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STATION KEEPING OF SATELLITE CONSTELLATIONS USING OPTIMUM IMPULSIVE MANEUVERS WITH TIME CONSTRAINT

Evandro Marconi Rocco
Marcelo Lopes de Oliveira e Souza
Antonio Fernando Bertachini de Almeida Prado

Paper presented at the Third International Conference on Nonlinear Dynamic, Chaos, Control and Their Applications in Engineering Sciences -
Campos do Jordão, Brazil, 31 July - 4 August, 2000.

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ABSTRACT

In this work we study the problem of orbital maintenance (transfers and corrections) of symmetrical constellations of satellites with minimum fuel consumption using impulsive maneuvers with time constraint. This time constraint imposes a new characteristic to the problem, that rules out the majority of the transfer methods available in the literature. Therefore, the transfer methods must be adapted to this new constraint. In the case of satellite constellations we still have the problem of simultaneously optimizing the maneuvers for all satellites using scarce resources. As an example, we can mention the situation which the Satellite Control Center of INPE will face soon with the launch of the next Brazilian satellites. INPE has only one Satellite Control Center; however, it will have to control several satellites simultaneously, an intermediate situation with the case of constellations. In this way an appropriate strategy should be adopted to control the satellites, seeking to minimize the fuel consumption and the time spent by the Control Center for each satellite. Thus, the goal of this work is to formulate and to study maneuver strategies that, in some way, even sub-optimal, makes possible to obtain solutions with small fuel consumption considering all the satellites in the constellation.

INTRODUCTION

The majority of the spacecrafts that have been placed in orbit around the Earth utilize the basic concept of orbital transfers. During the launch, the spacecraft is placed in a parking orbit distinct from the final orbit for which the spacecraft was designed. Therefore, to reach the desired final orbit the spacecraft must perform orbital transfers. Besides that, the spacecraft orbit must be corrected periodically because there are perturbations acting on the spacecraft. This becomes worse when the spacecraft composes a satellite constellation because in this case the positions and the spacecraft velocity in relation to all the others spacecrafts are more important than the position and absolute velocity. So, the corrections maneuvers can place the spacecraft in the nominal position or can place the spacecraft in a position different of the nominal, to save fuel or time. As examples of application of these maneuvers (transfer or correction) to isolated satellites we can mention the placement of a satellite in geosynchronous orbit, the maintenance of the orbit of a satellite, the interplanetary missions, rendezvous missions, interception missions, etc. In Brazil, we have important applications with the launch of the Remote Sensing Satellites RSS1 and RSS2 that belongs to the Complete Brazilian Space Mission and with the launch of the China Brazil Earth Resources Satellites CBERS1 and CBERS2.

As examples of application of these maneuvers applied in constellations we can mention the maintenance maneuvers made in the satellites of the constellations INMARSAT, GLOBALSTAR, NAVSTAR, GPS, that are constellations in development and they need these maneuvers to maintain the system operating. Besides the maintenance maneuvers, new satellites should be joined and, at the same time, others removed of the constellation, because the satellites have a smaller useful life than the constellation, turning periodic these placement and retreat maneuvers. In Brazil it is in study the project ECCO elaborated by INPE and by AEB that foresees the launch of 12 communication satellites in equatorial low orbit, establishing an innovative system of communication in Brazil, assisting remote areas as the interior of the Amazonian. We can also mention the case of similar satellites in simultaneous operation. Although they not form a constellation, the orbit maintenance of these satellites is very similar to the case of constellations, due to the likeness of the missions carried out by them, as it is the case of the Brazilian satellites SSR 1 and SSR 2; and Chinese-Brazilian CBERS 1 and CBERS 2. These satellites should be maintained as if they formed a constellation, because they have similar orbital elements and they carry out the same mission type; therefore it would be advantageous to maintain the satellites moved away some of the others in order to not have two satellites at the same time covering the same point of the terrestrial surface.

