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JOINT ESTIMATION OF ORBIT AND ATTITUDE OF SPIN STABILIZED ARTIFICIAL SATELLITES USING MAGNETOMETER AND SOLAR SENSORS MEASUREMENTS

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Abstract: This paper presents a procedure that uses the Extended Kalman Filter to refine, jointly, the orbit and attitude estimation given by Batch Least-Squares. It processes the measurements: radial and axial components of the geomagnetic field of a magnetometer and angle of the solar aspects of two solar sensors, both attitude conventional sensors.

Keywords: satellites, orbit, magnetometer.

1. INTRODUCTION

Attitude determination of a spin stabilized satellite in low orbit using magnetometer has been done by INPE on its first satellite of environmental data collection SCD-1, operating since 1993. To extend the function of this sensor to orbit determination is profitable for those missions, in which high accuracy in position and speed can be dismissed, in change of other benefits, as a lower cost. Safer precisions may be obtained from sophisticated sensors such as *GPS* (*Global Positioning System*) or from radars.

A magnetometer is a low cost sensor (in terms of space applications) and it has suitable technical characteristics (to its use), such as lightness, reliability and low power consumption. A procedure for orbit determination using it is also interesting as a standby resource in the satellite. Other authors have been researching this topic, some of them, aiming at the use of this resource for satellites automation [2-4].

The convergence of the estimation process (in procedure) was achieved successfully, by Least-Squares and refined by an Extended Kalman Filter. Results obtained from simulation with some of the SCD1 data, indicate that the procedure is able to provide the information of orbit and attitude jointly, with a position error around 100 Km.

It is part of the project: a study about the impact of the magnetical bias of the axial component in the orbit and attitude estimates and the development of algorithm that provides the initial orbit information based on the observation of the magnetometer and on the shortages of the solar sensor observations, characterizing the passage of the satellite in the Earth's shadow.

2. PROCEDURE BASIS

The procedure is divided in daily pre-processing and estimation process, and subdivided in short, mean and long periods, for systematic. An algorithm for the generation of the initial information of the orbit and attitude of an artificial satellite was developed and implemented in the *Matlab*® language, as well as the estimators. Such procedure is tested with simulated observations, with simulated and real collecting data of orbit and attitude of the SCD-1, whose orbit is almost circular, with 750km of altitude and inclination of 25°. The model of the orbital dynamics is the Keplerian (two-body problem closed-form) and the satellite is considered inertially stabilized. The geomagnetic field is modeled by a series of spherical harmonics of 10^{th} order and degree, with coefficients given by the IGRF-95.

2.1 Least-Squares Estimator

The method Least-Squares was originally applied to the parameters estimation. Nevertheless, the same technique can be extended to state estimation of stochastic processes. This way, the orbit and attitude dynamics and the observations are expressed as linear functions, or not, of the state [6].

In essence, this method minimizes the square of the difference between observations and their predicted values, provided the observations and the state are related. The solution minimizes the index of performance given by the sum square value of the residuals, in the vector notation:

$$\mathrm{Min}(\mathrm{J}(\mathbf{X})_k) = \{[\mathbf{Y}_k - h(\mathbf{X}_k)]^{\mathrm{T}}[\mathbf{Y}_k - h(\mathrm{X}_k)]\} \quad (1)$$

In which,

$\mathbf{Y}_k$ ..... observation vector of dimension m x 1;

$\mathbf{X}_k$ ..... state vector of dimension n x 1;

h ..... nonlinear vector observation function in the dimension m x 1;

k ..... $\forall\ k \mid k \in \mathrm{N}^*$;

T .... transpose.

The observation vector $\mathbf{Y}_k$ is a function of the state plus a white sequence:

$$\mathbf{Y}_k = h(\mathbf{X}_k) + v_k \tag{2}$$

2.2. Extended Kalman Filter

The extended Kalman filter is for a nonlinear system, as the Kalman Filter is for a linear system. The extended filter is essentially the same technique of Kalman filtering applied to nonlinear systems. The difference is the linearization, around the current state estimate.

