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Title **Orbit Control of CBERS-1 Satellite at INPE**

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ORBIT CONTROL OF CBERS-1 SATELLITE AT INPE

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ABSTRACT *– The CBERS-1 (China-Brazil Earth Resources Satellite) was launched on 14 October 1999. The first orbit maneuver which was fully accomplished under INPE's responsibility was executed on 11 April 2001. The maneuver design was based on the mission requirements in terms of maximum longitude phase drift, minimum altitude variations and frozen perigee. The main aspects of the maneuver design, execution, and analysis, are covered in the paper. The results of a post maneuver analysis, which provides a clear confirmation of the fairness of pre-maneuver computations, are presented and discussed in details.*

KEYWORDS: Orbit Control, Longitude Phasing Maneuvers, CBERS-1 Satellite, Flight Dynamics Operations.

INTRODUCTION

On 14 October 1999, a 1540 kg mass remote sensing satellite, the CBERS1 (China-Brazil Earth Resources satellite), developed and manufactured through a cooperation between Brazil and China was launched. This satellite is the first of four earth observation satellites foreseen to be developed within the cooperation program. The satellite is operated on a time shared basis by the two countries. After the launch until March 2001 INPE performed only TM monitoring, orbit determination and payload operations. Thereafter, during the next 6 months, the overall satellite control was assumed by INPE. This work gives, at first, a short overview of the CBERS mission and the main characteristics of its two-country shared operational activities. Following, the ground system for this mission is presented. During the period in which the overall CBERS-1 operations is under INPE's responsibility only the application of longitude phasing maneuvers are foreseen to be needed. This kind of maneuvers can be done by one single or two symmetric pulses, if besides the orbit semi-major axis also its eccentricity and perigee needs to be corrected. The first orbit maneuver fully computed [1-2] and executed under INPE's control center responsibility was executed on 11 April 2001, and deserved thus special attention. The maneuver objective was to correct the time evolution of the longitude phase drift, ΔL_0. The design of the maneuver [1] was based on the requirements of the CBERS mission in terms of maximum longitude phase drift, minimum altitude variations, frozen argument of perigee and maximization of the interval between two successive maneuvers. The Cuiabá TMTC (telemetry and telecommand) station was the only ground station used to implement the maneuver. After the definition of the maneuver time, the in-house maneuver software of CBERS mission [2] was used to compute and design the maneuver. The main aspects of the maneuver design, orbit determination and maneuver performance are covered in the paper. By making use of all the tracking data (range or range-rate measurements) available some time after the maneuver, a more accurate orbit determination was performed, and used to redesign the maneuver. This allowed the verification of the occurrence of only minor differences between the designed and the effectively applied maneuver, giving a clear confirmation of the fairness of pre-maneuver computations. The results of this post flight analysis of the maneuver [3] is also presented and discussed in details.

THE CBERS-1 SATELLITE

The CBERS mission (China-Brazil Earth Resources Satellites), is a space program which foresees the development, in cooperation with China, of four heliosynchronous earth observation satellites, with mass of about 1500kg. On 14 October 1999 the CBERS-1 (the first satellite of the CBERS series) was launched by the Chinese launcher Long-March 4B, from the Tayuan Launch Center, in the Popular Republic of China. It was placed in a frozen perigee helio-synchronous orbit with 778 km altitude and 26 days coverage cycle. The local time in the descending node is 10:30 am. This satellite is three-axis attitude stabilized and shall supply images from three kinds of optical instruments: a high resolution CCD camera, an Infrared Multi-Spectral Scanner (IMSS), and a Wide Field Imager (WFI). It is operated on a time shared basis by the two countries, according to the share of participation of each country on the satellite project. During the first 12 months China was responsible by the entire platform operation activities, and Brazil performed only TM monitoring, orbit determination and its needs in terms of payload operation. Starting from March of 2001 the total control of the satellite was put under Brazilian responsibility, for a period of 6 months. During this period, (ended on September 2001, when the overall CBERS-1 control returned to China responsibility) INPE has performed two orbit maneuvers to correct the time evolution of the orbit longitude phase drift. The first orbit maneuver computed and applied by INPE is fully described and commented in detail in the next sections. The second one is briefly mentioned at the end.