In this way, we can see that have two possible basic maneuvers: the transfers maneuvers and the corrections maneuvers. Both maneuvers are usually calculated minimizing: 1) the fuel consumption (because it isn't renewable in the space); 2) the spent time (to minimize the energy consumption of the batteries, or because it is necessary to perform the maneuver in visibility); for many methods. However few of them consider 1 and 2 simultaneously. For constellations they can correct the positions and/or relative or absolute velocities. And they can correct to the nominal value or to another value seeking to save time and/or fuel, number of maneuvers for satellite and total, duration and costs of the use of the control centers, ground tracking stations, etc.

OBJECTIVE

The objective of this work is to study the problem of the orbital maintenance (transfers and corrections) of symmetrical constellations of satellites, with minimum fuel consumption, using impulsive maneuvers with time constraint, and possibly considering: maneuvers with terminal points partially free or not; keplerian dynamics or disturbed. This time constraint imposes a new characteristic to the problem, that rules out the majority of the transfer methods available in the literature: Hohmann (1925), Hoelker and Silber (1959), Gobetz and Doll (1969), Prado (1989), etc. Therefore, the transfer methods must be adapted to this new constraint: Wang (1963), Lion and Handelsman (1968), Gross and Prussing (1974), Prussing (1969, 1970), Prussing and Chiu (1986), Ivashkin and Skorokhodov (1981), Eckel (1982), Eckel and Vinh (1984), Lawden (1993), Taur et al. (1995), etc.

This research is important because in many missions there are constraints like that. In certain cases there are direct time constraints (the maneuver has to be completed before a certain event); in other, those constraints can elapse from other situations as the necessity to perform the maneuver in visibility, that can be transformed in a time constraint. In the case of constellations of n satellites we still have the problem of simultaneously optimizing the maneuvers for n satellites using scarce resources. As an example, we can mention the situation which the Satellite Control Center of INPE will face soon with the launch of the next Brazilian satellites. INPE has only one Satellite Control Center; however, it will have to control several satellites simultaneously, an intermediate situation with the case of constellations. In this way an appropriate strategy should be adopted to control the satellites, seeking to minimize the fuel consumption and the time spent by the Control Center for each satellite. Thus, we can see that the limit of time has to be considered in the solution of the problem. In these cases, we may find the optimal way to maneuver each satellite individually, but not simultaneously. When we consider all the satellites is not simple to determine the optimal maneuver strategy that minimizes the fuel consumption with time constraint. Therefore, the goal of this work is to formulate and to study maneuver strategies that, in some way, even sub-optimal, makes possible to obtain solutions with small fuel consumption considering all the satellites in the constellation.

When we considered that all the satellites of the constellation should stay as close as possible of the nominal positions, we have to maneuver them periodically to eliminate the drift caused by the disturbances. But the relative positions of the satellites are more important than the absolute positions because in most constellations the main goal of the maneuvers is to keep the ground coverage, so the decision of when to perform the maneuvers depends on the analysis of the relative positions. In some cases we can consider, as a first approach, that all the satellites (in the case of symmetrical constellations) suffer the same disturbances and therefore they present the same drift, then the relative positions among the satellites stay constant. In this way, the terrestrial covering stays practically constant, for the case of small drifts, so is not necessary to maneuver the satellites. On the other hand, if one of the satellites is maneuvered, the relative position of that satellite with the others will change, and so, all the satellites should be maneuvered. Besides that, when the maneuvers are accomplished it may be more economical to place the satellites a little higher than the nominal positions, because in this way we increased the interval of time among maneuvers. Therefore, the decision of when we have to maneuver the satellites and how to perform this is very important and very complex for the case of constellations. All these subjects are consider in this work.

DEFINITION OF THE PROBLEM

We can define constellations of satellites as being a group of satellites that it carry out a certain mission (communication, remote sensing, global positioning, etc.). The constellations are usually developed so that it is possible to obtain global, zonal, regional or partial terrestrial covering, as we can see in the Figure 1. Basically, there are six types of satellite constellations, as shown in Figures 2 to 7.

