DESIGN OF SATELLITE CONSTELLATIONS FOR CONTINUOUS REGIONAL COVERING OF BRAZIL

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ABSTRACT

The objective of this work is the design of satellite constellations capable to cover the whole Brazilian territory continually. A constellation with this characteristic presents many applications, such as: telecommunication, remote sensing, etc. Although the mission of this constellation is the covering of Brazil, a similar constellation can execute the same mission in areas of the same latitude, such as: Australia, south of Africa and Indonesia. Thus, several types of constellations were tested and compared in such a way that they minimize the altitude and the number of satellites, maintaining the covering. In these constellations several values of eccentricity and inclination of the orbits were tested for different values of the perigee argument. Since this work intends to privilege the covering of the southern hemisphere, the perigee argument was adjusted on the northern hemisphere. However, part of the Brazilian territory is in the northern hemisphere, and most of it is close to the terrestrial equator, therefore, this work also considered a constellation with elliptic orbits and perigee in the plane of the equator, or close to it. In this case, for high eccentricity, the satellites spend most of their time in visibility in the Earth equatorial region. If the perigee were adjusted close to the equatorial plane, but on a north latitude, the satellites would spend most of the time in visibility in the area between the latitudes 10° north and 35° south, area in which Brazil is placed. These constellations were simulated to calculate the covering area of each one, allowing the comparison among them.

1. INTRODUCTION

The interest for the satellite constellations has been increased in the last decades. The constellations can be used in missions where the use of a single satellite would not allow the execution of the mission, at an acceptable cost. For example, if in a certain mission the objective is the continuous covering of some territory, it can be more economic to use a constellation with small satellites in low orbits than to use a geosynchronous satellite for such mission. And, if the territory to be covered is close to the Earth poles, a equatorial geosynchronous satellite cannot accomplish a satisfactory covering. Thus, the study of the constellations becomes interesting by the engineering point of view and also by the economic point of view.

Many authors have been researching satellite constellations, among them we can mention: Gobetz (1963); Easton and Brescia (1965); Walker (1969-1982); Ballard (1980); Draim (1985); Lang (1987). However, many of the developed constellations seek mainly the covering of northern hemisphere, as it is the case of the Molniya type constellations. In this work, some of those constellations were adapted to mainly produce a covering of southern hemisphere, but inside of the range of longitudes where Brazil is placed. The Brazilian territory is placed between 35° S to 10° N in latitude and 35° W and 75° W in longitude.

2. CONSTELLATIONS

Ten different constellations were studied: circular equatorial; geosynchronous elliptic equatorial at rate 1:2 and 1:3; geosynchronous elliptic inclined at rate 1:2; two geosynchronous elliptic inclined at rate 1:3; geosynchronous elliptic inclined at rate 1:2 combined with circular equatorial; geosynchronous elliptic equatorial at rate 1:2 combined with geosynchronous elliptic inclined at rate 1:2; and two Molniya type constellations.

The satellite constellation with circular equatorial orbits is the simplest constellation and it is design so that the satellites altitude is minimized. This leads not necessarily to a geosynchronous orbits, but orbits that are capable just to cover the Brazilian territory.

Elliptic orbits are chosen because the satellites spend most of their time in visibility in the apogee proximity, which is adjusted above the Brazilian territory. Since this work intends to privilege the coverage of the southern hemisphere, in inclined orbits, the perigee argument is adjusted in northern hemisphere.

2.1. CIRCULAR EQUATORIAL CONSTELLATION

This is the simplest constellation. The coverage areas for each satellite are circles over Earth. These circles must have intersections to form a continuous coverage area around the Earth equator. The half width of this area must have the minimum of 35° in arc, that is, the higher latitude of Brazilian territory. So, by spherical trigonometry, the swatch width for each satellite can be found (Brown, 1992). This swatch angle is related to altitude of satellite by expression:

$$\alpha = \frac{S}{2R_e} \qquad h = \left(1 - \frac{1}{\cos\alpha}\right)R_e \tag{1}$$

where h is the satellite altitude above Earth surface, S is the swatch width, R_e is the Earth radius and α is the central angle of coverage area.

This leads a minimum number of three satellites, with true anomaly of 0°, 120° and 240° and altitude of 9194.2km above Earth surface, but the satellites have a elevated ground track speed, which may lead to a tracking more difficult.

