000	35.000	11.8868	1.370913E-08
15 Dec 2018 04:56:02.000	35.000	11.8139	1.786457E-08
15 Dec 2018 04:57:02.000	35.000	11.5765	4.111430E-08
15 Dec 2018 04:58:02.000	35.000	11.1539	1.632241E-07
15 Dec 2018 04:59:02.000	35.000	10.5369	9.811465E-07
15 Dec 2018 04:59:59.541	35.000	9.7597	6.803400E-06

Time (UTCG)	Transmitter1-To-Receiver2 - EIRP (dBW)	Transmitter1-To-Receiver2 - Eb/No (dB)	Transmitter1-To-Receiver2 - BER
15 Dec 2018 12:09:53.461	35.000	9.8232	5.879412E-06
15 Dec 2018 12:10:53.000	35.000	11.1774	1.516855E-07
15 Dec 2018 12:11:53.000	35.000	12.2333	3.661116E-09
15 Dec 2018 12:12:53.000	35.000	12.3392	2.394810E-09
15 Dec 2018 12:13:53.000	35.000	5.9737	2.452578E-03
15 Dec 2018 12:14:53.000	35.000	19.8049	1.000000E-30
15 Dec 2018 12:15:53.000	35.000	32.0311	1.000000E-30
15 Dec 2018 12:16:53.000	35.000	28.8016	1.000000E-30
15 Dec 2018 12:17:53.000	35.000	27.6158	1.000000E-30
15 Dec 2018 12:18:53.000	35.000	31.9143	1.000000E-30
15 Dec 2018 12:19:53.000	35.000	19.3540	1.000000E-30
15 Dec 2018 12:20:53.000	35.000	6.4071	1.552679E-03
15 Dec 2018 12:21:53.000	35.000	12.3563	2.234729E-09
15 Dec 2018 12:22:53.000	35.000	12.2162	3.917748E-09
15 Dec 2018 12:23:53.000	35.000	11.1557	1.622937E-07
15 Dec 2018 12:24:51.721	35.000	9.8224	5.890084E-06

Figure 28 - Link Budget Analysis between Horizon and two Satellites of the Constellation

We can appreciate how for the major part of the time the BER is around 10^{-30}, value that indicates a perfect connection. Obviously during the period in which the plane is on the border of the satellite sensor, this value drops dramatically, as we could have expected.

In conclusion, to grant a valid and trustable world-wide coverage an additional plane would be required, while for the improvement of the Alaskan Air Situational Awareness, this 3plane 70° of inclination configuration is more than acceptable, since, also in that period spend in the border zone of one satellite's sensor, the plane will be under the coverage of one other satellite, granting the reception of its state.

One last detail upon the connection is the probability of reception, which deals with the ADS-B packet collision probability. To study further this problem is not among the purposes of this thesis, nevertheless here we would like to report an *Access Graph,* which shows the length of each connection. Indeed, since each connection is granted for several minutes, we could assume we would have the time needed to solve the collision and decode the packets in arrive.

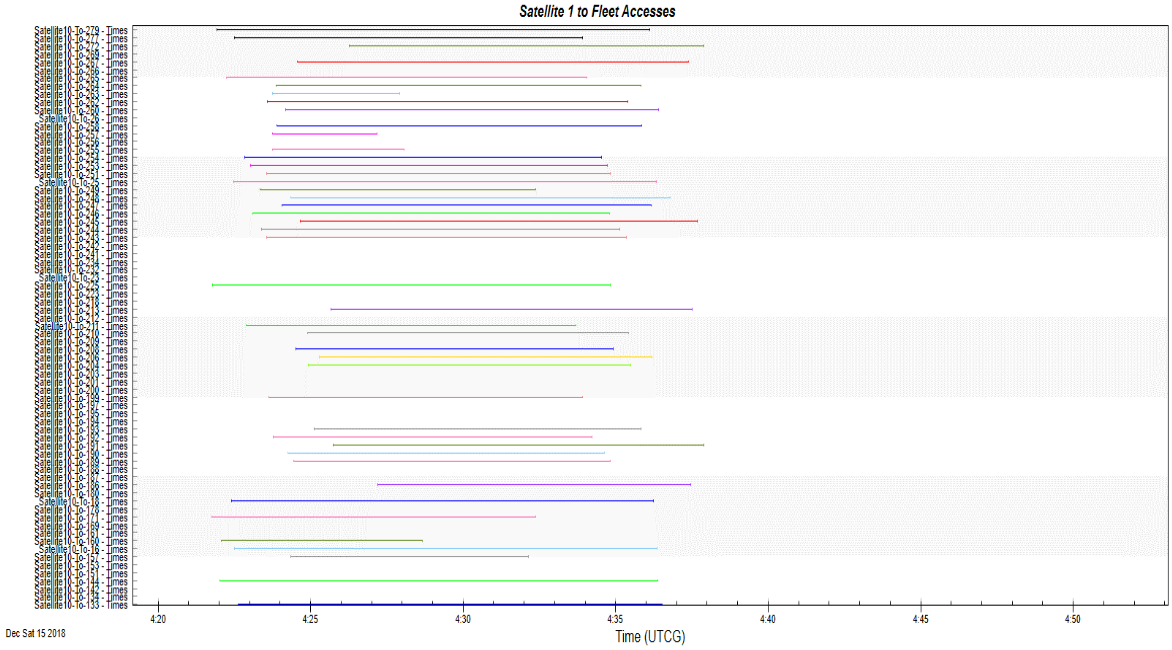


Figure 29 - ADS-B Simultaneous Receptions

2.2 Mission Deployment

In the previous paragraph we put the light on several constellation architectures, among which only some, fulfill the requirements of <15 min gap, between each contact with the Area of Interest.

These are:

-*Walker 90 - 8 - 600 (99% of satisfaction)*

-*Walker3 70 - 8 - 600*

-*Walker 90 - 9 - 600 (99% of satisfaction)*

The addition of a plane could be not required in the 90° inclination cases, since the improvement in the coverage would not worth the cost. On the other hand, a third plane would be necessary for constellations composed of planes with lower inclination and necessary in any case, whenever we would like to provide world-wide coverage. We want to remember that we lowered the inclination only to make possible deploy the constellation exploiting the nodal precession effect. A key role in the decision making would be the computation of the time needed to spread our planes in RAAN, utilizing the difference in altitude that dispositive like SHERPA could provide.

We will report more accurate specification in the relative chapter but here we would like to mention that the SHERPA tug, we took as an example, is able to put on orbit, through is variants, up to 2000 kg, also in GTO orbits. On the other hand, it is able to provide up to $\Delta V = 2.2 \frac{km}{s}$. This means that, even if is not recommended to use it directly to perform out of plane maneuver, its capability to raise or lower the semimajor axis is quite good.

Using the classic formula for the Nodal Precession Effect :

$$\dot{\Omega}_{J_2} = -\frac{3}{2}\frac{R_E^2}{\left(a(1-e^2)\right)^2} J_2\, n \cos i$$

We estimated that, in order to obtain, at 600 km of altitude and 70° of inclination, a 90° RAAN spread, we would need 300 km of difference in altitude between our satellites to deploy our constellation in around 9 months. This altitude increase would need approximately definitely less than 1 km/s of DeltaV. The idea is to use the Sherpa itself as carrier for the whole deployment time, since it has modulable thrusters to put a cluster of nanosatellites in higher orbit and then put them back on the design orbit once the RAAN spread is reached.

In the Chapter 3 we will use as design *Time Needed* to phase our satellite of 180 days, or 6 months. To be conservative, since the Constellation composed of 3 planes could be surely useful to take into consideration, we will aim to reach not 90° of RAAN spread but 240°, to compute the altitude needed to reach this spread within 6 months. In case we would choose 2 plane configuration, the altitude needed will be less and then, surely achievable.

Using a simple algorithm in Matlab to iteratively compute the Nodal Precession Rate, we computed that approximately a difference of 700 km would be needed to spread our satellite of 240° within 6 months.

On the other and, using the Vis Viva equation[1], and a classic Hohmann Transfer method, we computed a ΔV required of 143 *m/s,* that is perfectly obtainable by the littlest version of the SHERPA.

3. Control Strategies

Cubesat are extremely less expensive if compared to other big satellites, also, a constellation of multiple Cubesat is definitely more reliable, because if well designed, the failure of one unit almost never compromise the success of the whole mission.

This leads to much more possibilities, behind the pure academic study, but also to much more strictly *Power and Propulsion* constraints. An innovative concept for the orbit control, nowadays, is based on the use of the *Differential Air Drag Control,* while one other interesting method, useful with light spacecraft, as in our case, rely on the usage of *Electric Thrusters*.

3.1 Air Drag Controller

An interesting and innovative concept nowadays is given by the *Differential Air Drag Control Scheme*. Starting from the assumption that usually nanosatellites does not have big *Delta Velocity* capabilities, this concept grants us a way to perform an orbit-control using only the *ADCS,* acting then on the *Cross-sectional Area* of our satellites, or in the same way deploying and retracting the solar panel of our satellites.

