CALIBRATION METHODS OF MAGNETOMETERS ONBOARD THE SATELLITES

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Summary. The article creates an overview of calibration methods of 3D vector magnetometers, which are used on satellite boards. Concerning the satellite mission it is necessary to choose a convenient magnetometer, to perform initial tests, consequently to choose a suitable inverse model and applying a calibration methodology to find parameters of the inverse model. The article analyses F'SATI and Orsted satellites.

Keywords: satellite; magnetometers; calibration; F'SATI; Orsted

1. INTRODUCTION

Magnetometers placed on the satellite boards fulfil different tasks. They can be used to stop the satellite rotation after its launch from the missile [1], to determine the position or they are used for the Earth's magnetic field or the anomalies of the magnetic field mapping. All of these tasks require a precision sensor. Regardless of the sensor price and quality, the calibration is always essential. To systematic errors that influence outputs of a sensor belong mainly sensitivity, offset, linearity and orthogonality errors, cross-axis effect and hysteresis. In the article two different satellites using two various calibration methodologies are compared. It resulted from the fact that on the satellite boards different magnetometers were used, therefore also two different inverse models were chosen in regard to their dominant systematic errors, short and long term stability and temperature dependences. Following chapters create an overview of the abovementioned satellites - F'SATI nano-satellite from the French South African Institute of Technology and of the Oersted satellite from the Technical University of Denmark and of the used magnetometers and applied inverse models and calibration methodologies.

2. F’SATI

On the board of this satellite LEMI-011B fluxgate magnetometer was used. It was chosen based on its power consumption, weight, noise parameters, linearity and adaptability.

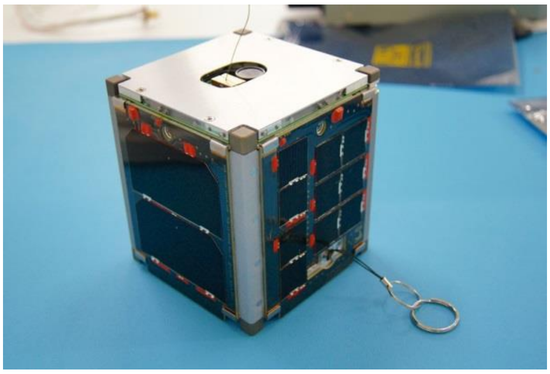

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Figure 1 F'SATI [2]

The magnetometer was tested in the term of the temperature dependence using the cycling and vibrations. For the calibration three-axial Helmholtz coil system placed in the magnetically clean environment of the South African National Space Agency (SANSA) [3] was used. The coil system involves a control system with a compensation algorithm for the dynamic suppression of the Earth's magnetic field. In this case a thin-shell calibration methodology was used. The method is based on the specified positioning applying 200 magnetic field vectors with the constant modulus of 50 μT. The following inverse model for the magnetometer was chosen:

$$\begin{bmatrix} \tilde{x} \\ \tilde{y} \\ \tilde{z} \end{bmatrix} = \begin{bmatrix} B_x & B_{xy} & B_{xz} \\ B_{yx} & B_y & B_{yz} \\ B_{zx} & B_{zy} & B_z \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} + \begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix} \tag{1}$$

where $\tilde{x}, \tilde{y}, \tilde{z}$ are estimations of the true measured quantity, B_x, B_y, B_z multiplicative constants, A_x, A_y, A_z additive constants. B_{yx}, B_{xy}, B_{zx}, B_{xz}, B_{zy}, B_{yz} are constants compensating non-orthogonalities.

This inverse model includes sensitivity, offset and orthogonality errors. In regard to the non-linearity specified to the value of 2 nT in the whole measurement range it is not necessary to consider the non-linearity correction. The particular calibration constants were achieved using the thin-shell method [4] that is based on the LMMSE estimation and it is position-independent. For the maximum precision achievement the sensor has to be positioned so to describe the whole sphere surface. Whereas only limited number of measurements is used, positions have to be chosen so to cover the situations with the maximum non-orthogonalities. From the inverse model it results that it is necessary to calculate 12 parameters using an iteration methodology. The iteration is based on the divide of the intervals to a half, therefore before the calibration for each parameter it is necessary to determine an interval, in which the presence of its value is expected. To the determined interval an evaluative criterion on the basis of which the given interval is searched has to be specified. It can be for example a standard deviation defined as:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N} ((\tilde{x}_i)^2 + (\tilde{y}_i)^2 + (\tilde{z}_i)^2 - |T|^2)^2}{N-1}} \tag{2}$$