2.2. GEOSYNCHRONOUS ELLIPTIC EQUATORIAL CONSTELLATION AT RATE 1:2

This configuration presents three satellites in equatorial and elliptic orbits. The keplerian elements at initial time, for all satellites are shown on Table 1.

Table 1: Keplerian elements for elliptic equatorial constellation at rate 1:2.

	Satellite 1	Satellite 2	Satellite 3
a [km]	26610.223	26610.223	26610.223
e	0.731	0.731	0.731
i [°]	0	0	0
ω [°]	90	90	90
Ω [°]	0	120	240
f [°]	150	180	210

where a is the semi-major axis, e is the eccentricity, i is the inclination, ω is the perigee argument, Ω is the right ascension of ascending node and f is the true anomaly.

Figure 1 shows the longitude for each satellite of this constellation. It can be seen in the figure that when a satellite is leaving the apogee proximity, another satellite is approaching the apogee. Because the value of semi-major axis, these orbits are almost geosynchronous at rate 1:2, and there are two regions of continuous visibility by the constellation, around 110° E and 75° W in longitude. The last is the region that contains Brazil. Therefore, this constellation can provide full time coverage of Brazil.

2.3. GEOSYNCHRONOUS ELLIPTIC EQUATORIAL CONSTELLATION AT RATE 1:3

This configuration is similar to the previous configuration. But now there are four satellites in equatorial and elliptic geosynchronous orbits at rate 1:3. The keplerian elements at initial time, for all satellites are shown on Table 2.

Table 2: Keplerian elements for elliptic equatorial constellation at rate 1:3.

	Satellite 1	Satellite 2	Satellite 3	Satellite 4
a [km]	20264.017	20264.017	20264.017	20264.017
e	0.6	0.6	0.6	0.6
i [°]	0	0	0	0
ω [°]	45	45	45	45
Ω [°]	198	290	22	94
f [°]	150	180	210	102

Figure 2 shows the longitude for each satellite of this constellation. When a satellite is leaving the apogee proximity, another satellite is approaching the apogee. There are three regions of continuous visibility by the constellation, around 175° E, 55° E and 65° W in longitude. The last is the region that contains Brazil. Hence, this constellation can provide full time coverage of Brazil.

2.4. GEOSYNCHRONOUS ELLIPTIC INCLINED CONSTELLATION AT RATE 1:2

Three satellites at 63.4° inclined orbits compose this constellation. Table 3 shows the keplerian elements for the satellites.

Table 3: Keplerian elements for elliptic inclined constellation at rate 1:2.

	Satellite 1	Satellite 2	Satellite 3
a [km]	26553.374	26553.374	26553.374
e	0.741	0.741	0.741
i [°]	63.4	63.4	63.4
ω [°]	45	45	45
Ω [°]	240	5.5	131
f [°]	150	180	210

It can be seen in Figure 3 that there are two regions of continuous visibility by the constellation, around 110° E and 75° W in longitude. The last region provide the covering of the Brazilian territory. Consequently, this constellation can provide full time coverage of Brazil. This type of constellation is similar to Molniya constellations, but the perigee is placed on the northern hemisphere. Thus, this kind of constellations will be called by Molniya type constellations.

2.5. GEOSYNCHRONOUS ELLIPTIC INCLINED CONSTELLATION AT RATE 1:3 A

Four satellites at 63.4° inclined orbits compose this constellation. Table 4 shows the keplerian elements for the satellites.

Table 4: Keplerian elements for elliptic inclined constellation at rate 1:3 A.

	Satellite 1	Satellite 2	Satellite 3	Satellite 4
a [km]	20264.017	20264.017	20264.017	20264.017
e	0.6	0.6	0.6	0.6
i [°]	63.4	63.4	63.4	63.4
ω [°]	45	45	45	45
Ω [°]	198	290	22	94
f [°]	150	180	210	120

This constellation allows to have two visible satellites at same instant, most of time, but their visibility period is short. This fact is shown in Figure 4. There are three regions of continuous visibility by the constellation, around 165° E, 40° E and 75° W in longitude. The last is the region that contains Brazil. Therefore, this constellation can provide full time coverage of Brazil.

