96-c-24

20TH, GIFU ISTS & 11TH IAS

Orbit Control Analyses of China Brazil Earth Resources (CBERS) Mission

Helio Koiti Kuga
Roberto Vieira da Fonseca Lopes
Kondapalli Rama Rao

INPE - DMC, BRAZIL

20th International Symposium on Space Technology and Science
Gifu, Japan
May 19 - 25, 1996

20th ISTS Secretariat
Hamamatsu-cho Central Building, 1-29-6 Hamamatsu-cho
Minato-ku, Tokyo 105
JAPAN

ORBIT CONTROL ANALYSES OF CHINA-BRAZIL EARTH RESOURCES SATELLITE (CBERS) MISSION

Hélio Koiti Kuga*
Roberto Vieira da Fonseca Lopes*
Kondapalli Rama Rao*

Instituto Nacional de Pesquisas Espaciais - INPE/DMC
CP 515 - São José dos Campos - SP
CEP 12201-970 BRAZIL

ABSTRACT

This work describes preliminary analyses performed in order to outline the orbit control software system of the CBERS mission in terms of semi-major axis correction maneuvers. A detailed analysis of the problem shows that there exist at least three approaches for these maneuvers. A nominally optimum maneuver strategy; a conservative one which takes various inaccuracies into account; and a relaxed one which avoids abnormally short maneuver cycles. All these strategies are analyzed in this work in detail; some preliminary numerical simulations are carried out; and some interesting comments are made. For the sake of completeness, suboptimal maneuvers at left boundary of dead-band are also studied.

INTRODUCTION

The recurrent property of a sun-synchronous orbit is due to a suitable choice of its semi-major axis. Nevertheless, the true semi-major axis a will present a secular decay, mainly due to air drag, driving the orbit away from its exact recurrent condition. Indeed, as a drifts from its recurrent, nominal value $\bar{a}$, the ground track slides continuously either eastwards or westwards, according to the sign of the difference $a-\bar{a}$. The aim of in-plane maintenance orbit maneuver is to assure that the ground track will remain within an acceptable dead-band ΔL. Theoretically, the optimum maneuver strategy achieves this goal while maximizing predicted interval between maneuvers. This is accomplished by offsetting the satellite semi-major axis from its nominal value whenever the ground track reaches the left boundary of the dead-band[1)].

According to this strategy, the offset is designed in such way that the ground track will drift westwards till the left boundary of the dead-band. Afterwards, it will drift eastwards toward the right boundary, when a next maneuver must take place, thus completing the maneuver cycle. All these orbit control maneuvers are analyzed in detail in this document. Besides, the effect of inaccuracies in the estimates of orbit parameter variations are considered and the fuel consumption aspects for in-plane maneuvers are studied.

COMPUTATION OF SEMI-MAJOR AXIS' OFFSET

The orbital period is given by:

$$T = 2\pi\sqrt{\frac{a^3}{\mu}}. \tag{1}$$

Linearization about nominal values results:

$$\delta T = 2\pi\frac{3}{2}\sqrt{\frac{\bar{a}}{\mu}}\delta a \text{, where } \delta T \equiv T-\bar{T};\ \delta a \equiv a-\bar{a}. \tag{2}$$

From the recurrent property of nominal orbit, the ground track at equator should revisit each Earth longitude with a periodicity of M days. During this cycle the satellite completes N orbits, which implies that:

$$N\bar{T} = M\frac{2\pi}{\Omega_\oplus}, \tag{3}$$

where $\Omega_\oplus$ is the Earth angular velocity, while M and N are integers. Nevertheless, for a given small δa, a small delay δT occurs in the true orbit period, as already given by Eq. (2). Therefore, at the end of the M-days cycle, instead of being back to the equator at same initial longitude, the satellite will be delayed a little bit. Indeed, when the satellite ground track effectively crosses the equator, there will be a drift δL due to Earth rotation, such that:

$$N\delta T = \frac{\delta L}{\Omega_\oplus R_\oplus}, \tag{4}$$

where $R_\oplus$ is the Earth mean equatorial radius.

