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Design of Small Satellite Constellations for Data Communication

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Abstract. Constellations of satellites, in particular using small satellites, are very popular nowadays, because they give reduced costs and flexibility to missions. This paper considers the problem of designing a constellation of small satellites for data communication, which means getting data from platforms fixed on the surface of the Earth and sending them to ground stations using satellites. The goal is to maximize the observation times and minimize the interval between passages by these platforms and ground stations. The time evolution of the constellation under the effects of perturbation forces is also studied, and estimates of the number of new satellites that need to be added to the constellation to keep a constraint of maximum revisit time below one hour are made. After that, simulations of satellite failures allow verification of the new values for the observation times and the time between visits when the constellation loses some satellites, looking for the possibility of using this constellation even in case of failures.

1 Introduction

An important problem in Astrodynamics is to design constellations of small satellites to make communications between platforms scattered through the Earth's surface that send data to satellites that needs later to be downloaded to ground receiving stations. There exist several applications for this type of problem, such as monitoring temperature, rainfall, fires, humidity, etc.

To accomplish this mission, it is important to study some details, like the duration of the observation times, which is the time that the constellation can see the platforms and ground stations. It is assumed that the satellite can communicate with the platform or ground station every time it is within the visibility cone.

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It is also assumed that the satellites have memory. onboard to store the data, so it is not necessary to communicate with one platform and one ground station at the same time to send data.

Another important parameter is the time between two successive passages by a platform, which we will call “revisit time”. This definition is applied when considering the whole constellation and not individual satellites.

These problems have to be considered when preparing the mission design. In particular, the mission considered here has a first constraint of keeping the revisit time below one hour, for all the platforms used. This is done to simulate a condition where it is necessary to get data quickly to follow the parameters evolution with a minimum delay. But this may not be always the case, and missions may exist where the average time between visits is the most important parameter. This scenario will also be evaluated, in particular when failures of satellites are considered.

As far as platforms and ground stations are concerned, we decide to study this problem using three platforms in the Brazilian territory: Macapá, Natal and Uruguaiana. The reason for these choices is that they cover different latitudes of the Brazilian territory, from North to South, and the latitude is the main parameter when designing the constellation. To receive data, we considered that we have ground stations in Cuiabá and Alcantara, which are two locations with different latitudes and where there are real antennas in Brazil.

Looking at orbits of the satellites, it will be assumed that all the satellites will be initially in circular orbits with radius of 450 km, which is a usual altitude for small satellites. The inclinations of the orbits of the satellites have to be similar to the latitude of the point to be observed. If it is below that, the satellite will never see the point and, if it is much higher, the percentage of the time in visibility will be too small. This orbital parameter has a particular large impact in the revisit times.

Since we have platform and ground stations in different latitudes and the orbits of the satellites are very low, it is necessary to build one sub-constellation for each platform to be observed, and then to verify the time evolution of the percentage of time in communication with each platform and the ground stations, to see if the constraint of one hour maximum revisit time is followed and if there is enough time to download the data. It is assumed that data can be downloaded at any of the two ground stations. The fact that we will have satellites with different inclinations is challenging in terms of astrodynamics, because all satellites suffer orbital perturbations [1, 2]. The most important ones at low altitudes are atmospheric drag [3] and the flattening of the Earth [4]. Atmospheric drag is mainly a function of the altitude of the satellites and, since all the satellites start at the same altitude and have similar shapes and masses, it will act equally on all satellites and this perturbation will not change too much the geometry of the constellation.

Another important point is related to the flattening of the Earth. Its effects depend on the semi-major axis, inclination and eccentricity of the orbit. It is well known that this disturbance generates a circulation of the longitude of the ascending node and in the argument of perigee. The motion of the perigee is not important, because all the orbits are near circular, but the motion of the longitude of the ascending node modifies the geometry of the constellation, which affect mainly the revisit times.

Therefore, the present research has the goal of studying options for orbital constellations that can be used to make these communications and also as a study case to see the effects of failures of individual satellites [5] in the observation and revisit times, both in terms of maximum and mean values. The idea is to design a constellation of satellites [6] that meet the coverage limits in terms of revisit (time between two consecutive passes) and have good observation times (the times where the satellites communicate with platforms and/or receiving stations). The limit in terms of maximum interval between visits is used to simulate a condition of a mission that needs to keep the time evolution of the data collected with minimum delay of time. In some other cases, the mean revisit time may be even more important. This possibility will be considered when failures of satellites are under study. If necessary, the data showed in this research give results that can be used to redefine the constraint in terms of mean revisit time.