This technique is more complete than the Least-Squares, because it takes into account the dynamic model errors and yet it is able to provide estimates immediately after the measurement sampling time, being suitable for real-time applications, characterizing as recursive and sequential.

Conveniently, one uses the Kalman recursive algorithm to process the measurements and evaluate the state vector estimate together with its error covariance matrix [5-7].

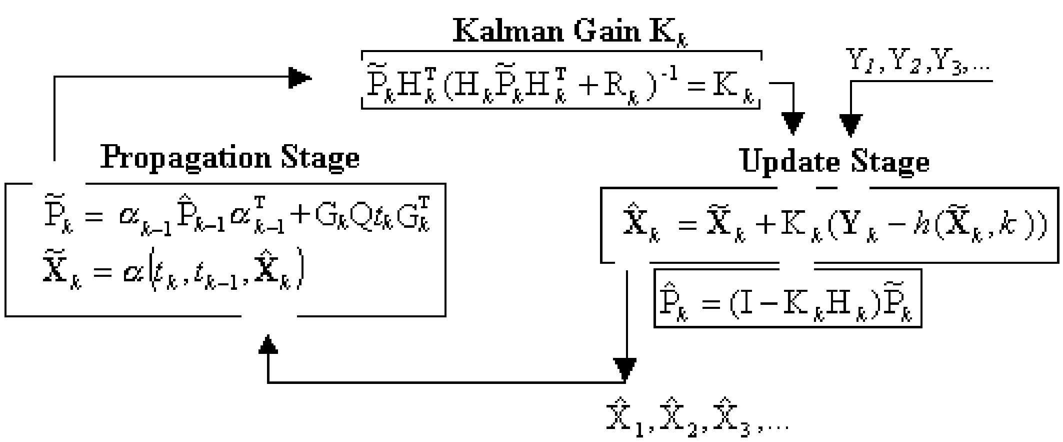

Fig. 1 Diagram of Kalman Filter interactive process.
Based on BROWN, 1997 p. 219.

2.3 Attitude Sensor

Attitude determination of an artificial satellite requires the use of sensors to observe some directions in the satellite frame that are given in the reference frame, such as the Sun, a planet, a star, the geomagnetic field, etc.

2.3.1 Magnetometer

Magnetometers are attitude sensors that provide the intensity and the direction of a magnetic field. They are suitable to space applications due to reliability, lightness, rigidity, low power consumption and robustness to large temperature scales [10], in spite of its inaccuracies.

Uncertainty in the model of the geomagnetic field, in the position of the satellite, as well as the residual field of the satellite itself contributes to the magnetic observation errors. Besides, there are errors due to the conversion equipment, to the data telemetry and processing of these measurements.

2.3.2 One Axis Digital Solar Sensor

A one axis digital solar sensor is an optical device that measures the angle between the Sun direction and the sensor reference axis when illuminated by the Sun, with a specified uncertainty level. Figure 2 shows the way this angle is obtained by the sensor:

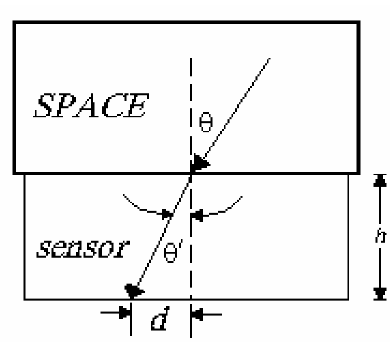

Fig.2 Optical Solar sensor of one axle
Based on Wertz , 1978 pg. 223.

3. BRIEF PROCEDURE DESCRIPTION

The measurements given by the solar sensor and magnetometer are sent to the computer, in which it is installed the software of the joint estimation procedure with modes initializing and routine, no additional costs relevant to the mission budget.

The initializing mode needs: the sensor sampling times and the information of when the solar sensor didn't observe the Sun.

The routine mode needs: an angle of the solar aspect and the intensity of the geomagnetic field to the directions radial and axial in the satellite frame.