As it takes M days (or, equivalently, N orbits) for the drag to cause a drift δL, the instantaneous drift rate with the aid of Eqs. (1), (2) and (4), is given by:

$$\dot{L} = \frac{\delta L}{N\bar{T}} = \frac{3}{2}\Omega_\oplus R_\oplus\frac{\delta a}{\bar{a}}. \tag{5}$$

Neglecting the non-linear terms in the semi-major axis decay, one may write:

$$\delta a = \delta a_0 + \dot{a}t, \tag{6}$$

where δa_0 is the offset and t is the time spent since last maneuver. Substituting Eq. (6) in Eq. (5) and carrying out the integration, it gives:

* Senior Researcher, Division of Space Mechanics and Control
Phone: 0055-123-256183 Fax: 0055-123-256226
E-mail: HKK@DEM.INPE.BR (Internet)

$$L = \frac{3}{2}\frac{\Omega_\oplus R_\oplus}{\bar{a}}\left(\delta a_0 \cdot t + \dot{a}\frac{t^2}{2}\right). \tag{7}$$

According to the optimum strategy, the offset must be such that the maximum drift equals the dead-band size ΔL, thus postponing next maneuver as long as possible.

Now, from Eq. (7), the necessary condition for maximum drift is:

$$\left.\frac{\partial L}{\partial t}\right|_{t^*} = \frac{3}{2}\frac{\Omega_\oplus R_\oplus}{\bar{a}}\left(\delta a_0 + \dot{a}t^*\right) = 0, \tag{8}$$

which yields:

$$t^* = -\frac{\delta a_0}{\dot{a}}, \tag{9}$$

$$\Delta L = L(t^*) = \frac{3}{2}\frac{\Omega_\oplus R_\oplus}{\bar{a}}\left(\frac{-\delta a_0^2}{2\dot{a}}\right). \tag{10}$$

Therefore, the offset is given by:

$$\delta a_0 = \sqrt{-\frac{4}{3}\frac{\bar{a}\dot{a}\Delta L}{\Omega_\oplus R_\oplus}}, \tag{11}$$

and the predicted interval between maneuvers is:

$$\Delta t = -2\frac{\delta a_0}{\dot{a}} = 2\sqrt{-\frac{4}{3}\frac{\bar{a}\Delta L}{\dot{a}\Omega_\oplus R_\oplus}}, \tag{12}$$

where $\dot{a}$ is the mean decay rate of a between the maneuvers.

EFFECT OF INACCURACIES IN δa_0 AND $\dot{a}$

The results of the previous item have neglected the effects of inaccuracies. In practice, however, inaccuracies must be taken into account in order to avoid that the ground track overpasses the dead-band. With this purpose, the following analysis recommends a conservative maneuver strategy instead of the theoretically optimal one. The new strategy prescribes an offset δa_c slightly smaller than δa_0 such that the ground track must lie inside the dead-band even in the worst case (see Fig. 1).

Let ξ and ε be respectively the relative accuracy of the predicted semi-major axis decay rate, and the accuracy of the maneuver correction under the effect of orbit/attitude determination/control system errors. Then, one may write:

$$\dot{a}_{effective} \geq \dot{a}(1-\xi), \tag{13}$$

$$\delta a_{effective} \leq \delta a_c + \varepsilon. \tag{14}$$

Therefore, the maximum ground track drift will be:

$$\operatorname*{Max}_t\{L_{effective}(t)\} = \frac{3}{2}\frac{\Omega_\oplus R_\oplus}{\bar{a}}\left(\frac{-\delta a^2_{effective}}{\dot{a}_{effective}}\right) \leq \frac{3}{2}\frac{\Omega_\oplus R_\oplus}{\bar{a}}\left[-\frac{(\delta a_c+\varepsilon)^2}{\dot{a}(1-\xi)}\right]. \tag{15}$$