where N is the number of measurements, $\tilde{x}_i, \tilde{y}_i, \tilde{z}_i$ are estimation of the compensated components of the magnetic fields in the i-th position and T is the magnetic induction modulus in the calibration place. Before the iteration procedure for each parameter it is necessary to know its minimum, maximum and mean value calculated as a mathematical average of the minimum and maximum value. Considering 12 parameters estimation the calibration will consist of 12 cycles. In each cycle the value of one parameter is found so to minimize the standard deviation defined in equation (2). During the calculations of the given cycle other already determined parameters are set to their determined mean value, otherwise the averaged mean value is used. In each cycle the interval of the presence of the determined parameter is reduced using three steps:

- 1st step: for all position estimation of the true values are calculated. Calculations are performed for the minimum, maximum and mean value of the given parameters, in generally marked as k_{min}, k_{max} and k_{mean}.
- 2nd step: calculated estimated values are appointed to the equation (2), whereby the standard deviation values marked as σ_{min}, σ_{max}, σ_{mean} are obtained.
- 3rd step: based on the σ_{min}, σ_{max}, σ_{mean} values the interval of the presence for the given parameter is modified as follows:

- if ($\sigma_{min} > \sigma_{mean}$)& ($\sigma_{max} > \sigma_{mean}$) then for the following step is the interval around the mean value k_{mean} reduced to a half.
- if ($\sigma_{min} < \sigma_{mean}$)& ($\sigma_{mean} < \sigma_{max}$) then $k_{max} = k_{mean}$ and the new k_{mean} value is calculated as the average from the k_{mean} and k_{max} values.
- if ($\sigma_{max} < \sigma_{mean}$)& ($\sigma_{mean} < \sigma_{min}$) then $k_{min} = k_{mean}$ and the new k_{mean} value is again calculated as the average from the k_{mean} and k_{max} values.

The resultant value of the standard deviation determines precision of the presented calibration procedure.

3. ORSTED

The Orsted satellite was launched in 1999 and its mission was to precisely map the Earth's magnetic field with it anomalies. There are two magnetometers on the satellite board. The first one is of an Overhauser type and the second one is a vector flux-gate magnetometer. Both of them are placed outside of the satellite body in a carrier placed in the distance of 8 m.

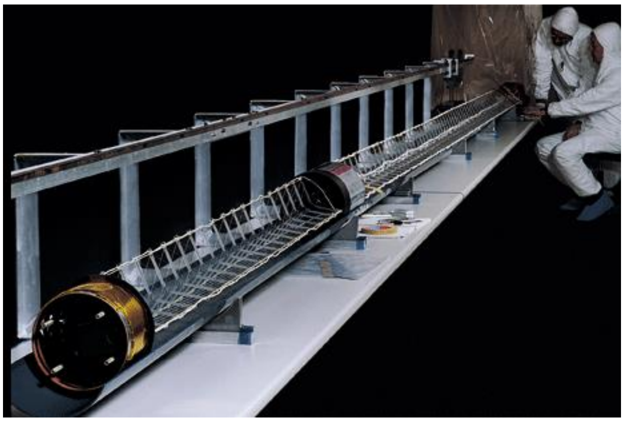

Figure 2 Orsted [5]

The calibration was performed for the full range of the Earth's magnetic field ±65536 nT. For the calibration of the flux-gate sensor a scalar methodology [6] using the information from the Overhauser magnetometer was used. Forasmuch as tests performed that the magnetometer has negligible non-linearities and cross-axis effects, the inverse model involved only sensitivity, offset and orthogonality errors. To achieve the best precision also the influence of the time dependence, temperature dependence of the sensor and of the electronics on the constants are considered. The inverse model in the matrix form can be written as:

$$B_{CSC} = \sqrt{(\mathbf{E}-\mathbf{b})^T \underline{\underline{\mathbf{S}}}^{-1} \left(\underline{\underline{\mathbf{P}}}^{-1}\right)^T \underline{\underline{\mathbf{P}}}^{-1} \underline{\underline{\mathbf{S}}}^{-1} (\mathbf{E}-\mathbf{b})} \tag{3}$$

