A SURVEY OF AUTONOMOUS ORBIT CONTROL INVESTIGATIONS AT INPE

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ABSTRACT *– A survey of the research on autonomous orbit control systems carried out at INPE is presented. INPE started working in this area in 1995 when an study on the feasibility of an autonomous control concept of the orbit longitude phase drift (ΔL_0) was performed, in cooperation with the French Space Agency (CNES). The use of DIODE (French autonomous navigator) simulated orbit observations was considered. Thereafter, following a world wide trend, the research work was re-directed to the investigation on the use of the GPS (Global Positioning System). At first, only the direct use of the coarse GPS navigation (geometric) solution was considered. In order to improve the results of the GPS based autonomous control, a GPS simplified navigator was developed and included in the control procedure. Samples of the results obtained in each phase of the research work are presented and commented in the work.*

KEYWORDS: Autonomous Orbit Control, Longitude Phase Drift, Autonomous Navigation, GPS, DIODE..

INTRODUCTION

With the advent of the modern positioning systems, like GPS and DORIS for instance, reliable and accurate autonomous navigation means are being more and more explored. Through such a system, the on-board availability of continuous and accurate knowledge of the satellite orbit makes feasible the idea of increasing the degree of autonomy of the orbit control system, reducing the need of ground interventions. Particularly attractive is the case of having autonomous control of the longitude phase drift, ΔL_0, for phased earth observation satellites, in order to maintain this parameter within an adequate range, so as to assure the repeatability of the satellite ground track. For this kind of mission, this parameter is the one which requires the higher corrective maneuver application rate.

INPE started working in this area in 1995 when an study on the feasibility of an autonomous control concept of ΔL_0 was performed, in cooperation with the French Space Agency (CNES) [1]. In this preliminary study, real and simulated orbit estimates from DIODE navigator [2] were used.

Three versions of autonomous orbit control procedures have been studied is this preliminary analysis. The first version computes the orbit correction amplitudes with help of a simplified model for the longitude drift time evolution, whose parameters are estimated in real time. The second one, however, always applies orbit corrections with the same, previously determined, amplitude, independently of the current conditions in terms of navigation error magnitude and solar activity. In the third version, however, the corrections amplitude are taken as a function of the current solar activity conditions.

Also analyzed, in this preliminary phase, was of the possibility of improving the autonomous orbit control performance by reducing the oscillations in the observations of $\dot{\Delta L_0}$ caused by the geopotential tesseral harmonics [3].

Thereafter, following a world wide trend, the study was directed to the investigation on the use of the GPS (Global Positioning System) instead of DIODE [4]. At first, the direct use of the coarse GPS navigation (geometric) solution was considered [5, 6]. This GPS solution presents inaccuracies in the position and velocity components of the orbit state vector, which are several orders of magnitude greater than the ones presented by the DIODE navigator, considered in the previous study. Complementing this analysis, an analysis of the influence of the maximal allowable maneuver application rate was performed [7].

Finally, a simplified GPS navigator was developed and its application to the autonomous orbit control was analyzed [8]. This navigator allowed the computation of improved orbit estimates from the GPS (geometric) navigation solution, without adding a significant computational burden to the autonomous orbit control procedure. It basically consists of a Kalman filtering process, which incorporates a procedure for automatic treatment of observation biases. Its introduction to the autonomous control procedure allowed to obtain a significant reduction in the variation range of ΔL_0.

A general description of the autonomous control concept is given in the next section. In another section, the main aspects of the preliminary study performed by INPE regarding this subject are presented and commented. After that, the performed feasibility analysis of directly applying the GPS navigation solution in the autonomous orbit control, is summarized. Following this, a new section presents and discusses the relevant results of the development of a simplified GPS navigator, and its application to autonomous orbit control. Closing the paper, final comments and conclusions are presented.

AUTONOMOUS CONTROL PROCEDURE

General Description

The Fig. 1 presents the general block diagram of the autonomous control system.