Therefore, this research should be able to help mission designers when proposing constellations of satellites to collect data, using an approach that is not available in the open literature.

2 Design of a basic constellation

A study was made to define the basic constellation to be used to solve this problem [7], where it was showed that the dynamics should include atmospheric drag, solar radiation pressure, lunar and solar perturbation and the flattening of the Earth. For the altitude considered for the satellites, the most important effects giving by the perturbation forces is an orbit decay and the regression of the longitude of the ascending node (Ω), which secular motion can be calculated by Eq. 2.1.

$$\dot{\Omega} = \frac{-3J_2R^2}{2p^2} nCos(i) \tag{2.1}$$

with J_2 the parameter that represents the flattening of the Earth (assumed to be 0.000108), R the equatorial radius of the Earth (assumed to be 6378 km), n the mean motion of the satellite, i the inclination, $p = a(1-e^2)$, a the semi-major axis and e the eccentricity. The atmospheric drag can be mathematically described by Eq.2.2.

$$a_d = -\frac{\rho v^2 C_d A}{2m} i_v \tag{2.2}$$

with a_d the acceleration due to drag, ρ the density of the atmosphere of the Earth, v the velocity of the satellite with respect to the atmosphere, C_d the drag coefficient (which defines the resistance to the flow given by the shape of the satellite), A the area of the cross section of the spacecraft, m the mass of the spacecraft and i_v the direction of motion of the satellite.

To be able to keep the constraint of maximum time between visits of less than one hour for the platforms selected (Macapa, Natal and Uruguaiana), 20 satellites are required for the constellation [7]. They are showed in Table **??**, where RAAN is the right ascension of the ascending node of the orbit of the satellite, *TA* is the initial true anomaly of the satellite, which is the initial location of the satellite in its orbit, and *i* is the inclination of the orbit of the satellite.

That information was obtained from numerical simulations of the whole constellation. We just used the idea that the satellites should be equally spaced in terms of orbital planes (to chose RAAN) and that the inclination should be a little bit higher than the latitude of the point to be observed.

3 Time evolution of the constellation

After having the initial constellation defined, it is important to make orbital propagation for all the satellites to see the evolution of the geometry of the constellation, in particular to verify how long time the constraint of maximum time between visits of less than one hour will hold, since this is the most important constraint of the mission. Tables 2 to 4 show this point. Table 2 shows the percentage of time with visibility (so communication) between the constellation and each platform and ground station used in the mission. It considers the constellation as a whole and do not emphasize which satellite is looking at the platform or ground station. As expected, Uruguaiana has smaller values, since it has the highest latitude and only the satellites that belong to the sub-constellation designed to

Satellite	RAAN	TA	i
1	0	0	0
2	0	180	0
3	0	0	7
4	0	180	7
5	120	120	7
6	120	300	7
7	240	240	7
8	240	60	7
9	0	0	31
10	0	180	31
11	72	144	31
12	72	324	31
13	144	288	31
14	144	108	31
15	216	72	31
16	216	252	31
17	288	216	31
18	288	36	31
19	300	30	31
20	300	210	31

Table 1: The Constellation

observe this platform can communicate with it. Natal can be observed by its own sub-constellation and sometimes by the satellites designed to see Uruguaiana, so it has the intermediate observation times. Remember that one satellite can see (so communicate) for some time with all the points with latitude smaller than its inclination, but never see points with latitudes higher than its inclination. Using this logic we can explain why Macapá has the largest observational times. Since it has the lowest latitude it can be seen by all the satellites of the constellation. Another important point to be observed is that the observation times with respect to the ground stations are of the same order of magnitude of the observational times of the platforms. If we consider that the platforms do not send data all the time and that the velocity to upload data is smaller than the download speed, we see that there is no problem of accumulating too much data onboard, even if there is no immediate passage by a ground station after getting the data, which occur only sometimes.

