SATELLITE ATTITUDE FOLLOW-UP: A FIRST-HAND EXPERIENCE WITH THE FIRST BRAZILIAN SATELLITE SCD1

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ABSTRACT - The first Brazilian satellite SCD1, designed and manufactured by the Instituto Nacional de Pesquisas Espaciais - INPE under the Complete Brazilian Space Mission (MECB) project, was launched on February 09, 1993 at 14:42:20 UTC by a Pegasus rocket of Orbital Sciences Corporation of USA. It is a spin-stabilized satellite and its thermal constraints prohibit the orientation of the spin-axis with respect to Sun's direction to rise above 90 degrees. Due to this condition, some type of spin-axis attitude monitoring was necessary during the useful lifetime of the satellite. Although various types of algorithms were developed for this purpose, unexpectedly, a software, which was developed during the satellite's mission analysis phase mainly in order to furnish the mission analysts with a fast, clear and integrated visualization of the preliminary attitude determination results and related aspects, was found useful for this purpose. For each orbit during a specified period, this software prepares and draws on a computer terminal, or optionally on a plotter, an inertial celestial sphere containing: the Sun's position; the Earth's shadow; the geomagnetic field vector trajectory; the satellite trajectory during its pass over a given ground station; and the attitude of the satellite spin-axis enveloped by its predicted uncertainty ellipse. A rational analysis of this map helps a mission analyst to select an optimum sub-set of satellite passes in order to achieve the best possible precision in the attitude determination process. However, besides fulfiling this main objective, after the SCD1 launch, the attitude follow-up software was found to be useful for various other purposes such as: the study of magnetometer bias fluctuations, observed from one pass of the satellite to other; an easy-monitoring of the spin-axis attitude etc. This software also helped the mission analysts to take some important decisions in improving the main attiude determination software. This paper narrates everything about the attitude follow-up software, starting from the initial idea based on which the software was developed till the developments along time and its final function. Being a debut of the attitude team of the flight mechanics group of INPE, the experience with SCD1 related to attitude determination process gave challenging problems as well as pleasant surprises, some of which are from the attitude follow-up software. The main idea of this work is to share our first-hand experience with the first Brazilian satellite SCD1 in the process of its attitude follow-up.

1 - INTRODUCTION

The first Brazilian satellite SCD1, which was launched on 9th February 1993, is a spin-stabilized satellite and its thermal constraints called for some type of monitoring of spin-axis attitude with respect to Sun's direction. During the mission analysis phase of SCD1, in order to supply the mission analysts with a fast and integrated visualization of the preliminary attitude determination of this spin-axis and its related aspects, it was planned to develop a software called "attitude follow-up software". It was thought that the information about the uncertainty in the preliminary determination of the spin-axis attitude would be helpful to schedule on-board computer tests and magnetic coil polarity commutation times. However, besides attaining this objective, during the Launch and Early Orbit Phase (LEOP) of the SCD1, this software turned out to be very useful for, at first, analyzing and then solving the problems surfaced in the attitude determination process of SCD1. This paper is aimed to explain briefly our experiences with the attitude follow-up software during the crisis period of first one-and-half month after the launch of the SCD1, in taking some important decisions in connection with the SCD1 attitude determination process.

2 - BASIC MATHEMATICAL THEORY

At first, the basic mathematical theory involved in the calculation of attitude uncertainty ellipse is briefly explained in this section. See the Ref. 1 for more details.

Firstly, a unit vector $\hat{A}$ is defined and its covariance is calculated as follows:

$$\hat{A} = \frac{\vec{\omega}}{|\vec{\omega}|} = \frac{\vec{\omega}}{\sqrt{\vec{\omega}^T\vec{\omega}}} \quad (1)$$

Then,

$$\Delta\hat{A} = \frac{\Delta\vec{\omega}}{\sqrt{\vec{\omega}^T\vec{\omega}}} + \vec{\omega}\left(-\frac{1}{2}\right)\frac{1}{\left(\vec{\omega}^T\vec{\omega}\right)^{3/2}}\left(2\vec{\omega}^T\Delta\vec{\omega}\right)$$

$$= \frac{\Delta\vec{\omega}}{|\vec{\omega}|} - \frac{\vec{\omega}}{|\vec{\omega}|}\frac{\vec{\omega}^T}{|\vec{\omega}|}\frac{\Delta\vec{\omega}}{|\vec{\omega}|}$$

$$= \left(I - \hat{A}\hat{A}^T\right)\frac{\Delta\vec{\omega}}{|\vec{\omega}|},$$

where I is the identity matrix.