2.6. GEOSYNCHRONOUS ELLIPTIC INCLINED CONSTELLATION AT RATE 1:3 B

Four satellites at 63.4° inclined orbits compose this constellation. Table 5 shows the keplerian elements for the satellites.

Table 5: Keplerian elements for elliptic inclined constellation at rate 1:3 B.

	Satellite 1	Satellite 2	Satellite 3	Satellite 4
a [km]	20264.017	20264.017	20264.017	20264.017
e	0.6	0.6	0.6	0.6
i [°]	63.4	63.4	63.4	63.4
ω [°]	90	90	90	90
Ω [°]	158	250	344	54
f [°]	150	180	210	120

This constellation allows to have two visible satellites at same instant, in most of time, but their visibility period is short, as can be seen in the Figure 5. The simulations showed that this constellation is capable to cover the whole southern hemisphere almost continually. Therefore, in Brazil region, there is at least one visible satellite.

2.7. GEOSYNCHRONOUS ELLIPTIC EQUATORIAL CONSTELLATION AT RATE 1:2 COMBINED WITH CIRCULAR EQUATORIAL CONSTELLATION

Four satellites in equatorial orbits compose this constellation. Two satellites are placed in geosynchronous elliptical orbits and the others in circular orbits. Table 6 shows the keplerian elements for the satellites.

Table 6: Keplerian elements for geosynchronous elliptic equatorial constellation at rate 1:2 combined with circular equatorial constellation.

	Satellite 1	Satellite 2	Satellite 3	Satellite 4
a [km]	26610.223	26610.223	16727.578	16727.578
e	0.745	0.745	0	0
i [°]	0	0	0	0
ω [°]	90	90	90	90
Ω [°]	50	230	140	140
f [°]	0	0	180	0

Figure 6 shows that there are two regions of continuous visibility, around 130° E and 60° W in longitude. Therefore, this constellation can provide full time coverage of Brazil.

2.8. GEOSYNCHRONOUS ELLIPTIC EQUATORIAL CONSTELLATION AT RATE 1:2 COMBINED WITH GEOSYNCHRONOUS ELLIPTIC INCLINED CONSTELLATION AT RATE 1:2

This constellation is composed by four satellites. Two satellites are placed in geosynchronous elliptical equatorial orbits and the others in geosynchronous elliptic inclined orbits. Table 7 shows the keplerian elements for the satellites.

Table 7: Keplerian elements for geosynchronous elliptic equatorial constellation at rate 1:2 combined with geosynchronous elliptic inclined constellation at rate 1:2.

	Satellite 1	Satellite 2	Satellite 3	Satellite 4
a [km]	26553.374	26553.374	26610.223	26610.223
e	0.741	0.741	0.745	0.745
i [°]	63.4	63.4	0	0
ω [°]	90	90	90	90
Ω [°]	320	140	220	40
f [°]	180	180	0	0

Figure 7 shows that there are two regions of continuous visibility, around 135° E and 55° W in longitude. Thus, this constellation can provide full time coverage of Brazil. Furthermore, it can be seen in the figure that, in most of time, there are two visible satellites at same instant.

2.9. MOLNIYA TYPE CONSTELLATION WITH 40° PERIGEE ARGUMENT

This Molniya type constellation, with three satellites, was adjusted with perigee argument over the northern hemisphere. So, in most of the time the satellites are placed on the southern hemisphere. The orbital elements for these satellites are shown on Table 8.

Table 8: Keplerian elements for Molniya type constellation with 40° perigee argument.

	Satellite 1	Satellite 2	Satellite 3
A [km]	26553.374	26553.374	26553.374
e	0.741	0.741	0.741
i [°]	63.4	63.4	63.4
ω [°]	40	40	40
Ω [°]	240	5.5	131
f [°]	150	180	210

The orbits are geosynchronous with rate 1:2, so they have two regions of continuous visibility. The orbital parameters were adjusted so that one of these regions is over Brazilian territory, as shown in Figure 8.

2.10. MOLNIYA TYPE CONSTELLATION WITH 90° PERIGEE ARGUMENT

This constellation has the same orbital parameters of the previous constellation, except the perigee argument, in this case 90°.

Table 9: Keplerian elements for Molniya type constellation with 90° perigee argument.