The satellites need to be tracking and controlled periodically, so the problem consists of choosing, considering all the visibility windows, which satellites will be tracking and controlled, during how long and starting from which instant, in the most economical and faster way possible. And all these functions should be accomplished in a certain time $t = t_{final} - t_{initial}$ that we will call: time of processing. That is the time spent for all the operations in an only iteration of the program.

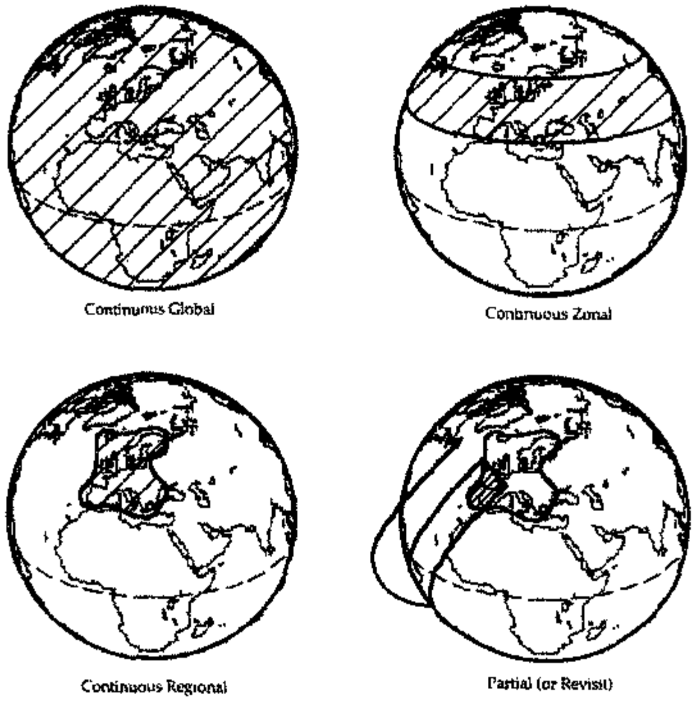

Fig. 1 – Types of Constellation Coverage.
Cf. Matossian (1997).

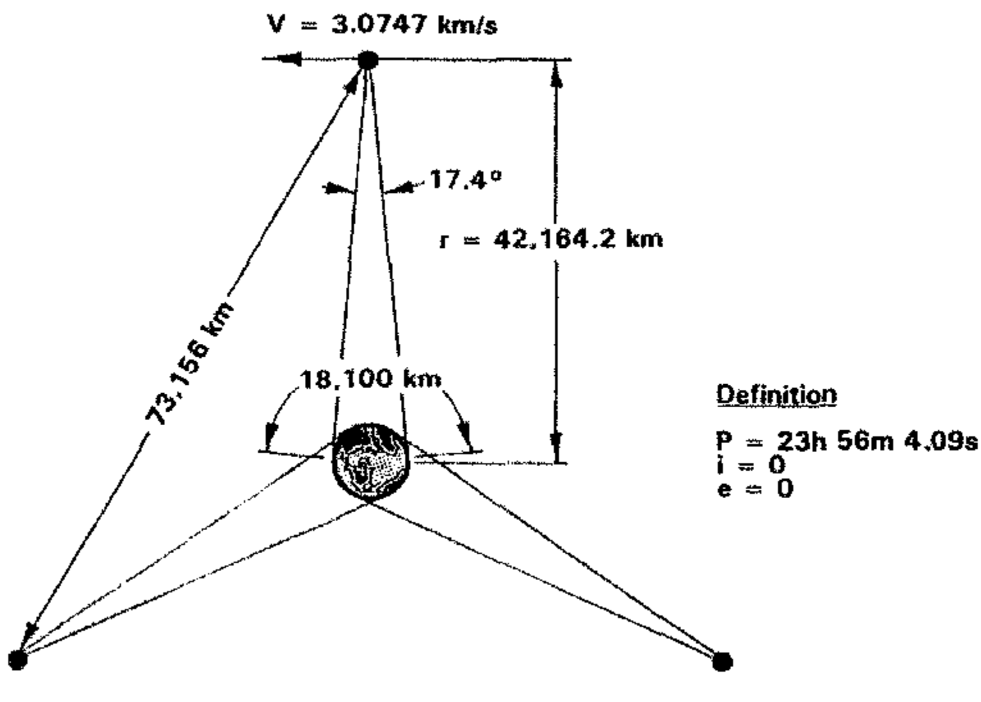

Fig. 2 – Geosynchronous Satellite Constellation.
Cf. Brown (1992).

