Research Article

Optimized Design and Calibration of the Triaxis Induction Magnetometer with Crosstalk and Nonorthogonality Compensation

Hongyu Shi,^{1,2} Yanzhang Wang,^{1,2} and Jun Lin^{1,2}

¹College of Instrumentation & Electrical Engineering, Jilin University, No. 938 Ximinzhong Street, Changchun 130026, China

²Key Laboratory of Geo-Exploration Instruments, Ministry of Education of China, No. 938 Ximinzhong Street, Changchun 130026, China

Correspondence should be addressed to Yanzhang Wang; yanzhang@jlu.edu.cn

Received 16 January 2016; Accepted 5 July 2016

Academic Editor: Andrea Cusano

Copyright © 2016 Hongyu Shi et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

An optimized triaxis induction magnetometer has been designed and calibrated to minimize the influences from the nonorthogonality and the magnetic flux crosstalk. Utilizing the nonlinear least square method, contributions due to the nonorthogonal assembly of three transducers are cancelled. The magnetic flux crosstalk is a frequency-dependent error component in the calibration of the triaxis induction magnetometer. Influences from the assembly density, the frequency, and the feedback amount are analyzed theoretically, and an optimized sensor configuration which has a smaller crosstalk is achieved. Moreover, a mathematical compensation algorithm has also been utilized to suppress the residues crosstalk ulteriorly. To validate the theoretical analysis, a triaxis induction magnetometer was manufactured and the experiment setup has also been built. The experiment results show that the cross-outputs of the transverse induction magnetometers have been significantly decreased about two orders, indicating that the proposed method is applicable for the triaxis induction magnetometer.

1. Introduction

It is the objective of this paper to achieve minimum contributions from the magnetic flux crosstalk among three transducers and nonorthogonality of the assembly accuracy. Nonorthogonality error occurs because of the mechanical precision of the individual magnetometer axes [1–10]. Magnetic flux crosstalk is a frequency-dependent component and is due to an unexpected magnetic flux distribution among three transducers [11, 12].

Various calibration algorithms have been proposed for the nonorthogonality in the past years. Transformation matrix between the orthogonality coordinate and the triaxis magnetometer coordinate is derived theoretically. Then, the calibration is considered as nonlinear estimation and calibration parameters can be achieved with different algorithms. Pylvänäinen introduced a calibration method based on recurring fitting of an ellipsoid to collected samples from the sensor [1]. Crassidis et al. developed alternative real-time algorithms based on the extended Kalman filter (EKF)

and unscented Kalman filter (UKF). Both algorithms provide accurate integer resolution in real time, but the UKF is more robust to large initial condition errors than the EKF [2]. Pang compared the calibration performance of UKF, two-step algorithm, and nonlinear least square methods, and the experimental results show that the nonlinear least square method has the smallest error average and standard deviation [3–5].

The magnetic crosstalk is another limitation for the measurement accuracy of the triaxis induction magnetometer. Regarding Grosz et al.'s research, a maximum crosstalk 27.7% is reached just above the resonant frequency of the primary coil where the secondary flux crosstalk dominates. Conversely, at a frequency just below the resonant frequency, the minimum crosstalk is achieved because of the compensation of the primary and secondary crosstalk flux [11]. Numerous investigations about the crosstalk have been published in recent years [11–19]. A strong enough negative-feedback flux is an effective way to decrease the crosstalk near the resonant frequency. And the secondary flux generated by the primary

FIGURE 1: The triaxis induction magnetometer (/mm).

FIGURE 2: The equivalent electronic circuit of the induction magnetometer.

coil above the resonant frequency has been suppressed. However, an unwanted increasing crosstalk below the resonant frequency emerges concomitantly. Paperno et al. proposed a mathematical compensation method for the crosstalk in 2011 [12]. The compensation is based on deriving crosstalk-free magnetometer outputs from a system of equations describing the magnetometer total outputs as a function of the applied field and the parameters of the triaxis induction magnetometer. But the dynamic range of the transducer output is too large and the resolution of the magnetometer is limited.