GROUND CONTROL SYSTEM

The Satellite Ground Control System of INPE and its functional structure composes the formally named Satellite Tracking and Control Center (CRC). This center is constituted by the Satellite Control Center (SCC), located in the city of São José dos Campos, and by the ground stations of Cuiabá (23° 12' S; 45° 51'W), and Alcântara (2°, 20' S; 44°, 24'W). A private dedicated communication network links these three sites. All the control actions are planned, managed and executed from the SCC. The real time application software for the CBERS satellite series was developed in Visual C++ language, on PC platforms. The Flight Dynamics System for the CBERS satellites is currently being migrated from DEC AXP 2100/M4-200 to PC platform. This system [4-5] operates in non real time using as input the tracking data (range, range-rate, and antenna pointing angles of azimuth and elevation), retrieved from the mission history files. Only the Cuiabá ground station is involved in the CBERS-1 control and, as a consequence. As a consequence, the flight dynamics experts monitors the satellite only during the satellite passes over the visibility region of the Cuiabá antenna, even during the execution of orbit maneuvers.

DESIGN OF THE MANEUVER

The design of the maneuver is based on the requirements of the CBERS mission, which are, basically, the following ones:

- Longitude drift less than 10km, based on the reference longitude 106.4°E
- Cycle maintenance of 26 days or 373 orbits
- To minimize the altitude variations, keeping argument of perigee frozen at 90° ± 5°
- Maximize interval between maneuvers

Longitude drift history

Figure 1 depicts the longitude drift history at successive orbit determinations during the period of March 01 to April 10, 2001. As it can be seen by this figure, on April 10 the drift was nearing the maximum allowed drift of 10km.

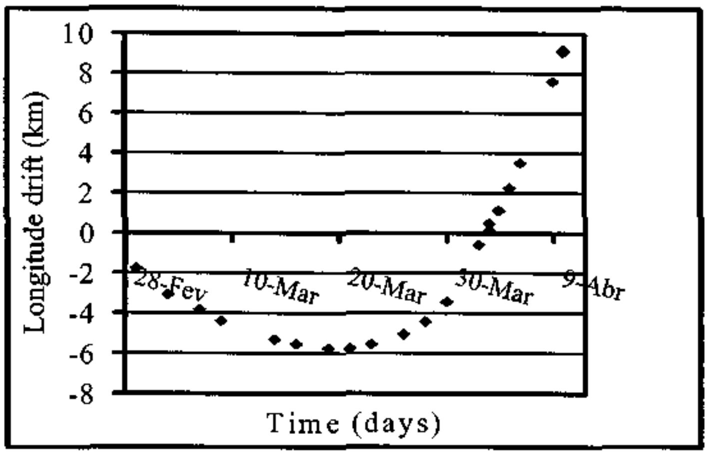

Fig. 1. Longitude Drift Before the Maneuver

Tracking geometry

The Cuiabá TMTC (telemetry and telecommand) station was used to implement the maneuver. The CBERS1 satellite passes over Cuiabá, available to monitor the maneuver, are described in Table 1.

Table 1. CBERS1 Passes Over Cuiabá Ground Station

Day	Start HH:MM (UTC)	Duration mm:ss	Maximum elevation(°)
10	12:27	09:16	6.4
10	14:03	14:50	72.5
10	15:47	04:29	1.2
11	00:50	09:52	7.3
11	02:27	14:46	62.7*
11	04:11	03:43	0.8

The passes with low elevation (≤ 8°) were disregarded, and the day pass of April 10 at 14:03 would introduce a rising of the argument of perigee to around 94.4°, clearly drifting from the prescribed 90° nominal. The night pass of April 11 at 02:27 UTC presents long duration, and good conditions for real time monitoring of the maneuver, and was thus selected to execute the maneuver (see * in Table 1). The following sequence of operations was executed:

- In pass of day 11 starting 00:50 UTC, upload of TC containing the maneuver parameters;
- in pass of day 11 starting 00:50 UTC, send pre-maneuver TCs (like turning on the heaters);
- in pass of day 11 starting 02:27 UTC, monitor the maneuver through TM;
- in pass of day 11 starting 02:27 UTC, after the maneuver, send post-maneuver TCs like turning off the heaters and the predicted post maneuver ephemeris (target).

Maneuver computation

After the definition of the maneuver time, the maneuver software of CBERS mission [3] was used to compute and design the maneuver. For the computation the following parameters were assumed:

- Nominal thrust level $T = 22N$
- Specific impulse of fuel $Isp = 220s$

The resulting computed maneuver parameters were:

- Date of beginning of maneuver: 2001 April 11 02:34:34.288 UTC;
- imparted velocity $\Delta V = 0.168173 m/s$ in the tangential direction;
- duration of thrust $\Delta t = 11.465s$;
- semi-major axis rising $\Delta a = 321.9m$;
- estimated time interval until the of next maneuver = 60 days;
- estimated fuel consumption $\Delta m = 117g$.