Taking:

$$\frac{3}{2}\frac{\Omega_\oplus R_\oplus}{\bar{a}}\left(\frac{-\delta a_0^2}{\dot{a}}\right) = \frac{3}{2}\frac{\Omega_\oplus R_\oplus}{\bar{a}}\left[-\frac{(\delta a_c+\varepsilon)^2}{\dot{a}(1-\xi)}\right], \tag{16}$$

it follows from Eqs. (10), (15) and (16) that:

$$L_{effective}(t) \leq \Delta L, \quad \forall t, \tag{17}$$

which satisfies the conservative strategy prescription. Solving Eq. (16) for Δa_c it results:

$$\delta a_c = \sqrt{1-\xi}\cdot\delta a_0 - \varepsilon. \tag{18}$$

As for the effective interval between the conservative strategy maneuvers, it will be given by:

$$\Delta t_{effective} = -2\frac{\Delta a_{effective}}{\dot{a}_{effective}} \in \left[\Delta t_{min}, \Delta t_{max}\right], \tag{19}$$

with:

$$\Delta t_{min} \equiv \frac{\sqrt{1-\xi}-\frac{2\varepsilon}{\delta a_0}}{1+\xi}\Delta t, \quad \Delta t_{max} \equiv \frac{\sqrt{1-\xi}}{1-\xi}\Delta t, \tag{20}$$

and Δt given by Eq. (12).

ANALYSIS FOR LOW RATE OF SEMI-MAJOR AXIS DECAY

As explained before, according to the optimum maneuver approach, maneuvers are supposed to take place at right boundary of dead band only. Likewise, the conservative maneuver approach prescribes that this property must be preserved even under the effect of inaccuracy. Positive increments in semi-major axis as well as the longest maneuver cycle are the main features of the conservative maneuver approach, in general.

Decreasing the semi-major axis does not only waste fuel but time as well, since firing backwards requires attitude half turn maneuver. Nevertheless, despite all those drawbacks, altitude decreasing maneuvers may become unavoidable. Actually, for $\dot{a}$ small enough, the minimum maneuver cycle becomes so short that it would not be feasible from the operational point of view. Furthermore, from Eq. (20), if $\delta a_0\sqrt{1-\xi} < 2\varepsilon$ the conservative approach clearly degenerates while Δt_{min} turns to be a meaningless negative

The left boundary maneuver approach recommends the minimum reduction in semi-major axis enough to avoid the left boundary of dead band to be overpassed. If the inaccuracy were negligible, the semi-major axis after maneuver would have been exactly equal the nominal one. Again, taking inaccuracies into account, one should have a slightly negative offset, namely δa_L.

Just as for the Eqs. (27) and (28), let L'_{min} and L'_{max} be the lower and upper bound of the ground track, respectively, after a left boundary maneuver:

$$L'_{min}(t) = \frac{3}{2}\frac{\Omega_\oplus R_\oplus}{\bar{a}}\left[(\delta a_L - \varepsilon)t + \dot{a}(1+\xi)\frac{t^2}{2}\right], \quad (37)$$

$$L'_{max}(t) = \frac{3}{2}\frac{\Omega_\oplus R_\oplus}{\bar{a}}\left[(\delta a_L + \varepsilon)t + \dot{a}(1-\xi)\frac{t^2}{2}\right]. \quad (38)$$