The purpose of this paper is to develop an optimized design and calibration method of the triaxis induction magnetometer. The magnetic flux-feedback principle has been utilized to suppress the crosstalk near the resonant frequency. Moreover, contributions from the assembling density, frequency, and feedback amount have been analyzed and an optimized sensor configuration with smaller crosstalk has been achieved. Moreover, a calibration method, in which, besides the mathematical compensation algorithms for the crosstalk, the nonorthogonality compensation has also been considered synthetically, is proposed to improve the calibration performance of the triaxis induction magnetometer.

To validate the proposed method, a triaxis induction magnetometer was manufactured. And the experiment results show that, after calibration, the cross-outputs of

the transverse induction magnetometers have been significantly decreased by two orders, indicating that the proposed method is applicable to the triaxis induction magnetometer.

2. Principle of the Triaxis Induction Magnetometer

The triaxis induction magnetometer and its equivalent electronic circuit are as shown in Figures 1 and 2 [20–24]. Three induction magnetometers are assembled orthogonally to sense the varied magnetic field in the space. R , L , and C are the resistance, inductance, and capacitance of the induction coil separately, L_f and R_f are the inductance of the feedback coil and the feedback resistance, M is the mutual inductance between the induction and feedback coils, A is the gain of the preamplifier, and V_o is the output of the preamplifier. V_o is calculated as follows:

$$V_o = \frac{-j2\pi fNS\mu_{app}B_{x,y,z}A}{1 + j2\pi f(RC + M(A/R_f)) - (2\pi f)^2LC} \quad (1)$$

$$= \frac{-j2\pi fN\Phi_p A}{1 + j2\pi f(RC + M(A/R_f)) - (2\pi f)^2LC}.$$

$B_{x,y,z}$ is the magnetic flux density in X-axis, Y-axis, and Z-axis transducers, μ_{app} is the apparent permeability of the core, and Φ_p is the primary magnetic flux in every transducer.

FIGURE 3: The coordinates of the triaxis induction magnetometer.

FIGURE 4: Crosstalk in the triaxis induction magnetometer.

3. Optimized Design and Calibration of the Triaxis Induction Magnetometer

3.1. Calibration of the Nonorthogonality. As shown in Figure 3, O - XYZ is the orthogonal coordinate and O - $X'Y'Z'$ denotes the triaxis induction magnetometer coordinate. The vertical axis OZ' is defined to be completely aligned with the OZ -axis. The OX' -axis lies in the plane defined by OX -axis and OZ -axis. And α is the angle between X' -axis and the forward direction of X -axis. γ is the angle between OY' -axis and the plane, which is defined by OX -axis and OY -axis. And β is defined as the angle between the projection of OY' -axis in the plane and the forward direction of OY -axis.

The transformation between two coordinates can be expressed as in (2). T_n is the coordinate transformation matrix. B_x , B_y , and B_z are the measured magnetic flux density in X -axis, Y -axis, and Z -axis, and B'_x , B'_y , and B'_z are the real magnetic flux density in X -axis, Y -axis, and Z -axis:

$$\begin{bmatrix} B'_x \\ B'_y \\ B'_z \end{bmatrix} = T_n \cdot \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} \quad (2)$$

$$= \begin{bmatrix} \cos \alpha & \cos \gamma \sin \beta & 0 \\ 0 & \cos \gamma \cos \beta & 0 \\ \sin \alpha & \sin \gamma & 1 \end{bmatrix} \cdot \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix}.$$

3.2. Optimized Design and Calibration of the Crosstalk. The crosstalk, which is due to an unexpected magnetic flux distribution in three transducers, is a specific error component of the triaxis induction magnetometer. Its strength mainly depends on the assembly density (D_c in Figure 1), the feedback amount (R_f), and the frequency (f).

3.2.1. Crosstalk Evaluation of the Triaxis Induction Magnetometer. The crosstalk due to the primary and the secondary magnetic flux is simulated by the FEM software Maxwell 15.0 and shown as in Figure 4.

As for the crosstalk due to the applied flux (Figure 4(a)), we can see that the applied vertical flux also flows in the transverse transducers and provides an additional contribution for the transverse output. Moreover, there is also secondary flux, generated by the current in the vertical induction coil, flowing in the transverse transducers (Figure 4(b)).