Tables 2 and 3 present the prescribed maneuver as computed by the software, one day beforehand. This is necessary for SCC to make all the preparations to implement the maneuver, such as generation of the maneuver flight plan, pack of the maneuver TCs, mount of the post-maneuver ephemeris upload, etc.

Table 2. Designed Maneuver in True of Date Osculating Elements

Osculating coordinates	Pre-maneuver	Target	Difference
x (km)	-6868.08389070	-6868.08389070	0.00000000
y (km)	147.29640193	147.29640193	0.00000000
z (km)	-2006.95063367	-2006.95063367	0.00000000
$\dot{x}$ (km/s)	-2.03643745	-2.03648349	0.00004603
$\dot{y}$ (km/s)	1.19153764	1.19156450	-0.00002685
$\dot{z}$ (km/s)	7.07983875	7.07999825	-0.00015951

Table 3. Designed Maneuver in True of Date Mean "Frozen" Elements

Mean Elements	Pre-maneuver	Target	Difference
a (m)	7148673.70928	7148995.61154	-321.90227
e	0.00116328	0.00115014	0.00001314
i (°)	98.49295078	98.49295078	0.00000000
Ω (°)	176.26948571	176.26948571	0.00000000
ω (°)	91.58599605	89.45168583	2.13431022
M (°)	252.07260658	254.20691537	-2.13430879

Longitude drift prediction

On the date of maneuver the longitude drift was 10.6km. Figure 2 shows the predicted behavior of the longitude drift after the maneuver. The semi-major axis decay rate used for prediction was around 4.7m/day. The next maneuver was foreseen to occur in about 60 days from April 11, i. e., June 09.

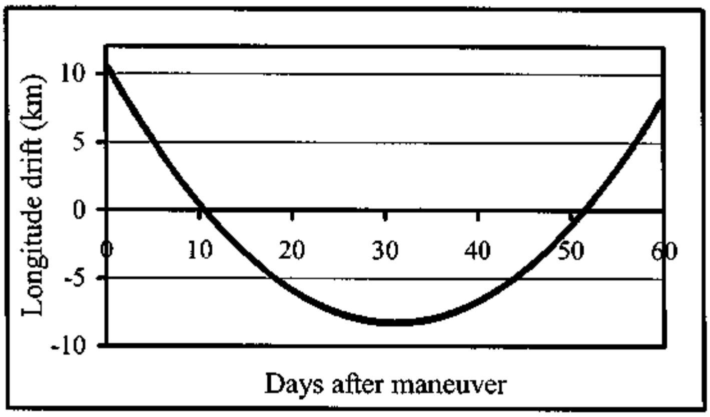

Fig. 2 – Longitude drift prediction from designed maneuver

Figure 3 shows the longitude drift history in 2 parts. The first part up to around day 26 (May 07) contains the actual measured longitude drifts through orbit determinations. The remaining part of the plot shows predictions from there on. At first glance we notice that the decay rate used to compute the maneuver was overestimated because it predicted the Maximum West drift excursion (-8km) to occur around 30 days after the maneuver (see Fig. 2). The best figure we have now is that the mean decay rate was in fact lower and the Maximum West drift excursion (-9.8km) will occur around 35 days after the maneuver. Also the net impact is that the next maneuver would now occur 65 days after the maneuver (instead of the designed 60 days). It is well known that the estimate of the decay rate is the hardest part of this process [6], because this depends on the atmospheric density, which in turn depends on the solar activity which is not so well predictable. At the end, we remark that at the time the internal maneuver report was written the last orbit determination available was on May 07.

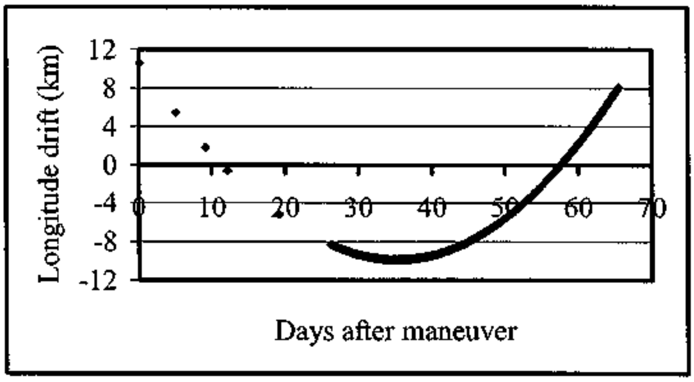

Fig. 3 – Longitude drift actual and prediction from 07 May 2001

POST MANEUVER DESIGN

This section presents the post flight design of the maneuver. In other words, we make use of all the tracking data (range or Doppler measurements) available, to perform more accurate orbit determination, and therefore to redesign the maneuver. Table 4 shows the maneuver redesigned using orbit determination based on range measurements, and Table 5 shows the same for Doppler measurements.

