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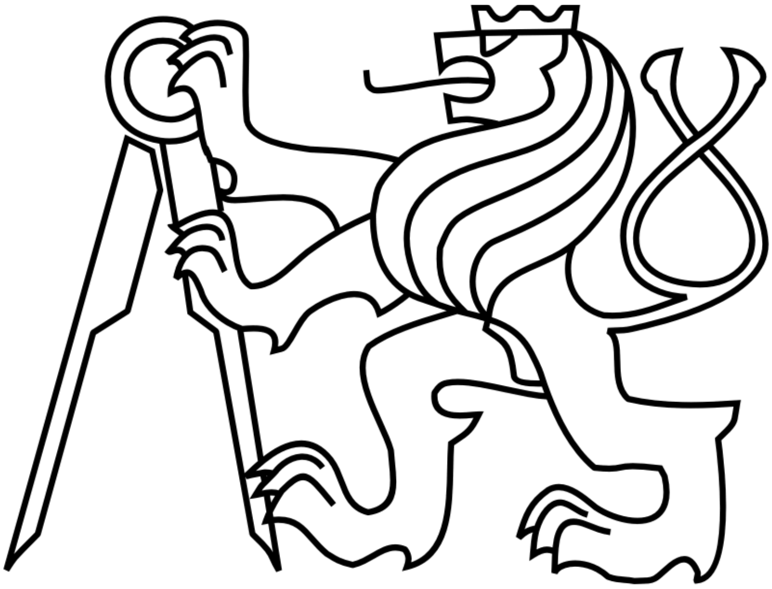

DOCTORAL THESIS STATEMENT

Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Measurement

Vojtěch Petrucha

CALIBRATION OF SELECTED SENSORS FOR SPACE APPLICATIONS

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Candidate: Vojtěch Petrucha
Establishment Address: Citov 160, 751 03 Brodek u Přerova

Supervisor: Doc. Ing. Petr Kašpar, CSc.
Department of Measurement
Faculty of Electrical Engineering of the CTU in Prague
Technická 2, 166 27 Prague 6

Reviewers:

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in the branch of study Measurement and Instrumentation
Faculty of Electrical Engineering of the CTU in Prague
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1. INTRODUCTION & CURRENT SITUATION OF THE STUDIED PROBLEM

Magnetometers are important instruments widely used in many fields of human industrial, scientific and leisure activities. Typical applications are in transport navigation, underground drilling related navigation, security, detection of ferrous objects, geology and Earth’s field observation. The more we need accurate measurements, the more it is necessary to develop and use precise instruments. These instruments typically require some kind of calibration in order to achieve their optimal designed accuracy.

The main topics of this thesis are therefore issues related to **magnetometers and magnetometer calibration.** The magnetic induction used for the applications mentioned above is typically within the range of the Earth’s magnetic field (magnitude 20-60 µT, varying with geographical location). This low magnitude, DC-low frequency magnetic field fits perfectly with the measurement range of **fluxgate and AMR** magnetometers.

Two main techniques are used for calibrating vectorial sensors of a magnetic field. The first principle uses a set of three coils to create arbitrary magnetic field vectors. These vectors are applied to the fixed DUT (Device Under Test), and the calibration parameters are derived from them and from the DUT’s response.

The second technique is “opposite” to the first technique. DUT is rotated in space in a constant Earth’s magnetic field in order to apply the whole range of the field to all three axes. The calibration parameters are again mathematically derived from the DUT’s readings and from its known field vector magnitude. This method offers one big advantage – there is no need for a coil system, which is expensive to build and maintain. However, it also has some limitations.

The motivation for testing the practical usability of the Scalar Calibration technique with some technical improvements arose during the stay at the magnetometry section of DTU Space/Technical University of Denmark. There was a need for fast and reliable on-site testing during the development stage, before going to an expensive and distant calibration facility. The work was started at DTU, and has been further developed at the Czech Technical University in Prague. At CTU in Prague, the demands are very similar, due to the development of AMR and fluxgate-based magnetometers for various applications.

