COBEM 2023
27TH INTERNATIONAL CONGRESS OF MECHANICAL ENGENEERING

ABCM
Brazilian Society of Mechanical Sciences and Engineering
27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-0317
OPTIMIZING COMMUNICATION FOR CATARINA CONSTELLATION´S NANOSATELITES

Guilherme Peinador Gomes [1]
guilherme.peinador@grad.ufsc.br
Rafael Gigena Cuenca [1]
rafael.cuenca@ufsc.br
Damylle Cristina Xavier Donati [1]
damylle.xavier@t2f.ufsc.br
Rodrigo da Silva Cardozo [1]
rodrigo.cardozo@t2f.ufsc.br
Talita Sauter Possamai [1]
talita.possamai@ufsc.br
[1] Federal University of Santa Catarina and Estr. Dona Francisca, 8300 - Bloco U - Zona Industrial Norte, Joinville - SC

The Brazilian Data Collection System (SBCD) comprises geostationary satellites and a series of devices and ground stations available to operate with such space systems in order to acquire data, mostly environmental, and feed climate and defense analysis in the Brazilian territory. However, the high cost of large satellite projects prevents the large-scale production of these systems, which, together with the restrictions on the availability of mostly national communication protocols, shows the tendency of the SBCD to become obsolete in the coming decades. Under this scenario, the Catarina Constellation project was created, to develop a constellation of nanosatellites that could be added to the SBCD, to lower the cost of replacing space systems, foster the Santa Catarina space industry and strengthen the relationship of the so-called triple helix, formed by industry, government and universities. However, for such a constellation to efficiently replace possible geostationary satellites, mission requirements must be fulfilled considering crucial design and operation variables for the constellation's operation, such as the number of satellites, chosen orbit parameters and launch time windows. In order to optimize communication between the satellites of Catarina Constellation's Fleet A and its designated earth stations, initially the ground station of Natal/RN, a genetic algorithm orbit optimization was conducted for a CubeSat. Using inclination, satellite altitude and the right ascension of the ascending node of each satellite as design variables. The genetic algorithm uses the roulette selection algorithm with single-point crossover and mutation to define the offspring and elitism to ensure that the best solution was kept during the generations, in order to decrease the computational cost, the evolutionary differentiation strategy was used. After analyzing the scenarios involving one variable and one satellite, two variable and one satellite, three variables and two satellites, and four variables and three satellites, it was deduced that inclinations proximate to zero degrees are associated with improved communication times. If interference between CubeSats is excluded, the total communication time is the sum of each satellite's individual communication time.

Keywords: *Catarina Constellation, nanosatelite, orbital mechanics, genetic algorithm, communication optimization*

1. INTRODUCTION

At the beginning of the twentieth century, the study of rockets started (Tsiolkovsky, 2004), and since then, satellites demonstrated great importance to communications (Evans *et al.*, 2011), but only in 1970 did the term satellite constellation was introduced (Walker, 1970).

When compared to a single satellite, a constellation provides several better points (Savitri *et al.*, 2017), although, to describe the path of the constellation are necessary six additional parameters per satellite, eccentricity (e), semi-major axis (a), inclination (i), Longitude of the ascending node (Ω), argument of periapsis (ω) and the true anomaly (θ) (Curtis, 2015). There are different types of constellations, such as Delta patterns (Walker, 1970), Rosette constellations (Ballard, 1980) and Streets of Coverage (Lueders and Ginsberg, 1974) and it is possible to compare the efficiency between each one of the constellation types considering the need for site-specific orbits of interest, the choice of a launch vehicle, the robustness of the satellites, the need for communication between satellites, and the need to mitigate collisions with space debris (Lang and Adams, 1998). To reduce the launch cost and have more release availability, symmetrical constellations are considered for this investigation.

In the last decades, the use of satellites has been reduced with the increase of nanosatellites and smaller satellites, motivated by the miniaturization of digital circuits and resulted in the reduction of size and mass, allowing the decrease in the launch price, because so, the nanosatellites started to be affordable to universities and private companies (Kramer and Cracknell, 2008; Bouwmeester and Guo, 2010; Heidt *et al.*, 2000; Waydo *et al.*, 2002). Despite the cost reduction, nanosatellites are not capable of having an efficient propulsion system because of their size, which makes it unable to perform great maneuvers, so they are limited to natural orbits (Abdelkhalik and Gad, 2011; Cappelletti *et al.*, 2020).