Table 3 shows the maximum revisit times (in minutes) for each platform and ground station for a period of one year. Since Macapa is observed by all the satellites, it has some small oscillations, but

Period	Alcantara	Cuiaba	Macapa	Natal	Uruguaiana
Days 0-30	9.50	2.29	9.71	7.08	5.35
Days 60-90	10.04	2.28	10.44	7.01	5.35
Days 150-180	9.90	2.24	10.29	6.87	5.26
Days 240-270	9.54	2.18	9.97	6.80	5.22
Days 330-360	9.37	2.15	9.85	6.61	5.13

Table 2: Percentage of observation times (%).

never exceeds the limit of one hour. On the opposite side, Natal and Uruguaiana has maximum revisit times that increase with time and, after about six months, they violate the constraint. It means that the control center of the mission needs to take some actions to avoid this situation.

Period	Alcantara	Cuiaba	Macapa	Natal	Uruguaiana
Days 0-30	49.37	235.77	47.96	49.06	48.58
Days 60-90	52.65	225.22	46.98	52.27	52.13
Days 150-180	57.58	223.49	45.49	57.22	57.11
Days 240-270	63.08	261.39	47.61	62.76	62.74
Days 330-360	68.95	232.34	47.00	68.54	68.84

Table 3: Maximum revisit times (minutes).

Table 4 shows the mean revisit times (in minutes) for each platform and ground station for the same period of one year. We see that there are no significant changes and all the values are much below one hour. It means that if we put the constraint of the mission as “to have a mean revisit time below one hour”, there would be no need to take actions to keep the constraint valid for one year.

Period	Alcantara	Cuiaba	Macapa	Natal	Uruguaiana
Days 0-30	18.56	78.45	20.04	26.01	37.35
Days 60-90	16.03	77.77	16.96	26.10	36.65
Days 150-180	16.15	77.92	16.96	26.28	36.94
Days 240-270	17.00	80.48	17.93	26.41	37.01
Days 330-360	16.94	79.48	17.60	27.07	37.04

Table 4: Mean revisit times (minutes).

Then, the only problem that we need to solve is the violation of the constraint of maximum revisit time below one hour. There are two choices to solve this problem. The first one is to make orbital maneuvers, which is considered in reference [7]. The conclusion is that fuel consumption is very small, but the satellites have to be more complex and more expensive to accommodate propulsion systems. The second choice, which is the main focus of the present paper, is to add more satellites to the constellation to fill up the gaps that appeared. To consider this possibility, we checked the orbital parameters of the satellites just before the time when the constraint is broken and then we insert some new satellites such that the constellation will have a better distribution. To find the number and locations of the new satellites to be added to the constellation we relied mostly in numerical propagation of all the satellites that belongs to the constellation. We inserted the new satellites in the largest gaps that the constellation has. We tried several numbers of satellites, starting from 1, until we got a number that gave revisit times below one hour. The results showed that it is necessary to add two more satellites focused in observing Uruguaiana e two more focused to see Natal. Table 5 shows the orbital elements of the new satellites to be inserted. Note that the orbital elements have to be the ones of the current orbit of the other satellites, after the decay, not the initial values. The satellites must be inserted on the dates 24-August, 31-August 2024, for the first two satellites, respectively, and 1-August 2024 for the last two satellites. The Keplerian elements (e = eccentricity, i = inclination, RAAN = right ascension of the ascending node, TA = true anomaly, a = semi-major axis) are, respectively, showed in Table 5.

e	**i (deg)**	**RAAN (deg)**	**TA (deg)**	**a (km)**
0.000535	6.963	346.96	59.324	6817.86
0.002252	6.99	52.07	35.146	6817.30
0.000847	31.06	42.71	282.375	6814.23
0.001181	30.91	164.22	329.658	6818.31

Table 5: New satellites to be inserted after 6 months.

After those insertions, there is no more violation of the constraints. Tables 6 to 8 show the percentage of observation times (%), the maximum revisit times (minutes) and the mean revisit times (minutes) after the insertion of the new satellites.