According to Grosz et al.'s research, the relative crosstalk ϕ_c is defined by the ratio of the crosstalk flux in the transverse transducer, to the primary flux in the vertical transducer, shown as follows [11, 12]:

$$\phi_c = \frac{\Phi_c \Sigma}{\Phi_p} = \phi_{cp} \cdot \frac{\Phi_p}{\Phi_p} + \phi_{cs} \cdot \frac{\Phi_s}{\Phi_p} = \phi_p + \phi_s. \quad (3)$$

ϕ_{cp} is the crosstalk coefficient due to unit primary flux, ϕ_{cs} is the crosstalk coefficient due to unit secondary flux,

FIGURE 5: The crosstalk due to the applied flux (the blue/purple/red solid lines, double crossed lines, and dotted lines indicate the primary flux in X-axis/Y-axis/Z-axis with $D_c = 28.5$ mm, 68.5 mm, and 98.5 mm separately).

FIGURE 6: The crosstalk due to the secondary flux (the blue/purple/red solid lines, double crossed lines, and dotted lines indicate the secondary flux in X-axis/Y-axis/Z-axis with $D_c = 28.5$ mm, 68.5 mm, and 98.5 mm separately).

Φ_p is the primary flux in the vertical transducer, Φ_s is the secondary flux generated by the induction coil in the vertical transducer, ϕ_p is the relative primary crosstalk compared to unit Φ_p and its value is equal to ϕ_{cp} , and ϕ_s is the relative secondary crosstalk compared to unit Φ_p . Φ_s is estimated as follows:

$$\Phi_s = \frac{1}{N} \left(L \frac{V_o}{A} j2\pi f C + M \frac{V_o}{R_f} \right). \quad (4)$$

Subjecting (1) and (4) to (3), ϕ_c can be expressed as

$$\phi_c = \phi_{cp} + \phi_{cs} \cdot \frac{1}{1 + 1/j2\pi f ((AM + j2\pi f R_f LC) / R_f (1 + j2\pi f RC))}. \quad (5)$$

The magnetic field in every axis can be estimated as in (6). Φ_x , Φ_y , and Φ_z are the measured magnetic flux in X-axis, Y-axis, and Z-axis, and Φ'_x , Φ'_y , and Φ'_z are the crosstalk-free magnetic flux:

$$\begin{aligned} \Phi_x &= \Phi'_x + \phi_c \cdot \Phi'_y + \phi_c \cdot \Phi'_z, \\ \Phi_y &= \phi_c \cdot \Phi'_x + \Phi'_y + \phi_c \cdot \Phi'_z, \\ \Phi_z &= \phi_c \cdot \Phi'_x + \phi_c \cdot \Phi'_y + \Phi'_z. \end{aligned} \quad (6)$$

The values of the apparent permeability μ_{app} and the core cross section S are equal compared with each other. Based on equation $\Phi = \mu_{app} \cdot B \cdot S$, (6) can be simplified as

$$\begin{bmatrix} B'_x \\ B'_y \\ B'_z \end{bmatrix} = \begin{bmatrix} 1 & \phi_c & \phi_c \\ \phi_c & 1 & \phi_c \\ \phi_c & \phi_c & 1 \end{bmatrix}^{-1} \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix}. \quad (7)$$

3.2.2. Optimized Design of the Assembly Density D_c . ϕ_{cp} and ϕ_{cs} depend on a set of transducer parameters, such as the core's material, the aspect ratio, and the geometry structure of the sensor configuration. In this paper, the core material is permalloy and the cross diameter is 8.5 mm. To achieve an optimized sensor configuration with a smaller crosstalk, the crosstalk with different D_c is simulated with the help of the FEM simulation software Maxwell 15.0, as shown in Figures 5 and 6.

As shown in Figures 5 and 6, the magnetic flux density in Z-axis has no significant differences with different D_c . The crosstalk magnetic flux density in X-axis and Y-axis varies from positive values to negative values (or from negative values to positive values), and the zero crosstalk point moves in concert with D_c . The configuration with $D_c = 98.5$ mm selected for the crosstalk in the transverses transducers can be mostly cancelled, and the residues crosstalk is $\phi_{cp} = 0.64\%$ and $\phi_{cs} = 0.93\%$.

FIGURE 7: ϕ_s simulation with different feedback amount and frequencies.

FIGURE 8: The crosstalk with different feedback amount.

3.2.3. The Influence of the Feedback Amount and Frequency. Based on (3), the total relative crosstalk ϕ_c depends on the relative primary crosstalk ϕ_p and secondary crosstalk ϕ_s . For a given triaxis induction magnetometer, ϕ_p has a constant amplitude and phase in the whole frequency band, while ϕ_s is varying with different feedback amount and frequencies, as shown in Figure 7.

