ANALYSIS OF AN AUTONOMOUS ORBIT CONTROL CONCEPT USING GPS

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Abstract

Formerly, investigations on the feasibility of an autonomous orbit control concept have been carried out within a cooperation frame between INPE and CNES. In that study the performance of a procedure for autonomous control of the Equator longitude phase drift (ΔL_0) control has been analyzed. The use of the DIODE (French autonomous orbit determination system, based on the DORIS tracking system) like navigator has been considered, in order to provide, in real time, the orbit estimates needed to feedback the control system. The obtained results, presented in previous papers, gave the motivation to drive the study to the investigation on the performance of an autonomous control concept considering the use of the GPS (Global Positioning System) to provide the autonomous orbit estimates. The GPS system is wide-world spread and its use is increasingly being considered for many future Earth missions as on-board navigation system. This paper presents and analyses the results obtained when the use of the coarse GPS navigation solution[1] is considered in the autonomous orbit control system.

Key words: GPS, DIODE, Autonomous Orbit Control.

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[2].

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. This kind of orbit correction maneuver is the one which requires higher application rates. The autonomous control of ΔL_0 will eliminate the need of ground based interventions to perform this task, which consequently will imply an important reduction in the ground operational load.

Formerly, within a cooperation framework between INPE and CNES a concept of an autonomous longitude phase drift control was analyzed. In this analysis, real and simulated SPOT2 and SPOT3 orbit estimates from the French DIODE navigator[3] were used to test the concept. The accuracy of the estimates issued by DIODE shows, nowadays, standard deviations of the order of centimeters in the position components of the orbit state vector and of order of millimeter/second in the velocity components. The results[3] of this study were very promising showing the feasibility of the autonomous control implementation. In addition, it showed the possibility of maintaining the variations of ΔL_0 restricted to a range ten times less than the one maintained nowadays with the conventional ground based control of the considered satellites.

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In a second phase of the study, the possibility of improving the autonomous orbit control procedure has been investigated, through the reduction of the oscillations in the observations of $\dot{\Delta L}_0$ (the first time derivative of ΔL_0**)** caused by the geopotential tesseral harmonics on the orbit inclination[5]. A simplified model of geopotential tesseral harmonics effect on the orbit inclination has been used and their effects on $\dot{\Delta L}_0$ could be reduced by about one order of magnitude. This allowed a significant increment on the performance of such concept of autonomous control of ΔL_0.

The study is nowadays directed to the investigation on the use of GPS (Global Positioning System) in the controller feedback loop, considering only its coarse navigation solution. This navigation 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. Data of the orbit of the French Earth remote sensing satellite SPOT was considered in the tests.

Two versions of the autonomous control procedure have been analyzed. The first one considers a kinematics parabolic model for the time evolution of ΔL_0, whose coefficients are estimated in real time with help of a Kalman filter. These estimates are used to compute the amplitude of each corrective impulse, whenever ΔL_0 reaches a predefined upper limit value. Its value is computed so as to cause an inversion in the sense of the ΔL_0 time evolution in such a way that the minimal value of the future parabolic evolution be coincident with the specified lower limit value. The second version of the autonomous orbit control procedure considers the application of constant impulses of small amplitude only, whenever it is needed, in order to maintain the value of ΔL_0 inside a tighter control range. Worst case conditions of solar flux and geomagnetic activity, both in terms of magnitude and of time variation have been considered in the test cases. The results, which can be considered very encouraging, are presented, discussed and compared with the previous ones.

Autonomous Control Procedure

The block diagram for the autonomous orbit control system is presented in Figure 1.