Now the covariance matrix $P_{\hat{A}}$ can be found to be:

$$P_{\hat{A}} = E\left\{\Delta\hat{A}\Delta\hat{A}^T\right\}$$

$$= \left(I - \hat{A}\hat{A}^T\right)E\left\{\frac{\Delta\vec{\omega}\Delta\vec{\omega}^T}{|\vec{\omega}|^2}\right\}\left(I - \hat{A}\hat{A}^T\right), \quad (2)$$

where $E\left\{\Delta\vec{\omega}\Delta\vec{\omega}^T\right\}$ is nothing other than the covariance matrix $P_{\vec{\omega}}$.

The next step is to compute the parameters of the uncertainty ellipse. Since the unit vector $\hat{A}$ is one of the eigen vectors of $P_{\hat{A}}$ with zero eigen value, it can easily be seen that the semi-major axis and the semi-minor axis of the uncertainty ellipse can be calculated with the help of the other two nonzero eigen values and the principal directions can be calculated with the help of respective eigen vectors.

The characteristic polynomial of $P_{\hat{A}}$ is given by:

$$|P_{\hat{A}} - \lambda I| = \lambda^3 + C_2\lambda^2 + C_1\lambda + C_0 = 0, \tag{3}$$

where $|..|$ is the symbol for determinant.

Now, partitioning the matrix $P_{\hat{A}}$ as:

$$P_{\hat{A}} = \begin{bmatrix} M_{2\times2} & m_{2\times1} \\ m^T_{1\times2} & P_{1\times1} \end{bmatrix}, \tag{4}$$

and using the Eq.(3), one obtains for the coefficients,

$$\begin{aligned} C_0 &= m^T.m.Tr(M) - m^T.M.m - P.|M| \\ C_1 &= P.Tr(M) + |M| - m^T.m \\ C_2 &= [P + Tr(M)] = -Tr(P_{\hat{A}}), \end{aligned} \tag{5}$$

where Tr(...) represents the trace of the matrix (...). But, using the fact that Â is one of the eigen vectors of $P_{\hat{A}}$ with zero eigen value, in the Eq. (3), one has:

$$C_0 = 0,$$

and consequently,

$$\lambda^2 + C_2\lambda + C_1 = 0. \tag{6}$$

Solving this equation for λ so as to get the other two eigen values, and also using the Eq. (5), one obtains:

$$\lambda = \frac{1}{2}\left[Tr(P_{\hat{A}}) \pm \left\{(Tr(P_{\hat{A}}))^2 - 4(P.Tr(M) + |M| - m^T.m)\right\}^{\frac{1}{2}}\right]. \tag{7}$$

The two corresponding eigen vectors are given by:

$$\hat{E}_i = \frac{1}{(\gamma_i^T\gamma_i + \psi_i^2)^{\frac{1}{2}}}\begin{bmatrix}\gamma_i \\ \psi_i\end{bmatrix}, \qquad i = 1,2 \tag{8}$$

where

$$\gamma_i = [M + \{\lambda_i - Tr(M)\}I].\vec{m},$$

$$\psi_i = \lambda_i^2 - \lambda_i.Tr(M) + |M|,$$

whereas

$$\hat{E}_3 = \hat{A}.$$

Now, writing the equation of the ellipse as:

$$\frac{x^2}{\lambda_1} + \frac{y^2}{\lambda_2} = 1,$$

the x, y parameters to determine the ellipse can be written as:

$$\begin{aligned} x &= (\lambda_1)^{1/2} \cos\theta \\ y &= (\lambda_2)^{1/2} \sin\theta \end{aligned} \qquad 0 \le \theta \le 2\pi \qquad (9)$$