The results show that the observation times and mean revisit times improved for all the platforms and ground stations, as expected, since the old satellites are still working well. The revisit time decreases and they stay below the one-hour limit at all times, before and after the insertion of the new satellites. The new satellites improved the maximum revisit times by filling the gaps in the original sub constellations, caused by the perturbations that changed the geometry of the constellation. The possibility of sending new satellites before the constraint was violated was also studied, with the goal of having an idea on what happens if the satellites are available before the time limit of the break of the constraint. Since Macapa never had problems with the constraint, we are not adding any dedicated satellite to this region. For Natal and Uruguaiana, we tested the option of adding two more satellites to each sub-constellation in May 1, four months after the initial deployment of the first satellites, instead of waiting six months. By looking at the time evolution of the satellites it is possible to see where to insert the satellites such that the constellation will have a better distribution. The main idea is to

Period	Alcantara	Cuiaba	Macapa	Natal	Uruguaiana
Days 0-30	9.50	2.29	9.71	7.08	5.35
Days 60-90	10.04	2.28	10.44	7.01	5.35
Days 150-180	9.90	2.24	10.29	6.87	5.26
Days 240-270	13.04	2.53	11.56	8.73	6.08
Days 330-360	12.17	2.50	11.27	8.34	5.97

Table 6: Percentage of observation times (%) after insertion of new satellites.

Period	Alcantara	Cuiaba	Macapa	Natal	Uruguaiana
Days 0-30	49.37	235.77	47.96	49.06	48.58
Days 60-90	52.65	225.22	46.98	52.27	52.13
Days 150-180	57.58	223.49	45.49	57.22	57.11
Days 240-270	34.71	233.20	47.61	48.72	52.99
Days 330-360	40.85	230.22	47.00	49.09	54.74

Table 7: Maximum revisit times (minutes) after insertion of new satellites.

Period	Alcantara	Cuiaba	Macapa	Natal	Uruguaiana
Days 0-30	18.56	78.45	20.04	26.01	37.35
Days 60-90	16.03	77.77	16.96	26.10	36.65
Days 150-180	16.15	77.92	16.96	26.28	36.94
Days 240-270	11.92	69.44	14.85	20.25	31.61
Days 330-360	13.23	68.03	15.45	21.57	31.68

Table 8: Mean revisit times (minutes) after insertion of new satellites.

place them where there are larger gaps in terms of right ascension of the longitude of the node. Table 9 shows the results.

After these insertions, we can verify the time evolution of the constellation. Tables 10 to 12 show the results. It is clear that the early insertion worked as good as the insertion made only near the limit of six months. So, it is possible to decide this point as a function of availability of satellites and launchers. One advantage of sending the satellites earlier is to be in the safe side with respect to failures, because there will be two more months with extra satellites in case of failures. Another advantage is that the observation times will increase and the mean revisit time will decrease.

One more point that needs to be considered now is to verify if there are frequent passes by ground stations to download data, so we can avoid storing too much information from the platforms in the satellites before having a chance of sending data to Earth. Figure 1 shows this type of result for a satel-

a (km)	e	i (deg)	ω	RAAN (deg)	f (deg)
6820.38	0.000881	30.87	305.28	307.62	277.50
6826.7	0.001630	31.03	100.59	68.678	69.98
6822.57	0.002198	6.77	240.12	303.23	325.33
6822.16	0.00232	6.99	125.56	180.00	326.85

Table 9: New satellites to be inserted after 4 months.

Period	Alcantara	Cuiaba	Macapa	Natal	Uruguaiana
Days 0-30	9.50	2.29	9.71	7.08	5.35
Days 60-90	10.04	2.28	10.44	7.01	5.35
Days 150-180	11.60	2.60	11.92	8.80	6.12
Days 240-270	11.13	2.53	11.53	8.68	6.07
Days 330-360	11.07	2.49	11.39	8.51	5.96

Table 10: Percentage of observation times (%) after insertion of new satellites in May 1.

Period	Alcantara	Cuiaba	Macapa	Natal	Uruguaiana
Days 0-30	49.37	235.77	47.96	49.06	48.58
Days 60-90	52.65	225.22	46.98	52.27	52.13
Days 150-180	57.58	220.37	40.59	48.17	51.47
Days 240-270	63.08	235.06	47.61	48.72	52.99
Days 330-360	68.82	230.22	47.00	49.09	54.74

Table 11: Maximum revisit times (minutes) after insertion of new satellites in May 1.

