FLIGHT DYNAMICS OPERATIONS OF INPE'S SATELLITE CONTROL CENTER

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ABSTRACT

An overview on the flight dynamics activities of satellite tracking and in-orbit control of INPE (National Institute of Space Research) is presented. First of all, a brief description of the INPE's Satellite Tracking and Control Center is presented with emphasis on the Flight Dynamics System. Next, the involvement in the satellite operation activities through the launching of satellites SCD1, SCD2, and CBERS1 is described. Finally, future satellites planned to be developed by INPE, alone or in cooperation with other space agencies, and their main characteristics are presented and commented.

RESUMO

Apresenta-se uma visão geral das atividades de Dinâmica de Vôo para monitoramento e controle de satélites do INPE. Inicialmente, descreve-se o Centro de Rastreio e Controle de Satélites com ênfase no sistema de Dinâmica de Vôo. Em seguida descreve-se o envolvimento em atividades de operação de satélites com o lançamento dos satélites SCD1, SCD2, e CBERS1. Por fim, comenta-se e apresenta-se os futuros satélites, e suas principais características, a serem desenvolvidos pelo INPE, individualmente ou em cooperação com outras agências espaciais.

1. **INTRODUCTION**

The Satellite Tracking and Control Center (CRC) is responsible for the planning, management and execution of all INPE satellite operations activities (Rozenfeld et al., 1994). This center is composed of the Satellite Control Center (SCC) and two ground stations, Cuiabá and Alcantara, which are linked by a Data

Communication Network, called RECDAS. The two S-band ground stations are almost identical in terms of hardware configuration. Cuiabá, however is the only one equipped with a receiver of Data Collecting Platforms (DCP) being also the data receiving station of the SCD1 and SCD2 satellites payload. The ground station besides performing monitoring and control of the ground station equipment, hosts, in addition, a copy of the SCC real time software. This feature added robustness to the INPE's ground control system, since it makes the ground stations able to replace the SCC in contingency cases. Besides, it allowed to reduce the number of satellite controllers in about 50%, by transferring to the Cuiabá ground station all the satellite operation activities during periods of vacations, free days or eventual absences of SCC personnel.

Two satellites are currently fully controlled by CRC: SCD1 and SCD2. Besides these two there is the Chinese-Brazilian satellite CBERS1, launched in October, 1999. The control during the first year in orbit is under Chinese responsibility, whereas from March 2001 on, the entire control of CBERS1 will be under Brazilian responsibility, for a period of 6 months. Nonetheless, the CRC controls the satellite payload, during the satellite passes over the Cuiabá ground station. The images generated by optical instruments are received by a specific antenna of Cuiabá and later processed by the Image Generation Division of INPE.

A brief description of the INPE's ground system is presented in the section 2. In the section 3 it is presented a description of the SCC Flight Dynamics System, giving emphasis to the main functions and interfaces. The section 4 is dedicated to the satellite SCD1, explaining the purpose of its mission and its performance. The Data Collecting System is described in the section 5, including comments about its evolution, since the beginning of operation, with the launch of the SCD1, until the current days. The launch of the SCD2 and CBERS1 are, respectively, commented in the sections 6 and 7. The work is closed with a general view of the next satellites being currently planned or developed by INPE.

2. GROUND CONTROL SYSTEM

As mentioned above, the Satellite Ground Control System of INPE and its functional structure composes the CRC. This center is constituted by the SCC, located in 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 communication network named RECDAS links all these three sites. The geographical location of the station of Cuiabá, close to the geometric center of South America, allows the coverage of most of its land. On the other hand, since the Alcântara ground station is located in the neighborhood of the Alcântara Launching Center, it can track satellites launched from this site since its orbit injection. The ground stations establish the contact between the ground system and a satellite, when the satellite enters in the range of its antennas. The signal transmitted by the satellite is acquired by the antenna of the station, establishing a descending telecommunication link (down-link). The down-link signal contains telemetry information about the satellite working status. Once the down-link is acquired, the ground station establishes an ascending link (up-link), and sends telecommands to the satellite as well as executes ranging measurements sessions.