Obviously, this leads to some constraints we should take care about. At first, of course, using Air Drag, we cannot perform maneuver able to lead to an increase of the altitude, but we can only perform a decrease of the orbit itself. In this case, the satellite which orbit would be lowered through a time passed in *high drag profile*, would be faster than the other left in *low drag profile.*

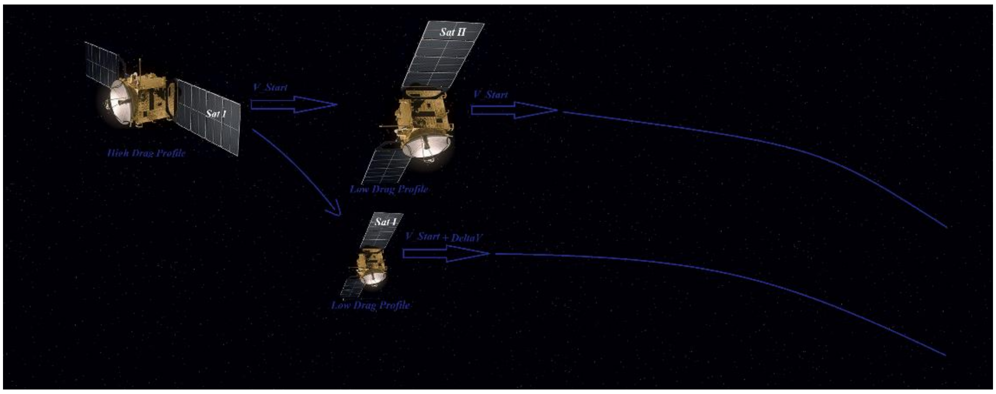


Figure 30 - Air Drag Controller Concept

This leads to the second constraint: the orbit degradation. If with common control strategies we have to spend our efforts to optimize while thinking about the *Time to Perform the Maneuver and the Delta Velocity Required,* in this case we do not have *DeltaV* limits anymore, paying on the other hand with an orbit degradation, that will become our new design driver. Indeed, in the less time we will want to perform our spreading, the bigger will be the Δa to obtain the separation needed, in the time chosen.

3.1.1 Control Algorithm

In order to design and implement a *Control Algorithm*, we decide to use *MATLab,* introducing a system of equations referenced in [2].

GVE's Physical Model

In *LEO* most preponderant effects are given by Atmospheric Air Drag and by the J2 Perturbations, since higher order effect are orders of magnitude less important. For this reason we decided to implement the model mentioned which, starting from *Gauss Variational Equations,* introduces Air Drag Effect, and is sophisticated enough to let us validate our Control Algorithm, even without introducing control-related effect, since we will actuate only through the *ADCS,* changing the *Cross-Sectional Area* of our Satellite, providing differential air drag effect.

Indeed, the most important output of our algorithm will be the profile of Cross Sectional Areas changes for each satellite.

The model follows:

$$\dot{\xi} = A(\xi) \quad whereas\ \xi\ is\ the\ state\ vector\ \ \xi = \begin{pmatrix} a \\ e \\ i \\ \Omega \\ \omega \\ M_a \end{pmatrix}$$

$$and\ A\ is\ 6x1\ Vector$$

$$A = \begin{pmatrix} -2\rho_p a^2 n K_d \left[I_0 + 2eI_1 + \frac{3e^2}{4}(I_0 + I_2)\right] e^{-(\beta(r - r_{start}))} \\ -\rho_p a n K_d \left[2I_1 + e(I_0 + I_2) - \frac{e^2}{4}(5I_1 + I_3)\right] e^{-(\beta(r - r_{start}))} \\ 0 \\ -\frac{3}{2} J_2 n \left(\frac{R_e}{p}\right)^2 \cos(i) \\ -\frac{3}{4} J_2 n \left(\frac{R_e}{p}\right)^2 (5\cos^2(i) - 1) \\ n + \frac{3}{4} J_2 n \left(\frac{R_e}{p}\right)^2 \sqrt{1 - e^2}\, (3\cos^2(i) - 1) \end{pmatrix}$$

where is easy noticeable that inclination is not affected since we did not consider asymmetric Geopotential effects.

"..*where* ρ_p *is the atmospheric density at perigee,* β *the inverse of the atmospheric scale height, p the parameter of the orbit, n the mean motion, Re the* *equatorial radius, J2 the Earth oblateness coefficient,* $K_D = \frac{SC_d}{2m}$ *the drag factor, Cd the drag coefficient, and S the reference area of the drag coefficient"* [2]

In addition, I0-I3 are *Bessel Modified Function of the First order,* with argument $\beta(r - r_{start})$. The equations have been slightly modified if compared to the original mentioned in [2]; this because the authors used that for the orbit maintenance problem, using a density changes related to eccentricity. On the other hand we took into consideration, the changes in density related to the decrease of the mean *a* parameter.

In order to define our density parameters, we have chosen the NRLMSISE-2000 model for the density and the Scale height vs Altitude from the MSIS Atmosphere, according to the following figure and tables:

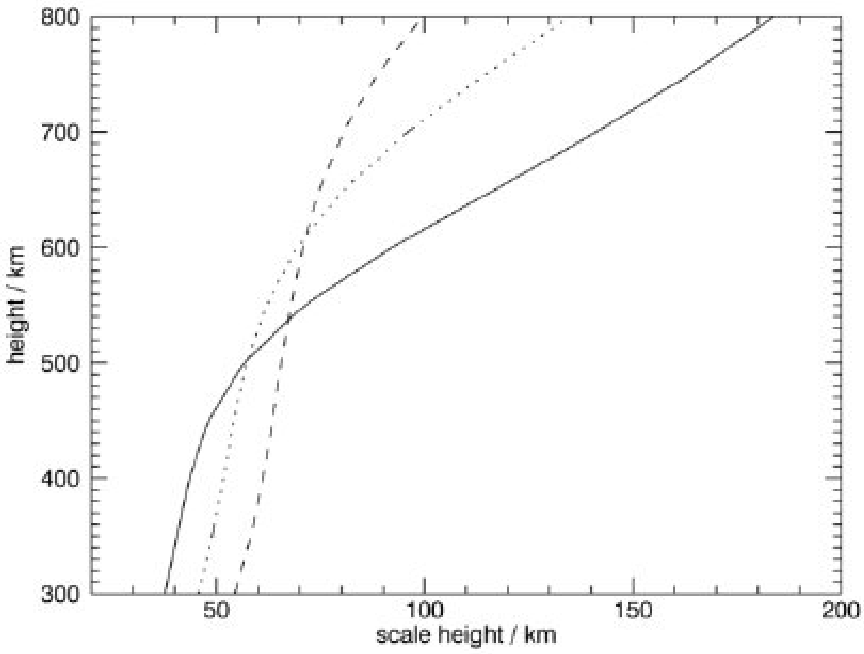


Figure 31 - Scale Height Vs Altitude - MSIS Atmosphere Model from [13]

Table 1 - Density Vs Altitude - NRLMSISE-2000 from [14]

Height,[km]	Mass_density, g/cm-3
500.0	7.749E-16
525.0	5.399E-16
550.0	3.796E-16
575.0	2.692E-16
600.0	1.927E-16
625.0	1.391E-16
650.0	1.015E-16

Control Algorithm Concepts and Working-Flow

To design our controller we started from the assumption all of our satellites will be released in approximately same orbit and with the same orbital parameters.

The slight difference between them we will let our algorithm to organize them in a *slotter* according to their altitude and consequently according to them velocity. Indeed, to optimize the maneuver we should make the faster satellite be the last in our constellation, if referred to the slower.

These two satellites will be then our references for all the others in the middle. Indeed, once chosen some crucial parameters like the Time Needed to perform the maneuver, the numbers of satellites and the starting orbital parameters, our code will provide at the same time a simulation able to let us verify the feasibility of the deployment and a *first-analysis* control profile, given by the time spent by each satellite respectively in high or low drag profile, as explained in the introduction of this chapter.

We validated our model using *GMat,* using a simple RK98 propagator and acting on the cross section of the two satellites we decided to use as a sample case.

Considering almost-circular orbit, the most useful for our purpose, we were able to make a first analysis based on the mean angular motion and the time needed to spread our satellites, computing so the Δa needed to spread the first and the last satellite within the limited time chosen.

At this point the control proceed to propagate the orbit of our two first satellites, using an high-drag profile for the last one, until the altitude needed to perform the spreading within the time windows is reached, keeping on propagating while the needed ΔT_a is reached, before finally put the first satellite in high-drag mode to make it reach the lower altitude in our constellation, the one of the last satellite. This while taking into consideration that while maneuvering the satellites will keep on spreading. If we would not do this, there would be a constant difference in the mean motion of the satellites leading to a periodic relative motion between them.