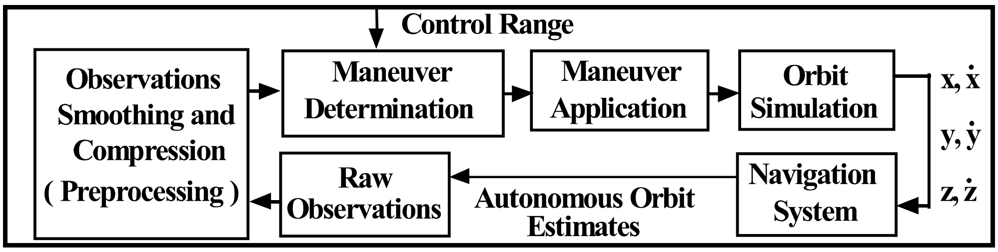

Fig. 1. Block Diagram for the autonomous orbit control system

The first task of the autonomous orbit control process is the computation of raw observations of ΔL_0 and $\dot{\Delta L_0}$ from the orbit estimates issued by the navigator. The following equations are used in this task:

$$\Delta L_0 = a_e \cdot [\Delta\Omega + \frac{\Delta\alpha}{(N + P/Q)}] \tag{1}$$

$$\dot{\Delta L_0} = -\frac{3\pi}{T_{te}}\left(\frac{a_e}{a_R}\right)(1-\varepsilon)\left[\Delta a - \left(\frac{da}{di}\right)_p \Delta i\right], \tag{2}$$

where T_{te} is the mean solar day; a_e is the Equator radius, a_R is the reference orbit semi major axis;

$$\varepsilon = \frac{7}{3}\frac{T_{te}}{T_{so}} + \frac{7}{2} J_2 \left(\frac{a_e}{a}\right)^2 [4\cos^2(i) - 1] \; ; \quad \text{and} \quad \left(\frac{da}{di}\right)_p = -\frac{2}{3} a.\tan(i) \frac{T_{te}}{T_{so}} \frac{(1+\eta)}{(1+\varepsilon)} \; ; \qquad (3)$$

where: T_{so} = 1 year and $\eta = 12\ J_2 (T_{so}/T_{te})(a_e/a)^2 \cos^2(i)$.

It is assumed constant solar flux during the time interval between the application of two successive orbit correction maneuvers, which implies in having constant *da/dt* (*a* being the orbit semi-major axis) during this interval. Under this assumption, the time evolution curve of ΔL_0 is almost parabolic, and (calling $\Delta t = t - t_0$) the simplified model given by Equation 4 can be used by the maneuver computation process, to foresee the time evolution of the Equator longitude phase drift.

$$\Delta L_0(t) = \Delta L_0(t_0) + \dot{\overline{\Delta L}}_0(t_0)\Delta t + \ddot{\overline{\Delta L}}_0(t_0)\Delta t^2/2 \qquad (4)$$

Considering this model the time derivative of ΔL_0, $\dot{\overline{\Delta L}}_0(t)$, is given by:

$$\dot{\overline{\Delta L}}_0(t) = \dot{\overline{\Delta L}}_0(t_0) + \ddot{\overline{\Delta L}}_0(t_0)\Delta t \qquad (5)$$

The computed raw observations of $\dot{\overline{\Delta L}}_0(t)$ are preprocessed in real time, in order to achieve data smoothing by curve fitting, validation and redundancy reduction. The preprocessed values are used as observation, by a Kaman filtering process which provides real time estimates of the parabolic model coefficients $\hat{\dot{\overline{\Delta L}}}_0(t_k)$ and $\hat{\ddot{\overline{\Delta L}}}_0(t_k)$, k=1, 2, ... It can be observed that the coefficients of Equation 5 are the same last two coefficients of Equation 4. Estimates of the remaining coefficient, of Equation 4 ($\Delta L_0(t_k)$) are computed with help of the following equation:

$$\hat{\overline{\Delta L}}_0(t_k) = \left[\sum_{i=0}^{k-1} p_i \overline{\Delta L}_0(t_i) + p_k \overline{\Delta L}_0(t_k)\right] / \left(\sum_{i=0}^{k-1} p_i + p_k\right) \qquad (6)$$

where p_0, p_1,... p_k are weighting factors.

The estimates $\hat{\overline{\Delta L}}_0(t_k)$, $\hat{\dot{\overline{\Delta L}}}_0(t_k)$ and $\hat{\ddot{\overline{\Delta L}}}_0(t_k)$ are used by the block "Maneuver Determination and Computation" to determine the need of maneuvers and to compute the required correction amplitudes. In order to test the autonomous control procedure, the control loop is closed with help of a realistic orbit simulator, from whose outputs the navigator orbit estimates are simulated.