This inability to make maneuvers indicates the importance of choosing the best orbit. Based on the literature review, diverse authors conducted studies on the design and optimization of nanosatellites constellation systems (Abdelkhalik and Gad, 2011; Lewis, 2021; Marsili-Libelli and Alba, 2000; Melaku and Kim, 2023; Meziane-Tani *et al.*, 2016; Savitri *et al.*, 2017). For the problem of optimization, the most used approach is the evolutionary algorithm, which is highly inspired by the work of Charles Darwin, the Darwinian natural selection theory for evolution (Darwin, 2004). There are several types of evolutionary algorithms, two examples are: genetic algorithms, presented in the investigation Goldberg and Goldberg (1989), and genetic programming, used in the investigation Koza and Poli (2005).

This paper discusses the optimization process for a nanosatellite constellation for regional coverage without inter-satellite links (ISLs), and, to perform the orbit optimization process, the genetic algorithm is adopted. The objective of the mission is in the first moment to ensure the occurrence of communication with the antenna (a single objective genetic algorithm).

2. MISSIONS DESIGN

The mission of Constellation Catarina is to launch a constellation of nanosatellites with missions ranging from data collection to Earth imaging defined by stakeholders of each smaller set of nanosatellites called fleets. Constellation Catarina Fleet A is composed of two CubeSats (2U and 3U) and is a data collection mission developed by the Federal University of Santa Catarina (UFSC) and the SENAI Institute for Innovation in Embedded Systems (ISI-SE) with support from the Brazilian Space Agency (AEB). The general objective of Constellation Catarina is to promote the aerospace industry in the state of Santa Catarina and to train human resources, using the tripod that involves AEB, UFSC, and ISI-SENAI (Donati *et al.*, 2022) while providing services to contribute to the SBCD system.

For the present work, the optimization process considers the communication between the CubeSat and the Natal Multi-Mission Station, located in Natal - RN with the following coordinates -5.8717778^o N, -35.206864^o W.

3. OPTIMIZATION FORMULATION

Because the main objective of the mission of the fleet A is to ensure communication with the ground station, the optimization problem to be resolved consists in maximize the communication time fraction in relation to the flight time, t_{com}/t_{flight}, been t_{com} the total communication time of the constellation and t_{flight} the total flight time of constellation. To do so, each satellite orbit is simulated individually and the communication time series is evaluated for each satellite. Each communication time series is used to compose the total time communication of the constellation without duplicity when multiple satellites are communication at same time.

A total of 4 cases was investigated:

Table 1. Cases investigated

Case	# Sat	# Variables
1	1	i
2	1	i, SMA
3	2	i, SMA, $Raan_2$
4	3	i, SMA, $Raan_2$, $Raan_3$

where i is the orbit inclination, SMA is the semi-major axis, $Raan_1$ is fixed in 0^o, $Raan_2$ and $Raan_3$ are the right ascension of the ascending nodes for the second satellite 2 and 3, respectively. The restrictions applied to the optimization are the upper and lower bounds to the variables and they are the same for every case. That limits are:

Table 2. Variable Upper and Lower Bounds

Variable	Lower Bound	Upper Bound
i	0	180^o
SMA	6850	7200
$Raan_2$	0^o	360^o
$Raan_3$	0^o	360^o

In order to solve the optimization problem, it was chosen the genetic algorithm as solver (Confessore *et al.*, 2001; Goldberg and Goldberg, 1989; Marsili-Libelli and Alba, 2000; Melaku and Kim, 2023; Meziane-Tani *et al.*, 2016; Petrovski *et al.*, 1998; Savitri *et al.*, 2017; Thengade and Dondal, 2012). This algorithm is stochastic and uses the natural phenomena of genetic inheritance and Darwinism for survival, and borrows the vocabulary from genetics. Each time the algorithm runs on a population of chromosomes a multi-directional search is performed in a potential solution space. This search must balance two objectives: find the best solution and search the whole space (Michalewicz, 1996).

It was chosen the GA implementation available by Pygad library (Gad, 2021). The GA selected has the following parameters: a population of 20 individuals, random mutation with 10% probability, 3 individual elitism, single-point crossover, Steady State Selection (Goldberg and Deb, 1991) and a maximum of 100 generations. For this paper, ten optimization processes were performed with different seeds of implementation.