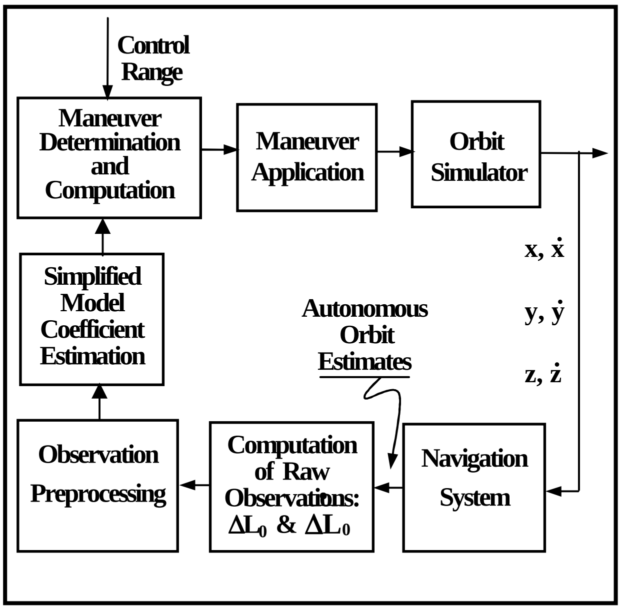

Figure 1. Block Diagram

The first task of the autonomous control process consists of the computation of raw observations of ΔL_0 and $\dot{\Delta L}_0$ from the autonomous orbit estimates issued by the navigator. The computed raw observations of $\dot{\Delta L}_0$ are, then, preprocessed in real time, in order to achieve data smoothing by curve fitting, validation and redundancy reduction. In the case of DIODE navigator, for instance, the data are generated at a high rate (one orbit estimate each 10 seconds) if compared with the mean time evolution of ΔL_0 and $\dot{\Delta L}_0$**.** As a consequence, the computed observations of ΔL_0 and $\dot{\Delta L}_0$ present a high degree of redundancy, which can be removed in order to reduce the quantity of data to be further processed by the orbit control process. The same rate will be considered for GPS orbit estimates and, in this way, the observations of $\dot{\Delta L}_0$, computed from these estimates**,** will also be submitted to the same kind of preprocessing. The raw observations of ΔL_0 and $\dot{\Delta L}_0$ are computed, from the navigator orbit estimates, with the help of the following equations:

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

$$\dot{\Delta L}_0 = -\frac{3\pi}{T_{te}}\left(\frac{a_e}{a_R}\right)(1-\varepsilon)\left[\Delta a - \left(\frac{da}{di}\right)_p \Delta i\right], \qquad (2)$$

where T_{te} is the mean solar day (86400 s); a_e is the Equator Earth radius, a_R is the reference orbit semi major axis;

$$\varepsilon = \frac{7}{3}\frac{T_{te}}{T_{so}} + \frac{7}{2} J_2 \left(\frac{a_e}{a}\right)^2 [4\cos^2(i) - 1]; \tag{3}$$

$$\left(\frac{da}{di}\right)_p = -\frac{2}{3} a.\tan(i) \frac{T_{te}}{T_{so}} \frac{(1+\eta)}{(1+\varepsilon)}; \tag{4}$$

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. Considering this assumption, the time evolution curve of ΔL_0 is almost parabolic. Under this assumption, calling $\Delta t = t - t_0$, the simplified model of ΔL_0 given by Equation 5, can be used, by the maneuver computation process, to foresee the evolution of the Equator longitude phase drift.

$$\Delta L_0(t) = \Delta L_0(t_0) + \overline{\dot{\Delta L}}_0(t_0)\Delta t + \overline{\ddot{\Delta L}}_0(t_0)\Delta t^2/2 \tag{5}$$

Considering $\Delta L_0(t)$ modeled by Equation 5, its time derivative $\overline{\dot{\Delta L}}_0(t)$ is, then, given by:

$$\overline{\dot{\Delta L}}_0(t) = \overline{\dot{\Delta L}}_0(t_0) + \overline{\ddot{\Delta L}}_0(t_0)\Delta t \tag{6}$$

The preprocessed values of $\overline{\Delta L}_0(t_k)$ and $\overline{\dot{\Delta L}}_0(t_k)$, where t_k is the time tag of the k^{th} compressed observation issued by the preprocessor, are used as observation, by a Kaman filtering process which provides, in real time, the estimates of the coefficients of Equation 2: $\overline{\hat{\dot{\Delta L}}}_0(t_k)$ and $\overline{\hat{\ddot{\Delta L}}}_0(t_k)$. It can de observed that the coefficients of Equation 6 are the same last two coefficients of Equation 5. In this way, in order to have estimates of the complete set of coefficients of both equations (that is, equations 5 and 6) only one coefficient, $\Delta L_0(t_k)$, remains to be estimated. This remaining estimate is directly computed from the following equation:

$$\overline{\hat{\Delta L}}_0(t_k) = \left[\sum_{i=0}^{k-1} p_i \overline{\Delta L}_0(t_i) + p_k \overline{\Delta L}_0(t_k)\right] / \left(\sum_{i=0}^{k-1} p_i + p_k\right) \tag{7}$$

where $p_0, p_1, \ldots p_k$ are weighting factors.