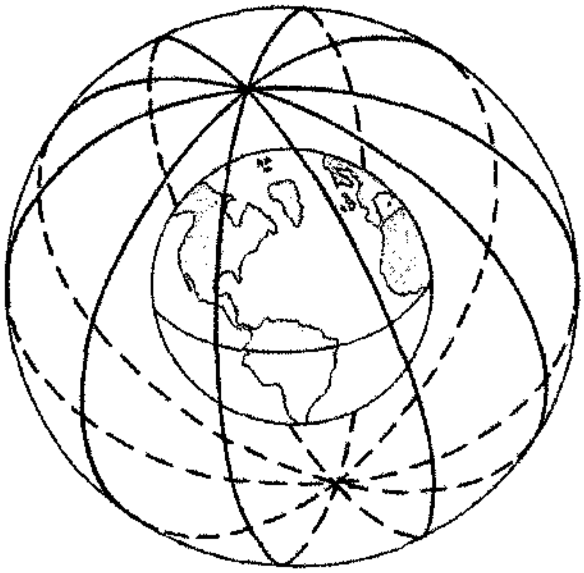

Fig. 3 – Polar Orbit Constellation.
Cf. Gobetz (1963).

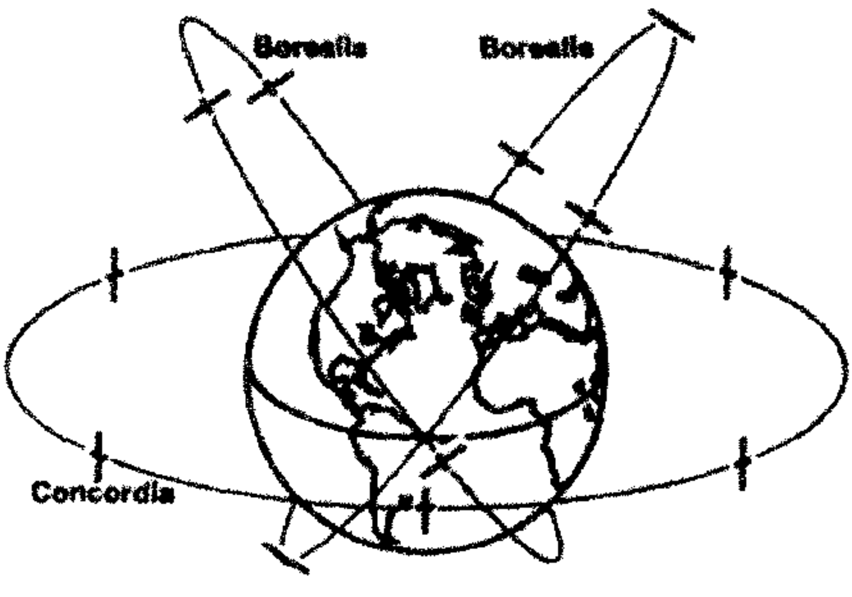

Fig. 4 – Ellipso Mobile Satellite System Orbits.
Cf. Shah et al. (1997).

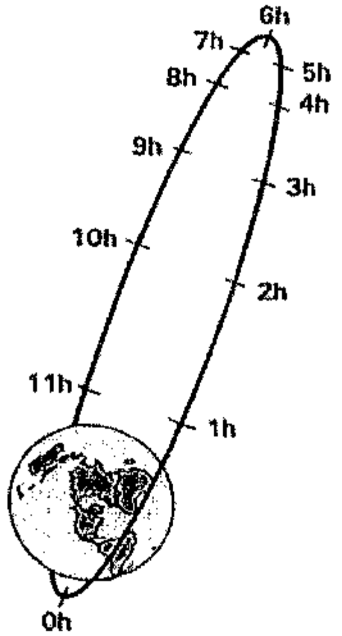

Fig. 5 – Molniya Orbit.
Cf. Brown (1992).