Determination of Maneuver Needs

The following three versions of the autonomous control procedure have been studied:

- **a -** Variable Amplitude Corrections
- **b -** Constant Amplitude Corrections.
- **c -** Adaptive Amplitude Corrections.

Both procedures consider the same process of determining the need of maneuver applications. Due to orbital decay the satellite ground track drifts Eastward. One semi-major axis increment is assumed to be needed to correct the time evolution of ΔL_0 each time the two conditions below are both satisfied:

$$\hat{\overline{\Delta L}}_0(t_k) > \Delta L_{0sup} - n.\sigma(t_k) \qquad (7)$$

$$\hat{\dot{\overline{\Delta L}}}_0(t_k) > \dot{\overline{\Delta L}}_{0sup} + n_p.\sigma_p(t_k), \qquad (8)$$

where ΔL_{0sup} and $\dot{\overline{\Delta L}}_{0\,sup}$ are previously chosen control limit values; $\sigma(t_k)$ and $\sigma_p(t_k)$ are the standard deviations of $\hat{\overline{\Delta L}}_0(t_k)$ and $\hat{\dot{\overline{\Delta L}}}_0(t_k)$ and n and n_p are two previously chosen real numbers.

Variable Amplitude Corrections

This version computes each orbit correction so as to cause a change in the sense of $\Delta L_0(t)$ in such a way that the minimum value to be attained, considering the parabolic model of Equation 4, will be equal the previously chosen lower limit of control. In order to maximize the time interval between the execution of two successive maneuvers, only positive semi-major axis correction is allowed to be applied. Calling t_{man} the instant of a maneuver application, and assuming that ΔL_{0inf} is the previously chosen inferior limit of ΔL_0, and that the evolution of ΔL_0 is modeled by Equation 4, then the value of $\dot{\Delta L}_0(t_{man})$ (called $\dot{\Delta L}_{0C}$) for which $\hat{\Delta L}_{0min}(t/t_{man}) = \Delta L_{0inf}$ can be found to be given by:

$$\dot{\Delta L}_{oc} = \sqrt{2.\hat{\ddot{\Delta L}}_o(t_{man}).[\hat{\Delta L}_o(t_{man}) - \Delta L_{o\,inf}]} \tag{9}$$

Considering some approximations which could be assumed for phased helio-synchronous orbits at CBERS1 like altitudes, and assuming that *da/dt* is constant between two successive maneuvers then it can be easily deduced the following equation:

$$\Delta v_T = -\frac{T_{te}.V.[\hat{\dot{\Delta L}}_{oc} - \hat{\dot{\Delta L}}_o(t_{man})]}{6\pi\pi._e} \tag{10}$$

where Δv_T is the tangential velocity increment needed to correct the time evolution of ΔL_0 and V is the absolute value of the satellite speed. Whenever one orbit correction is applied to the satellite, the coefficient estimation procedure, mentioned above, is automatically re-initialized in order to avoid filter divergence.

Constant Amplitude Corrections

The Constant amplitude corrections version of the autonomous orbit control procedure does not perform computation of orbit correction amplitudes. The amplitude of corrections has always the same pre-determined value, independently of the current conditions in terms of navigation errors magnitude and solar activity. Each time the Equations 7 and 8 are both satisfied one semi-major axis increment with the constant considered amplitude, are applied in order to correct the time evolution of ΔL_0.

Adaptive Amplitude Corrections

The solar activity is divided in several variation ranges, and one single value of orbit correction amplitude is previously associated to each one of these ranges. When the application of an orbit correction is verified to be needed, the control procedure autonomously selects the correction amplitude which corresponds to the current solar activity condition. The previous amplitude association to solar activity range is done in function of $\ddot{\Delta L}_0(t)$, which directly depends on the solar activity, and is estimated during the control procedure application. The estimate of $\ddot{\Delta L}_0(t)$ corresponding to the maneuver application instant defines what correction amplitude is to be applied.

PRELIMINARY STUDIES

In the preliminary studies, both real and simulated from a DIODE like navigator were used to perform the tests on the autonomous control concept. The orbit estimates was simulated at a rate of 1 estimate set each 10 seconds, with rms errors of 10m in the position and 0.001 m/s in the velocity components of the state vector. The performance of the proposed autonomous control has been analyzed over a simulation period of about one year, considering worst conditions in terms of solar activity variation. The solar flux 11-year cycle has been shortened into one year simulation, with a very high maximum (360 in flux units), and kept the 27-day cycle oscillations due to solar rotation. The main aspects and obtained results for each control procedure version are presented in the next subsections.