Follow the Algorithm Control Flow:

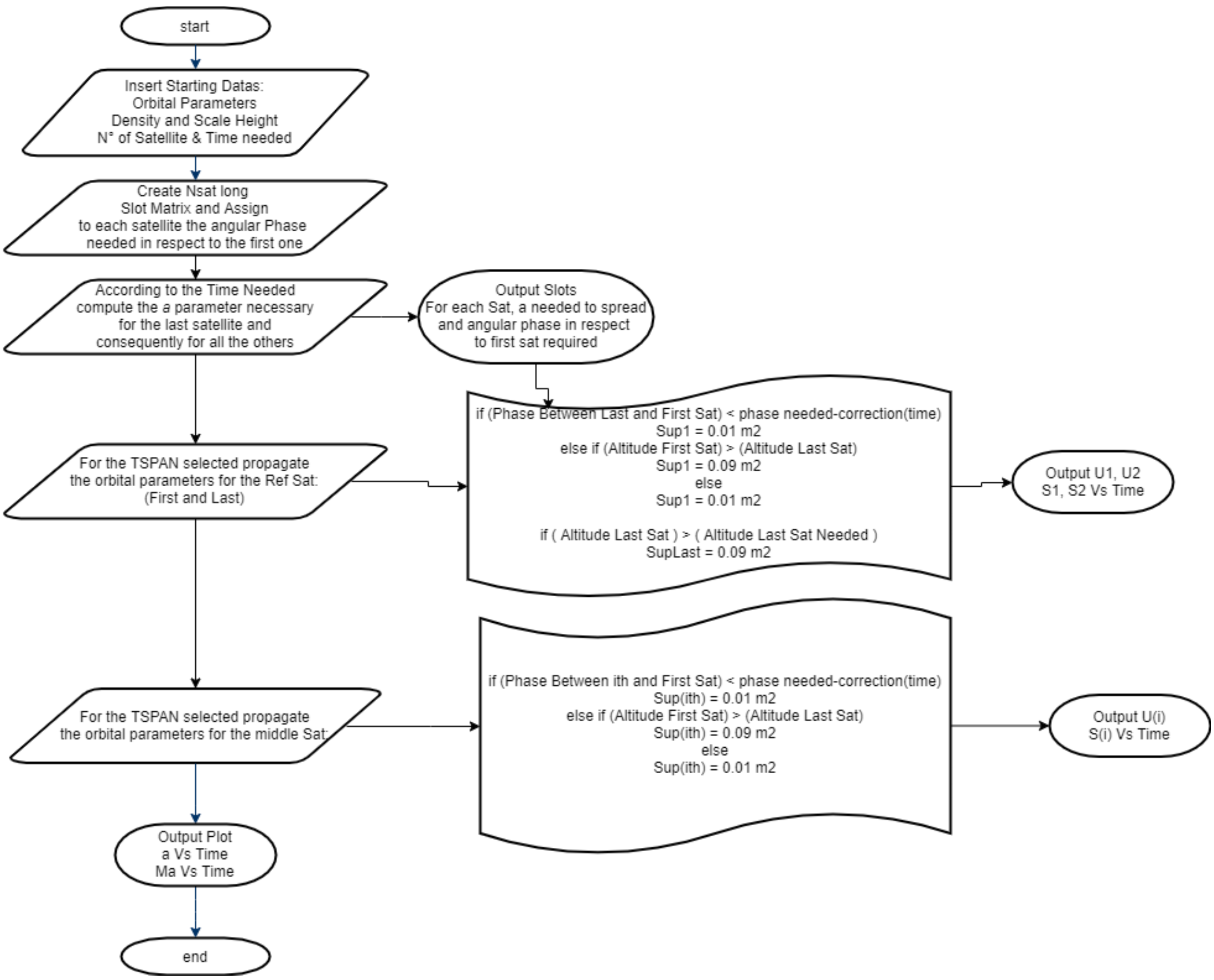


Figure 32 - Control Algorithm Flow-Chart

The algorithm in conclusion, at first make the last satellite of constellation spread from the first one and later on, make all the others, first included, “decide” when to enter high drag profile once the right phasing between each and the last is reached, properly corrected taking into consideration that while reaching the lower altitude, the satellites will keeping on spreading. More sophisticated concepts could introduce the transition between high and low drag profile but actually the difference is supposed to be very little.

3.1.2 Scenario Results

Two satellite in General LEO

At first, we tried to spread only two satellites on a general LEO with the following parameters :

$$\Delta t_{need} =$$

$$\xi = (6900\ km\ , 0.02\ , 85°\ , 0°\ , 90°\ , 0°\ )$$

Time required to perform the maneuver set to 120 days.

To show the results we decided to enlarge the Time Span over one year and an half to verify the maintenance of the spreading reached and to plot the behavior of the *a* parameter (*semi major axis)* and that one of the *Mean Anomaly* in the first *200 minutes , for 200 minutes after 75 day and finally the last 200 minutes of the period chosen, together with the phase difference between the satellites along the time.*

Moreover, we obtained a $\Delta a_{need} = 1265\ m$ to perform the 180° degree of spread between the two satellites within the time selected and consequently a final semi-major axis of about 6890.9 *km,* after the whole period of one year and an half. This is due to the natural perturbation, starting from *6900 km* and maneuvering in order to achieve the spread within 120 days. Indeed, choosing a *Maneuver Time of 300 days,* as an example, we reduce the spread in semimajor axis needed, also the time spent in high drag profile. This led to a final *a* of about 6891.7 *km.* Of course, this algorithm could be useful to study the optimization between time needed and orbit degradation, in order to better chose the design parameter of the maneuver time according to our need in term of velocity of spreading and mission lifetime.

Additionally, even if this code is capable to let us simulate and study the problem, it could be used to provide as an output, the control for our satellites, provided as the time window spent by each satellites respectively in *high or low drag profile.*

Following the Plot obtained:

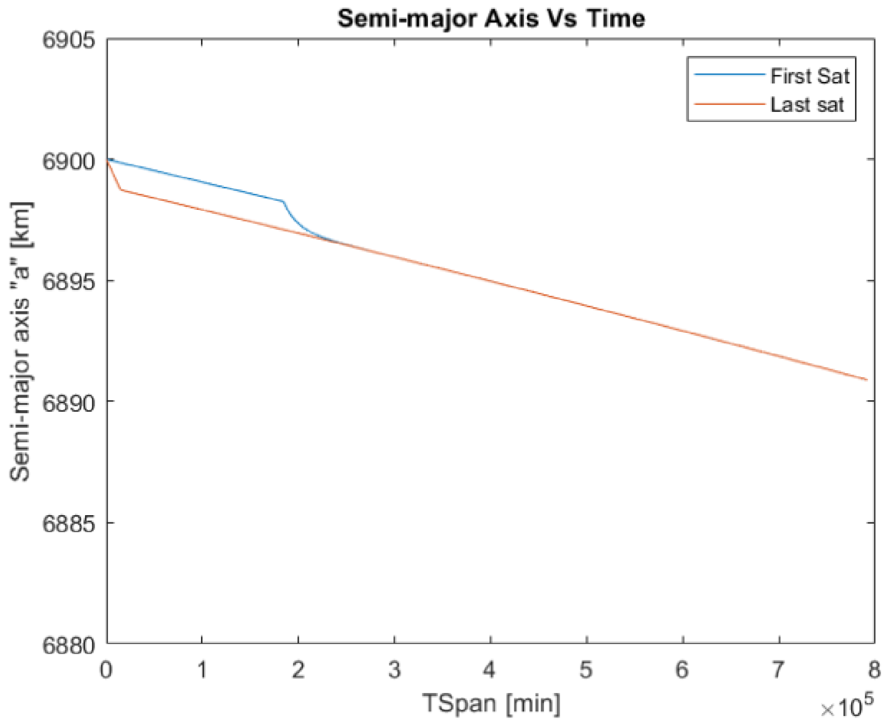


Figure 33 - SemiMajor Axis behaviour – 2 Sats in General LEO

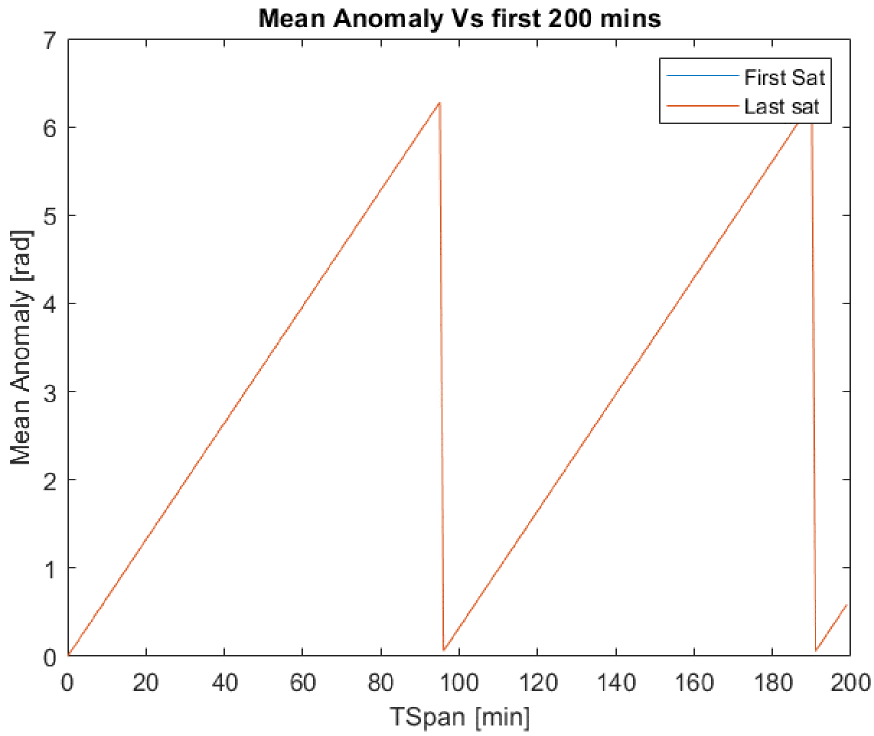


Figure 34 - Mean Anomaly at the beginning

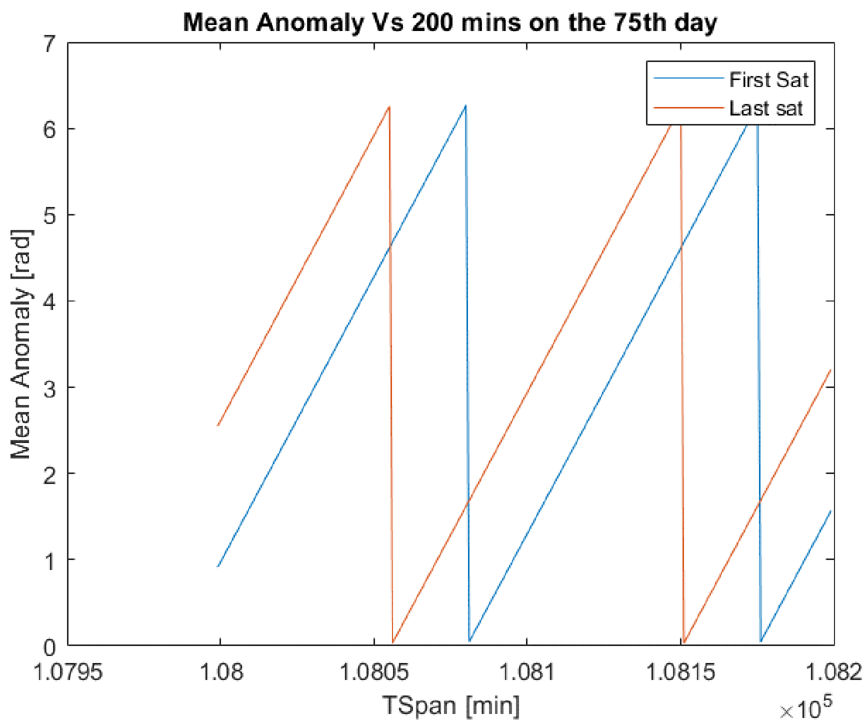


Figure 35 - Mean Anomaly after 75 days

Here we could take a look at the behavior of our mean anomaly and its progressive spreading along the time.

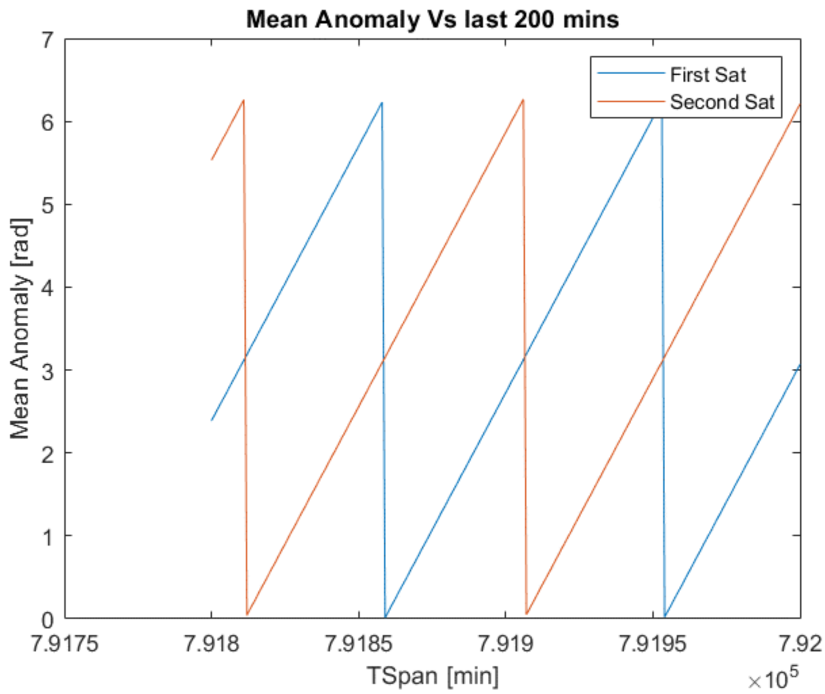


Figure 36 - Mean Anomaly After 550 Days

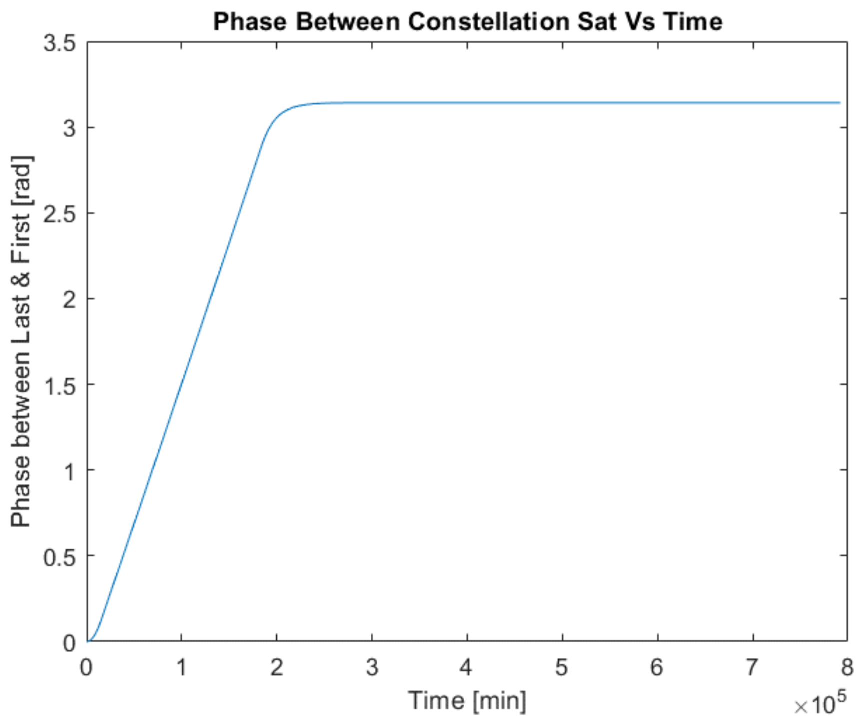


Figure 37 - Phasing Along Time

In order to achieve our spread in about 120 days at that altitude we need a $\Delta a = 1265\ m$ while we should maneuver (an in this context as maneuver we want to intend to be in high drag profile) the second satellite for about 249 hours, wait for the spreading time of 128 days and finally maneuver the first satellite (in order to make it match the lowest altitude and put to 0 the difference in the *mean angular motion*)

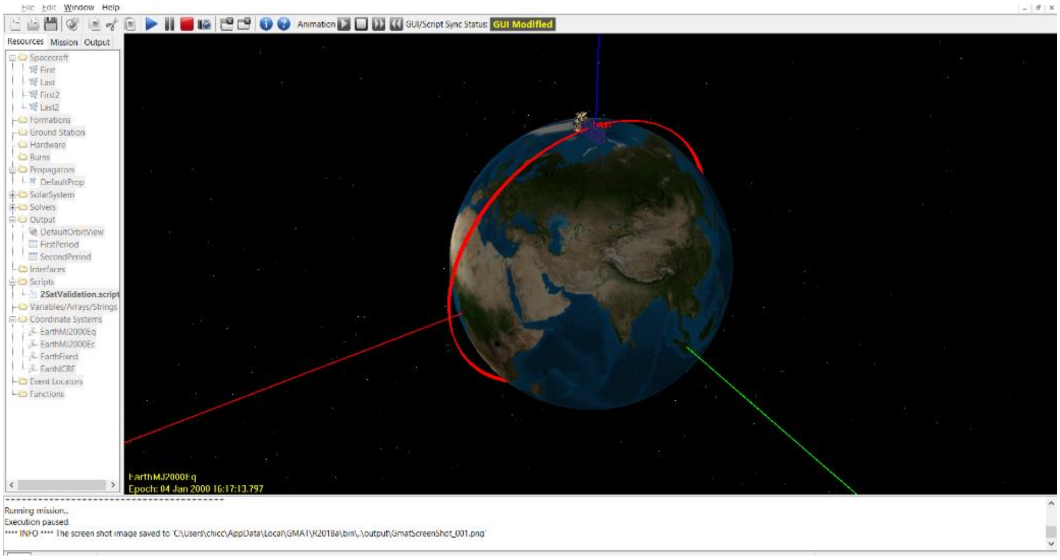
GMat Validation

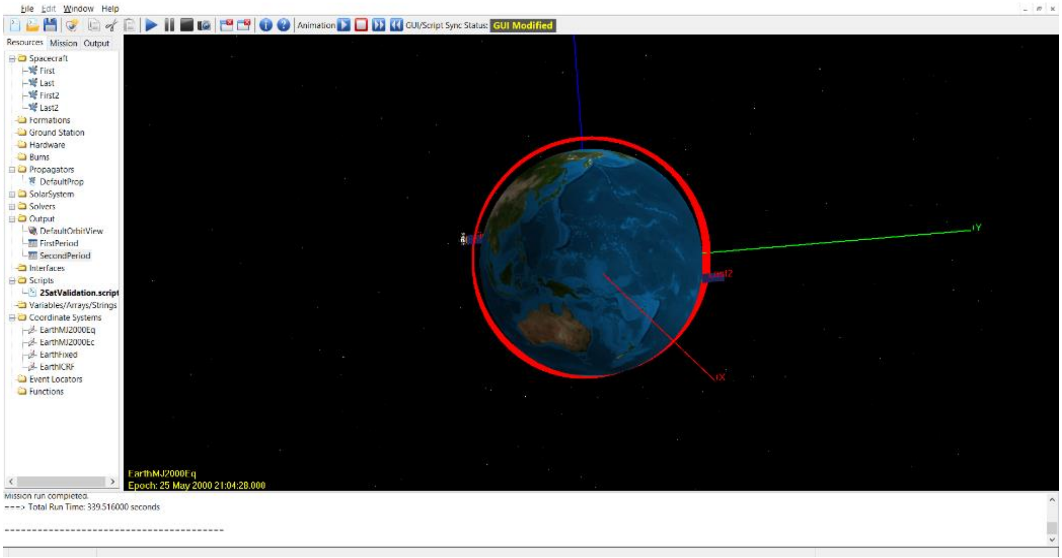
As mentioned, in order to validate the model chosen and to prove the feasibility of our controller, we decide to implement our result in *GMat, Nasa Open-source Code* very useful to propagate satellite motion with several kind of features.