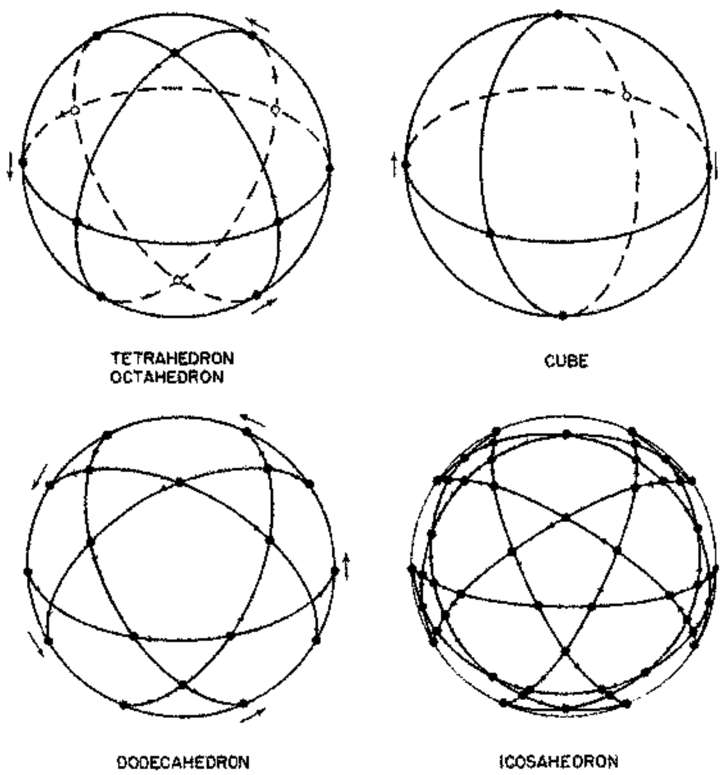

Fig. 6 – Polyhedron Orbit Constellation.
Cf. Gobetz (1963).