All the control actions are planned, managed and executed from the SCC. When the satellite enters in the range of the ground station, the SCC is connected to the ground station through RECDAS, in order to be able to communicate in real time with the satellite. The SCC then assumes the overall control of the satellite, monitoring the satellite TM (telemetry) data, sending the needed telecommands and executing ranging sessions. These operations are executed from the SCC operation consoles, with help of the Real Time Application Software of the SCC, called SICS (System of Satellites Control). For the CBERS satellite series new Real Time Application Software was developed in C++ language for PC platforms. Other important application software of the SCC is the Flight Dynamics System (Kuga, 1997). This system operates in non real time from the data stored in the mission history files. This file, which contains the satellite telemetry and ranging data, is updated by the SICS, covering all satellite passes over the ground stations tracking antenna. The stored ranging data are used in the orbit determination process (Kuga, 1997; Orlando and Kuga, 2000), through which the knowledge of the satellite orbit is periodically updated and maintained in compliance with the mission accuracy requirements.

3. FLYGHT DYNAMICS SYSTEM

The Fig. 1 illustrates the basic functions and the operating mode of the SCC Flight Dynamics System (Orlando and Kuga, 2000; Orlando et al., 1997). The system operates in non real time using as input the measurements of the satellite attitude sensors (sun sensors and magnetometer, in the case of the SCD1 and SCD2) and tracking data (radar range and range-rate; azimuth and elevation angles), retrieved from the mission history files. All housekeeping data generated over the entire mission period are automatically recorded in these files.

Four basic processes composes the SCC Flight Dynamics System (Kuga, 1997): orbit determination, orbit propagation, attitude determination and attitude propagation. Both determination processes are executed once a week during the routine phase of the satellites operation.

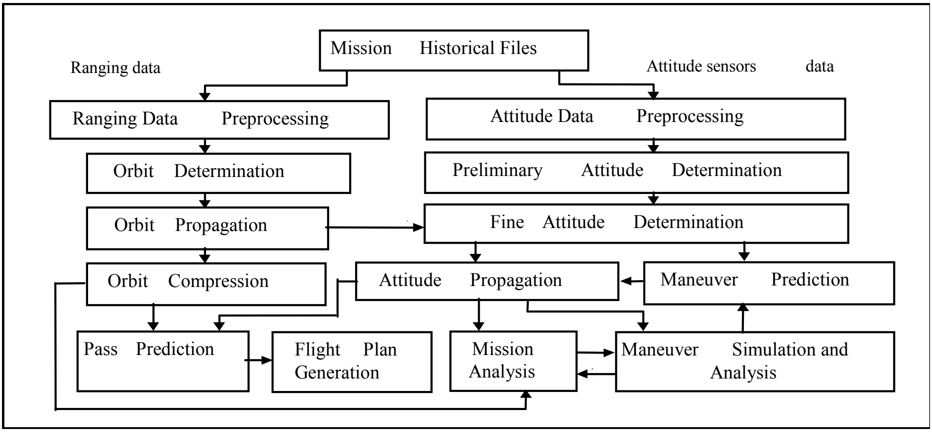

Fig. 1. Flight Dynamics System

The orbit determination process has two basic stages: data preprocessing and orbit estimation. The preprocessing consists of an initial preparation of the tracking data, where procedures of data validation, compression, calibration and conversion to engineering units, are applied. The orbit estimation process applies to the preprocessed data a least squares estimation procedure, which computes the best orbit, which fits these data. The orbit model considers the following effects: geopotential up to the desired order and degree; atmospheric drag; solar radiation pressure; luni-solar attraction; precession; nutation; polar motion; atmospheric refraction effects (tropospheric and ionospheric) and electromagnetic wave propagation delays.