where $\mathbf{B}_{\mathbf{CSC}} = (B_1, B_2, B_3)^T$ is a column vector of the true value estimation, $\mathbf{E} = (E_1, E_2, E_3)^T$ is a column vector of the output non-calibrated magnetometer data, $\mathbf{b}$ is a column vector of the offsets, $\underline{\underline{\mathbf{S}}}$ is the diagonal sensitivity matrix and $\underline{\underline{\mathbf{P}}}$ is the orthogonality matrix. The abovementioned matrices can be expressed as:

$$\mathbf{b} = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} \tag{4}$$

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$$\underline{\underline{\mathbf{S}}} = \begin{pmatrix} S_1 & 0 & 0 \\ 0 & S_2 & 0 \\ 0 & 0 & S_3 \end{pmatrix} \tag{5}$$

$$\underline{\underline{\mathbf{P}}} = \begin{pmatrix} 1 & 0 & 0 \\ -\sin(u_1) & \cos(u_1) & 0 \\ \sin(u_2) & \sin(u_3) & \sqrt{\left(1-\sin^2(u_2)-\sin^2(u_3)\right)} \end{pmatrix} \tag{6}$$

The u_1, u_2 and u_3 values are angles between the magnetometer axes. As sensitivities and offsets are the functions of time t, of the sensor temperature T_S and of the electronics temperature T_A, we can write compensating equations:

$$\begin{aligned} S_i &= S_{0,i} + S_{A,i}T_A + S_{S,i}T_S + S_{t,i}t \\ b_i &= b_{0,i} + b_{A,i}T_A + b_{t,i}t \end{aligned} \tag{7}$$

Together we have 9 temperature independent and 15 time and temperature dependent parameters, which are summarized in the **m** model:

$$\mathbf{m} = \left(b_{0,i}, S_{0,i}, u_i, b_{A,i}, b_{t,i}, S_{A,i}, S_{S,i}, S_{t,i}\right)^T \tag{8}$$

where i = 1, 2, 3. For the determination of these parameters the linearized robust least-squares method was used. For the k-th iteration of the least-squares estimator may be written as:

$$\mathbf{m}^{k+1} = \mathbf{m}^k + \delta\mathbf{m}^k \tag{9}$$

$$\delta\mathbf{m}^k = \left[\left(\underline{\underline{\mathbf{G}}}^k\right)^T \underline{\underline{\mathbf{W}}}_d^k \underline{\underline{\mathbf{G}}}^k + \underline{\underline{\mathbf{W}}}_p\right]^{-1} \cdot \left[\left(\underline{\underline{\mathbf{G}}}^k\right)^T \underline{\underline{\mathbf{W}}}_d^k \delta_d^k + \underline{\underline{\mathbf{W}}}_p\left(\mathbf{m}^k - \mathbf{m}_p\right)\right] \tag{10}$$

where $\delta\mathbf{d}^k = B_{OVH} - B_{CSC}(\mathbf{E}, \mathbf{m}^k)$ is the data residual vector of the k-th iteration,

$$\underline{\underline{\mathbf{G}}}^k = \left.\frac{\partial\mathbf{d}(\mathbf{m})}{\partial\mathbf{m}}\right|_{\mathbf{m}=\mathbf{m}^k} \tag{11}$$

is the data kernel matrix, $\underline{\underline{\mathbf{w}}}_d^k$ is the diagonal data weight matrix, $\mathbf{m}_p$ is the a priori model vector, and $\underline{\underline{\mathbf{w}}}_p$ is a diagonal matrix with the weights w_p that are associated to these a priori values. B_{OVH} is a modulus of the magnetic induction vector measured by the scalar magnetometer. The $\mathbf{d}(\mathbf{m})$ vector contains data measured by the fluxgate magnetometer. The calibration was performed using the positioning platform, which was used to rotate the sensor in the 3D space so to uniformly cover the sphere surface. Together 84 measurement points were analysed. As the stimulation field the Earth's magnetic field was used.

4. CONCLUSION

To achieve the best measurements results each sensor including those ones that fulfil mission on the satellite boards has to be calibrated. In the article two different satellites varies in the used sensors, applied inverse models, calibration methods and the whole mission demands. Whilst the F'SATI is the commercial satellite available for universities, the Oersted satellite is used for the Earth's magnetic field and its anomalies mapping. By the selection of the methodology the following procedure is used. A suitable sensor is chosen and initial tests are performed, whereby good linearity, small own noise, high sensitivity and in the whole necessary measurement range are expected. Based on the test results a convenient inverse model is created and calibration coefficients are determined using suitable calibration methods.

Acknowledgement

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