Variable Amplitude Corrections

The Fig.2 shows the best results, which have been obtained in the preliminary studies with the Variable Amplitude Corrections version of the autonomous control procedure, when no tesseral effect correction is applied. DIODE like estimates were simulated with standard deviation of 30 m in the position components of the orbit state vector, and 0.01 m/s in the velocity ones. One can see from Fig. 2 that the longitude phase drift remained inside a restrict range of about -200 to 400m. This result can be considered a very satisfactory one, since for SPOT2 and SPOT3 this parameter should nominally be maintained inside the range of $\pm$ 3000 m.

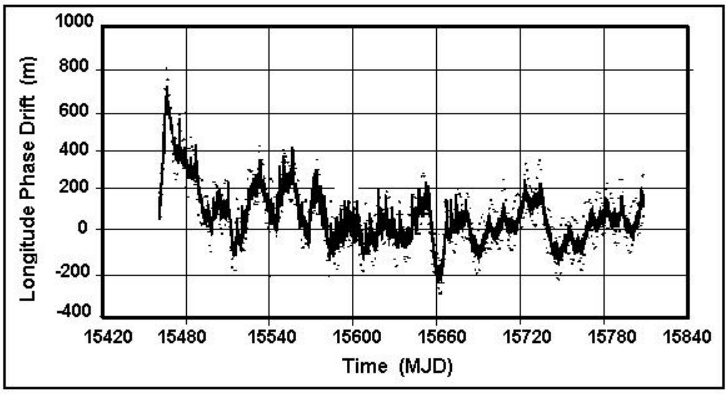

Fig. 2. ΔL_0 vs time : Variable Amplitude Corrections

The influence in the observations of $\overline{\Delta \dot{L}_0}$ of correction for the effects of the geopotential tesseral harmonics on the orbit inclination has been analyzed. A revised issue of the Ustinov's theory for near circular orbits, considering tesseral terms up to J_{44} , has been considered [9] in a simplified form, by assuming the approximations: $\sin(i) \cong 1$ $(i \cong 90°)$ and $T_{te}/T_{sa} << 1$. The longitude phase drift remained, in this improved case, restricted to a reduced variation range of about ±200 m, displaying, in this way, a significant increase in the autonomous orbit control performance.

Constant Amplitude Corrections

The Fig. 3 shows the results obtained with the application of the constant amplitude corrections version of the autonomous orbit control procedure to the same test case of the previous subsections. The constant semi-major axis correction Δa has been taken equal to 8m. One can see from Fig. 3 that the curve of ΔL_0 tends to increase when the solar activity is higher. On the other hand, under low solar activity one can see that relatively important negative deviations occurred. This means that, at the considered maximal maneuver rate (1 correction per orbit) the correction amplitude is not large enough to reduce the error, when under strong solar activity. On the other hand, when under weak solar activity conditions, the chosen correction amplitude shows to be excessively large.

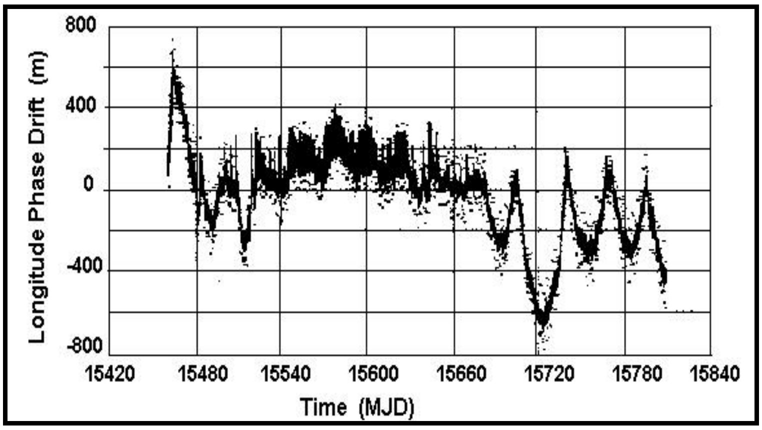

Fig. 3. ΔL_0 vs time: Constant Amplitude Corrections

Adaptive Amplitude Corrections

The situation explained above for the previous case should be avoided by the adaptive amplitude corrections procedure which, basically, is an improved version of the previous one. The Fig. 4 presents the results obtained by the application of this procedure to the same case of the subsections just above. Comparing the curve presented in Fig 4 with the one of Fig. 3 one observes, besides a reduction in the ΔL_0 variation, the absence of the above commented problems presented by the constant amplitude corrections version of the autonomous orbit control procedure.