4. PROBLEM FORMULATION

From the two-body problem, it is possible to write each of the six orbital parameters as ordinary differential equations taking into account their variation due to perturbation, these equations are called planetary Lagrange equations. The Gauss equations from the Lagrange format avoids that the perturbations are conservative and its premise is to derive in time the algebraic equations that determine the six orbital parameters mentioned above, resulting in the set of Gauss equations (Curtis, 2015).

$$\frac{dh}{dt} = rp_s \tag{1}$$

$$\frac{de}{dt} = \frac{h}{\mu}\sin\theta p_r + \frac{1}{\mu h}[(h^2+\mu r)\cos\theta + \mu e r]p_r \tag{2}$$

$$\frac{d\theta}{dt} = \frac{h}{r^2} + \frac{1}{eh}\left[\frac{h^2}{\mu}\cos\theta p_r - \left(r + \frac{h^2}{\mu}\right)\sin\theta p_s\right] \tag{3}$$

$$\frac{d\Omega}{dt} = \frac{r}{h\sin i}\sin(\omega+\theta)p_\omega \tag{4}$$

$$\frac{di}{dt} = \frac{r}{h}\cos(\omega+\theta)p_\omega \tag{5}$$

$$\frac{d\omega}{dt} = -\frac{1}{eh}\left[\frac{h^2}{\mu}\cos\theta p_r - \left(r + \frac{h^2}{\mu}\right)\sin\theta p_s\right] - \frac{r\sin(\omega+\theta)}{h\tan i}p_\omega \tag{6}$$

where $r = \frac{h^2}{[\mu(1+e\cos\theta)]}$ and p_s, p_r and p_ω are the perturbations.

From the initial orbital parameters, defined by the mission, it is possible to integrate the system of ordinary differential equations and find its variation with time. For this, an ODE integration package in Python called ODEINT, based on a FORTRAN library, was used. It is known that for LEO orbits, the two most prominent perturbations are the dynamic drag and the perturbation due to the flattening of the Earth. The combination of these generates angular velocity and the loss of motion energy, causing the nanosatellite to re-enter the atmosphere. Figure 1 shows the area of a satellite's view of the Earth. This circle is called the access area and represents the entire surface that the satellite can communicate and/or observe.

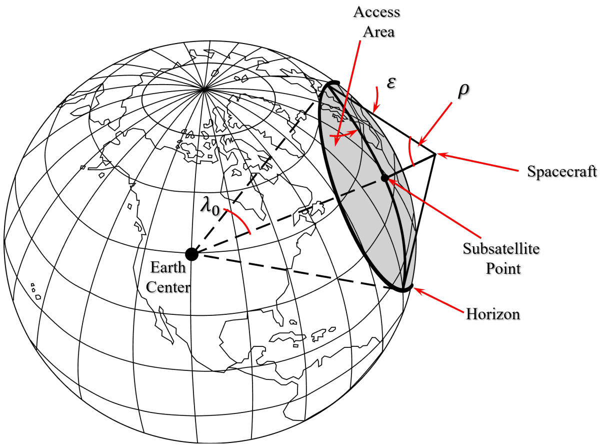

Figure 1. Relationship between geometry as seen from space and from the center of the Earth.

From Fig. 2, we take the vectors from the center of the Earth to the satellite (VTS = Earth radius + altitude), from the center of the Earth to the ground station (VTG), and from the satellite to the ground station (VSG). From this triangle formed, a communication criterion (γ) is the angle between the VTG and VSG vector has to be greater than 90°plus the minimum elevation angle of the antenna of the ground station.

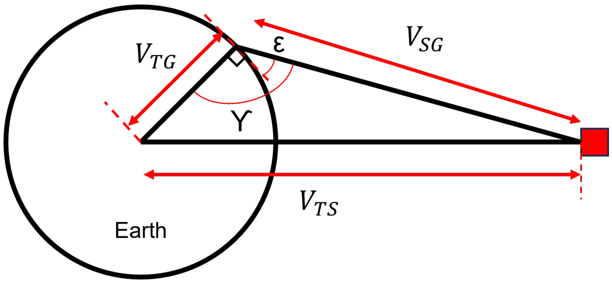

Figure 2. Relationship between the angles of the satellite, target, and center of the Earth.