The attitude determination process, which is applied in a weekly routine, comprises three stages: attitude sensor data preprocessing, preliminary attitude determination and fine attitude determination. The preprocessing is applied separately to a group of attitude sensor data collected in all the satellite passes of the previous week. In this process, the data collected in a single pass is reduced to n estimates of the magnetic aspect angle (angle between the spin axis and the geomagnetic field), n being the number of the successive groups of 32 measures collected during the satellite pass; one estimate of the solar aspect angle; and one estimate of the satellite spin rate.

The preliminary attitude determination has as input the preprocessing results. Its output consists of an estimate of satellite angular velocity vector, ω, for every single satellite pass over the ground station. The process of fine attitude determination uses such results, encompassing the period of one week. From the preliminary ω-s estimates, this last process generates a single refined epoch estimate of $\hat{\omega}$, a single estimate of the residual magnetic moment of the satellite (main cause of the spin axis precession), and a single estimate of the eddy current parameter (main cause of the decay of the satellite spin rate). These estimates are considered in the model of attitude prediction.

Both the attitude and orbit propagation processes maintain updated orbit and attitude data files which comprise, besides the whole past of the mission, a future period of three months. These data are used, every three weeks, for the generation of a pass prediction report to support the activities of tracking and control of the satellite. Additionally, this report serves as input for a software that automatically generates the flight operations plan to be followed during the predicted satellite passes. The flight plan contains all the control actions which shall be executed during each pass: the telecommands to be sent to the satellite, the telemetry parameters to be monitored and ranging sessions to be executed.

4. THE SCD1 SATELLITE

The SCD1 is the first satellite projected, built and operated in orbit by INPE. It was successfully launched on February 9, 1993 at 14:42:20 UTC, by the North American Pegasus launcher, manufactured by OSC ("Orbital Sciences Corporation"). This launcher possesses an innovative concept in terms of satellite launchers. It is transported fixed to an airplane wing until a certain point where it is released. After some seconds of free fall its propellers are activated, beginning the launch. SCD1 was injected in a circular orbit of approximately 750 km of altitude and 25° inclination relative to the Equator plan (Rozenfeld et al., 1996; Kuga and Kondapalli, 1993). Currently, around 7 years after its estimated nominal one year lifetime, the SCD1 still presents a surprising over-performance in terms of global working status. Its mission is to relay to a receiving station (Cuiabá), the data collected by a network of automatic environmental Data Collecting Platforms (DCPs) spread over practically the whole Brazilian territory (Yamaguti et al., 1994). Now also the Alcântara ground station is being equipped to receive the SCD1 payload signal.

The SCD1 is spin stabilized in attitude (120rpm just after the orbit injection). It has the shape of an octagonal prism. All of its faces, but one are recovered by solar cells. The uncovered face is used for heat dissipation by the satellite thermal control subsystem. For this reason the direct incidence of solar light on that face should not happen, to avoid thermal problems that could damage the satellite equipment. To avoid this the solar aspect angle should be smaller than 90°. A satellite thermal analysis performed just after its launching, revealed that an excessive heating of the payload could happen, if the solar aspect angle reached values less than 60°. Considering this additional constraint, the allowable variation of this angle became restricted to the range from 60 to 90°. In order to keep the solar aspect angle inside this band the SCC must command a spin axis maneuver whenever the angle approaches one of the limit values. This constraint is measured through the SCD1 attitude determination process (Lopes et al., 1994). The control torques are produced by activating, by telecommand, a magnetic torque coil of the attitude control subsystem. When activated, the torque coil generates a magnetic moment, which interacting with the geomagnetic field produces a torque that acts in the sense of reorienting the satellite spin axis.

5. ENVIRONMENTAL DATA COLLECTING SYSTEM

The existing network of environmental data collecting platforms (DCP) in the beginning of the SCD1 lifetime consisted of only about 20 DCPs. Due to the excellent satellite performance the DCP network was greatly expanded, not only in terms of number of platforms but also in terms of applications diversity, showing a growing interest of the users in the provided services.