3.1 Pre-processing

The pre-processing is carried through the short period tasks. Each set of 32 measures carried through in 16 seconds is compressed as follows. The radial component of the magnetic field rotates around the satellite spin axis. Thus, the biased measurements describe a sinusoid whose bias and amplitude are adjusted. By removing the bias, the sinusoid starts oscillating around the origin. The amplitude value is the input to the next stage, together with the axial component that remains biased.

3.2 Initial estimate

1. From the solar sensor observation outages one obtains the entrances and exits of the satellite on and from the Earth's shadow. From this, one evaluate the orbit period;
2. From the orbit period one evaluates the corresponding orbit altitude under the assumption of a circular orbit;
3. With the mesh grid function of the *Matlab*® a mesh of longitudes and latitudes is generated;
4. The geomagnetic field strength are evaluated by the GEOMAG [11] function in the estimated altitude for each latitude and longitude of the mesh. Candidate solutions to the satellite position over the Earth in the beginning and in the end of the data sample are selected by matching the evaluated strengths with the observed ones.
5. Then, the process above is refined for a narrow mesh around the initial candidate solutions.
6. The compatibility of each pair of candidate solutions regarding time and distance covered is checked.
7. Finally, the initial position is selected from the candidate solutions by minimizing the magnetic strength residue over the whole sample period. The velocity is then evaluated from the Keplerian orbit model.

3.3 Estimation process

The estimation process carried through the tasks of medium and long periods. Least-Squares techniques and Extended Kalman Filter are used in this stage for state estimation and its refinement, respectively. The position, speed, attitude estimates and their error covariance matrix are first obtained by Batch Least-Squares, under the Keplerian orbit model. Such fixed lag estimates periodically fed the Extended Kalman Filter in order to be jointly estimated under a slightly more realistic dynamic model, as described below.

3.3.1 Medium period: Algorithm Batch Least-Squares

With the initial estimate available the estimator of Batch Least-Squares begins the processing of the measures of the attitude sensors using the algorithm developed by reference [2].

In this step the state vector contains the satellite's position vector, the velocity vector and the unit vector in the satellite's spin axis direction, all in the *i*-th sampling time t_i, and written in the inertial system, respectively:

$$\mathbf{X}_\mathbf{i} \equiv \left\{ \mathbf{r}_\mathbf{i}^\mathbf{T} \quad \mathbf{v}_\mathbf{i}^\mathbf{T} \quad \hat{\mathbf{s}}_\mathbf{i}^\mathbf{T} \right\}^T \tag{3}$$

The dynamic systems are considered exempt of any disturbing.

The attitude is represented by a constant unit vector along the satellite spin axis.

The propagation of the orbit parameters is developed, and implemented in FORTRAN® by reference [8].

3.3.2 Large period: Extended Kalman Filter

The estimates obtained by the Least-Squares turn to be observations for the Extended Kalman Filter (EKF), which process them to provide the refined estimates of orbit and attitude of the satellite. The relation between the state and the observation is therefore the identity function. The dynamic model takes into account the disturbing effect of a white noise.

4. SIMULATIONS RESULTS

Every 60 minutes, a set of sampled measurements is processed by the Least-Squares, which provides the position, speed and attitude estimates and their respective error covariance matrix. The Extended Kalman Filter processes them to update and propagate the state vector from hour to hour. The one day simulation results are presented in only one graphic in order to compare the results from the two steps of the estimation process.

The results from two of the simulations carried through in this work are presented, which show the impact of the magnetic bias on the estimates.

The graphics show the position, speed and attitude errors, as well as the magnetic residue in the radial and axial components.