Period	Alcantara	Cuiaba	Macapa	Natal	Uruguaiana
Days 0-30	18.56	78.45	20.04	26.01	37.35
Days 60-90	16.03	77.77	16.96	26.10	36.65
Days 150-180	13.63	66.90	14.20	20.40	31.55
Days 240-270	14.45	69.21	15.01	20.59	31.59
Days 330-360	14.03	68.14	14.76	20.65	31.63

Table 12: Mean revisit times (minutes) after insertion of new satellites in May 1.

lite of the sub-constellation that observes Uruguaiana. The pink points show the time when we have communication of the satellite and Cuiaba, the green points show the time when we have communication of the satellite and Alcantara and the red points show the time when we have communication of the satellite and the platform located in Uruguaiana. It is clear that we have very frequent passages by both ground stations after every passage by the platform, so we can always download data. The situation is similar for all other satellites and platforms, but the results are not showed here to save space. The plot on the top is made for one year and the plot below for one day.

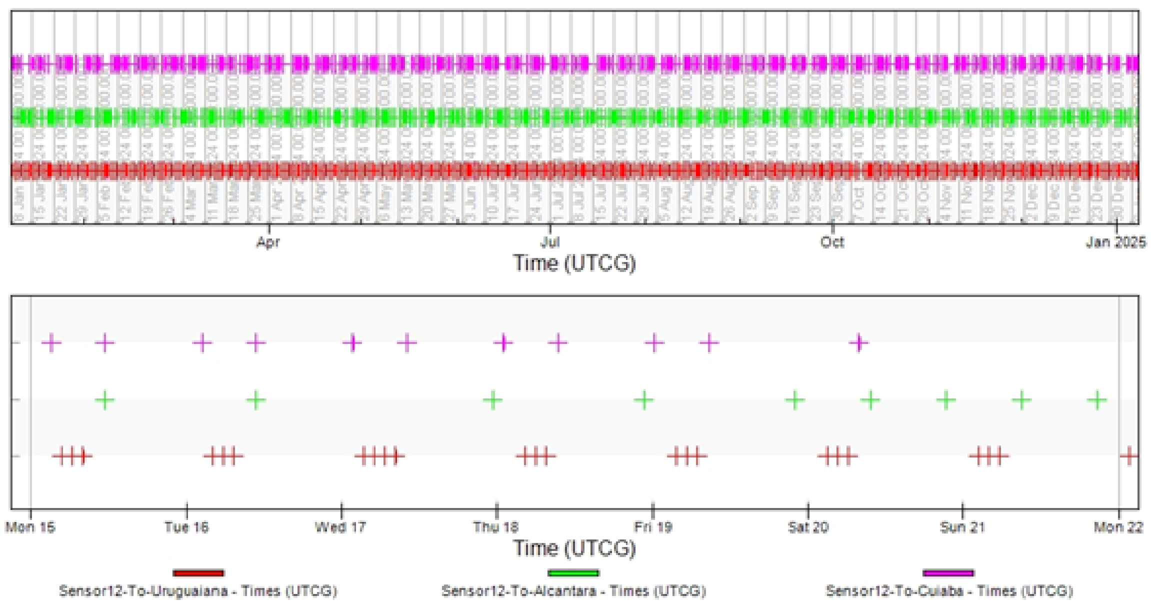

Fig. 1: Passages of one of the satellites observing Uruguaiana by Cuiaba (pink points), Alcantara (green points) and Uruguaiana (red points). Top: one year simulation, bottom: one day simulation

4 Results considering failures

The next step is to consider the possibility of failures in the satellites, which is a problem linked to validation and verification of Cyber systems, under development in the ADVANCE project [8, 9, 10, 11, 12]. It means that we need to study the time evolution of the constellation, but considering that one or more of the satellites will fail and it will not be able to communicate. To simulate this scenario, we use the nominal constellation and removed satellites considered under failure. Several simulations were made testing removing satellites that belong to different orbital planes of each sub-constellation, and they showed that there are no important differences in the results obtained in terms of observation times, maximum and mean revisit times for all the platforms. We also know in advance that there are small effects of the satellites that belong to one sub-constellation in the other platforms that are not the goal of the sub-constellation. In this way, we removed satellites from one until a number of satellites that leaves just one in each sub-constellation to measure the effects in terms on all the parameters observed. After that we measured the observation times, the maximum times between visits and the mean revisit times. The results are shown in Figs. 2 to 4.