Nowadays the network has about 314 operational DCPs, 239 in acceptance and installation, 150 in acquisition and other 71 which are under maintenance. So, if one considers only the operating platforms there was a growth of 16 times the initial number. The total number, however, is of about 774 platforms, that is to say, 38 times more. The DCP application involves areas such as the meteorology, hydrology, agricultural planning, geomagnetism, chemistry of the atmosphere, tides monitoring and studies of the rain forest regeneration, mainly.

In spite of the SCD1 be still today presenting a satisfactory performance, before its launch it was considered an experimental satellite. Thanks to its excellent performance, it became an operational satellite, having completely fulfilled the objectives for which it was conceived. The continuity of the Environmental Data Collecting Program, with an ever increasing number of users, demanded the launching of a new data collecting satellite to replace the SCD1. This was assured with the launching, on October 22, 1998, of the SCD2, the second Brazilian satellite entirely developed by INPE.

6. THE SATELLITE SCD2

The second environmental data collecting satellite developed by INPE, the SCD2, was launched on October 22, 1998, by the American launcher Pegasus, the same vehicle which inserted in orbit the SCD1. The airplane L-1011 transporting Pegasus with the SCD2, took off of Canaveral's Cape Basis, Florida, at 21:05 (Brazil local time). On Atlantic, 57 minutes after the take off, the launcher Pegasus with the SCD2 was released from the airplane. The shot of the first stage happened 5 seconds after the liberation of the rocket. Exactly at 22:12:57 (approximately 11 minutes after the shot), it happened the separation between the satellite and the launcher last stage, which successfully ended the orbit insertion of the SCD2.

Approximately 12 seconds after the separation between the satellite and the launcher third stage, the SCD2 entered into the visibility region of Alcântara ground station. The ground station immediately acquired the satellite signal, which indicated that the satellite housekeeping transmitter that should be activated automatically during the separation, was successfully activated. The received telemetry indicated that the satellite did not present any working problem.

The SCD2 orbit injection occurred with an high degree of fidelity to the designed orbit. The satellite was injected into an orbit quite close to the nominal one, as can be verified by comparing the values of the nominal and actual parameters, which are presented in the Table 1. The application of the flight dynamics procedures followed a routine very similar to the one followed for the SCD1 (Orlando et al., 1998; Kuga et al., 1999).

Table 1. Nominal and Actual Orbit Elements of the SCD2

Orbit Element	**Nominal Value**	**Actual Value**
Semi-Major Axis (m)	7133893	7128550
Eccentricity	0.000756	0.000023
Inclination (°)	24.987	25.001
Right Ascension of Ascending Node (°)	219.912	219.774
Argument of Perigee (°)	348.543	291.050
Mean Anomaly (°)	124,478	183.595
Injection Time (Brazil local time)	23/10/98 22:12:01.12	23/10/1998 22:12:57

Two additional constraints were imposed to the SCD2 orbit concerning its relative positioning with SCD1. Both satellites perform 14 orbits every 24 hours. Due to the 25° inclination of the orbit plane relative to the Equator, only 8 orbits are visible to the Cuiabá ground station range. In this way, in 24 hours there is a time interval corresponding to 6 orbits (approximately 10 hours) during which there are no SCD2 passes over Cuiabá. Taking this into account, the orbit parameters of the SCD2 were chosen in a such way that its cycles of sequential passes over Cuiabá are complementary to the ones of the SCD1. During the periods in which there are no passes of one of the satellites then, there are passes of the other one. Besides, the SCD2 were spaced from the SCD1 in the orbit in such a way that a pass of one satellite will only happen some time after the pass of the other. It was verified that both constraints were perfectly respected in the launching.

Concerning the satellite attitude after the orbit injection, it was very close to the nominal. The most restrictive attitude constraint to be respected, was that the sun light could not directly reach the upper and lower satellite faces with an incidence angle greater than 10°. This means that the sun aspect angle, directly measured by the sun sensors, shall be maintained between 80° and 100°. The sun sensor measurements indicated that, after the SCD2 orbit injection, this angle was of 90.3°, quite close therefore to the ideal value of 90°.