Table 1- Simulation Scenarios

Orbital Dynamic Noise	0,1
Attitude Dynamic Noise	1×10^{-11}
Altitude Error	1 km
Axial component magnetic bias	1 mG
Initial estimative	Automatic

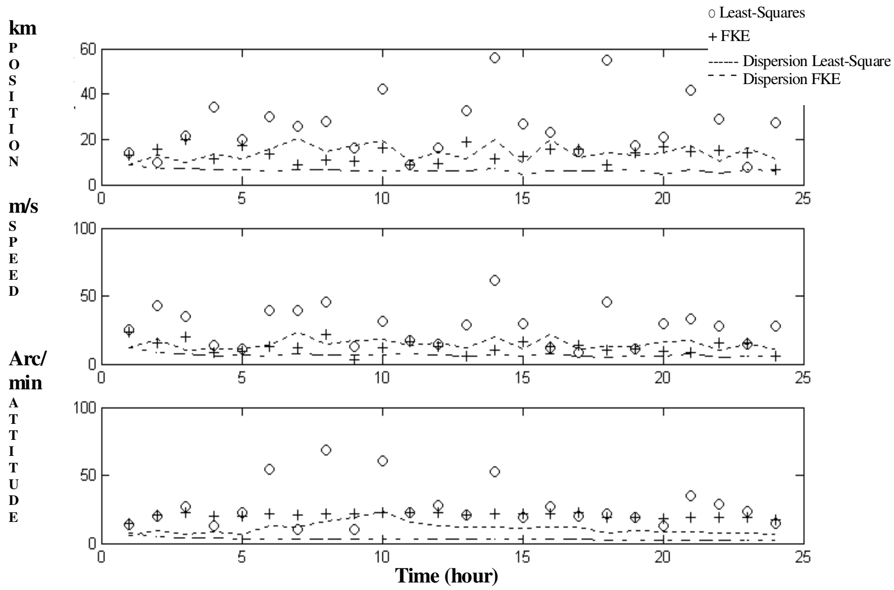

Fig. 3 – 1mG axial bias errors.

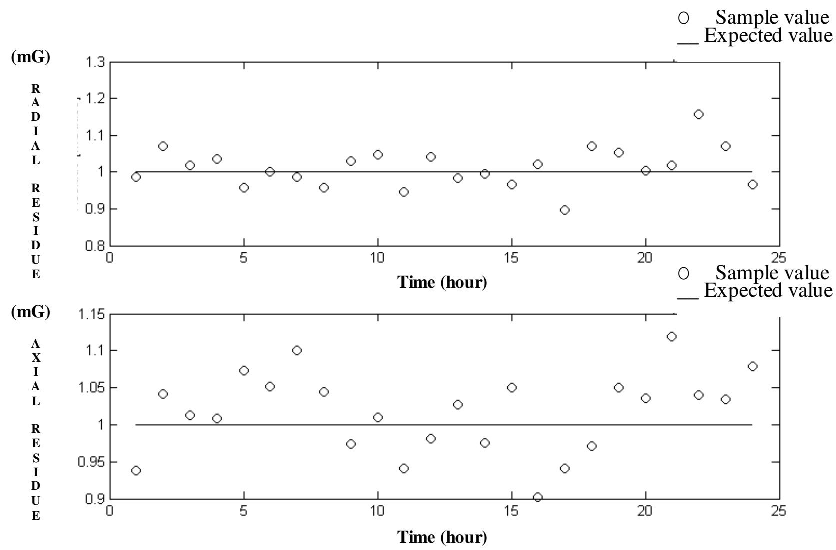

Fig. 4 – 1mG Residues.

Under similar conditions, except the higher bias value of 3mG, the following results were obtained.