From Figure 7 we can see that, compared with ϕ_p , ϕ_s has large phase differences below the resonant frequency, the same phase at high frequency band. Moreover, with the feedback resistance increasing, ϕ_s is decreasing at low frequency band and increasing at resonant frequency. At frequency band higher than the resonant frequency, the feedback has no significant influence and ϕ_s approaches ϕ_{cs} .

Moreover, ϕ_c with different feedback amount and frequencies has also been calculated, as shown in Figure 8.

At frequency band below the resonant frequency, ϕ_c is equal to ϕ_p approximately for ϕ_s is so small that it can be neglected (see Figure 7). The minimum value is approached at frequency just below the resonant frequency, where ϕ_p is mostly cancelled by the reversed ϕ_s . At the frequency just above the resonant frequency, ϕ_c reaches its maximum value due to the maximum ϕ_s . At frequency band higher than

the resonant frequency, ϕ_c reaches $(\phi_p + \phi_s)$ for ϕ_p is in phase with ϕ_s .

Therefore, if a low crosstalk below the resonant frequency is needed, or in some specific situation we want to get a high sensitivity near the resonant frequency, a light feedback is a better choice. But if you want to achieve a smaller crosstalk near the resonant frequency, a deep feedback is preferred.

3.3. Calibration of the Triaxis Induction Magnetometer. Considering the calibration equations for the nonorthogonality and the crosstalk, as evaluated in (2) and (7), the calibration model of the triaxis induction magnetometer can be derived as follows:

$$\begin{bmatrix} B'_x \\ B'_y \\ B'_z \end{bmatrix} = \begin{bmatrix} 1 & \phi_c & \phi_c \\ \phi_c & 1 & \phi_c \\ \phi_c & \phi_c & 1 \end{bmatrix}^{-1} \cdot \begin{bmatrix} \cos \alpha & \cos \gamma \sin \beta & 0 \\ 0 & \cos \gamma \cos \beta & 0 \\ \sin \alpha & \sin \gamma & 1 \end{bmatrix} \cdot \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix}$$

FIGURE 9: The preamplifier circuit (X-axis as example).

FIGURE 10: The established experiment setup.

$$= \frac{1}{2\phi_c^3 - 3\phi_c^2 + 1} \cdot \begin{bmatrix} 1 - \phi_c^2 & \phi_c^2 - \phi_c & \phi_c^2 - \phi_c \\ \phi_c^2 - \phi_c & 1 - \phi_c^2 & \phi_c^2 - \phi_c \\ \phi_c^2 - \phi_c & \phi_c^2 - \phi_c & 1 - \phi_c^2 \end{bmatrix} \cdot \begin{bmatrix} \frac{V_x}{S_x} \\ \frac{V_y}{S_y} \\ \frac{V_z}{S_z} \end{bmatrix} \cdot \begin{bmatrix} \cos \alpha & \cos \gamma \sin \beta & 0 \\ 0 & \cos \gamma \cos \beta & 0 \\ \sin \alpha & \sin \gamma & 1 \end{bmatrix} \cdot \begin{bmatrix} \frac{V_x}{S_x} \\ \frac{V_y}{S_y} \\ \frac{V_z}{S_z} \end{bmatrix} \quad (8)$$

V_x , V_y , and V_z are the outputs of the triaxis induction magnetometer, and S_x , S_y , and S_z are the sensitivities of the X-axis, Y-axis, and Z-axis induction magnetometers. Based on (8), the output voltages of the triaxis induction magnetometer are calibrated and compensated.

4. Experiment

4.1. Experimental Setup. To validate the method proposed above, a triaxis induction magnetometer was manufactured

as shown in Figure 1, and its parameters are shown in “Notations” section.

The preamplifier circuit (X-axis as an example) of the sensor is as shown in Figure 9. Dual-JFET is utilized in the first-stage for it has a high input impedance.

The experiment setup is also established as shown in Figure 10.

The applied magnetic field B is generated by the Helmholtz coils (green part, driven by current source Keithley 6221). The yellow square indicates the area where the magnetic field is uniform. The red circle in the uniform field area is the platform to fix the triaxis induction magnetometer (blue cube in the red circle). The outputs of the sensor are measured by the Agilent 35670A and processed utilizing the nonlinear least square method (programmed by the MATLAB software) [3].