Table 4 – Post flight redesign of maneuver using ranging orbit determination

Mean Elements	Pre-maneuver	Target	Difference
a (km)	7148.67266523	7148.99455268	-0.32188745
e	0.00116128	0.00114770	0.00001358
i (°)	98.49127098	98.49127098	0.00000000
Ω (°)	176.27030124	176.27030124	0.00000000
ω (°)	92.17376744	90.04223393	2.13153351
M (°)	251.48514084	253.61667293	-2.13153209

Table 5 – Post flight redesign of maneuver using Doppler orbit determination

Mean Elements	Pre-maneuver	Target	Difference
a (km)	7148.67349869	7148.99538668	-0.32188799
e	0.00116143	0.00114794	0.00001349
i (°)	98.49362586	98.49362586	0.00000000
Ω (°)	176.27005816	176.27005816	0.00000000
ω (°)	92.05743489	89.92489349	2.13254140
M (°)	251.60144833	253.73398831	-2.13253998

The values of these tables should be compared to those of Table 3, which were computed on day before the maneuver. We can see meaningless differences, and most important, around less than 1m difference in the semi-major axis values. This proves the goodness of pre-maneuver computations.

ORBIT DETERMINATION AND MANEUVER PERFORMANCE

This section presents the post flight orbit determination results. In this case, all the tracking data (range or Doppler measurements) available, before, during and after the maneuver, were used to perform precise orbit determination (OD). Table 6 summarizes the final results comparing the results of orbit determination using range or Doppler measurements for the epoch 2001-April-11 02:34:34.288 UTC. The target values were taken from the designed maneuver in Table 3.

Table 6 – Comparison of target with post maneuver orbit determination

Mean Elements	Maneuver Target	Range OD	Doppler OD	Difference with range OD	Difference with Doppler OD
a (m)	7148995.611	7148993.377	7148993.151	2.234	2.460
e	0.00115014	0.00111435	0.00111793	0.00003579	0.00003221
i (°)	98.49295078	98.49324574	98.49311717	-0.00029496	-0.00016639
Ω (°)	176.26948571	176.27048174	176.27076978	-0.00099603	-0.00128407
ω (°)	89.45168583	90.92974026	91.24288735	-1.47805443	-1.79120152
M (°)	254.20691537	252.72970290	252.41502227	1.47721247	1.7918931

We recall that the following requirements are stated for the orbit maneuver execution of CBERS mission:

- Error in semi-major axis $\Delta a \leq 50$m
- Error in eccentricity $\Delta e \leq 0.0001$
- Error in inclination $\Delta i \leq 0.01°$
- Error in argument of perigee $\Delta\omega \leq 5°$

A quick look into Table 6 and Tables 4-5 shows that the actual semi-major axis rising was Δa=320.7m if we use the range OD solution and Δa=319.4m for the Doppler OD solution. Both solutions are well within 2.5m of the designed Δa = 321.9m, which characterizes an excellent performance of the thruster. Indeed, the under-performance of 2.5m, represents less than 1% of error, which is quite an impressive accuracy to a 20N class thruster.

We can also see, from Table 6, that all the other orbit elements are conforming to the stated requirements for the maneuver:

- Actual error in semi-major axis $\Delta a \leq 2.5$m
- Actual error in eccentricity $\Delta e \leq 0.00004$
- Actual error in inclination $\Delta i \leq 0.0003°$
- Actual error in argument of perigee $\Delta\omega \leq 1.8°$

Table 7 shows the estimation of impulsive velocities yielded by the maneuver. The residual radial and cross track components of the impulse appear mainly due to the attitude control which can not keep accurately the nominal attitude during the maneuver duration. It is prescribed a deviation of at most 2° for the attitude pointing. The cross-track component is not well observed as can be seen by the standard deviation of the estimates, whereas the along track component is the most observable one.