Nowadays, more than two years after launch, all the SCD2 subsystems present a thoroughly satisfactory performance. Differently from the SCD1, the SCD2 has an autonomous system for spin rate control, by magnetic actuation. This system maintains the satellite spin rate between 32 and 36rpm. The Attitude Control Subsystem showed a very satisfactory overall performance during the entire SCD2 operation period. Thanks to the execution, by telecommands, of spin axis maneuvers, the sun aspect angle was confined to its nominal variation range, rigorously respecting the imposed constraints.

7. THE CBERS SATELLITES

Among the space missions being developed by INPE one of the most important is the CBERS mission (China-Brazil Earth Resources Satellites), that foresees the development, in cooperation with China, of four 1540kg each heliosynchronous earth observation satellites. These satellites shall supply global image coverage in cycles of 26 days, from three kinds of optic instruments:

a - A high resolution CCD camera, generating images in 5 spectral bands, with resolution better than 20m and a ground track sweep of about 113km width.

b - An Infrared Multi-Spectral Scanner (IRMSS), generating images with resolution from 80m to 160m, and ground track sweep of about 120km width.

c - A Wide Field Imager, designed in Brazil, with 256 meters resolution and ground track sweep of about 885 km.

The first satellite of the CBERS series, CBERS1, was successfully launched in 14 October 1999, 01:15 (Brazil Local Time), by the Chinese launcher Long-March 4B, from the Tayuan Launch Center, in the Popular Republic of China. Besides the three optic instruments listed above, the CBERS1 carried also a data collecting transponder being able to receive and retransmit the signals generated by the DCP network of the Environmental Data Collecting System. The values of the mean orbit elements just after the orbit injection (14-Oct.-1999, 03:28:58.34 GMT) were: **a** (semi-major axis) = 7114355m; **e** (eccentricity) = 0.0011040; **i** (inclination) = 98.55425°; Ω (right ascension of the ascending node) = 17.30022°; ω (argument of perigee) = 45.82733°; **M** (mean anomaly) = 347.41464°.

On November 3 the Chinese Control Center began the execution of the positioning orbit maneuvers, with the purpose of placing the satellite into its operational heliosynchronous orbit. This initial phase lasted until 08-Nov.-1999, 03:35:29 GMT. The mean orbit elements presented after maneuvers were: **a** = 7131484m; **e** = 0.002154; **i** = 98.555°; Ω = 21.788°; ω = 103.510°; **M** = 118.038°.

The CBERS1 did not present any significant operation problem. The results of the in-orbit acceptance tests performed by INPE confirmed the wealth of its subsystems. The satellite control will be shared between Brazil and China, in a way proportional to the participation of each country in the project. It was agreed that China will be responsible by the satellite operation during the first year, since the date of satellite in-orbit acceptance. After that, from beginning of March 2001, Brazil will be in charge of the satellite operation, during the next 6 months. Nevertheless, even when the control is under Chinese responsibility, INPE will control the satellite payload to supply the needs concerning the Brazilian applications. So, during the satellite passes over Cuiabá, the INPE's SCC will send the telecommands involved in the payload operation; monitor the telemetry; execute ranging sessions and perform the orbit determination. A specific Cuiabá antenna is responsible for acquiring the image data generated by the satellite optical instruments. These data are recorded in the ground station and later sent to Cachoeira Paulista where they are processed.

In parallel to CBERS1, INPE developed also two scientific satellites, the SACI-1 and SACI-2. The first one was launched as pig-back together with the CBERS1. It was ejected from the launcher last stage 25 seconds after the insertion of CBERS1, practically in the same orbit, at 761km altitude. This satellite, which should be tracked exclusively by a INPE's reception station installed in Natal, Rio Grande do Norte state, unhappily presented some working problems which made not possible the acquisition of its signal. The launch of the SACI-2, on December, 11, 1999 by the Brazilian launcher VLS, unfortunately failed due to launcher problems.