	Satellite 1	Satellite 2	Satellite 3
A [km]	26553.374	26553.374	26553.374
e	0.741	0.741	0.741
i [°]	63.4	63.4	63.4
ω [°]	90	90	90
Ω [°]	189.5	315	80
f [°]	150	180	210

Because the choice of these orbital parameters, the satellites at apogee proximity remain almost stationary. This fact may become the satellite tracking easier than the cases above.

3. CONCLUSIONS

Ten different constellations had their Brazilian territory coverage aspects studied. The study was limited to the development of the constellations with the objective to cover continually the Brazilian territory, without analyzing other aspects as development, launch and operational costs. Therefore, to select the best constellation would be necessary to consider this other aspects. Therefore, the choice of the best constellation becomes a multi-objective problem. The analysis of this multi-objective problem is not the goal of this work. An introduction of this topic, applied to a satellite constellation, could be found in Rocco et al. (2003). In any way, analyzing Figures 1 to 9, it can be obtained the following conclusions.

The circular equatorial constellation achieves the coverage with only three satellites with altitude of 9194.2km. This constellation covers a range of 35° N to 35° S in latitude about Earth equator, but it has satellite ground track speed elevated.

The geosynchronous elliptic equatorial constellation at rate 1:2 presented two regions of continuous

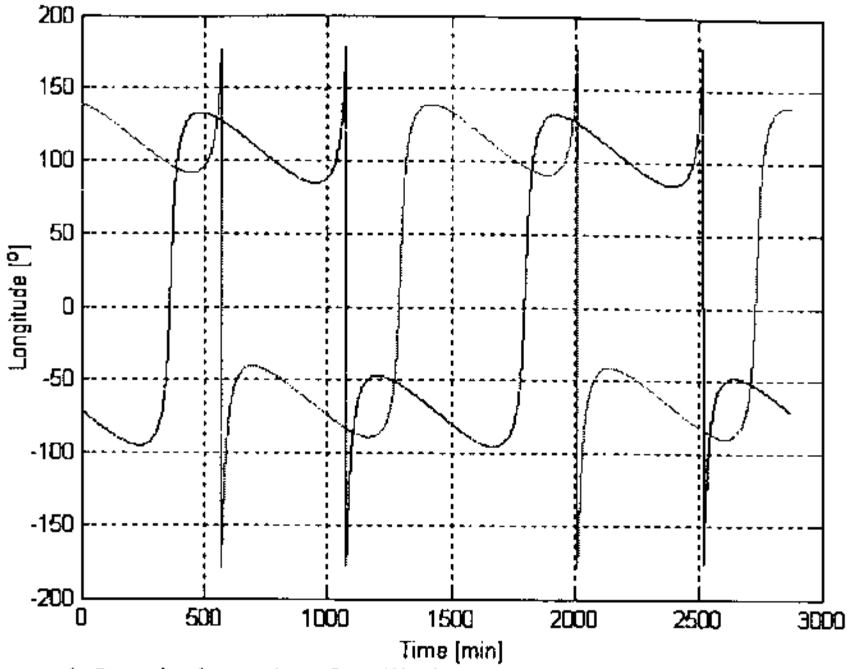

Figure 1: Longitude *vs.* time for elliptic equatorial constellation at rate 1:2.