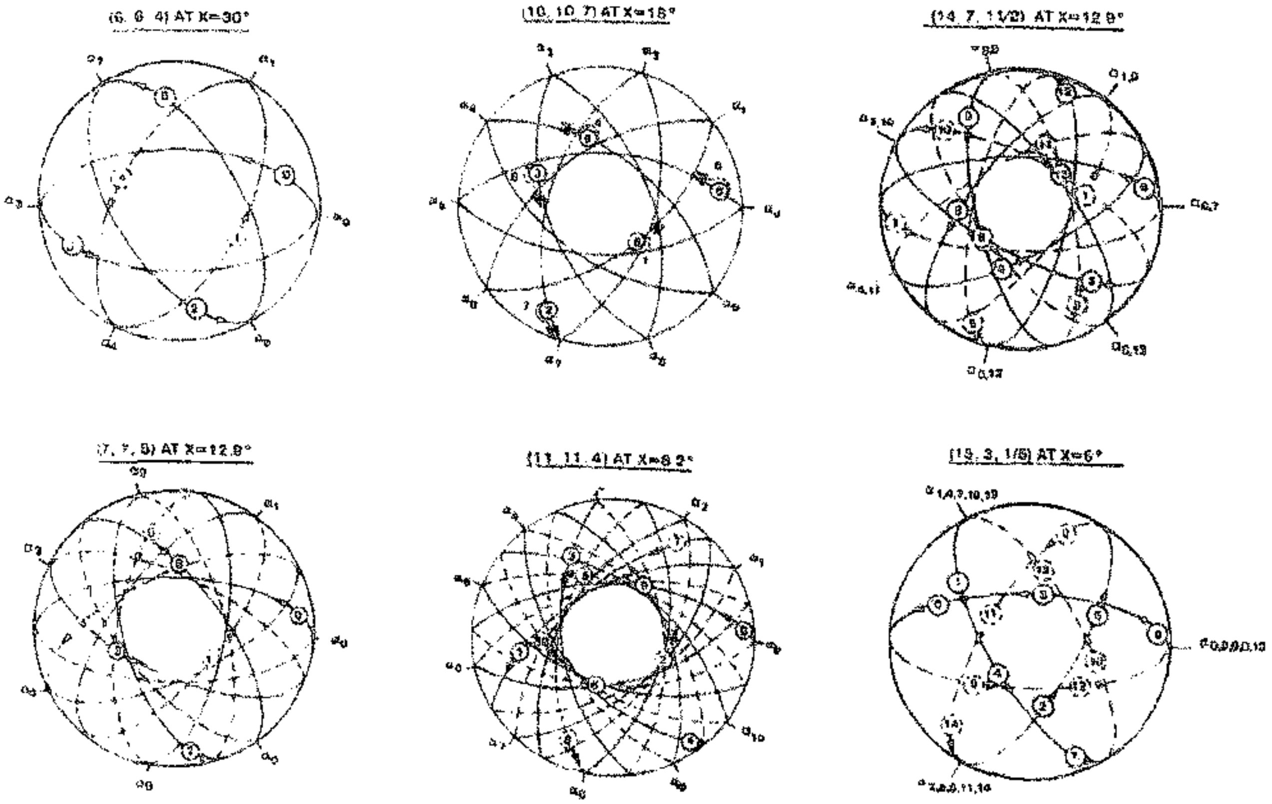

Fig. 8 –Types of Rosette Constellation.
Cf. Ballard (1980).

In this work we consider as a first approach, symmetrical constellations of satellites of the type Rosette. This constellation type was developed independently by Walker (1970) in Great Britain and by Mozhaev (1972) in the Soviet Union. It consists of a constellation with several orbital plans of same inclination, distributed symmetrically along the equator.

The problem can be defined as being to find a control method that, applied to a satellite constellation, be capable to control the satellites, executing the transfer maneuvers in a certain time, so that the fuel consumption of all satellites of the constellation is minimum.

Thus, we have a dynamic system that can be described by a group of variables that constitute the state of the system. Such variables are denominated state variables. The temporary evolution of the state of a system is described by a system of ordinary differential equations of first order:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = f(x,u,t) \tag{1}$$

where the variables $u_1,\ldots,u_m$ are the control variables. This equations are denominated state equations. Once known the control variables in an interval of time $[t_0,\ t_f]$ and given the initial conditions:

$$x_i(t_0) = x_{i0} \quad i = 1,\ldots,n \tag{2}$$

the solution of (1) is only determined.

Considering that the spacecraft propulsion system is able to apply an impulsive thrust and that the maneuver for each satellite will be made through two impulsive velocity increments with magnitudes Δv_1 and Δv_2. We have that the total velocity increment for each satellite is given by:

$$V = \Delta v_1 + \Delta v_2 = F(\mathrm{X}) \tag{3}$$

where X is an arbitrary variable for the transfer.

The time spent in the maneuver for each satellite is given by:

$$T = \mathrm{G}(X) \tag{4}$$

Therefore, the problem is the minimization of V for a prescribed T. If the time for the maneuver is prescribed, being equal to a value T_0, we have the constrained relation:

$$T - T_0 = 0 \tag{5}$$

In that way, we should consider the performance index for each satellite given by:

$$J = V + \lambda(T - T_0) \tag{6}$$

Considering the n satellites of the constellation we have:

$$\begin{aligned} J_1 &= V_1 + \lambda_1(T - T_1) \\ J_2 &= V_2 + \lambda_2(T - T_2) \\ &\vdots \\ J_n &= V_n + \lambda_n(T - T_n) \end{aligned} \tag{7}$$