Finally, defining a vector $\vec{V}(\theta)$ as:

$$\hat{V}(\theta) = x\hat{E}_1 + y\hat{E}_2 + \left(1 - x^2 - y^2\right)^{1/2} \hat{A},$$

the right ascension α and the declination δ of the point (x, y) in celestial sphere are given by:

$$\begin{aligned} \alpha(\theta) &= \tan^{-1}\left(V_2 / V_1\right) \\ \delta(\theta) &= \sin^{-1}(V_3) \end{aligned} \qquad (10)$$

where V_i are the components of the vector $\hat{V}(\theta)$.

3- DISCUSSION AND DESCRIPTION OF THE DRAWING

In this section is discussed the selection of a reference frame (with respect to its center and orientation) and the information to be shown visibly in the picture. Due to some thermal constraints, the negative side of the satellite spin-axis vector is forbidden to tilt towards the Sun. In other words, the projection of the positive side of the spin-axis vector should always be in a great circle around the Sun, and the Earth's shadow can be depicted as the forbidden region. Hence, in order to show this forbidden region for the satellite, at first it was decided to show in the picture the position of the Sun and the Earth's shadow. The Sun's position is represented by a unit vector in the direction of the Sun, which is almost at infinite distance, and consequently, it is independent with respect to the center of the reference frame. On the other hand, regarding the reference frame orientation, it would be difficult to draw the said great circle in any arbitrary reference frame due to Sun's apparent motion along the ecliptic. Hence, to facilitate the drawing, it was decided to draw the picture in an inertial reference frame where Sun would remain always at the centre on the zero meridian and the Earth's shadow evenly divided at the edges.

It was decided to represent the geomagnetic field also by a unit vector parallel to the geomagnetic field vector at the instantaneous positions of the satellite around the Earth. Again, in this case also, it is independent of the center of the reference frame. With respect to the orientation, at the first instance, an Earth-fixed frame seems to be a suitable choice since the geomagnetic field rotates along with the Earth. However, the satellite spin-axis direction is inertially fixed and its attitude is determined in the inertial frame. Consequently, the direction of the geomagnetic field vector also should be represented in the same inertial frame.

In order to show the satellite motion around the Earth, the relative vectorial position of the satellite with respect to the Earth, while crossing a given ground station visibility circle, was chosen. Here, the most natural choice of the reference frame would be an Earth-centered and Earth-fixed one. However, an inertial frame also would suffice although it would introduce a small artificial deformation in the ground station visibility circle due to the Earth's rotation during the 20 min. contact time of satellite- ground station.

Now, both the spin-axis and the uncertainty ellipse are usually represented by unit vectors with given attitude in a satellite-centered celestial sphere (Ref. 2). Contrary to this tradition, an inertial right ascension-declination coordinate system in celestial sphere is taken as basis and the picture is drawn. Here, since the angles, not the distances are dealt with, it is hoped that this choice of the reference frame does not cause any confusion in understanding the picture. For the sake of clarity, however, it was decided not to draw the visibility circle of the ground station considered.

4 - MAIN CHARACTERISTICS OF THE SOFTWARE

As explained in the previous section, the attitude follow-up software prepares and draws, for each orbit during a specified period, a map on an Earth-centered inertial celestial sphere, containing: the Sun's position; the Earth's shadow; the geomagnetic field vector trajectory; the satellite trajectory during its pass over the ground station; and the attitude of the satellite spin-axis enveloped by its predicted uncertainty ellipse. It is also indicated on the top of the screen, as an additional information, whether the sun-sensor is illuminated or not during that specific pass. The map is drawn on a computer terminal screen with impressive colours and also there is a provision to draw on a graphic plotter or on a laser printer. This map would help the mission analysts to select, rationally, an optimum subset of passes so as to retain the best accuracy in the attitude determination process. As stated elsewhere, besides this main aim, the software offerred several other fruitful applications, some of which had never been thought of before the satellite was launched, which are described in the following sections. Two typical maps generated by the software are given in Figs.1 and 2.