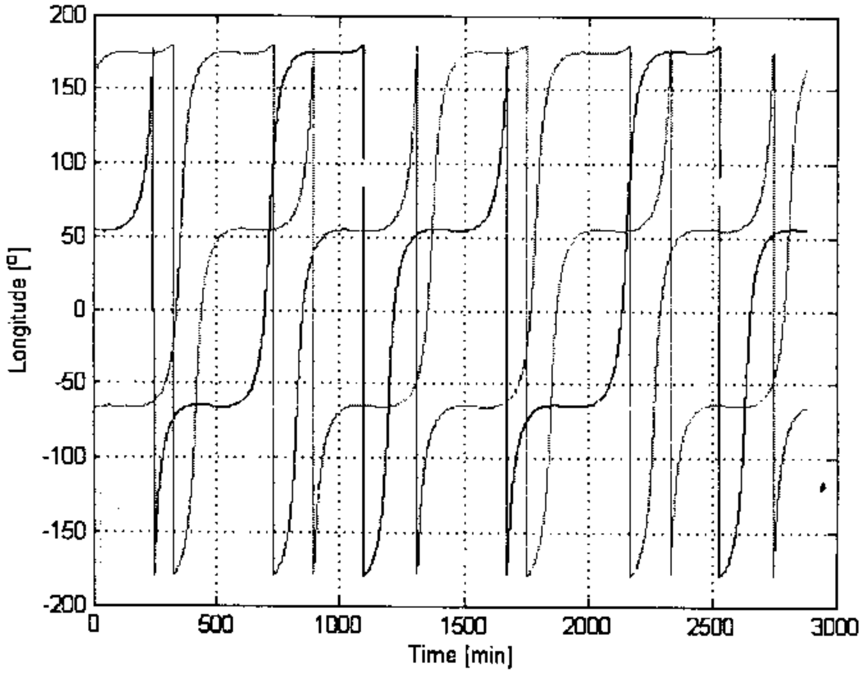

Figure 2: Longitude *vs.* time for elliptic equatorial constellation at rate 1:3.

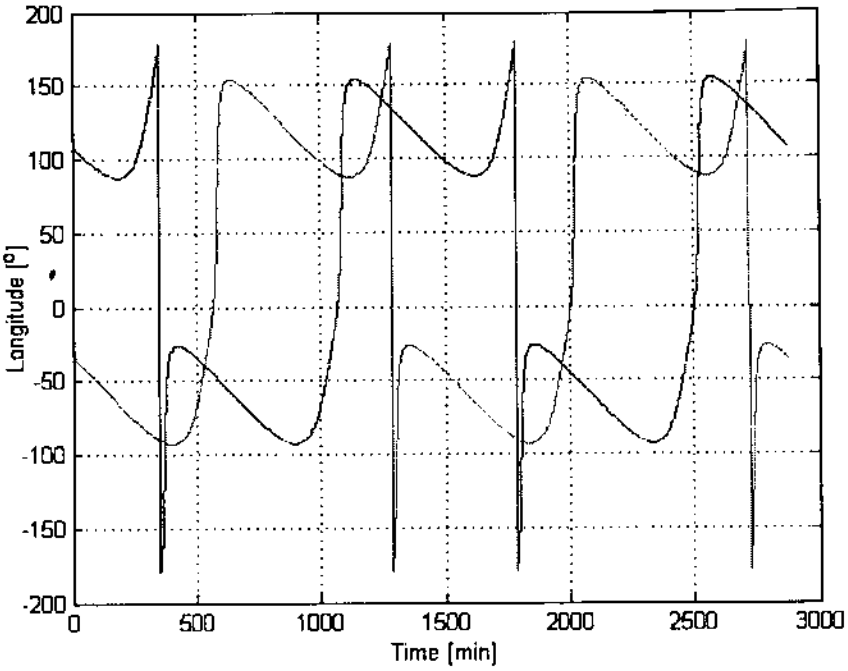

Figure 3: Longitude *vs.* time for elliptic inclined constellation at rate 1:2.