8. UPCOMING SATELLITES

Two data collecting satellites (SCD1 and SCD2) and two remote sensing satellites (SSR1 and SSR2) were initially foreseen by INPE, as part of a program called MECB (Brazilian Complete Space Mission). To these four satellites other two data collecting ones were added: the satellite SCD2-A, whose launch in November of 1997, by Brazilian launcher VLS, failed, and the SCD3. This last one, besides having a data collecting transponder, should also serve as test to a three-axis attitude control system, being developed for use in future satellites. The orbit of these satellites initially heliosynchronous, was changed to equatorial, restricting the work area of coverage of the satellite optical instrument, between the parallels 5°N and 15°S, but increasing the revisit rate from about once per month to 14 times a day.

The Table 2 presents the future missions that are, currently, in development or planning phases in INPE. Among these missions it must be mentioned the CBERS mission that foresees the development, in cooperation with China, of three new satellites. The second satellite of this series, the CBERS-2, currently in integration phase in the Laboratory of Integration and Test (LIT) of INPE, will be launched by the end of 2001. The other future satellites, listed in the table 2 are:

• FBM (French-Brazilian Microsatellite)

The FBM is a scientific micro-satellite being developed in a cooperation agreement between Brazil (INPE) and France (CNES - "Centre National D'Études Spatiales"). It should be injected into a circular orbit with 750km altitude, and 6° inclination. One of its axes will be pointed to the sun, with a precision of the order of 0.5°. The FBM will transport the following Brazilian experiments: **APEX:** monitoring the protons, electrons and alpha particles, in the inner earth magnetosphere; **PDP: m**easuring the ionosphere plasma density, temperature and structure near Equator; **CPL:** space qualifying a capillary pumped loop for active thermal control; **CBEMG:** investigating the nucleate boiling and critical heat flux in confined space between two plates under microgravity conditions; **FLUXRAD:** evaluating and qualifying a sensor for measurement of the net flux of radiation of the Sun and earth albedo. The French experiments are still being defined.

• SABE (Argentinean, Brazilian and Spanish Satellite)

The SABE is a satellite dedicated to the monitoring of water, food production and environment. It is being developed in a cooperation agreement between Brazil, Argentina and Spain. This satellite shall supply, in real time, images with high spatial, temporal spectral and radiometric resolution. It will be injected in a circular heliosynchronous orbit, with 803km altitude, 98.6° inclination, and revisit cycle of 4 days. The local time of the descending node will be 11:00am. It will be a three axis attitude stabilized satellite.

• SSR1 and SSR2 (Remote Sensing Satellites)

The SSR1 and SSR2 will be small Earth observation satellites for monitoring the tropical area. They will be injected into a low altitude (905km) equatorial orbit (0° inclination). The onboard optical instruments will cover the equatorial area comprised between 5° North latitude and 15° South latitude, which corresponds to a sweep area of 2200km. This orbit supplies a revisit interval shorter than two hours, with more than five useful image acquisitions per day.

Table 2. Next Satellites of INPE

	CBERS2	FBM	SABE	SSR1/SSR2	SCD3
Inclination	98.5º	6º	98.6º	0º	0º
Altitude (km)	778	750	1100	905	900
Attitude	3-axis	3-axis	3-axis	3-axis	3-axis
Mass (kg)	1540	89	510	~190	~300
Launch Date	2001	2003	2005	2005/2009	2007

9. FINAL COMMENTS

The launching of SCD2 repeated the success of SCD1. The SCD2 represented a step ahead in terms of technological know-how of INPE and ensured continuity of the environmental data-collecting project. The same can be told about the CBERS1 which is also equipped with a data collecting transponder. The performances of all the three satellites are flawless and reliable which proves the human resources capability of INPE in terms of research, development, and operation. The CRC (Tracking and Control Center) presented a very positive technical evolution. The experience in operating small satellites, with non-stop growing operational load, improved the skill of the staff. It is very important that the knowledge gained from long lasting satellite operations continue to be applied steadily, in order to enhance the operational efficiency.

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