In the case of this study, the ground station in Natal has a minimum elevation of 15°for valid communication, and applying the trigonometry from Fig. 2, the minimum angle is equal to 105°. In Eq. 7 the communication criteria is applied to the Natal ground station:

$$\gamma = \pi - \arccos \frac{\vec{V_{TS}} \cdot \vec{V_{SG}}}{|\vec{V_{TS}}||\vec{V_{GS}}|} - \arccos \frac{\vec{V_{TG}} \cdot \vec{V_{TS}}}{|\vec{V_{TG}}||\vec{V_{TS}}|} \geq 105° \quad (7)$$

This equation is solved for each step of the orbital propagator and, if it satisfies the communication condition, it is considered that there is communication and is added to the total CubeSat communication time serie. At the end of the simulation, this information is used to calculate the communication time fraction, used in the optimization process.

In order to validate the propagation code and the calculation of the CubeSat communication fraction, the results obtained were compared with the simulation data in the GMAT software. For this, the same initial data from the orbital propagation code was entered into GMAT and the total communication time and communication fraction in both cases were calculated and the difference between the two results was around 2%.

5. RESULTS AND DISCUSSIONS

Because the computational cost is a concern, first it was evaluated the minimum number of simulated orbits needed to have an accurate communication time fraction reliable. In Fig. 3 it can be seen for 3 different inclinations, that for 300 orbits the mean communication fraction presents an asymptotic behaviour.

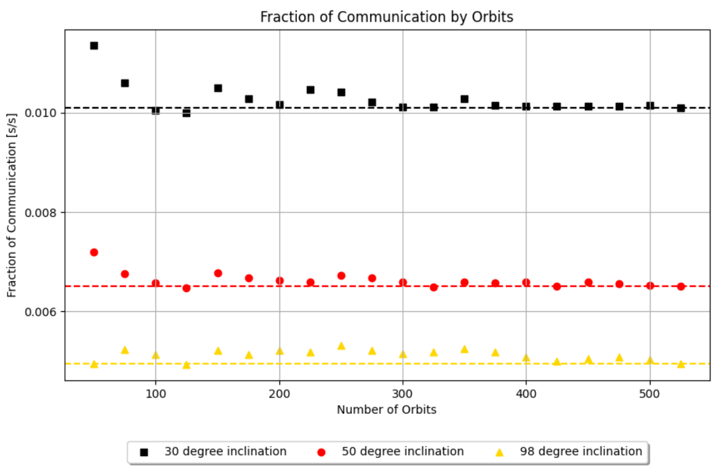

Figure 3. Fraction of Communication by orbits

For a first optimization, only the orbits inclination was used as its variable, as defined in Tab. 1, bounded by the limits defined in Tab. 2. The GA optimization was performed for 10 random different seeds and theses evolution are presented on Fig.4. That evolution shows the change in the best solution found by the GA. Only 100 generations was needed to find the best time fraction as 6.6% for a inclination of 178.5^o.

From the analysis of Fig. 4, it can be seen that beside the different first generation solutions, all running converged to a very close value after the 100^{th} generation.