The left boundary maneuver optimal condition is:

$$\delta a_L : \dot{L}'_{max}(0) = 0, \quad (39)$$

which easily yields:

$$\delta a_L = -\varepsilon. \quad (40)$$

From Eqs. (37) and (38), the left boundary maneuver cycle $\Delta t_{L\_effective}$ will obey:

$$\Delta t_{L\_min} \le \Delta t_{L\_effective} \le \Delta t_{L\_max}, \quad (41)$$

with:

$$\Delta t_{L\_min} \equiv \mathrm{Min}\{t: L'_{min}(t) = 0, \forall t > 0\}$$

$$= \frac{\sqrt{\left(\frac{\varepsilon}{\delta a_0}\right)^2 + \frac{1+\xi}{4}} - \frac{\varepsilon}{\delta a_0}}{1+\xi}\Delta t, \quad (42)$$

$$\Delta t_{L\_max} \equiv \mathrm{Min}\{t: L'_{max}(t) = 0, \forall t > 0\}$$

$$= \frac{\Delta t}{2\sqrt{1-\xi}} = \frac{\Delta t_{max}}{2}. \quad (43)$$

Comparing Eqs. (32) and (42) one finds:

$$\Delta t_{L\_min} < \Delta t_r. \quad (44)$$

This must be taken into account when deciding which maneuver strategy will be followed. The purpose here is just to give subsidy to that final decision. Fortunately, as it will be shown in item 8, the difference is not remarkable when the relaxed approach becomes imperative. At the limit $\dot{a} \to 0$ the difference vanishes:

$$\lim_{\delta a_0 \to 0} \Delta t_{L\_min} = \Delta t_{inf}. \quad (45)$$

FUEL CONSUMPTION FOR IN-PLANE MANEUVER

From the two-burns method, under the impulse velocity increment assumption, one has:

$$\frac{\Delta a}{2a} = \frac{\Delta V_1}{V} + \frac{\Delta V_2}{V}, \quad (46)$$

$$\frac{\Delta e_x}{2} = \frac{\Delta V_1}{V}\cos u_1 + \frac{\Delta V_2}{V}\cos u_2, \quad (47)$$

$$\frac{\Delta e_y}{2} = \frac{\Delta V_1}{V}\sin u_1 + \frac{\Delta V_2}{V}\sin u_2, \quad (48)$$

where ΔV_i is the tangential velocity increment at true anomaly u_i, and Δa, Δe_x and Δe_y are the corrections in respective orbit parameters.

The fuel consumption is proportional to the amount $|\Delta V_1| + |\Delta V_2|$. The amount S defined by:

$$S \equiv \left(\frac{\Delta a}{2a}\right)^2 - \left[\left(\frac{\Delta e_x}{2}\right)^2 + \left(\frac{\Delta e_y}{2}\right)^2\right], \quad (49)$$

plays a special role for the consumption analysis. Since from Eqs. (46) to (49) S may be given by:

$$S = \left(2\sin\frac{\Delta u}{2}\right)^2 \frac{\Delta V_1}{V}\frac{\Delta V_2}{V}, \quad (50)$$

where $\Delta u \equiv u_2 - u_1$, two different cases will arise:

1) **Non degenerate case:** $S \ge 0$, whence $\Delta V_1 \cdot \Delta V_2 \ge 0$. In such case, from Eq. (53):

$$|\Delta V_1| + |\Delta V_2| = V \cdot \frac{|\Delta a|}{2a}, \quad \forall \Delta u; \quad (51)$$

2) **Degenerate case:** $S < 0$, whence $\Delta V_1 \cdot \Delta V_2 < 0$. Here, from Eqs. (46) and (51):

$$|\Delta V_1| + |\Delta V_2| = V\sqrt{\left(\frac{\Delta a}{2a}\right)^2 - \frac{S}{\left(\sin\frac{\Delta u}{2}\right)^2}}. \quad (52)$$

Clearly, the consumption will be minimum when $\Delta u = \pi$. Under this optimum condition one has:

$$|\Delta V_1| + |\Delta V_2| = V\sqrt{\left(\frac{\Delta a}{2a}\right)^2 - S},$$

$$= V \cdot \frac{|\Delta e|}{2}, \quad (53)$$

where $|\Delta e| = \sqrt{\Delta e_x^2 + \Delta e_y^2}$.