Table 7 – Estimated impulsive ΔV of the maneuver

Impulsive velocity components	Solution from range OD	Solution from Doppler OD	Designed	Difference to range solution	Difference to Doppler solution
Radial track	0.0247 ± 0.0006	0.0093 ± 0.0003	0	0.0247	0.0093
Cross track	0.0021 ± 0.0010	-0.0049 ± 0.0010	0	0.0021	-0.0049
Along track	0.1679 ± 0.0000	0.1675 ± 0.0000	0.168173	-0.000273	-0.000673
Total	0.16972	0.16783	0.168173	0.001547	-0.000343

Neglecting the residual components of the impulsive velocity of the maneuver, we can see that the under-performance of the thruster is very small. The thrust can be modeled approximately by:

$$m\frac{\Delta V}{\Delta t} = T \tag{1}$$

where T is the thrust, m is the satellite mass (1540Kg), ΔV is the impulsive velocity, and Δt is the duration of thrust. On the other hand, the corresponding semi-major axis rising is related to ΔV by:

$$\Delta V = \frac{1}{2}\Delta a\frac{V}{a} \tag{2}$$

where V is the satellite velocity (7467m/s), and a is the nominal semi-major axis (≈7148.845m). Thus, a small variation $\delta\Delta a$ reflects directly to a corresponding δT given by:

$$\frac{1}{2}\frac{mV}{a\Delta t}\delta\Delta a = \delta T \qquad (3)$$

Thus, the $\delta\Delta a$=2.5m translates to δT=0.175N, which is at residual level. It means that the nominal 22N should be corrected to 21.82N. Owing to the residual magnitude of the under-performance, we conclude that any correction is premature and that no calibration factor needs to be used for a while.

OUT OF PLANE MANEUVER PREDICTION

The satellite was injected into an orbit with an inclination offset so that no maneuvers would be required for the first 02 years. The inclination at launch was around 98.55°. The mission requirement is:

- Nominal inclination i = 98.50435°
- Descending Equator crossing at 10:30 am
- Maximum cross time error of 5 minutes

Figure 4 shows the actual and predicted inclination, and the Equator crossing time delay. In September 2001 the Equator crossing time delay was around 4 minutes, and therefore an out of plane maneuver is foreseen to take place around January of 2002, when the delay reaches 5 minutes.

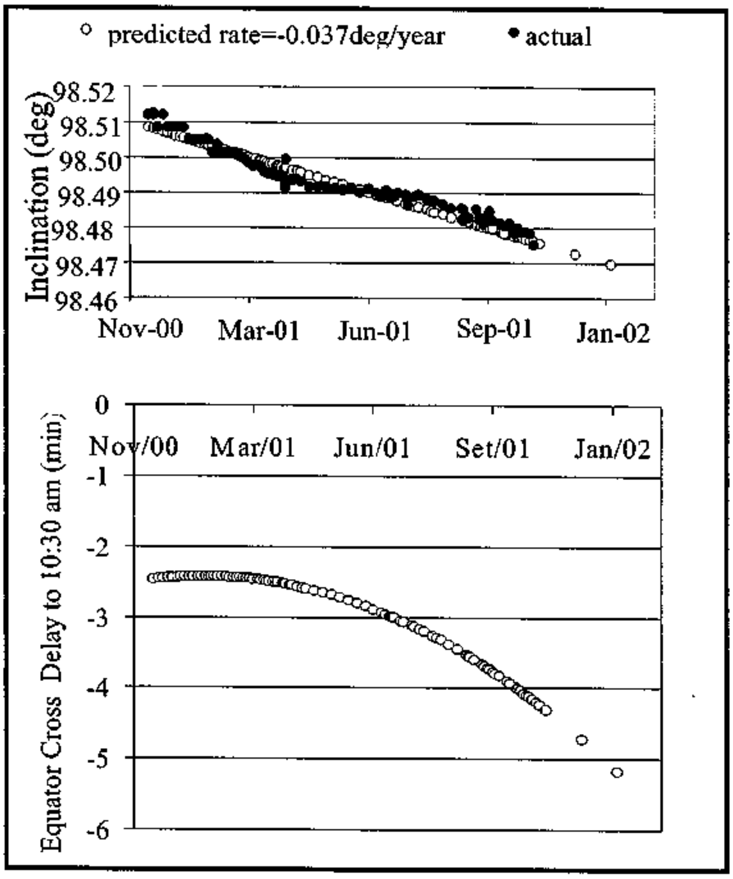

Fig. 4 – Actual and predicted inclination and Equator crossing time delay

FINAL COMMENTS

In conclusion, the first orbit maneuver applied by the INPE's Satellite Control Center to CBERS-1 can be considered a very satisfactory one, since the time evolution of the orbit longitude phase drift was adequately corrected, in order to maintain the compliance with the related mission constraints. After this maneuver INPE applied another one, on 05 July 2001, during a period of relatively large solar activity. At this time the actual rising of semi-major axis was Δa=197.4m with 3.2% error or 6.4m. The thruster performance was such that the actual along track impulse was ΔV = 0.1022m/s with error of 4.2% or equivalently 0.0043m/s.

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