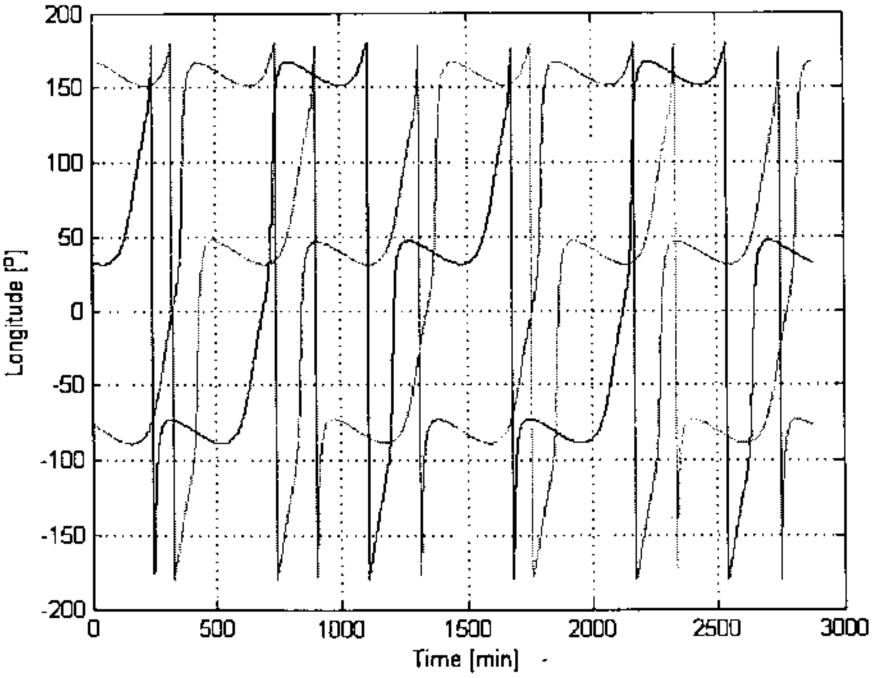

Figure 4: Longitude *vs.* time for elliptic inclined constellation at rate 1:3 A.

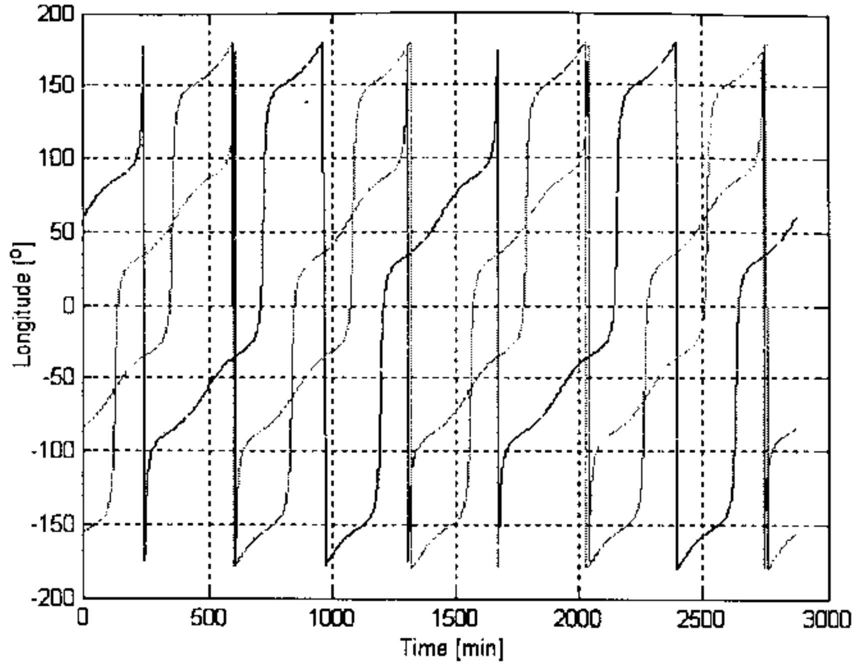

Figure 5: Longitude *vs.* time for elliptic inclined constellation at rate 1:3 B.