Summarizing, the general optimum consumption condition is such that:

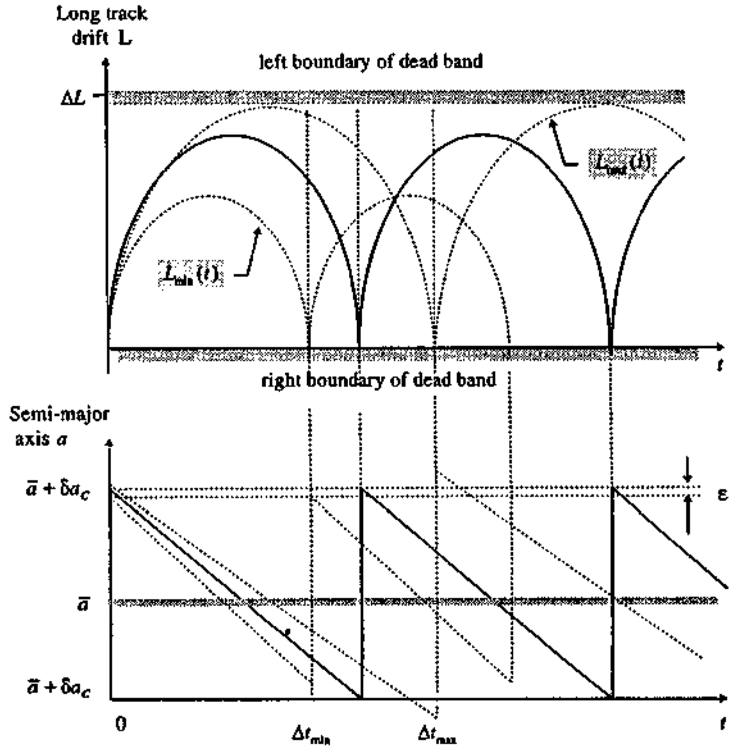

Fig. 1 - Conservative Maneuver Strategy

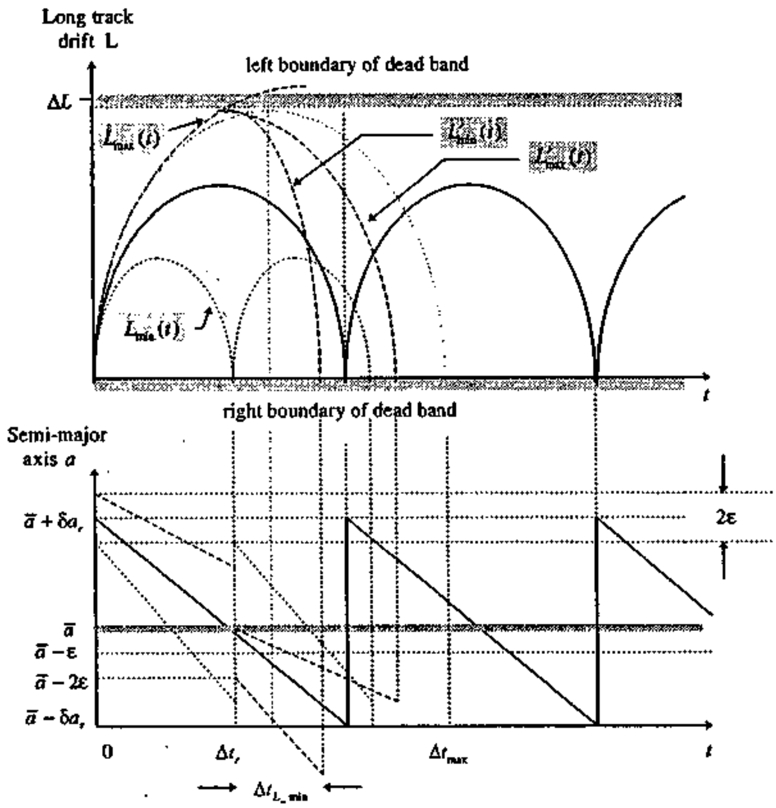

Fig. 2 - Relaxed Maneuver Strategy