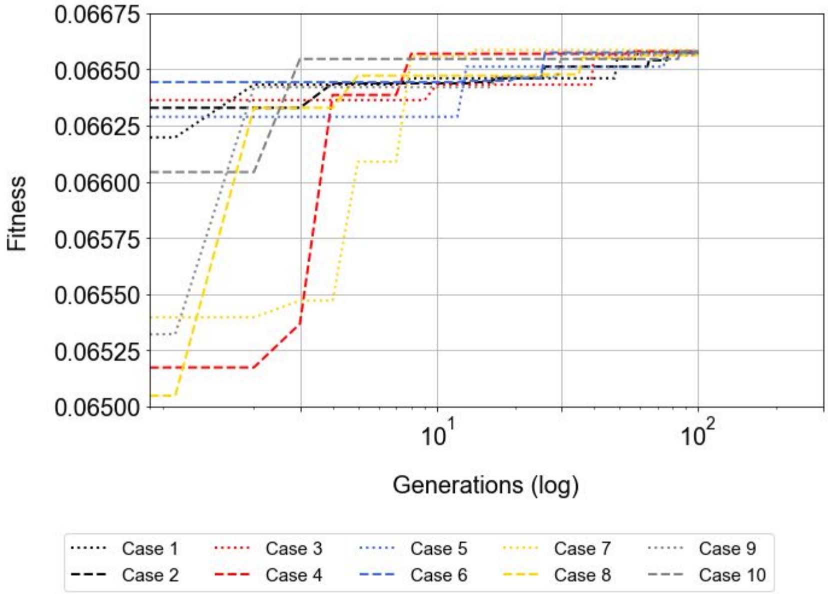

Figure 4. Best Fitness Evolution

5.1 Analysis with two variables and one satellites

For this initial scenario, the optimization parameters consist of the inclination and semi-major axis (SMA). Fig.5 depicts the correlation between inclination and fitness. The symmetry of this relationship at a 90-degree angle is evident, with the best fitness values being very close to 0 and 180. This is because the antenna's proximal location to the equator necessitates an orbit inclination of approximately 0 degrees, ensuring optimal communication time. In Fig.6, the line represents the mean value of the Optimizations' fitness of the 10 runnings, and the error bars depict their standard deviation. Not surprisingly, the standard deviation reduces with he generations, indicating the Optimization convergence for the value of communication fraction about 8.37% for an inclination of 179.90^o and a SMA of 7199.84.

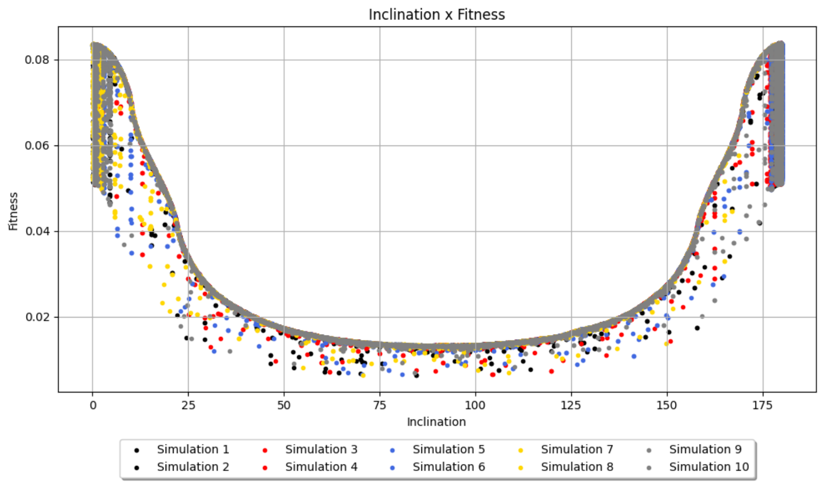

Figure 5. Inclination x Fitness

5.2 Analysis with three variables and two satellites

Examining the case of two satellites and three optimization variables according Tab. 1]. Fig 7 displays the tested Raan values and their corresponding fitness values across all simulations. A plateau is evident in the solution, as multiple Raan values exhibit the highest fitness. For $Raan_2$ in the ranges of 0^o - 40^o and 140^o - 180^o, the fitness behaviour is due to the simultaneous of the views of the two satellites, by the ground station. For values out of these ranges, when there is not simultaneous communication, the fitness equals the sum of the fraction of each satellite. In Fig. 8 displays the fitness mean value between the 10 runnings and it standard deviation. A significant standard deviation for the firsts generations

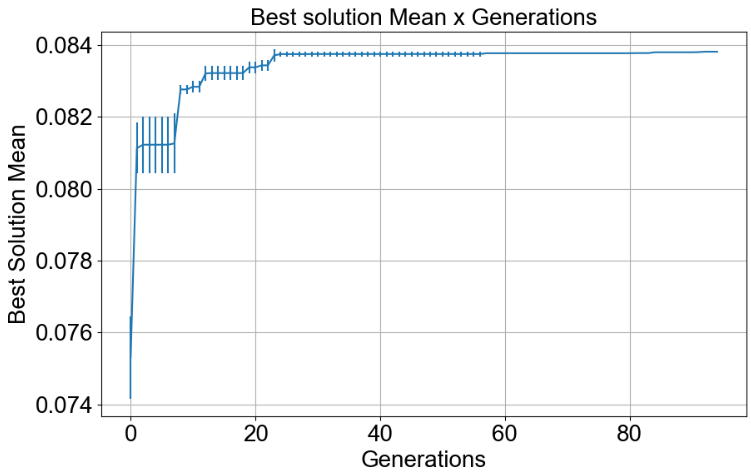

Figure 6. Best Solution

are observed in comparison with the 2 variables case, but after the twentieth generation, it has already converged with a 16.7% communication fraction for a inclination of 0^o , for a 7199km of SMA and a $Raan_2$ of 204^o.