The estimates $\overline{\hat{\Delta L}}_0(t_k)$, $\overline{\hat{\dot{\Delta L}}}_0(t_k)$ and $\overline{\hat{\ddot{\Delta L}}}_0(t_k)$ are used by the block “Maneuver Determination and Computation” to determine the need of maneuvers and to compute the required correction amplitudes. 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

In this work two types of autonomous control procedures are studied:

a - Variable Corrections Amplitude
b - Constant Corrections Amplitude.

These two procedure have been presented in previous works and will be briefly described here. More details can be found in references 1 and 2.

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 following conditions are both satisfied:

$$\overline{\hat{\Delta L}}_0(t_k) > \Delta L_{0sup} - n.\sigma(t_k) \tag{8}$$

$$\overline{\hat{\dot{\Delta L}}}_0(t_k) > \overline{\dot{\Delta L}}_{0sup} + n_p.\sigma_p(t_k), \tag{9}$$

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

Variable Corrections Amplitude

In the Variable Corrections Amplitude Procedure the amplitude of each correction is computed so as to cause a change in the sense of the time evolution of ΔL_0, in such a way that the minimum value to be attained, considering the model given by Equation 5, will be equal the previously chosen low limit of control. The application only of positive corrections to the orbit semi-major axis is allowed, in order to maintain the value of ΔL_0 inside the control ranges. This strategy implies in the maximization of the time interval between the execution of two successive maneuvers.

One assumes that ΔL_{0inf} is the previously chosen inferior limit of ΔL_0 and that t^+_{man} is a time just after the application of an orbit correction. Then considering the evolution of ΔL_0 modeled by Equation 5, the value of $\overline{\dot{\Delta L}}_0\,(t^+_{man})$ for which $\hat{\overline{\Delta L}}_{0min}(t/t_{man}) = \Delta L_{0inf}$ can be easily found by:

$$\overline{\dot{\Delta L}}_{oc} = \sqrt{2.\,\hat{\overline{\ddot{\Delta L}}}_o(t_{man}).[\hat{\overline{\Delta L}}_o(t_{man}) - \Delta L_{o\,inf}]} \quad (10)$$

Considering some approximations which could be assumed for phased helio-synchronous orbits at SPOT like altitudes, and assuming da/dt as constant between two successive maneuvers one can arrive at the following equation[4,5]:

$$\Delta v_T = -\frac{T_{te}.V.[\hat{\overline{\dot{\Delta L}}}_{oc} - \hat{\overline{\dot{\Delta L}}}_o(t_{man})]}{6\pi.a_e} \quad (11)$$

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 is automatically re-initialized in order to avoid filter divergence.

Constant Corrections Amplitude

By the Constant Corrections Amplitude Procedure, there is no computation of orbit correction amplitudes. The amplitudes of corrections have always the same pre-determined value, independent of the current conditions in terms of navigation errors magnitude and solar activity. Each time the conditions given by Equations 8 and 9 are both satisfied one semi-major axis increment, with the constant pre-determined amplitude, are applied to correct the time evolution of ΔL_0.

GPS Navigation Solution

The aim of the study is to verify 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 the French DIODE navigator. Typical root mean square errors of the coarse GPS estimates are of 100m in position and 1m/s in velocity. Added to this random errors these estimates shows 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.

To test the performance of the described autonomous orbit control procedures, the GPS orbit estimates has been simulated, considering the random and systematic error levels mentioned above, at the rate of one estimate set every 10 seconds (the same rate of the DIODE estimator). A SPOT satellite like orbit has been considered in the simulation (phased, helio-synchronous with mean altitude of about 837 km). Tesseral effect correction makes no sense in this case, since the level of the related oscillations, on orbit inclination are less than the inaccuracy level of the estimate on this parameter.

Worst conditions in terms of solar activity variation have been considered (Fig.2).