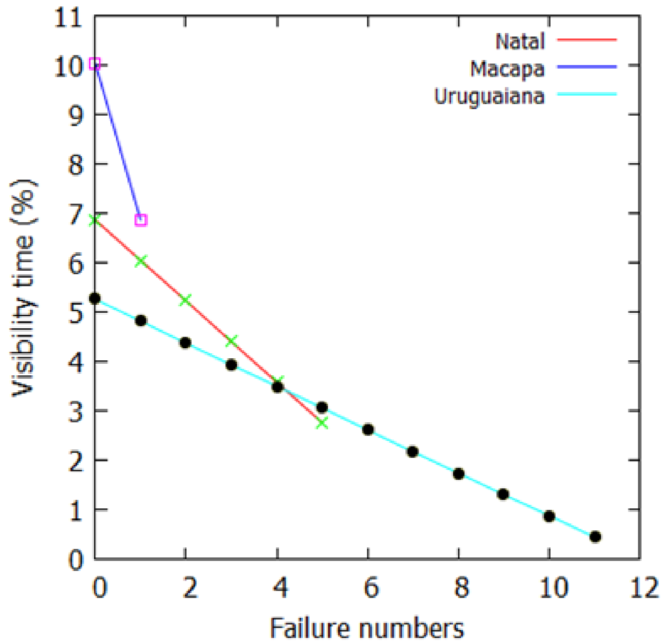

Fig. 2: Observation time as a function of the number of satellites that failed

The results plotted in Fig. 2 are expected. The contributions in the observation times of each satellite are independent from each other, so the decrease of this parameter with the number of satellites that fails is linear. In this way, we can use the data to build analytic equations that gives the observational times (y) as a function of the number of satellites that failed (x). They are showed in Eqs. 4.1 to 4.3, together with the variance of residuals.

$$Macapa: \ y(x) \ = \ -3.178x + 10.052, \tag{4.1}$$

$$variance \ of \ residuals: \ 8.13333 \times 10^{-31}.$$

$$Natal: \ y(x) \ = \ -3.178x + 10.052, \tag{4.2}$$

$$variance \ of \ residuals: \ 5.22433 \times 10^{-6}.$$

$$Uruguaiana: \ y(x) \ = \ -0.4383x + 5.2507, \tag{4.3}$$

$$variance \ of \ residuals: \ 3.35443 \times 10^{-6}.$$

The maximum time between visits has more oscillations, so they not always linear, but they can be approximated by more complex functions, like polynomials. The results are showed in Fig. 3. They increase when fewer satellites are available, as expected. The analytical approximations found are showed in Eqs. 4.4 to 4.6.

$$Macapa: \ y(x) \ = \ 6.388x + 47.008, \tag{4.4}$$

$$variance \ of \ residuals: \ 3.35443 \times 10^{-10}.$$

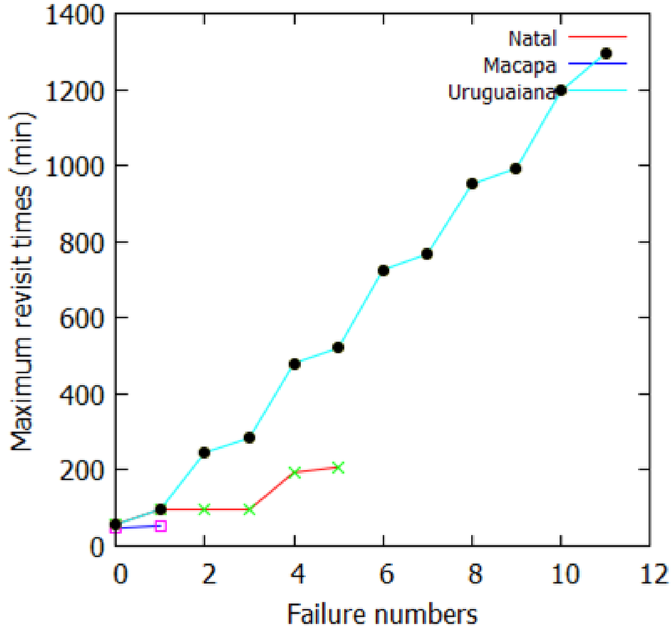

Fig. 3: Maximum time between visits as a function of the number of satellites that failed.