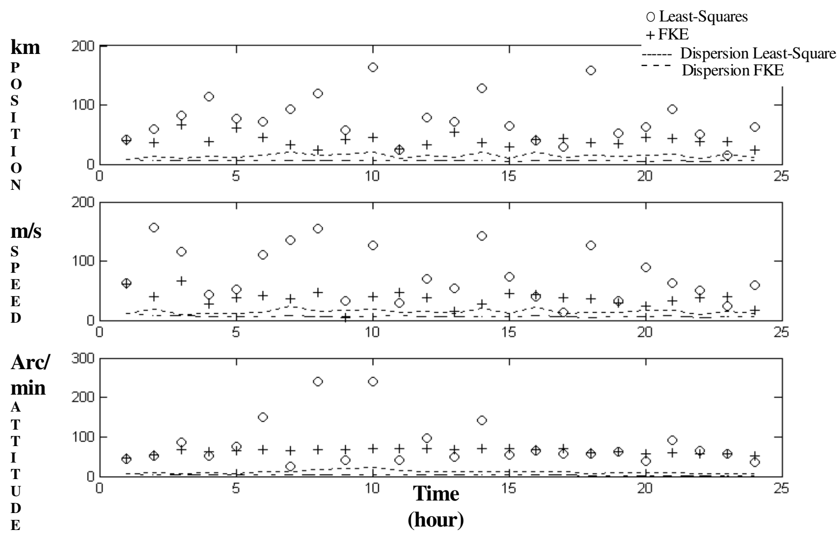

Fig. 5 – 3mG axial bias errors.

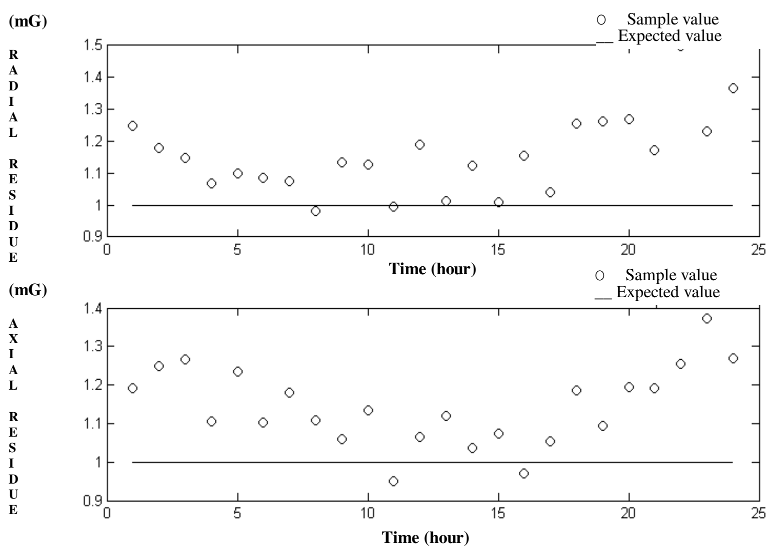

Fig. 6 – 3mG Residues.

Table 2 - Square average errors for simulations as a function of the magnetic bias value.

***bias* [mG]**			
1	3	5	10
Least-Squares			
Position [Km]			
28,77	84,53	141,40	272,32
Speed [m/s]			
30,54	88,94	148,48	288,54
Attitude [arc-min]			
31,19	97,82	163,74	304,01
Kalman Extended Filter			
Position [Km]			
13,75	40,82	68,57	146,61
Speed [m/s]			
13,38	38,62	64,58	134,82
Attitude [arc-min]			
20,51	64,15	108,17	227,93
radial component [mG]			
1,01	1,16	1,42	2,28
axial component [mG]			
1,02	1,15	1,38	2,15

5. CONCLUSION

The results obtained from the measurement processing were promising. The bias due to the satellite own magnetic field is strongly connected to the accuracy of the estimates, besides the dynamic models.

The use of the Extended Kalman Filter, as shown in Table 2, was able to mitigate the effect of the dynamic error model and improve the accuracy of the Least-Squares estimates.

Nevertheless, it was found that the bigger the magnetic bias, the bigger the position, speed and attitude errors. Such simulations carried through under the same conditions show how poor the states estimative gets, as the axial component bias grows. This is important, because magnetic coils used by the control system, also contributes for the magnetic bias effect over the SCD-1 satellite.

Therefore, before a realistic implementation on a space mission, one recommend to include (among others) the axial component magnetic biased in the joint estimation process. Another improvement could be possibly achieved by considering the disturbing effect due to the magnetic residual torques in the attitude dynamics model and, using an improved model to the orbital dynamics that takes into account the Earth flattening (J_2) coefficient, for example.

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