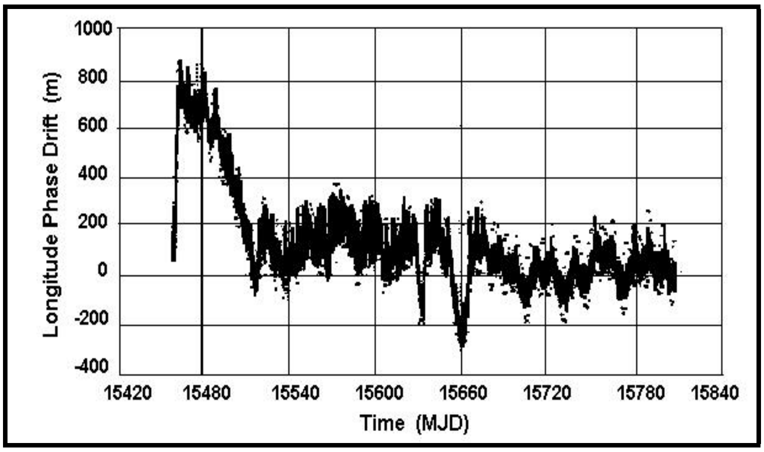

Fig. 4. ΔL_0 vs time: Adaptive Amplitude Corrections

USE OF THE GPS NAVIGATION SOLUTION

Thereafter, following a world wide trend, the study was directed to the investigation on the use of the GPS (Global Positioning System) instead of DIODE. At first, the aim of the study was the analysis of the feasibility of straightforward application of the GPS coarse navigation solution in the presented autonomous orbit control procedures. The GPS coarse orbit estimates are several order of magnitude less accurate than the ones issued by DIODE. Typical root mean square errors of the coarse GPS geometric estimates were of 100m in position and 1m/s in velocity, before Selective Availability was turned off. Added to such random errors these estimates showed systematic variations with values of the order of 100m and duration of about 1 to 15 minutes. These variations occur due to the changes of the set of GPS satellites which are visible to the on-board GPS receiver. Each GPS satellite has its own systematic error and, in this way, each time a satellite goes out of the GPS receiver antenna coverage region, or a new satellite enters in this region, the systematic error of the global navigation solution is prone to change its value. The autonomous orbit estimates corresponding to the GPS coarse navigation solution have been simulated by the addition of a gaussian white noise to the simulated orbit state vector. The Fig. 5 presents the results obtained by the application of the constant amplitude corrections version of the control procedure.

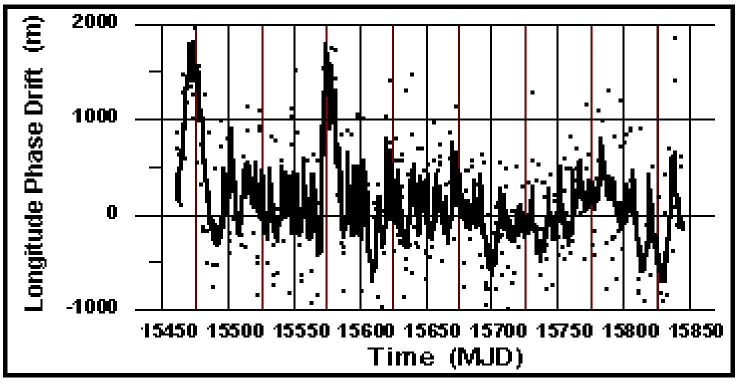

Fig. 5. ΔL_0 vs time: Constant Amplitude Corrections (GPS)