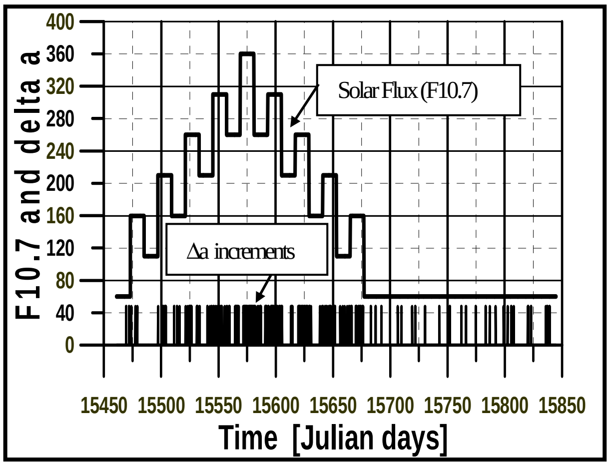

Fig. 2. Solar Flux Conditions

The solar flux 11-year cycle has been condensed purposely into one year simulation, with a very high maximum (360 in $F_{10.7}$ flux units), and kept the 27-day cycle oscillations due to solar rotation. It is to be noted that the solar flux has been simulated by discrete values along successive time intervals. The discontinuities presented by such a variation curve adds difficulty to the autonomous control system performance, which actually will not be faced, with this intensity, in the real world. The consideration of these worst conditions, during such a long simulation period, is to assess the robustness characteristics of the analyzed procedure.

Tests Results

The performance of the proposed autonomous control procedures has been analyzed on a SPOT-like orbit (mean altitude of 837 km), over a simulation period of about one year, considering worst conditions in terms of solar activity variation. Fig.3 shows the time profiles considered for the solar flux and magnetic activity index.

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 standard deviation of the added noise are taken according to the GPS coarse orbit estimates errors mentioned in the former session *"GPS Navigation Solution"*. Also incorporated to the simulated orbit estimates are the systematic errors which affect these data, as explained in the same session.

The main obtained results are the following:

a. Variable Corrections Amplitude

The Figure3 shows the results, obtained by the first control procedure type (Variable Corrections Amplitude) over a simulation period of about 400 days, considering the use of ΔL_0 observations which have been computed from simulated orbit estimates of the GPS coarse navigation solution. The upper part of the figure presents the obtained curve for the time evolution of ΔL_0. The lower part shows the applied Δa increments. As commented in an above session, the GPS coarse estimates have been simulated considering both the random and systematic errors presented by this GPS solution (100 m in position, 1m/s in velocity and systematic variations with values of up to 100m and duration of about 1 to 15 minutes). The considered control limits, which have been considered in the simulation, whose results are depicted in Fig. 3, are the following:

$$\Delta L_{0sup}=0,\ \Delta L_{0inf} = -100\text{m},\ \overline{\dot{\Delta L}}_{0sup} = 0, \text{ and } n = n_p = 0$$

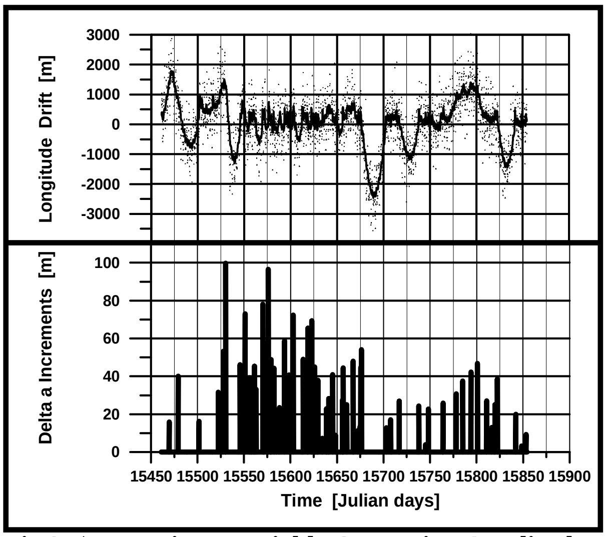

Fig.3. ΔL_0 vs. time: Variable Correction Amplitude

The Figure 4 presents the time evolution curve of ΔL_0, obtained in a previous work[5], where the orbit estimates have been simulated with standard deviations of 30 m in the position and 0.01 m/s in the velocity components.