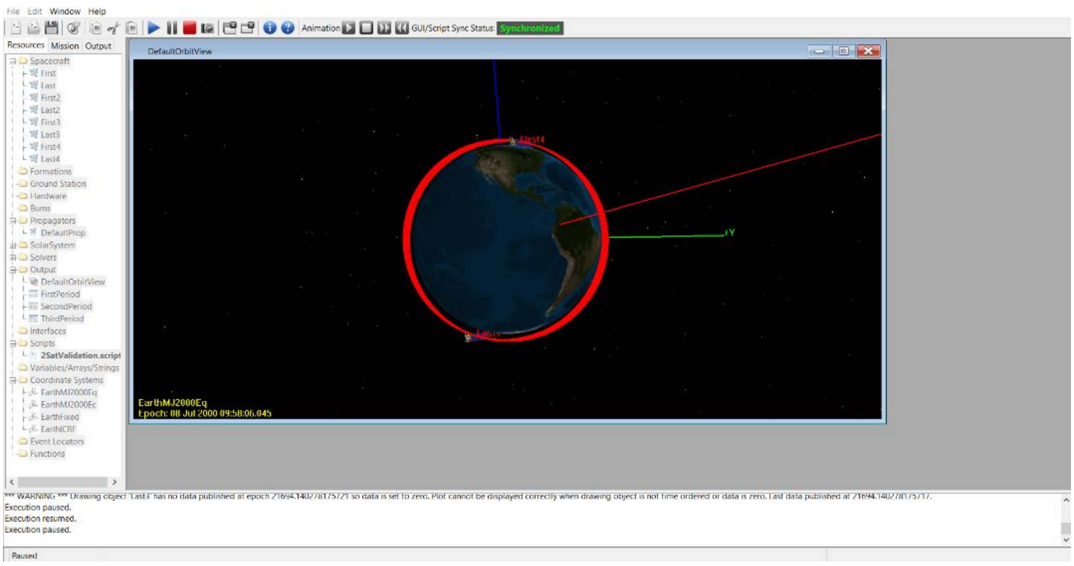
We adopted an RK98 Propagator with MSISE-90 Drag Model, inserting as the specification of the spacecraft propagated, that ones from our Cubesat.

Mass = 3 kg and respectively for low and high drag profile 0.01 m^2 *and 0.09* m^2

Following 3 screenshot chosen after the first period of last satellite maneuver, at the end of the maneuver time of *128 days* and after 210 days.







Eight Satellite in General LEO

At second we used the algorithm to spread eight satellites on a general LEO with the following parameters :

$$\xi = (6900\ km\ , 0.02\ , 85°\ , 0°\ , 90°\ , 0°\ )$$

Time required to perform the maneuver set to 120 days.

To show the results we decided to use the same output of the previous scenario. Noticeable is that we left same atmosphere parameters since no changes in the starting orbit were made.

In this case, the use of the same *Time for Maneuver* but a larger number of satellites led to a noticeably larger Δa_{need} since now, the phase between the last and the first satellite that must to be reached is not 180° anymore but on the contrary is given by a division of 360° by the number of satellites, leading to 315° of phase.

Following the plot obtained in this second scenario:

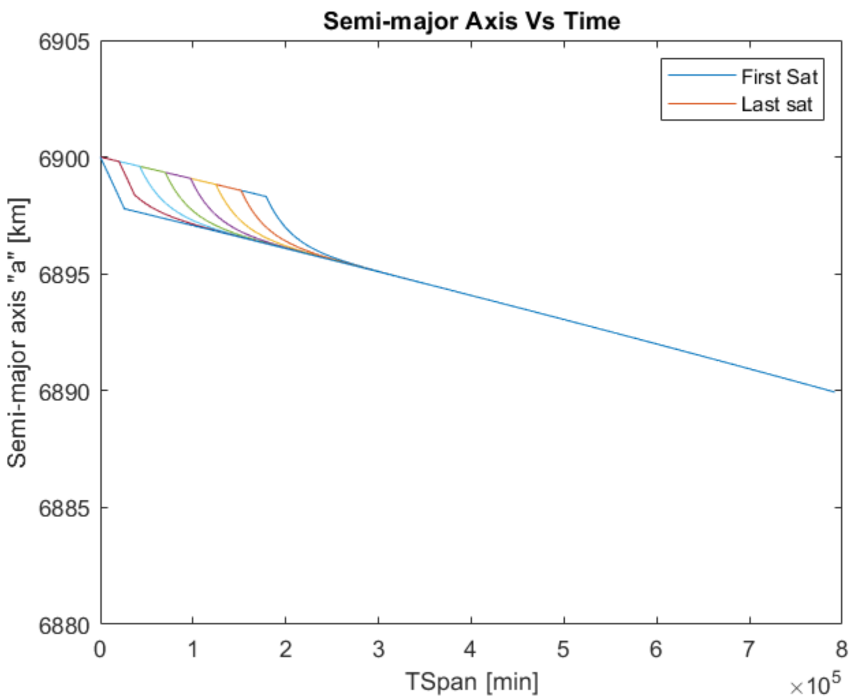


Figure 38 - SemiMajor Axis Vs Time (8 Sat General LEO)

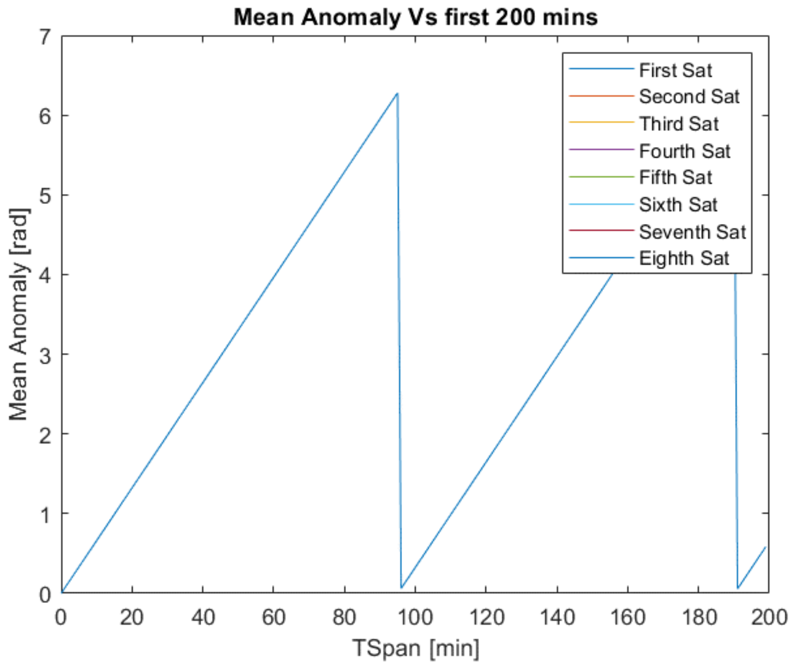


Figure 39 - Mean Anomaly Vs First 200 Mins (8 Sat General LEO)

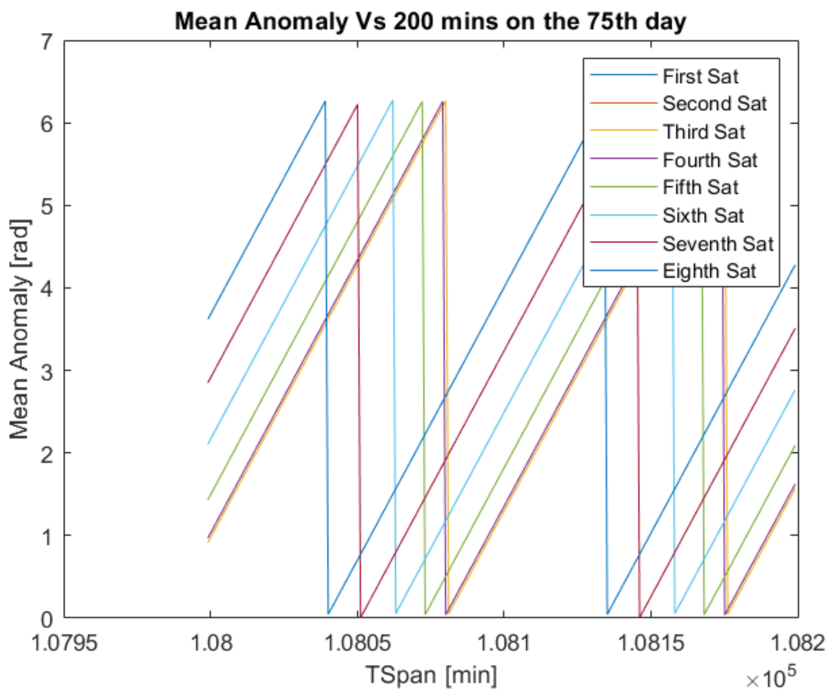


Figure 40 - Mean Anomaly Vs 200 Mins after 75 days (8 Sat General LEO)