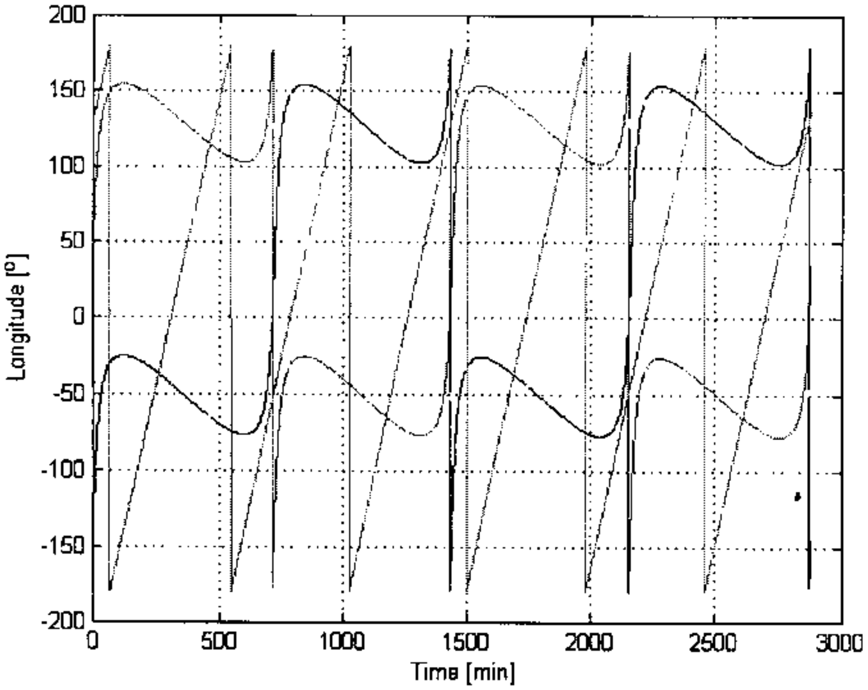

Figure 6: Longitude *vs.* time for geosynchronous elliptic equatorial constellation at rate 1:2 combined with circular equatorial constellation.

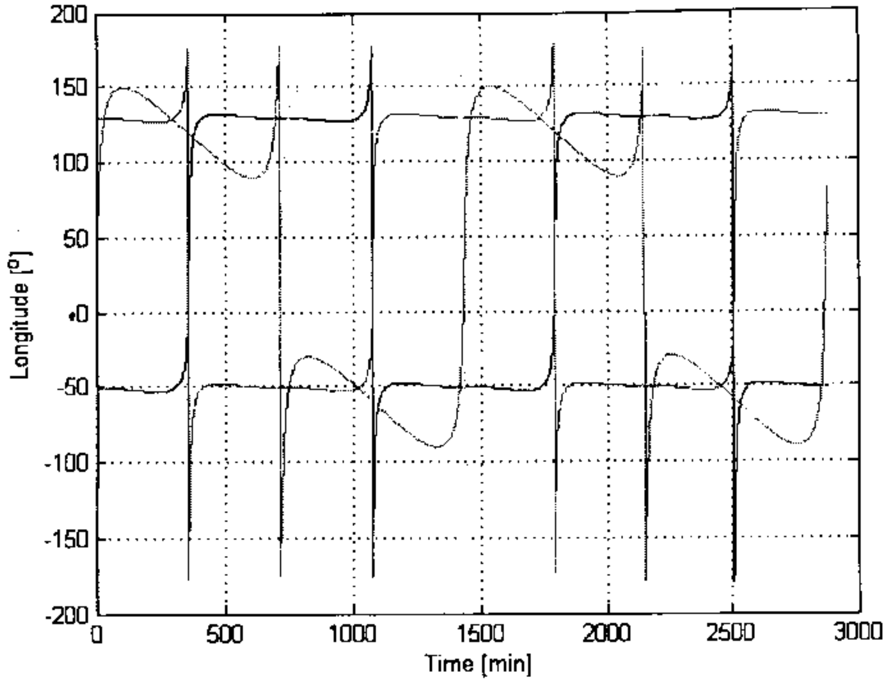

Figure 7: Longitude *vs.* time for geosynchronous elliptic equatorial constellation at rate 1:2 combined with geosynchronous elliptic inclined constellation at rate 1:2.