1.1. Calibration with a 3D coil system

This technique uses a coil system, usually with three independent axes, to generate arbitrary magnetic field vectors which are measured by the DUT, which is placed in the center of the coils. This method allows full calibration of the DUT. The output consists of three offsets, three sensitivities, three non-orthogonalities and transformation coefficients (matrix 3 x 3), which provide measurements in the desired reference frame. The method also allows the user to check DUT linearity, for each independent axis, and, with a thermostatic box, all temperature dependencies, i.e. offset, scales and angles. Application of an AC field allows the user to measure the frequency response of the DUT. This approach thus requires a dedicated facility with coils, a coil current controller and other expensive equipment. In order to achieve high precision and stability, the location for the coil system must be held at a constant temperature, which is extremely expensive. Periodic calibrations must be made and field monitoring during the operation is necessary. A magnetic “vacuum” is usually created first in order to suppress the Earth’s magnetic field, and its variations and the desired vectors are then superimposed on it. The number of institutes that operate or have direct access to such facilities is limited, and it is not usually easy for external companies to use them, due to time and price issues. More information concerning this type of procedure can be found in [1],[2],[3],[4],[5].

1.2. Scalar calibration of vectorial sensors

The second technique is generally known as “scalar calibration”. It can be described as a “poor-man’s” calibration technique, because fairly precise calibration requires only a device that digitizes the DUT’s output. The scalar field value for a specific location can be obtained from a model [6], which can achieve scalar field precision ~0.1 %, and the rest involves mathematical processing of the measured data. There are various options for this: iterative, linearized, or ellipsoidal transformation algorithms. In order to obtain additional information or greater accuracy, more sophisticated equipment is needed. This is the topic of the present thesis.

The scalar calibration procedure and improvements to it with the use of additional equipment are described below. A complete introduction to scalar calibration is given in [7]. The most important part of the procedure is data collection. The DUT, a tri-axial vector magnetometer or accelerometer, is positioned in an appropriate static magnetic or gravitational field. The positioning is performed in such a way that all the measurement axes of DUT are exposed to the whole available field range. The Earth’s magnetic field is ~30-50 µT, and the gravitational field is 1 g ~9.82 $m.s^{-2}$. The positioning can be established in several ways. Free-hand positioning, i.e. slow, smooth movement of a magnetometer, is the simplest way. Some kind of mechanical non-magnetic frame with two axes of freedom and with mechanical stops for different angular positions is another option. This offers the advantage that the angular positions are defined and repeatable. The optimal uniform sample distribution positioning scheme can be achieved with respect to the “pseudo random” free hand method. Knowledge of the angular position for each sample allows a plot of residuals to be constructed, and this can provide additional information about the linearity of the sensor. The drawback is that the positioning is very slow and inconvenient due to its human “drive”. Automation of the positioning is therefore desirable. The data acquisition procedure can be repeated many times in order to reduce the errors or to measure time-temperature dependencies. Automation involves the application of drives and sensors, which is difficult due to the need for very high magnetic cleanliness of the positioning platform, since a field gradient would cause significant errors. This problem is discussed and a solution presented in the chapter on Design and Realization.

The output of the DUT is digitized in each angular position by any DAQ unit that provides sufficient resolution, low noise and high stability. An example of a structure that fulfils these requirements is also presented. A major advantage is its small size and USB power supply, which facilitates transportation and enables operation at distant calibration sites where no power network is available.

The calibration parameters are extracted from the measured data by means of mathematical calculations. Several approaches have been published [7],[8],[9]. They are explained in the Theoretical Background chapter of the dissertation thesis. The calibration parameters are three offsets, three sensitivities and three non-orthogonalities. Additional information about linearity, combined for all axes, can be derived from the residual distribution plot. Unlike the coil system, there is no information about the reference frame transformation matrix, which transforms the measured data to some external reference frame defined e.g. by the DUT package. This requires an additional procedure.