Therefore the performance index for all the constellation is given by:

$$J = \sum_{i=1}^{n} V_i + \lambda_i(T - T_i) = \sum_{i=1}^{n} J_i \tag{8}$$

This problem can be treated in analytic and/or numeric way, making use of numeric routines of integration and the solution for the contour problem in two points (Two Point Boundary Value

Problem). However, due to the complexity of the performance index when we considered all the satellites of the constellation, the optimal solution becomes quite difficult of obtaining. The difficult increase if we also consider position constraints, what certainly should be considered for the case of constellations because the relative positions of the satellites should be considered, and those position constraints still depend on the constellation type studied (Rosette, Ellipso, Polyhedron, etc.). Therefore, the obtaining of a sub-optimal solution becomes more viable.

PRESENTATION OF THE METHOD

A possible alternative to solve the problem would be the use of algorithms capable to consider all the constellation and to find a sub-optimal solution. In the literature we can find some works that use algorithms of this type: Agnèse and Brousse (1998), Brousse et al. (1998), Brochet et al. (1998), Folta et al. (1998), etc. In this work we use the algorithm shown in the Figure 9.

The functions carried out by the several boxes shown in the Figure 9 are described concisely below:

1. It establishes the contact between the satellite and the ground station;
2. Established the contact, the position and velocity measures are made, in other words, the X, Y, Z, $\dot{X}$, $\dot{Y}$ and $\dot{Z}$ are determined;
3. It is verified if the satellite was already maneuvered or not during a same iteration of the control program, through the verification of the actual time of the satellite;
4. If the actual time is smaller than the final time, the orbit of the satellite is determined with the measures X, Y, Z, $\dot{X}$, $\dot{Y}$ and $\dot{Z}$;
5. It is verified which should be the orbital elements (nominal elements) for the satellite;
6. The differences between the current elements and the nominal elements are calculated;
7. With base in the differences among the current and nominal orbital elements the decision is made if the maneuver should be accomplished or not;
8. They are defined which are the orbital elements that should be obtained after the accomplish of the maneuver;
9. It calculates the optimal transfer maneuver with time constraint;
10. The maneuver is perform;
11. The current orbital elements of the satellite are considered and do not perform any correction maneuver;
12. The position and velocity measures are made, in other words, the X, Y, Z, $\dot{X}$, $\dot{Y}$ and $\dot{Z}$ altered by the maneuver are determined;
13. The propagation of the orbital elements for the next iteration is accomplished;
14. The time of processing is transmitted to the satellite;
15. Updating of the time of processing.

CONCLUSIONS

We can divide the problem in three main parts: the choice of when and which satellites should be maneuvered; the calculation of the optimal maneuver with time constraint for each satellite; and the propagation of the orbit of each satellite, as it can be seen in the diagram of the Figure 9.