One can see that, as expected, the control range is increased when the GPS navigation solution replaces the DIODE like navigator. Anyway, the control procedure successfully maintains the values of ΔL_0 under control during all simulated interval (about 1 year), even under the very severe solar flux conditions considered in the simulation. This enlarged control range (of about -1000m to 1700m, as seen by Fig. 5) can, however, be considered as a satisfactory one, since the nominal variation range specified for ΔL_0, for some existing phased Earth observation satellites, are larger than it (10,000m in the case of CBERS1, for instance). The results presented in the Fig. 5 are a little better than the ones that have been obtained, in the same case, with the application of the procedure version of variable correction amplitudes. As the constant amplitude corrections version does not computes the amplitude of correction as a function of the estimates of the parameters of the simplified model of ΔL_0 (t), it does not face the risk of computing values of correction which are excessively large or small. It always applies the same amplitude correction, when needed, only changing the correction applications rate. Since it avoids the application of excessively large or small corrections, this procedure version presents higher robustness characteristics than the variable amplitude corrections version.

ANALYSIS OF THE MAXIMAL ALLOWABLE MANEUVER APPLICATION RATE

The results presented in last section considered a very high sampling rate of the GPS orbit estimates: 1 estimate set every 10 seconds. This sampling rate is the same one taken in previous studies, when a DIODE-like navigator was used. In addition, a very high maximal allowable application rate of one semi-major axis correction per orbit period was assumed. Due to this, a further analysis of the influence on the autonomous control procedure performance of the maximal allowable maneuver application rate has been developed. This analysis has been carried out considering the application of the procedure version which considers adaptive corrections amplitude. Actually, such version was the one that presented the best performance among all the ones analyzed in previous studies. The same worst case conditions, in terms of solar activity assumed in the previous investigations, have been considered. The obtained results showed the feasibility of imposing limits to the orbit correction rate to a minimal value of, at least, one per day. Emphasis shall be given on the fact that this result was attained by considering the simulation of the autonomously generated coarse GPS navigation solution, instead of a more accurate system. The rate of generation of these estimates could be reduced from 1 estimates set each 10 seconds to one set each minute. The work can, yet, be complemented in future investigation in order to find the lower limit values of both the navigator estimates generation and maneuver application rates.

USE OF A SIMPLIFIED GPS NAVIGATOR

Complementing the studies, the use of a simplified GPS navigator, in order to supply the needed autonomous orbit observations (instead of the direct use of the GPS navigation solution) has been analyzed. Orbit simulation of the China-Brazil Earth Resources Satellite was used for this analysis. The idea behind using a simplified navigator was to allow the computation of improved orbit estimates from the GPS (geometric) navigation solution, without adding a significant computational burden to the autonomous orbit control procedure. The simplified navigator consists, basically, of a Kalman filtering process, which incorporates a procedure for automatic treatment of observation biases. On the other hand, the goal of the control is to provide autonomous control of the Equator longitude phase drift (ΔL_0) of low-Earth phased orbits, thanks to the on-board availability of orbit estimates, autonomously generated by the navigator.

As presented above, even under worse case conditions in terms of solar activity, the autonomous control successfully maintained the Equator longitude phase drift ΔL_0 restricted to an excursion range of about -1000m and 1700m. The introduction of the simplified navigator to the autonomous control procedure, successfully improved the control results, significantly reducing the variation range of ΔL_0. Both realistic and worse case conditions in terms of solar activity were considered in the simulation. This study has been carried out considering the application of a version of the autonomous orbit control procedure, which considers only the application of semi-major axis corrections with a constant, previously chosen amplitude. Some improvements have, however, been implemented. In the original version the raw observation of both ΔL_0 and its first time derivative, $\dot{\overline{\Delta L_0}}$, were computed from each simulated set of GPS orbit estimates. Now only the ΔL_0 observations are computed from the orbit estimates. The needed observations of $\dot{\overline{\Delta L_0}}$ are directly computed, in a numerical way, from the last computed observations of ΔL_0. Such approach increased the accuracy of the $\dot{\Delta L_0}$ observations and, as a consequence, the performance of the autonomous control process. A maximal maneuver application rate of about one pulse per orbit was considered. It was also considered a GPS observation rate (and consequently the navigator output rate) of 1 estimate each 9 seconds. Only one among 20 orbit estimates sets successively issued by the navigator is used by the control system.

The results considering the incorporation of the GPS simplified navigator to the autonomous control system, under critical solar activity condition, are shown in Fig. 6. The same observation rate above considered for the simplified navigator analysis was considered. Although the navigator supplies orbit estimates at a rate of 1 set each 9 seconds, the autonomous control procedure only used one of such sets each 9 minutes.