$$Natal: \; y(x) \;=\; -2.77358x^5 + 30.1125x^4 - 104.777x^3 + 125.43x^2 - 8.50933x + 57.97, \tag{4.5}$$

$$variance\ of\ residuals: \; 9.75411 \times 10^{-24}.$$

$$\begin{aligned} Uruguaiana: \; y(x) \;=\; & -0.0020041x^11 + 0.121306x^10 + -3.1993x^9 + 48.2495x^8 - \\ & 458.903x^7 + 2861.82x^6 + -11777.4x^5 + 31334x^4 + -51044.3x^3 + 45334.4x^2 \\ & -16255.2x + 57.11, \end{aligned} \tag{4.6}$$

$$variance\ of\ residuals: \; 1.30502 \times 10^{-13}.$$

The mean times between visits also increase when satellites fail, as expected. The results showed in Fig. 4 quantify these expectations. It is also possible to find analytical approximations based in curve fitting, as written in Eqs. 4.7 to 4.9. Figure 4 is very important because it can be used to look at a different constraint of this problem. Suppose that there is no reason to avoid any revisit time large than one hour and we look at mean revisit times below one hour. In this case, Fig. 4 shows that we can still keep the constellation working well even if we have four failures in the sub-constellations that observe Macapa and Uruguaiana and one failure of the two satellites that observe Macapa. This is very important to see the robustness of the constellation.

$$Macapa: \; y(x) \;=\; 4.002x + 17.878, \tag{4.7}$$

$$variance\ of\ residuals: \; -2.52435 \times 10^{-29}.$$

$$Natal: \; y(x) \;=\; 0.0404167x^4 - 0.187315x^3 + 0.860694x^2 + 2.97382x + 26.3787, \tag{4.8}$$

$$variance\ of\ residuals:\ 0.0192063.$$

$$Uruguaiana:\ y(x)\ = 39.2013 + 1.04459e^{\frac{x}{2.14353}+0.654567}, \tag{4.9}$$

$$variance\ of\ residuals:\ 0.0123847$$

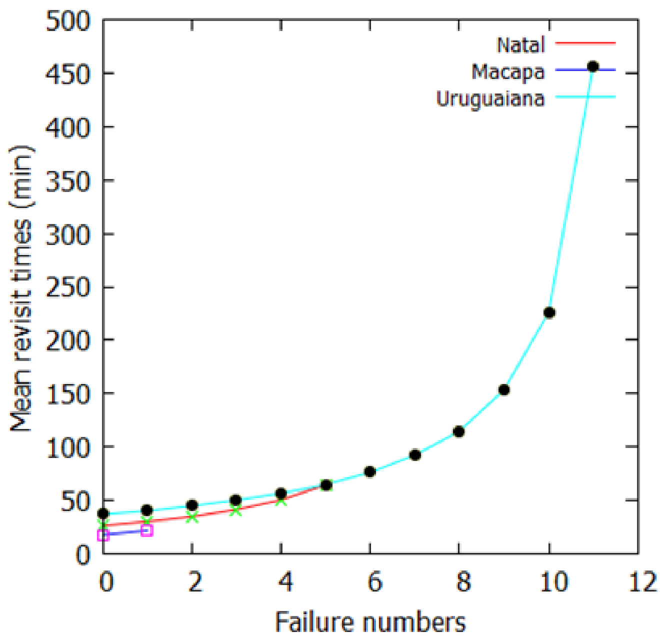

Fig. 4: Mean time between visits as a function of the number of satellites that failed.

5 Conclusions

The present paper focused in designing a constellation of small satellites to get data from platforms scattered in the Brazilian territory and then download them to receiving ground stations. The platforms are in Macapa, Natal and Uruguaiana, while the receiving ground stations are in Cuiaba and Alcantara. The results showed that a constellation with 20 satellites in circular orbits with altitude of 450 km arranged in different orbital planes can make the observations respecting the constraint imposed by the mission of having interval between visits of less than one hour for six months. After this time, it is necessary to add four more satellites in specific locations to keep the constraint satisfied for one year. The question of failures of satellites was also considered, and the results showed the linear reduction of observation times and the non-linear increase of the maximum and mean revisit times. It was even possible to obtain empirical equations relating those quantities to the number of satellites that failed.

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