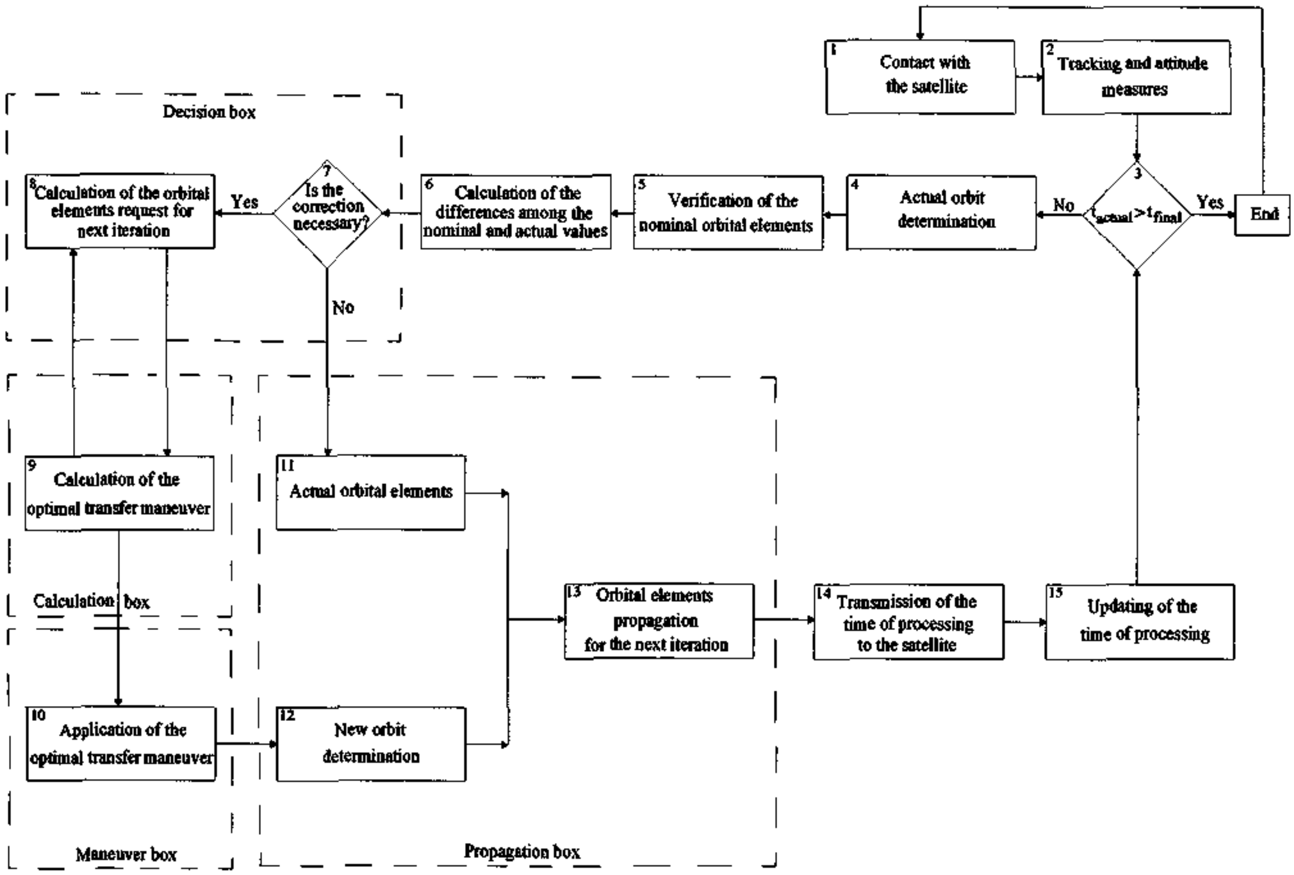

Fig. 9 – Flow diagram.

The main contribution of this work is the decision box development. The calculation box was already developed in Rocco (1997) and Rocco et al. (1999). In the decision box the satellites which will be maneuvered must be selected. To do this, it should be verified if the differences among the nominal elements and the actual elements are inside of the tolerance, and if these differences are increasing or decreasing along the time. Besides that it should be verified the fuel consumption and the time spend in the maneuver for each satellite and also for all satellites that will be maneuvered; and beyond this, how these maneuvers will affect the mission (covering area, interruption of the operation of the satellites, etc.). To determine the fuel consumption, calculations should be made to determine the optimal transfer maneuver for each satellite. In this way it is necessary a feedback of the decision box after the optimal transfer maneuvers have been obtained in the calculation box. This feedback is necessary because there are situations where punishing the fuel consumption or the time spends for a certain satellite, we can obtain an economy when we considered the whole constellation. Like this, the decision box should have capacity to compare all the possible combinations of maneuvers and to choose that is feasible and that minimizes the consumption of fuel of all the constellation.

Until the moment, all the boxes shown in Figure 9 they were already implemented, and were considered, as a first approach, only two satellites simultaneously for to test the algorithm developed. The tests have shown that the algorithm reaches the objectives. However, the work is in the beginning. We hoped to obtain results considering three or more satellites as soon as possible.

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TÍTULO

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Astrodynamics, Orbital Transfer, Optimal Control, Time Constraint; Station Keeping, Satellite Constellation.