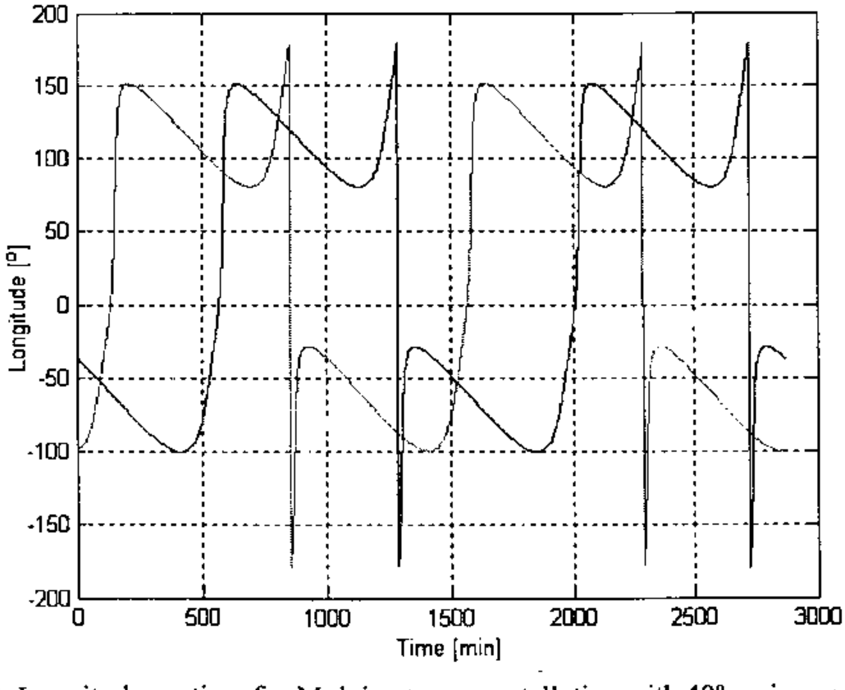

Figure 8: Longitude *vs.* time for Molniya type constellation with 40° perigee argument.

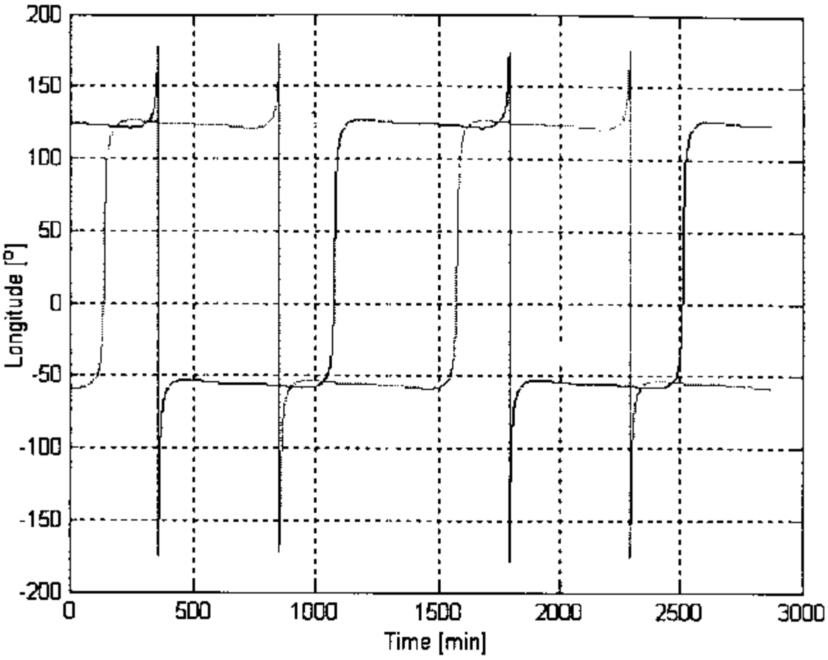

Figure 9: Longitude *vs.* time for Molniya type constellation with 90° perigee argument.

coverage and the geosynchronous elliptic equatorial constellation at rate 1:3 presented three regions of continuous coverage, one of them adjusted to Brazilian region. The satellites of the constellation with rate 1:3 presented a smaller altitude than the satellites of the constellation with rate 1:2. The geosynchronous elliptic inclined constellations presented a similar behavior.

Both Molniya type constellation can cover the Brazilian territory, but the Molniya with perigee argument of 90° provide the satellite ground track almost fixed, when the satellite is near to the apogee.

The combined constellations also provided full time coverage of Brazil.

If it would be considered that the smaller variation of the longitude, result in a better constellation, it can be obtained the following classification:

Table 10: Classification considering the minimum longitude variation.

1	Molniya type constellation with 90° perigee argument
2	Geosynchronous elliptic equatorial constellation at rate of 1:2 combined with geosynchronous elliptic inclined constellation at rate 1:2
3	Elliptic equatorial constellation at rate 1:3
4	Elliptic inclined constellation at rate 1:3 A
5	Elliptic equatorial constellation at rate 1:2
6	Geosynchronous elliptic equatorial constellation at rate of 1:2 combined with circular equatorial constellation
7	Elliptic inclined constellation at rate 1:2
8	Molniya type constellation with 40° perigee argument
9	Elliptic inclined constellation at rate 1:3 B
10	Circular equatorial constellation

Considering the minimum satellite altitude, the best constellation is the circular equatorial constellation. And considering the minimum number of satellites, all constellations utilized three satellites except the geosynchronous constellations at rate 1:3 and combined constellations, that utilized four satellites.

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