5 - PREPROCESSING OF MAGNETOMETER DATA

Problems due to improper preprocessing of magnetometer data became apparent early during the mission (Ref. 3). The main problem found at the initial stage was that all magnetometer data were rejected by the automatic preprocessing software. In order to solve this problem, an effort was made to model and evaluate the magnetometer bias fluctuations observed from one pass to the next. During this phase, the attitude follow-up software is found to be useful in two ways. At first, it showed that the unmodelled fluctuations are closely related with, among various other factors, the satellite pass through the magnetosphere and the time of the day. Secondly, it permitted to easily select a pair of cross passes of the satellite, which was helpful to test an ingenious method for determining the magnetometer z-axis bias. Of course, because of inconsistent results obtained by this method, the computation of the magnetometer z-axis was abandoned eventually, but the attitude follow-up software was useful here to select few passes which could have determined the attitude.

6 - MONITORING OF SUN-ASPECT ANGLE

Thermal control constraints of the SCD1 prohibit the satellite bottom side to get illumination, and one of the most important functions of the satellite attitude control system was to avoid the sun-aspect angle to rise above 90 degrees. The information provided by the attitude follow-up software regarding the illumination of the sun-sensor made it easy to monitor the spin-axis attitude which must remain outside the Earth's shadow.

DATE & GMT: 2/10/93 6:46:56 SUN SENSOR OFF

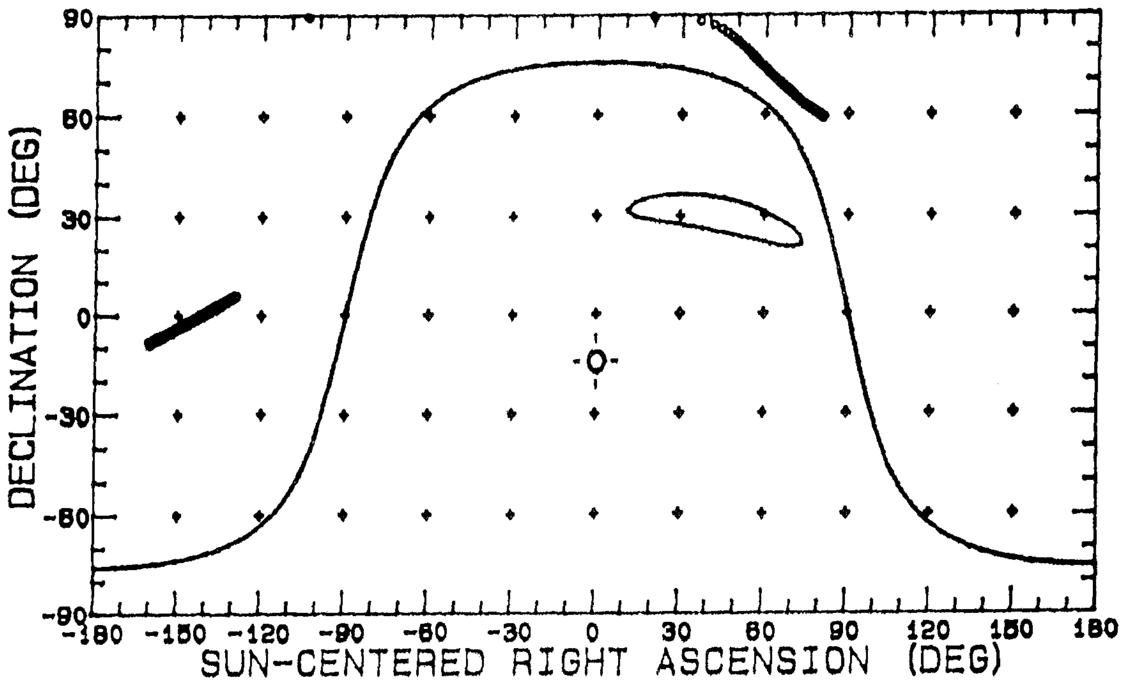