4.2. Experiment Results. The sensitivities of different axes of the triaxis induction magnetometer were calculated, as shown in Figure 11. We can see that it has a sensitivity of 40 mV/nT @ 100 Hz and 100 mV/nT @ float part.

The calibration of the triaxis induction magnetometer, including the nonorthogonality and the crosstalk compensation, has also been done. In detail, the magnetic flux is

FIGURE 11: Sensivities of the triaxis induction magnetometer.

FIGURE 12: The calibration result of the triaxis induction magnetometer.

applied in Z-axis direction, and the normalized cross-outputs of the transverse induction magnetometers (X-axis and Y-axis) have been measured and calibrated based on (8), as shown in Figure 12.

We can see that, compared with utilizing the magnetic flux-feedback, the crosstalk of the X-axis and Y-axis induction magnetometers is decreased about two decades approximately in the whole frequency band. Moreover, compared with utilizing the compensation algorithm proposed by Paperno et al. [12], a lower crosstalk is achieved near the resonant frequency (3 kHz approximately in this paper). It is because the high crosstalk near the resonant frequency has been suppressed by the negative-feedback flux. Then, the residues crosstalk is compensated using the compensation algorithm.

5. Conclusions

To improve the performance of the triaxis induction magnetometer, an optimized design and calibration method are proposed and validated in this paper. The nonorthogonality is cancelled based on the coordinate transformation. With

the help of the FEM software Maxwell, an optimized sensor configuration which has a smaller crosstalk is achieved. Finally, the calibration model including the nonorthogonality and the crosstalk compensation of the triaxis induction magnetometer is built. The experiment results show that the cross-outputs have been decreased about two decades in the whole frequency band, which is much more efficient than using either the negative-feedback flux or the mathematical compensation algorithm.

The crosstalk factor due to the applied and the secondary flux is evaluated with the help of the FEM simulation software in this paper. As for further investigation, it will be meaningful to build a numerical model used for the crosstalk coefficients evaluation.

Notations

- L_c : Permalloy core length (218 mm)
- d_c : Equivalent core cross diameter (8.3 mm)
- N : Induction coil turns (20000)
- μ_{app} : Apparent permeability of the core (215)

R_x, R_y , and R_z :	DC resistance of the induction coil (2.7 k Ω , 2.7 k Ω , and 2.7 k Ω)
C_x, C_y , and C_z :	Capacitance of the induction coil (48 pF, 46 pF, and 52 pF)
L_x, L_y , and L_z :	Inductance of the induction coil (17.6 H, 17.4 H, and 17.9 H)
M_x, M_y , and M_z :	Mutual inductance of the coil (18.3 mH, 17.6 mH, and 18.7 mH)
R_f :	Feedback resistance (20 k)
A :	Gain of the preamplifier (760)
$\alpha/\beta/\gamma$:	The nonorthogonal angles (0.15/0.08/0.34).

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

This work is sponsored by National Natural Science Foundation of China (no. 40904053 and no. 41274183).

