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In-flight vector magnetometer calibration for FY-3E satellite

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The FY-3E meteorological satellite was launched by China on July 5, 2021. The orbit of the satellite is sun-synchronous with an orbit altitude 836 km and orbit period 102 min. The satellite is equipped with a triaxial anisotropic magnetoresistance magnetometer to detect ultra-low frequency waves in the magnetosphere. The magnetometer sensor is situated on the satellite truss. It is approximately 1 m away from the satellite body to reduce the effect of spacecraft fields. However, a completely magnet-free environment is impossible in the satellite; thus, the measured magnetic field will be contaminated by the residual magnetic field of the satellite. The magnetometer was designed as a highly stable linear instrument. It is an anisotropic magnetoresistance magnetometer and it was calibrated on ground. However, the calibration configuration on ground was not the same as in-flight configuration; for example, solar panels were not operational. Therefore, the offsets in-flight are changed from the values that were determined on ground. Moreover, additional errors are still present owing to the mechanical stress and thermal stress during the spacecraft launch process [1–4]. These errors include bias produced by the satellite body, and misalignment between of the sensors' sensitive axes and spacecraft reference axes. Therefore, in-flight re-calibration is routinely necessary [1].

Scalar magnetometers are usually used to perform calibration on orbit [1,5]. It uses the magnetic field intensity and it is scalar calibration which is not includes the orientation. Obviously, vector calibration which can include the orientation calibration is superior. Moreover, equipped a scalar magnetometer is a high cost and usually it also need a sufficiently long pole to reduce the influence of satellite remanence [5]. Unfortunately, FY-3E does not comprise a scalar magnetometer. This paper presents an efficient and easy to implement method for in-flight calibration of vector magnetometers. It uses vector geomagnetic field model (an approximate Earth's magnetic field model) to calibrate the sensors. It can estimate the bias produced by the satellite remanence and the misalignment between of the sensors' sensitive axes and spacecraft reference axes. We aim to perform a calibration to detect transient physical signals such as small structure of quasi-static field aligned current (FAC) and waves, which is crucial to space weather research.

For an ideal vector magnetometer in a satellite body coordinate system, the sensors' three sensitive axes are consistent with those of the satellite. However, in practice, misalignment angles exist between them [6,7]. Moreover, the magnetometer would have an offset owing to the satellite remanence. Therefore, in practice, the measured magnetic field $\begin{pmatrix} B'_x \\ B'_y \\ B'_z \end{pmatrix}$ by the sensors are a function of the real magnetic field $\begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix}$ in an ideal satellite body coordinate system. They

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can be calculated as follows:

$$\begin{pmatrix} B'_x \\ B'_y \\ B'_z \end{pmatrix} = \begin{pmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ c_{31} & b_{32} & b_{33} \end{pmatrix} \times \begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix} + \begin{pmatrix} B_{x0} \\ B_{y0} \\ B_{z0} \end{pmatrix}, \tag{1}$$

where b_{11}, b_{12}, b_{13}, b_{21}, b_{22}, b_{23}, b_{31}, b_{32}, and b_{33} are related to the misalignment between the sensors' three sensitive axes and the satellite body's coordinate system. B_{x0}, B_{y0}, and B_{z0} are related to the bias produced by the satellite remanence.

Solving (1) we can obtain the following:

$$\begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix} = \begin{pmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ c_{31} & b_{32} & b_{33} \end{pmatrix}^{-1} \times \left[\begin{pmatrix} B'_x \\ B'_y \\ B'_z \end{pmatrix} - \begin{pmatrix} B_{x0} \\ B_{y0} \\ B_{z0} \end{pmatrix} \right]. \tag{2}$$

This problem can be described using a linear equation. To solve this equation, one need at least four sets measured magnetic fields values and known magnetic fields values. Multiple values and using least squares methods can improve the calculation accuracy.

As mentioned previously, in-flight calibration requires a series of known magnetic fields. In this study, we used an independent magnetic field from the 13th-order international geomagnetic reference field (IGRF) model. The model's accuracy is estimated to have a formal root mean square (rms) error over the Earth's surface of only 5 nT, though the actual error could be larger than that [4]. The relative error is estimated to be less than 1/2000. However, since the IGRF model does not include the magnetic field induced by the magnetospheric current systems, the independent magnetic field should be chosen strictly for low latitude regions (geomagnetic latitude MLAT between −60° and 60°). Furthermore, all data points out of the magnetometer's range and large-amplitude spikes (considered to be caused by the satellite itself) were excluded. We applied this method to three-month data (Jul., 2021–Oct., 2021) with a 1 s sampling rate (one sample every 1 s). This dataset comprised approximately 7777800 measurements. After merging the derived calibration coefficients with eq. (2), we have (in unit of nT):

$$\begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix} = \begin{pmatrix} 1.0007 & -0.0438 & -0.0096 \\ -0.0110 & 1.0011 & -0.0178 \\ 0.0221 & 0.0327 & 0.9977 \end{pmatrix}^{-1} \times \left[\begin{pmatrix} B'_x \\ B'_y \\ B'_z \end{pmatrix} - \begin{pmatrix} -124.2699 \\ -607.2710 \\ -654.9231 \end{pmatrix} \right]. \tag{3}$$

Using eq. (3), we can obtain the corrected magnetic field values of the in-flight measurement data.

Figure 1 shows the data of one orbit flight wherein IGRF was subtracted after correction. The data after correction clearly shows the transient physical signals whose amplitude is ~50 nT when the satellite crosses the auroral oval region.

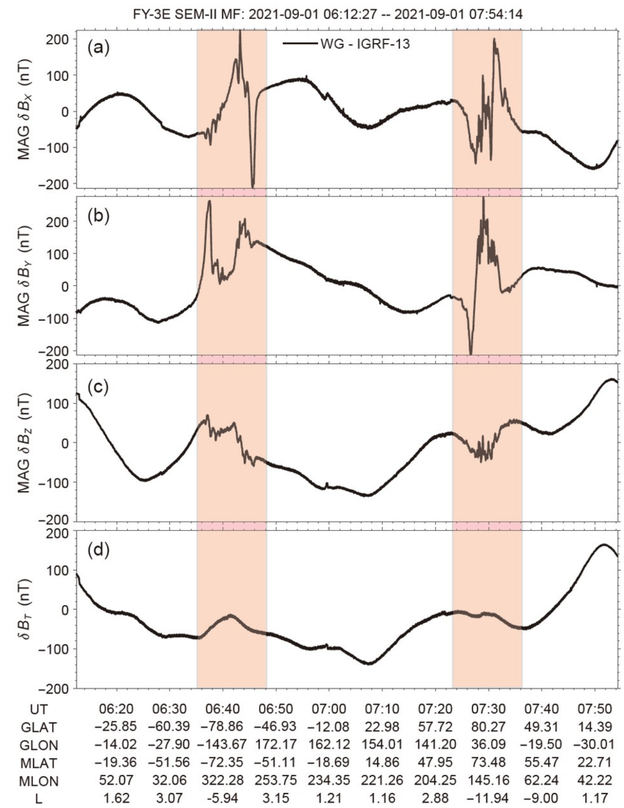

Figure 1 (Color online) One orbit flight data of magnetic field in geomagnetic coordinate, wherein IGRF is subtracted after correction, clearly showing the field-aligned currents (shaded).

Subsequent analysis of the data showed they are small structure of quasi-static field aligned current (FAC) and waves. The results verify that the proposed method can be an alternative method for in-flight calibration of a three-axis vector magnetoresistance magnetometer used for space weather research.

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