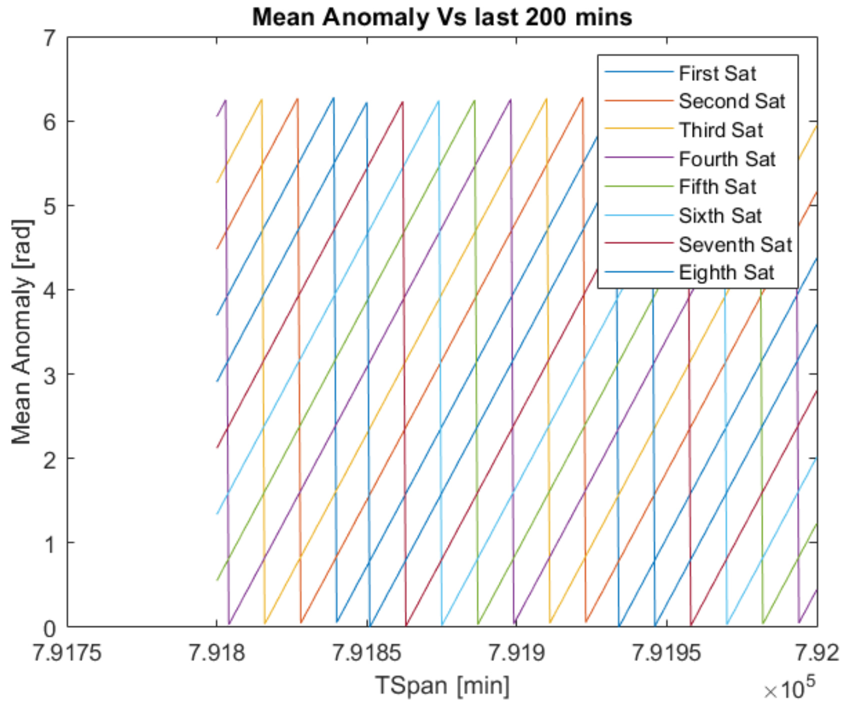


Figure 41 - Mean Anomaly Vs Last 200 Mins (8 Sat General LEO)

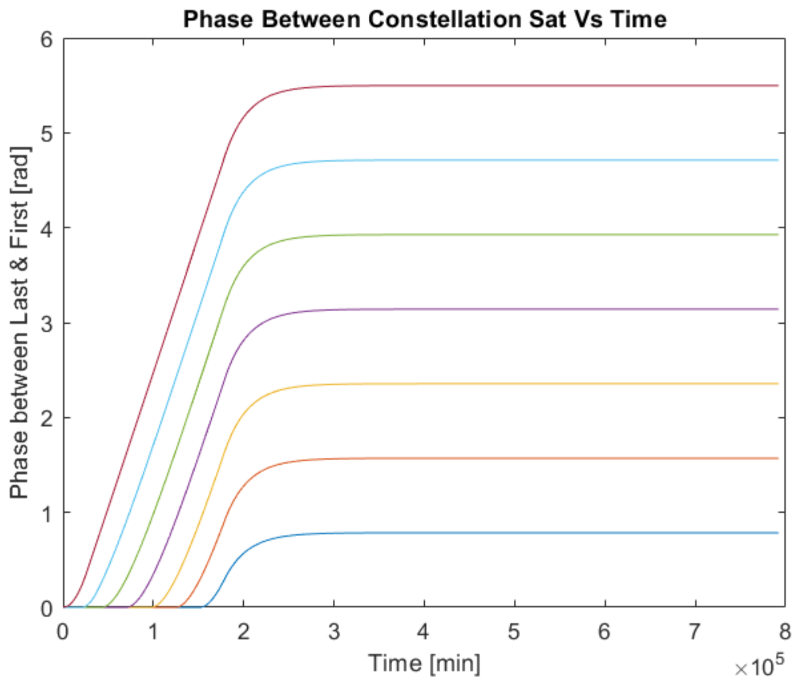


Figure 42 - Phasing Over Time (8 Sat General LEO)

It easy to notice how it keeps working enlarging the number of satellites. However, in this case, the difference in the *SemiMajor Axis* needed to obtain the right spread within the time chosen is $\Delta a_{need} = 2213\ m$

Since this could be too large, in the next scenario we will use a little bit larger time window.

Nine Satellite in an Optimized Orbit for ATM

Finally, we used the algorithm to spread nine satellites on a LEO optimized for our ATM purposes, with the following parameters:

$$\xi = (6978\ km\ , 0.02\ , 85°\ , 0°\ , 90°\ , 0°\ )$$

Time required to perform the maneuver set to 180 days.

To show the results we decided to use the same output of the previous scenario. In this case we enlarged the time window to perform the maneuver. Indeed, in this case, the altitude is quite higher, and also the satellite, are more than before. This could lead to a very large Δa to perform the maneuver, also due to the reduction of the density at that altitudes.

With the time chosen the $\Delta a_{need} = 1499\ m$ is definitely less than in previous scenario.

Following the plot obtained, we did not insert the Mean Anomaly at the beginning in this case since it could have been redundant but, for this case we decided to show the control profile as well, of the all satellites and also of the first one, zoomed one. This because, the control profile plot is not that intuitive and the behavior is quite similar among the different cases we took as an examples.

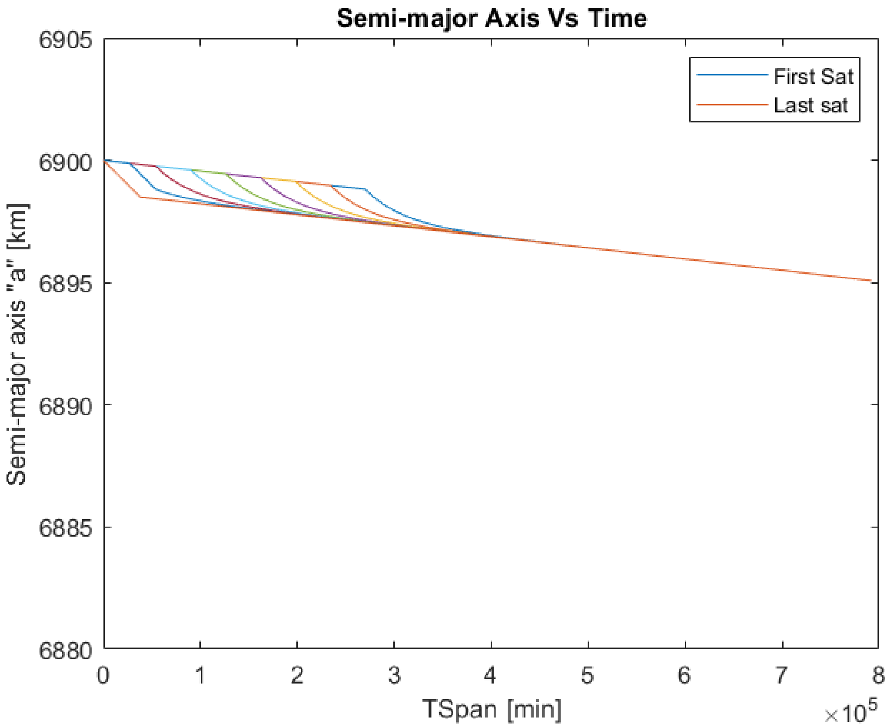


Figure 43 - SemiMajor Axis Vs Time (9 Sat , ATM Optimized LEO)

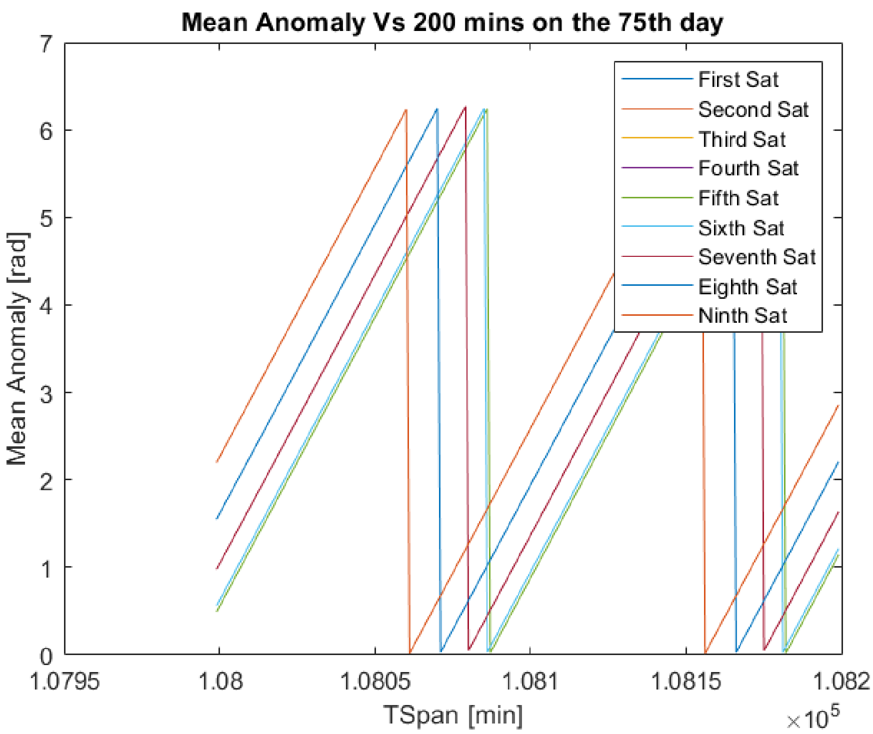


Figure 44 - Mean Anomaly Vs 200 mins after 75 days (9 Sat , ATM Optimized LEO)