References

- [1] T. Pylvänäinen, "Automatic and adaptive calibration of 3D field sensors," *Applied Mathematical Modelling*, vol. 32, no. 4, pp. 575–587, 2008.
- [2] J. L. Crassidis, K.-L. Lai, and R. R. Harman, "Real-time attitude-independent three-axis magnetometer calibration," *Journal of Guidance, Control, and Dynamics*, vol. 28, no. 1, pp. 115–120, 2005.
- [3] H. Pang, J. Li, D. Chen et al., "Calibration of three-axis fluxgate magnetometers with nonlinear least square method," *Measurement*, vol. 46, no. 4, pp. 1600–1606, 2013.
- [4] C. C. Foster and G. H. Elkaim, "Extension of a two-step calibration methodology to include nonorthogonal sensor axes," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 44, no. 3, pp. 1070–1078, 2008.
- [5] D. Gebre-Egziabher, "Magnetometer autocalibration leveraging measurement locus constraints," *Journal of Aircraft*, vol. 44, no. 4, pp. 1361–1368, 2007.
- [6] H. Pang, S. Luo, Q. Zhang et al., "Calibration of a fluxgate magnetometer array and its application in magnetic object localization," *Measurement Science and Technology*, vol. 24, no. 7, Article ID 075102, 2013.
- [7] H. Pang, Q. Zhang, W. Wang et al., "Calibration of three-axis magnetometers with differential evolution algorithm," *Journal of Magnetism and Magnetic Materials*, vol. 346, pp. 5–10, 2013.
- [8] J. Včelák, P. Ripka, J. Kubík, A. Platil, and P. Kašpar, "AMR navigation systems and methods of their calibration," *Sensors and Actuators A: Physical*, vol. 123–124, pp. 122–128, 2005.
- [9] J. M. G. Merayo, P. Brauer, F. Primdahl, J. R. Petersen, and O. V. Nielsen, "Scalar calibration of vector magnetometers," *Measurement Science and Technology*, vol. 11, no. 2, pp. 120–132, 2000.
- [10] V. Petrucha, P. Kaspar, P. Ripka, and J. M. G. Merayo, "Automated system for the calibration of magnetometers," *Journal of Applied Physics*, vol. 105, no. 7, Article ID 07E704, 2009.
- [11] A. Grosz, E. Paperno, S. Amrusi, and T. Szpruch, "Minimizing crosstalk in three-axial induction magnetometers," *Review of Scientific Instruments*, vol. 81, no. 12, Article ID 125106, 2010.
- [12] E. Paperno, A. Grosz, S. Amrusi, and B. Zadov, "Compensation of crosstalk in three-axial induction magnetometers," *IEEE Transactions on Instrumentation and Measurement*, vol. 60, no. 10, pp. 3416–3422, 2011.
- [13] J. C. Dupuis, *Optimization of a 3-axis induction magnetometer for airborne geophysical exploration [M.S. thesis]*, University of New Brunswick, 2001.
- [14] J. J. Abbot and R. K. Kunze, "Micro-strip crosstalk compensation using stubs," U.S. Patent Application Publication, 2010/0327989 A1, December 2010.
- [15] M. Samplón, J. S. Artal, J. Letosa, A. Usón, and F. J. Arcega, "Evaluation of errors associated with crosstalk magnetic fields using finite element method in high electrical current measurement," in *Proceedings of the International Conference on Renewable Energy and Power Quality (ICREPQ '05)*, Zaragoza, Spain, March 2005.
- [16] N. Tziony, M. Itzkovich, and N. Moriya, "Electrical circuit for crosstalk reduction," U.S. Patent 6 711 215, March 2004.
- [17] A. Plotkin, O. Shafrir, E. Paperno, and D. M. Kaplan, "Magnetic eye tracking: a new approach employing a planar transmitter," *IEEE Transactions on Biomedical Engineering*, vol. 57, no. 5, pp. 1209–1215, 2010.
- [18] M. Steinlin, S. Weikert, and K. Wegener, "Open loop inertial cross-talk compensation based on measurement data," in *Proceedings of the 25th Annual Meeting of the American Society for Precision Engineering (ASPE '10)*, pp. 101–104, Atlanta, Ga, USA, November 2010.
- [19] C. D. Onal, B. Sümer, and M. Sitti, "Cross-talk compensation in atomic force microscopy," *Review of Scientific Instruments*, vol. 79, no. 10, Article ID 103706, pp. 1–7, 2008.
- [20] C. Coillot, J. Moutoussamy, P. Leroy, G. Chanteur, and A. Roux, "Improvements on the design of search coil magnetometer for space experiments," *Sensor Letters*, vol. 5, no. 1, pp. 167–170, 2007.
- [21] C. Coillot and P. Leroy, *Induction Magnetometers Principle, Modeling and Ways of Improvement*, InTech, 2012.
- [22] H. C. Šran and P. Ferreau, "An optimized low-frequency three-axis search coil magnetometer for space research," *Review of Scientific Instruments*, vol. 76, no. 4, Article ID 044502, 2005.
- [23] A. Roux, O. Le Contel, C. Coillot et al., "The search coil magnetometer for THEMIS," *Space Science Reviews*, vol. 141, no. 1–4, pp. 265–275, 2008.
- [24] O. Le Contel, P. Leroy, A. Roux et al., "The search-coil magnetometer for MMS," *Space Science Reviews*, vol. 199, no. 1, pp. 257–282, 2014.