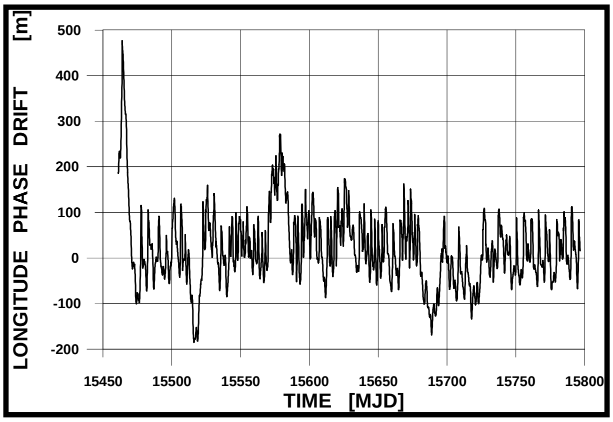

Fig.4. ΔL_0 vs time: Previous Results

By comparing the results shown in Figure 3, with the ones obtained in previous work presented in Figure 4, one sees that, as expected, the controlled range of ΔL_0 has been increased when the GPS navigation solution accuracy is considered. In the previous results, as one can observe from Figure 4, the variation of ΔL_0 remained inside a range of about ±100m. By changing the navigator by the coarse GPS solution the variation range of ΔL_0, as expected, increased one order of magnitude, as one can see by Figure 3. One see from this Figure, that the lower and upper limits are now of the order of about -2500m and 1500m, respectively. Anyway, the autonomous control system successfully maintains the values of ΔL_0 under control during all simulated interval, even under the very tough solar flux conditions considered in the simulation. The observed enlarged control range can be, however, considered as a satisfactory one, since the real operation of some existing Earth observation satellites, which operate into helio-synchronous phased orbits, considers the maintenance of ΔL_0 within an allowable range of ±3000m and over (15000m in the case of the China Brazil Earth Resources Satellites).

b. Constant Corrections Amplitude

Figure 5 shows the results obtained for the autonomous control procedure which considers the application of only constant corrections amplitude, always it is needed. The following control limits have been considered in this case:

$\Delta L_{0sup}=0$,

$\Delta L_{0inf} = -0m$,

$\dot{\Delta L}_{0sup} = 0$, and

$n = n_p = 0$

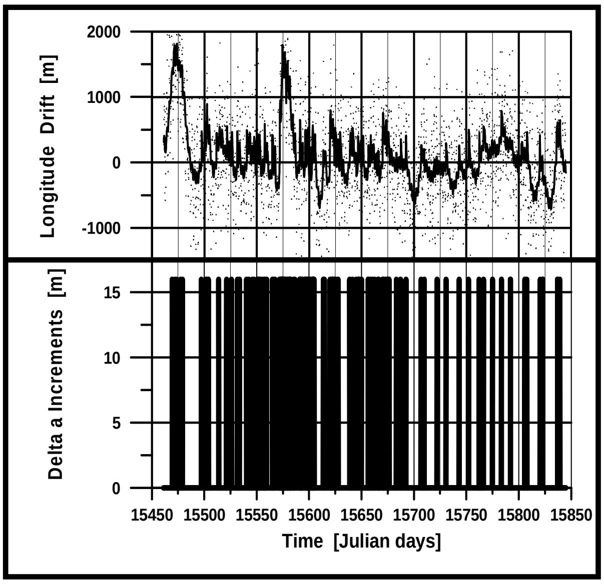

Fig.5. ΔL_0 vs. time: Constant Corrections Amplitude

One observes from Figure 5 that, in this case, the variation of ΔL_0 remained into a small reduced range, if compared with the results of the first case, presented in Figure 3. The lower and upper limits values of the variation range of ΔL_0, as shown in Figure 5, are now, respectively, of -1000m , 1700m. By comparing Figures 3 and 5, the constant corrections amplitude procedure shows a performance somewhat better than the one presented by the first procedure (variable correction amplitudes). As the second procedure does not compute the amplitude of correction, as a function of the estimates of the parameters of the considered simplified model of the time evolution of ΔL_0 (Equation 5), 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, in an automatic way, the rate of corrections application. The occurrence of these changes in correction rate is a function of the current solar activity conditions, which are directly reflected by the estimates of $\ddot{\Delta L}_0$. In this way, by avoiding the application of excessively large or small corrections the constant corrections procedure presents higher robustness characteristics than the variable corrections procedure. The results of both procedures can, nevertheless, be considered plainly satisfactory, as commented before.

Conclusions

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

Indeed, the current investigation has focused on the feasibility of using the autonomously generated coarse GPS navigation solution, instead of a more accurate system. The preliminary results, shown in this work, are very promising, since both types of developed autonomous control procedures shown satisfactory performance, which comply with the requirements imposed to the Equator phase drift control of most of existing satellites.

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