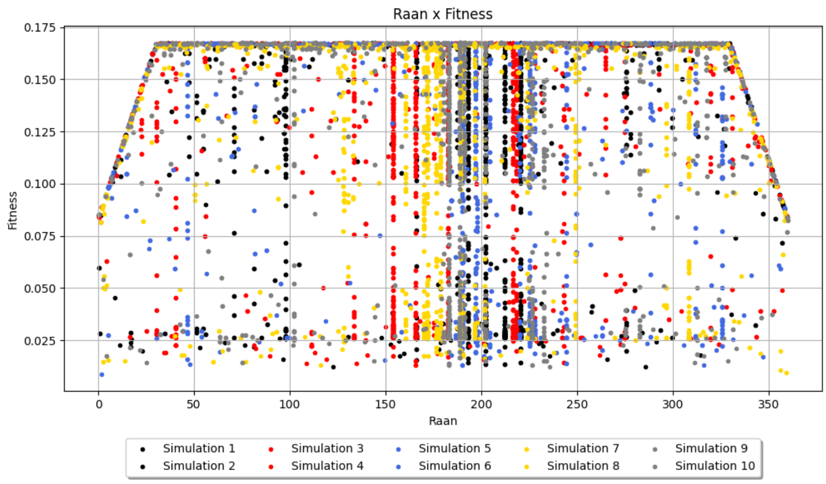

Figure 7. Raan x Fitness

The plot in Fig. 9 was generated to show the effect of the SMA on the communications fraction. To assess this impact, four simulations were performed using 30 degrees of inclination and changing the SMA to 6800, 6900, 7000, and 7100 kilometers. A direct relationship is observed between the orbit altitude and the communication fraction as the viewing area of the satellite expands with altitude. This outcome is consistent with expectations.

5.3 Analysis with four variables and three satellites

Now, let us analyze a situation with three satellites and four optimization variables - inclination, altitude, Raan of satellite two, and Raan of satellite three. The results of the algorithm's tested solutions were used to generate the ensuing graphs. Fig 10 displays the best solution's progression as the standard deviation decreases and converges at around 25% communication fraction for a 0^o, a 7199km SMA, a 177^o $Raan_2$ and a $309^o Raan_3$. Additional images could be produced, but they would be challenging to visualize due to the surface also has the interference illustrated in Fig 7.