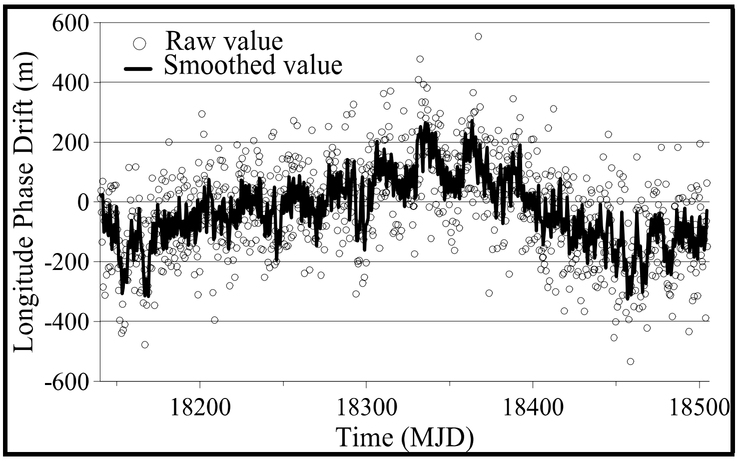

Fig. 6. ΔL_0 vs. Time: Use of Simplified GPS Navigator, Under Critical Solar Activity

By comparing the results of the current investigation, depicted in Fig. 6, with the ones related to a previous analysis, presented above, one can see that the inclusion of the simplified navigator to the autonomous orbit control procedure produced a significant reduction in the variation range of ΔL_0. The mean (smoothed) value of ΔL_0 remained in a range of about ±300m, which is about one order of magnitude lower than the previous case, where the coarse navigation solution was directly used in the autonomous control procedure. By improving the accuracy of the GPS coarse navigation solution, the use of the simplified navigator allowed, as expected, to obtain a consequent improvement of the autonomous control performance. The obtained results can be considered very promising. They reveal that a very relevant increment in the autonomous control accuracy can be obtained, with a relatively low increment in terms of the overall computational load imposed to the controller by the simplified navigator. In addition, these results indirectly show satisfactory robustness characteristics of the simplified GPS navigator, since the accomplished tests considered, always, a long simulated period (about one year). It can be inferred from Fig. 6 that, during the entire simulated period, the navigator performed very conveniently, since any degradation occurred in the navigator performance would have na impact in the overall performance of the autonomous control system.

5. CONCLUSIONS

The previous studies, considering a DIODE like navigator system as the source of autonomous orbit estimates, showed the feasibility of the autonomous orbit control concept. The results show a very satisfactory performance and good robustness characteristics, even under the worst case conditions considered in the tests. Further improvement, which consisted of the correction of the geopotential tesseral harmonics effects on the orbit inclination incremented the performance of the analyzed concept of autonomous control.

The investigation was then directed on the feasibility of using the autonomously generated GPS navigation solution, instead of a more accurate DIODE like orbit estimation. The results were very promising, since both types of developed autonomous control procedures have shown results which complied with the requirements imposed to the real Longitude phase drift control of existing satellites.

The analysis of the influence on the autonomous control procedure performance of the maximal allowable maneuver application rate showed the feasibility of imposing limits to the orbit correction rate to a maximal value of, at least, one per day. It shall be given emphasis on the fact that this result was attained by considering the simulation of the autonomously generated coarse GPS navigation solution, instead of a more accurate system. The rate of generation of these estimates was reduced from 1 estimates set each 10 seconds to one set each minute.

Finally, the use in the control procedure of a simplified GPS navigator, instead of the direct use of the GPS navigation solution has been analyzed. As expected, the use of more accurate orbit estimates in the computation of the needed observations of ΔL_0 improved the performance of the autonomous orbit control. Even under worse case conditions, in terms of solar activity, the longitude phase drift was maintained by the controller inside a reduced range of ±300m. This represents a relevant gain in terms of accuracy when compared with the results of a previous work, where the coarse GPS navigation solution was directly applied in the orbit control process. Another positive aspect which must be mentioned is that, due to the navigator simplicity, the obtained gain in terms of autonomous control performance did not imply in a prohibitive rise to the computer processing burden.

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