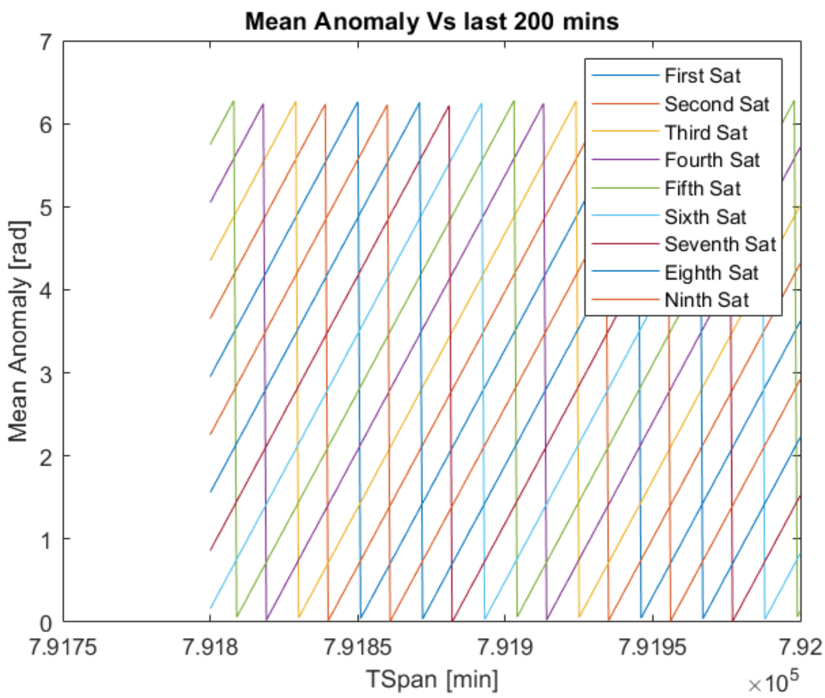


Figure 45 - Mean Anomaly Vs Last 200 Mins (9 Sat , ATM Optimized LEO)

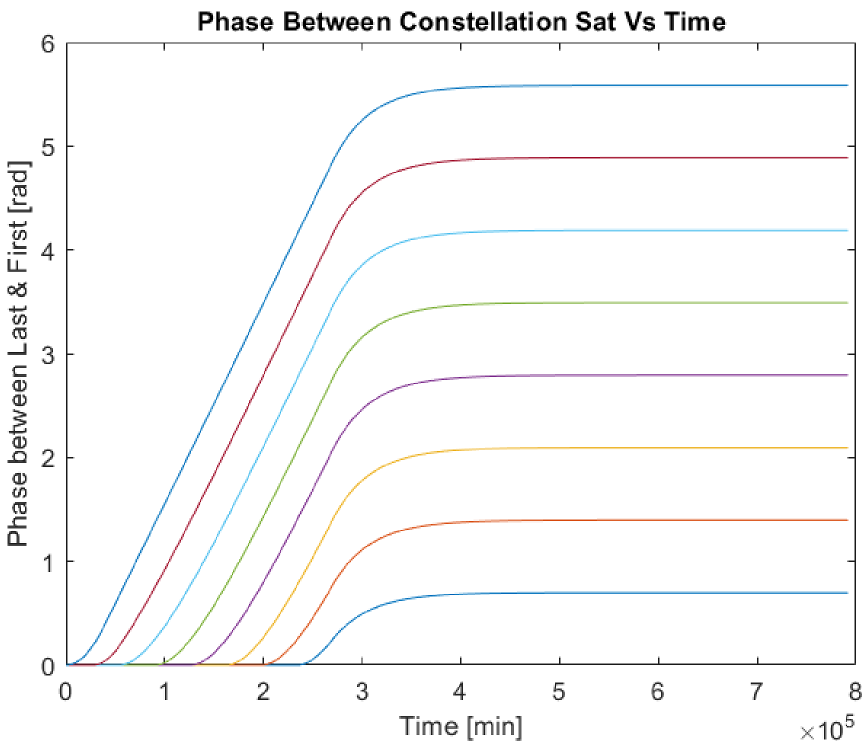


Figure 46 - Phasing Along Time (9 Sat , ATM Optimized LEO)

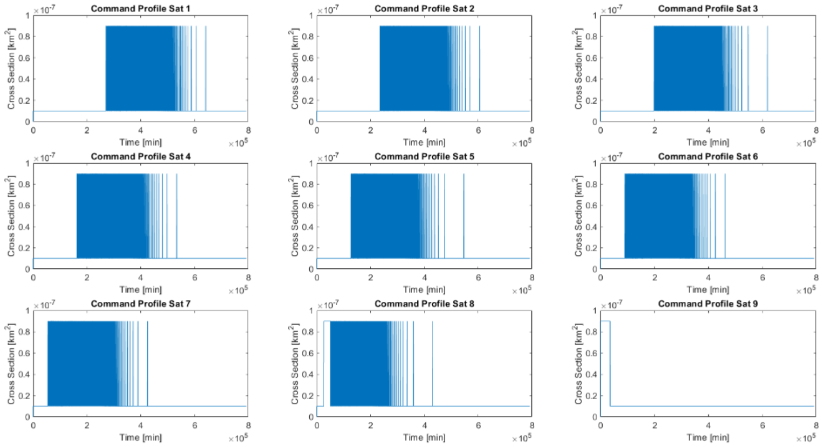


Figure 47 - Control Profile All Satellites

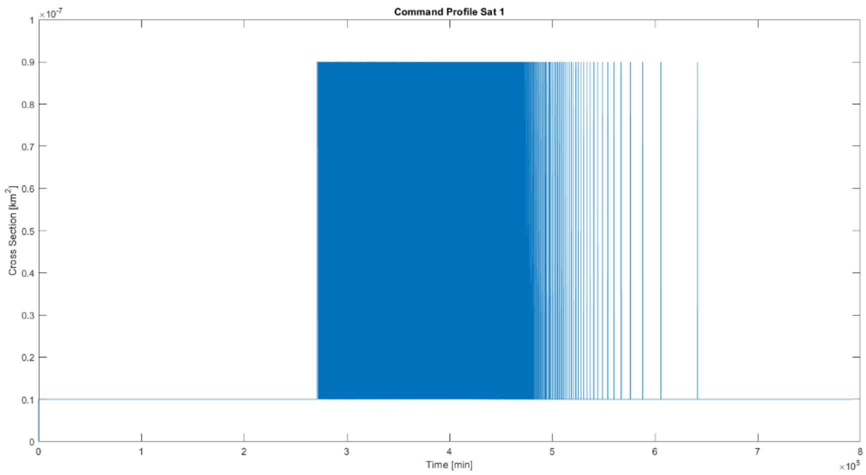


Figure 48 - Control Profile Sat I

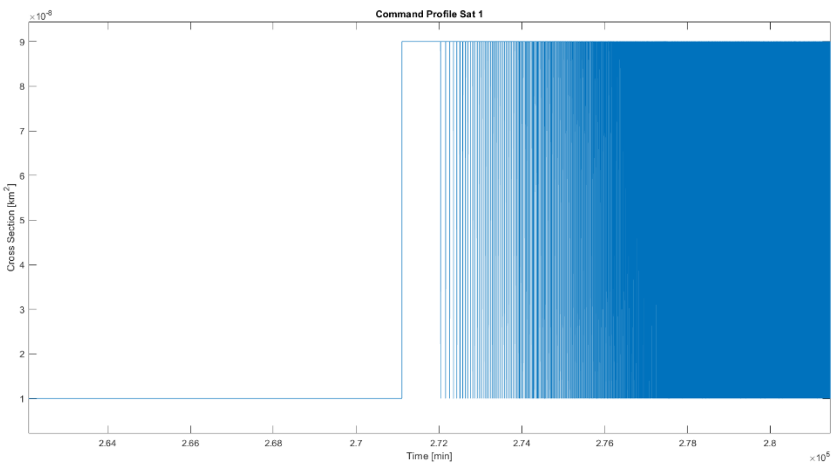


Figure 49 - Control Profile Sat I Enlarged

4. Technology State of Art

Educational purposes have been the first interests behind the CubeSat development, with the most of them being developed as universities projects, since them were simple in construction and affordable in prices. Nevertheless the exploiting of low cost sensors and Commercial-of-the-Shelf parts, made progressively more and more interesting the cubesat field, also in the eyes of the companies and the private sector, since them start to allowing many task that previously needed multimillion euro framework, to be accomplished by these nanosatellites, at a small fraction of the original cost and in a more reliable way, since as mentioned, the loss of an unit in a cubesat constellation, almost never lead to the mission's failure.