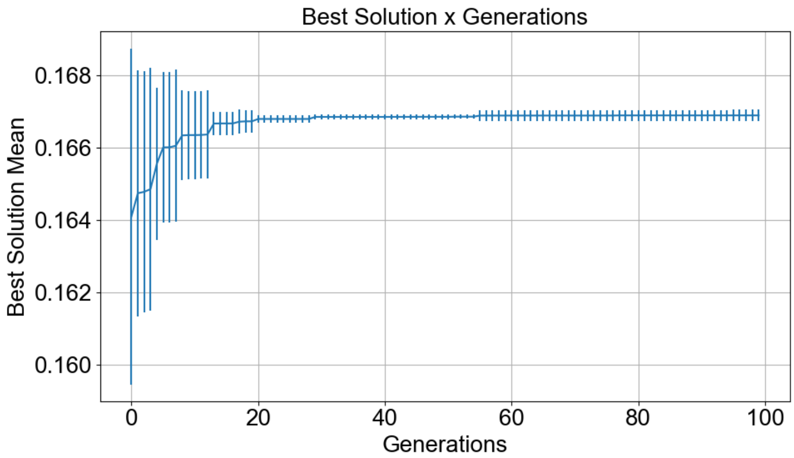

Figure 8. Best Solution

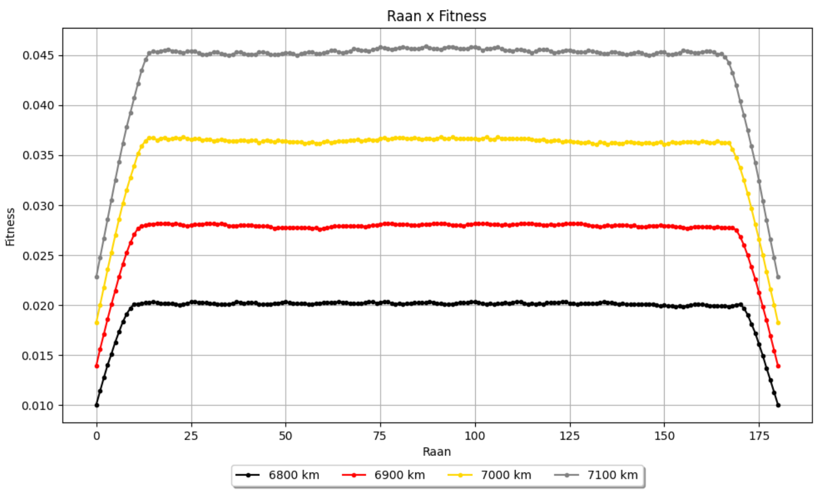

Figure 9. SMA Influence

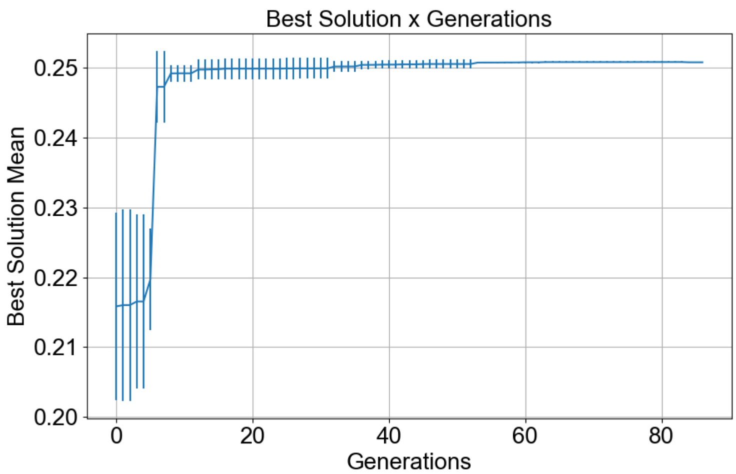

Figure 10. Best Solution

5.4 Comparing Results

All the results obtained during the simulations are outlined in Tab. 3.

The simulations indicate that the optimum inclination for communication is near zero or 180 degrees due to its sym-

Table 3. Comparing Results

# Case	1	2	3	4
# N^o of Variables	1	2	3	4
# N^o of Satellites	1	1	2	3
# Fraction of Communication	6.6%	8.37%	16.7%	25%
# Inclination	178.5^o	179.9^o	0^o	0^o
# SMA	6800 km	7199 km	7199 km	7199 km
# $RAAN_1$	0^o	0^o	0^o	0^o
# $RAAN_2$	–	–	204^o	177^o
# $RAAN_3$	–	–	–	309^o

metry at 90 degrees. Additionally, the semi-major axis (SMA) leads to maximum communication when its value is close to the upper boundary. The principal effect of the right ascension of the ascending node (RAAN) is the interference between two satellites. In this scenario, only one satellite is considered to have effective communication when two or more satellites are present in the communication area. Disregarding this case, maximum communication fraction necessitates separating the CubeSats, using a delta pattern similar to what was first discussed by Walker in 1970.

6. CONCLUSION

This article discusses the optimization of the orbit for the Catarina Constellation mission, focusing on communication between the CubeSat and the Natal Multi-Mission Station in Natal/RN. The aim is to optimize the orbit to correspond with the longest communication time during the total orbit time for maximum communication capacity.

To solve this problem, a code utilizing Gauss equations is employed to propagate the satellite orbit. This code is coupled with another verification code which utilizes trigonometry between the Cubesat and the ground station. It should be noted that the Natal Multi-Mission Station imposes a communication restriction with a 15 degree elevation. Subsequently, the genetic algorithm is utilized to optimize this objective whereby the inclination, the Semi-Major Axis (SMA), and the Right Ascension of the Ascending Node (Raan), each with its individual bounds, are considered as the optimization problem's variables.

In order to improve future work on orbit propagation, it is recommended to incorporate CubeSat decay and lifetime information. Additionally, provide information regarding the amount of passes and their respective communication times in order to analyze possible limitations on communication frequency.

7. ACKNOWLEDGEMENTS

We would like to thank the Laboratório de Computação Científica (LCC) at Universidade Federal de Santa Catarina (CTJ-UFSC) for providing computational resources.

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