The full-text of the dissertation thesis provides information about the relevant patents, calibration sites, available commercial calibration systems, and state-of-the-art instruments concerning the topic (scalar and vector magnetometers, DAQ systems).

2. AIMS OF THE DOCTORAL THESIS

The main goal of the thesis is to develop a complete system for scalar calibration of magnetometers, to test the system and evaluate the results. The system should provide results comparable in accuracy to those provided by the calibration sites mentioned in section 1.1, and make such results available for institutes that do not manage a precise vector-coil based calibration system. The project can be divided into a number of major phases.

- **a)** Examine the feasibility of an automatic, computer controlled non-magnetic positioning system, design and construct it.
- **b)** Develop and manufacture all the necessary accessories – electronic control unit, dedicated data acquisition. There was no suitable DAQ unit available, and this work will provide experience that can be further used for a magnetometer with digital data output, i.e. the next generation of d).
- **c)** Develop and/or modify the firmware and software needed for the whole calibration procedure: the control unit and DAQ unit firmware, PC software for positioning and DAQ control, and mathematical calibration algorithms.
- **d)** In order to compare the published calibration results, and for a comparison with commercially-available magnetometers, develop a fluxgate magnetometer with vector compensation of the measured magnetic field. Its high linearity and preciseness should show the quality of the calibration system and procedure, which may otherwise be hidden by DUT’s own errors.
- **e)** Evaluate the construction and calibration results in order to judge the applicability of the proposed calibration system, its components (DAQ, the vectorially compensated magnetometer), and make a proposal for their further development and for possible improvements.

3. WORKING METHODS

Complex equipment consisting of mechanical, electrical and software tools has been designed, developed and tested in the scope of the thesis. Finally this equipment has been used to calibrate several instruments; the results are presented in Results chapter. This chapter provides a description of four very important devices designed and developed in the scope of this doctoral thesis. First, a bi-axial version and a tri-axial version of the calibration platform are presented, then a design of the data acquisition module with high resolution is described. Finally, the development of a vectorially compensated tri-axial vector fluxgate magnetometer is discussed. The main purpose of this magnetometer is to test the calibration system. It should offer very high linearity of its transfer function, which is essential for the tests, and for understanding the calibration results.

3.1. Bi-axial non-magnetic calibration platform

The design and development of this platform was started at DTU SPACE, under the supervision of Jose M.G. Merayo). DTU SPACE uses two basic sensors: **CSC** – Compact Spherical Coil [24] and **CDC** – compact detector coil **[25]**). CSC is spherical in shape with a diameter of 82 mm; CDC is rectanguloid, with dimensions 55x47x32 mm. The basic requirement was to accommodate these two sensors and possibly some other sensors with maximum dimensions of **100 x 100 x 100 mm and a maximum weight of 0.5 kg**. Generally, the platform should be as large as possible in order to get maximum free space or distance between the sensor and the structure, in order to achieve better magnetic field homogeneity. Practically, the dimensions were limited by the available drives and by the requirement for easy transportability. The maximum acceptable dimensions would be approximately 500 x 500 x 500 mm. The only functional requirement was automatic positioning in two mutually perpendicular axes with accuracy and repeatability of ±1 degree.

System conception

Fig. 3.1 presents the overall system conception. There is a control computer which runs two synchronized programs. The first program has a list of predefined positions that we want to reach with the platform. It communicates with the electronic control unit via the USB interface, which acts as a simulated serial port. The second program is used to sample the output of the magnetometer, using any available three-channel DAQ device connected through a Serial, Ethernet, USB or GPIB bus. Finally, the calibration algorithm processes the data and calculates the calibration constants. The electronic control box is driven by a single-chip microcontroller, which receives the commands from PC and controls the motor drivers, while sensing the feedback from the optical incremental sensors. The non-magnetic platform accommodates the DUT (magnetometer or accelerometer), and implements the positioning process.