The term CubeSat is used to describe a particular class of nanosatellite, the one based on a common standard, whose basic units is a 10cm edge cube, 1U. Putting several basic units together lead to several CubeSat possibilities, like 2U, 3U (the most widely used), 6U and so on. Each unit can host several payload, ADCS, OnBoard Propulsion System. The standardization of the vector lead to a standardization of the deployment systems as well, enabling the possibility to have multiple launch possibilities as secondary payload, on the most common launches.

4.1 Launch Possibilities

Aiming to save in fuel costs and multiple launches, several Constellation Deployment Strategies have been studied. At first, using the Differential Air Drag control, we were able to spread our satellite in the launch orbit, without any need of propulsion but rely on the altitude and orbital parameter provided by the launcher.

On the other hand, our mission cannot be accomplished using one single orbital plane and the small size of cubesats does not allow the presence of huge propulsion capability onboard, that the orbital plane change, usually requires. An interesting approach could be the use of the Nodal Precession effect, caused by the natural orbital perturbations, to spread our orbital planes in RAAN.

Unfortunately, the nodal precession strongly varies according to the inclination of our orbits, and for our objectives, an high inclination is required, leading to a small nodal precession effect. To let then our satellites spread in RAAN in an acceptable amount of time, an huge difference in altitude will be required. Using one single launch, the only possibility would be the use of a new launcher system, called SHERPA, a kick stage developed by Andrews Space. Riding atop the final stage of the launcher, the space tug will be able to provide an additional impulse able to spread in altitude our satellites.

Using the differential air drag between the satellites in bigger orbit and in the lower one, we will be able to slowly decrease their semimajor axis, in order to decrease the relative nodal precession velocity to zero. Of course, if we would leave our satellite on orbits with different semimajor axis, we will obtain the spread in RAAN needed, but this will periodically come back to zero.

4.2 On-Board Propulsion

At the very beginning, nanosatellites were not provided with onboard propulsion system. Only recently them started to include propulsion system, starting with the CanX-2, 2008. A 3U CubeSat, provided with a cold gas propulsive system, able to generate a thrust of 35 mN with a $\Delta V = 35\frac{m}{s}$, weighting 500 g. The major part of the “nano” propulsion system nowadays are simply based on the miniaturization of the traditional ones, especially for col-gas systems, actually very popular thank to their simplicity, that directly translates into reliability.

Hot-gas systems could be used as well, to provide bigger impulse, like the STAR thruster proposed by ATK company, for the 1U topology, able to provide a thrust of 170 N and a ΔV of 1.3 km/s . On the other hand, chemical rockets offer a very low degree of flexibility and not that efficient, overall. To improve the flexibility, several array based systems have been proposed.

An innovative and "futuristic" concept, is definitely the usage of the electric propulsion thrusters, that are increasingly becoming popular. These seems to be a natural solution for the CubeSats, since them are able to provide incredibly high specific impulse, allowing the reduction of the storage of onboard propellant mass. On the other hand, the thrust developed by these systems is usually very low and this, that could be a problem for the bigger satellites, could be completely forgettable as in the CubeSat usage, the mass to be pushed, is order of magnitude lower. Within this category, the most important systems are base on the Lorentz force, for the Pulsed Plasma Thrusters, and the Hall Thrusters.

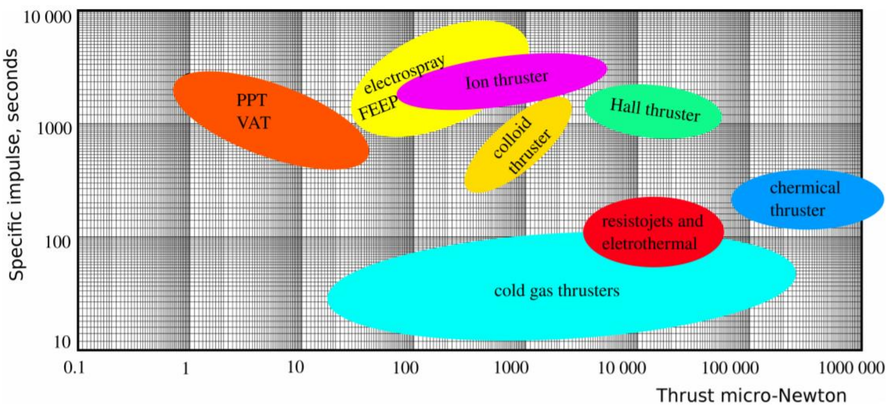


Figure 50 – On Board Propulsion Systems Comparison

4.3 Space Based ADS-B System

The Automatic Dependent Surveillance – Broadcast signal is a periodically transmitted set of data, automatically transmitted by the aircrafts Mode-S transponder at 1090 MHz, containing aircrafts IDs, position and velocity. Usually received by ground station and used for air traffic control matters. Nowadays this system is the state-of-art for the major part of the commercial and high performance aircrafts, with recent EUROCONTROL and FAA indications that make mandatory for all high performance aircraft to be equipped with an ADS-B transponder, before 2020. The ADS-B system is designed to provide an 80NM range, leading to a difficult to use it over oceans and large land areas with limited infrastructure coverage.

Indeed, the Space Based ADS-B is the concept to use Low Earth Orbit satellite to receive packages to relay them to ground stations or other stakeholders, possibly trough the use of Geostationary communication Satellites. Among the two concepts now available, we worked on the On-line one, meaning in one medium fleet of satellites connected real-time to air traffic control infrastructure via geostationary data relay, against the Off-line one, which, for a smaller investment, would lead to a post-processed study of the datas collected during the operational life of this smaller fleet, leading anyway to an improvement of en-route calculations and an increase air space efficiency.

On the other hand, the online concept, requiring bigger investment, would be able to provide global full-time situational awareness of the air traffic situation, helping in search and rescue situation, determining the route of aircraft whenever them would be outside of radar-covered areas and helping the operational air traffic control, allowing significant reduction in the inter aircraft spacing, providing benefits in terms of fuel consumption and flight time.

4.4 GOMX Platform and AD modification

As an example bus we decided to use the 2 kg GOMX-1 satellite, with payload for air traffic monitoring from Space, with a mission aiming to the demonstration of the capability to receive ADS-B signals broadcasted by aircraft, by nanosatellite platform. The payload was composed of a deployable helical antenna linked to an ADS-B receiver module. Antenna was tuned to 1090 MHz, design frequency for ADS-B signals and was 40cm long when deployes. Before stopping working after

6 months operational life, the GOMX collected over 3.5 million Mode S Frames, containing position/velocity data.

Focusing on the platform, it was composed of COTS products from GomSpace, including power system based on 30% efficient cells, UHF communication and magnetically actuator on 3-axis. A 2U Cubesat with deployable UHF antennas for telecommanding and telemetry and a deployable helical antenna for the reception of the ADSB signal. The payload antenna will be Nadir pointing all times, thanking to the autonomous 3-axis ACS, based on magnetic actuation and ADS composed by sunsensors, magnetometer and rate-gyros.

In our project we slightly modified this version, using a 3U Cubesat, provided by deployable solar panel. This not only will lead to an increased power capacity, but will allow an increased difference in the cross sectional area of our platform, in the different drag-profile. Indeed, while with the GOMX-1, the maximum ratio between high and low -drag profile was just 2, in our case the maximum ratio will be 9, using a 3U cubesat with deployable solar panel.

4.5 Antenna Specification

Even if it was not the first not the only example of Space-Based ADS-B communication, we decided to base our research on the GOMX, being it the first Cubesat which tried to accomplish these objectives. The main payload has been indeed a deployable helical antenna, with, as mentioned, 10 dB of gain at ADS-B working frequency of 1090 MHz. As we talked about, ADS-B signals have been designed to work with a nominal range of 80NM, leading to the need to compensate the dramatically increased path-loss, with high sensitivity RF front-end, able to provide amplification and a first down-conversion of the signal. Follows the FPGA that samples, decoding, the signal, finally ready to be stored and utilized.

Following, the Antenna specifications:

- Helical Shaped Antenna

- 40 cm length – deployed
- 10 dB of Gain
- 1090 MHz Tuning Frequency
- 9 cm of Diameter

5. Conclusion

In this thesis we tried to deal with two different but coupled problems. At first we tried to go through the so-called Pre-Phase 0, to design, according to our design drivers related to the mission's objectives, like Area of Interest, Maximum Allowed GAP, several constellation able to fulfill the mission's requirements, proposing different possibilities and qualifying them utilizing several factors, like the satisfaction of the ICAO criteria, the deployment costs, the connection and coverage quality, ending up with the solution which could fit our problem the best.

At second instance, we faced a new Orbit Control Concept, especially useful with nanosatellites, in general provided with little onboard propulsion capabilities: the *Differential Air Drag Control Concept.* We designed and implemented an Algorithm, useful both to judge the feasibility and the applicability of this concept to the characteristics of our Cubesats and our mission, providing timing, orbit degradation features and control profile needed to satisfy our need, within certain amount of times. This algorithm could indeed be useful to study the impact of the time we would need to deploy our constellation, on the orbit itself, to better choose a proper solution.

Possible future improvements for this work, could be the perfection of the Control Algorithm, introducing, as an example, better density changes profiles with the decreasing altitude, a focus on the Antenna Design and Specifications or on the Mission Launch and Initialization.

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