Fig. 1: A typical map generated by attitude follow-up software

DATE & GMT: 2/10/93 17:35:44 SUN SENSOR ON

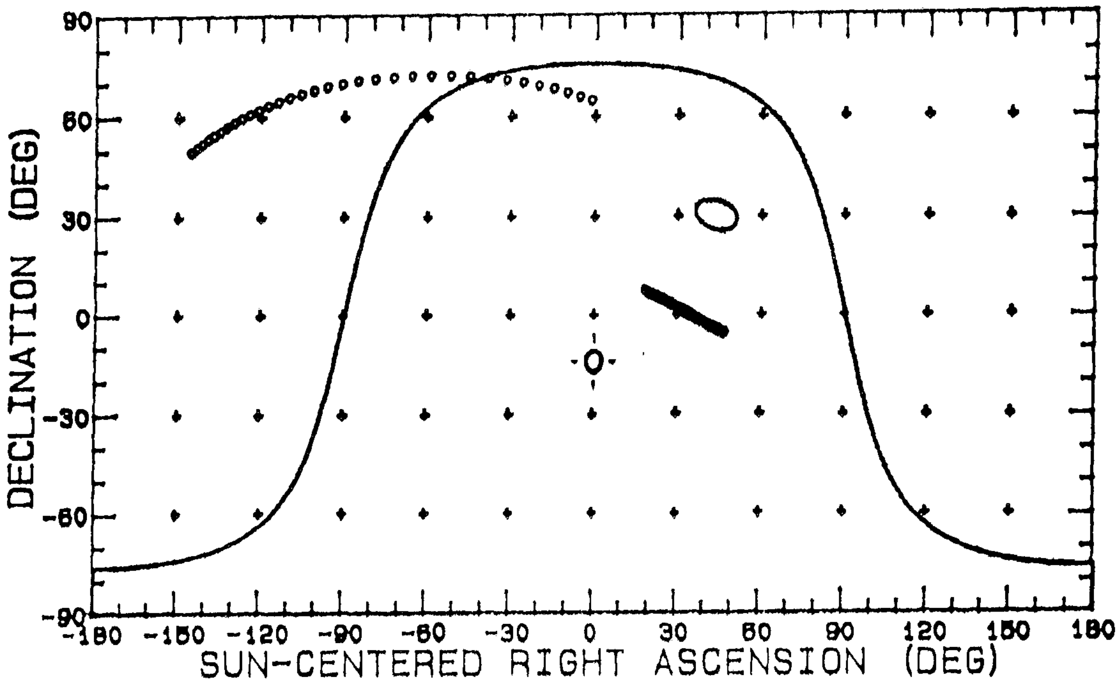

Fig. 2: Another typical map generated by attitude follow-up software

7 - RECOGNITION OF UNCERTAINTY PATTERNS

From a long sequence of maps generated by the attitude follow-up software, one could recognize some patterns which determine the accuracy level in the preliminary attitude determination process. For example, it became clear that descending passes over Cuiabá tracking station experience a larger variation in the geomagnetic field direction than the ascending ones and consequently offer a better attitude observability.

As an other example, during the winter season over southern hemisphere, small angles between Sun's direction and geomagnetic field vector are found to occur very often and this caused a seasonal degradation of attitude observability.

The a-priori knowledge of uncertainty patterns was useful to schedule on-board computer tests and magnetic coil polarity commutation times. Since these activities usually invalidate the attitude data, it was preferable to perform them in those passes which show the worst attitude determination performance and in this connection the attitude follow-up software was found to be very useful.

8 - CONCLUSIONS

Looking at the applications, one can only conclude that the attitude follow-up software not only drew impressive colour pictures that certainly highlighted the preliminary attitude determination process, but also proved to be a useful tool, especially during the dramatic first few weeks of the SCD1 lifetime.

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