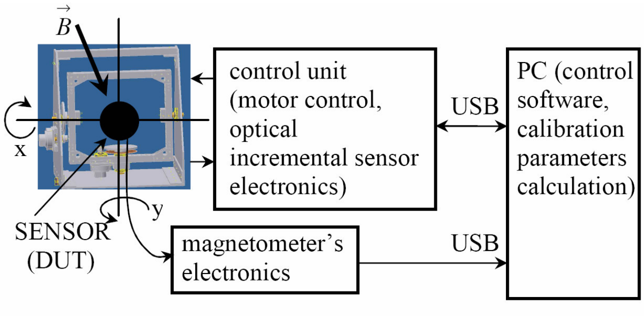

Fig. 3.1 Overall system topology

Fig. 3.2 shows the conception of the non-magnetic platform in greater detail. There are two axes of rotation: roll: ±180 deg, pitch: ±90 deg, which enable all positions needed for the calibration algorithm to be reached, i.e. points uniformly covering the surface of a sphere with the radius of the magnetic field vector magnitude. What is important is the marked North-

South position of the platform with respect to the magnetic field vector, neglecting the declination. The pitch axis of rotation must be perpendicular to the field vector.

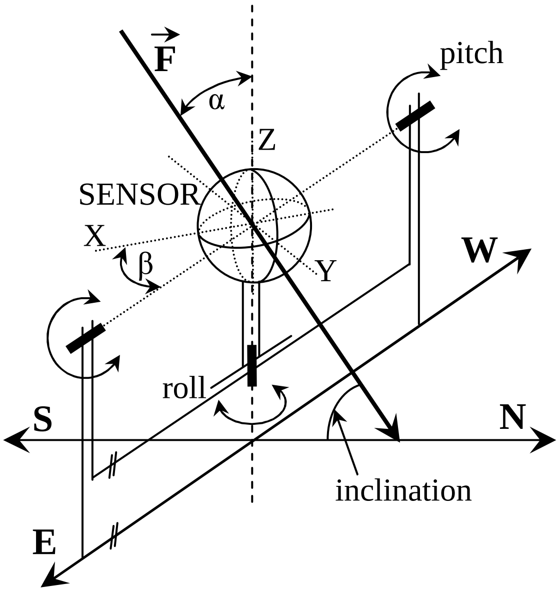

Fig. 3.2 Non-magnetic platform conception

The platform was completed almost at the end of a six-month internship at DTU Space. Due to time constraints, only a basic evaluation was made of the functionalities and parameters. Several positioning sequences ran smoothly, and there was no significant change in the final position that would otherwise indicate a problem with the angular position sensing. No special sensor holder was developed, but the platform can handle both required sensors with a sufficient margin. The sensor head of the magnetometer was placed directly on the top of the center wheel for final testing, see Fig. 3.3. Ideally, should have been in the center of rotation of both axes. No calibration results from this platform are available, due to lack of time, but the experience and knowledge gained during the development work were immediately applied when constructing the tri-axial calibration platform, see the next chapter.

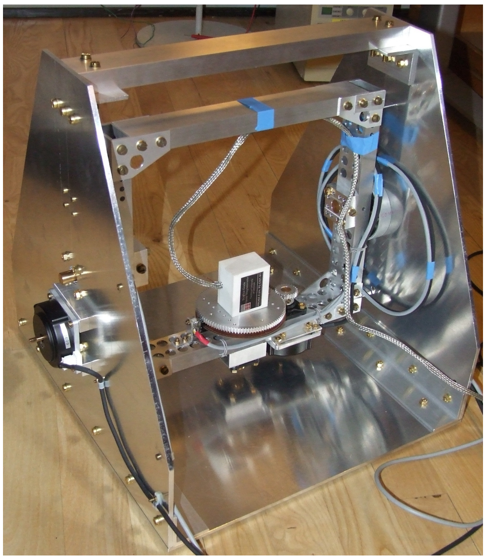

Fig. 3.3 Completed platform with the CDC sensor (not ideally positioned – it should be in the center of rotation)

3.2. Tri-axial non-magnetic calibration platform

This system was proposed, designed and developed at the Czech Technical University in Prague as a logical step and consequence of the work carried out at DTU Space, Denmark. A third axis of freedom was added to the design; it enables complete testing of an electronically tilt compensated fluxgate compass module. This early work preceded work on the calibration system.

Design requirements

As mentioned above, the mechanical size of the device was mainly constrained by the compass module dimensions. The compass module is a cylinder 50 mm in diameter and 230 mm in length. It would have been better to have had a platform bigger. This would have enabled higher field homogeneity, and better positioning of the compass module, with the magnetic sensors in the center of rotation. However, no more powerful version of the piezoelectric motors was available. The "useful payload dimensions" were therefore limited by the weight of the structure and by the available motor torque.

Fig. 3.4 presents the conception of the platform. It is very similar to the bi-axial version. The novel element is the addition of the yaw axis. The compass module allows estimation of the azimuth in almost any position, see Fig. 3.5. In order to test the calibration of the vector magnetometer and the accelerometer, and their mutual position with respect to the mechanical frame, three axes of freedom are needed. The azimuth should remain constant for any roll value (0-360 deg) and for pitch values ranging from -80 to 80 deg. The azimuth loses its sense, or is not defined, for pitch = 90 or -90 deg. In addition, of course, it should be possible to test it for any arbitrary azimuth (yaw) value. The device that was made meets all these requirements. In the case of scalar calibration, the yaw axis can be used to set the inner frame up perpendicular to the Earth's magnetic field vector.

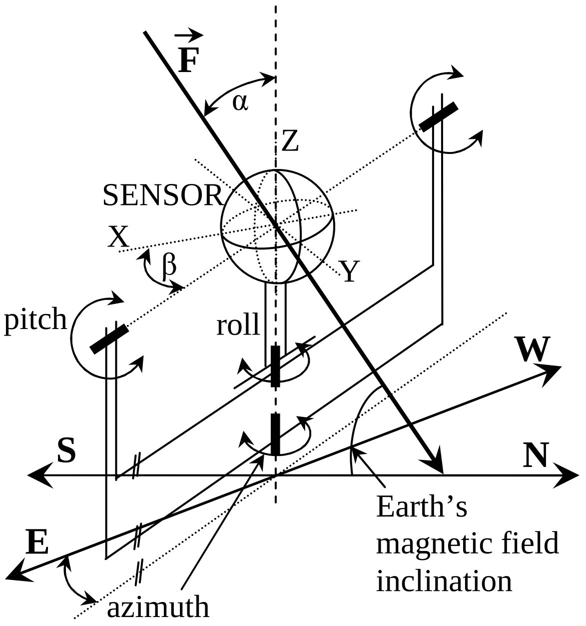

Fig. 3.4 Tri-axial non-magnetic platform conception

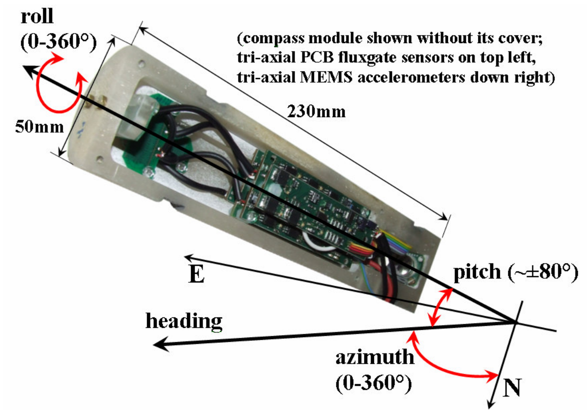

Fig. 3.5 Electronic compass module – azimuth with respect to yaw, pitch and roll.

Fig. 3.6 presents the whole system topology used for scalar calibration of magnetometers. The Non-magnetic Platform Control software has a set of predefined positions, loaded from an external file. It communicates with the electronic control unit (piezoelectric motor drivers) through the USB-based serial interface. Once the new position is reached, using information from the optical incremental sensors, the software sends a UDP packet to the data acquisition control software. The DAQ control software triggers the measurement of the DUT’s output voltage via the USB-based serial line interface. The DAQ unit measures the output voltage, and the software stores the values for further processing. Simultaneously, the scalar magnetometer provides the magnitude of the magnetic field vector, which is used in the calibration algorithm. After all positions have been reached, the system goes to its starting position and is ready for a new cycle.

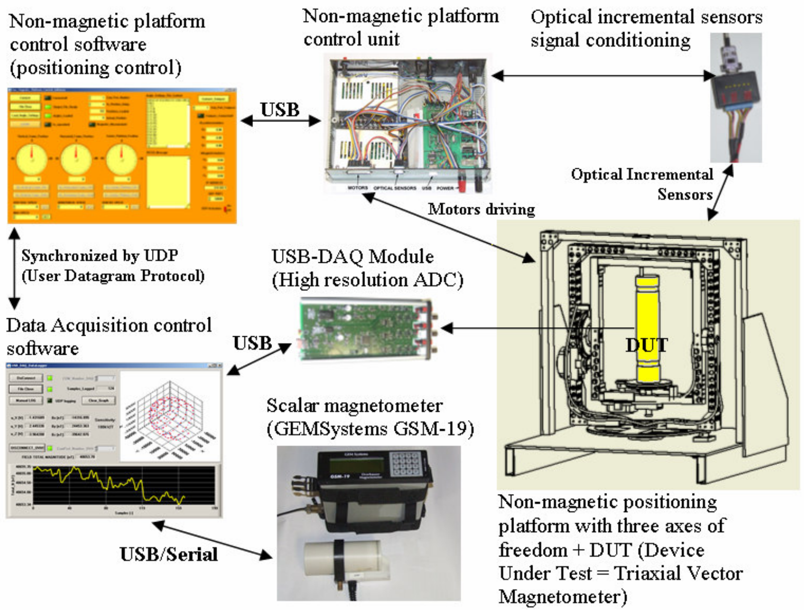

Fig. 3.6 Complete system for scalar calibration

The design of the platform was started in 2008, and the main parts were completed in 2009. Since then, the platform has been in use for making measurements and has been continually improved. Magnetic contamination has been eliminated, the DUT holder has been improved, and control software has been developed and optimized. The device that has been developed seems to be unique worldwide, e.g. [26] uses a non-magnetic mechanism to calibrate AMR-based magnetometer modules, but the principle and the construction are completely different. Only simple tests have been applied to evaluate the properties of the system, e.g. a laser pointer was attached to the sensor holder to test the **repeatability of the positioning ~1deg. The main evaluation of the system comes from the results of the scalar calibrations, which are very promising and are further discussed in the Results section.** The calibration results indicate that there is still some magnetic field non-homogeneity caused by ferromagnetic materials in the parts. This causes errors, but only a complete redesign of the device could solve this problem. The operation of the complete system is relatively reliable and “smooth”, though there is occasionally a DUT cable jam, which needs to be improved.

3.3. *Three-channel USB DAQ module with simultaneous sampling*

This instrument has been designed and developed in order to provide high-precision three-channel voltage measurement, comparable to 6.5 digit DMM - e.g. HP34401 - in a smaller package, which would be more convenient for frequent transfers to the calibration site. The device is powered from USB, which is another benefit, as it is not dependent on the 230 V power network.

The device uses three delta-sigma converters (integrated circuit ADS1281, Texas Instruments) to transfer the measured voltage to digital data. Two newly available converters were tested at the beginning of the development. ADS1274 contains four simultaneously sampled delta-sigma cores in one package, and ADS1281 is a single channel converter. The output noise has been compared for various configurations: ADC, voltage reference, and for different power supply sources: USB powered, battery operated. The output voltage noise, i.e. for the shorted input, was approximately six times lower for ADS1281 (303 nV_{RMS}) than for ADS1274 (1.89 μV_{RMS}). The values are affected by the overall PCB design, by slightly different sampling rates and other factors, but it is clearly visible that ADS1281 outperforms ADS1274. Voltage reference REF5025 was slightly better than ADR445, producing <5 % less noise. The difference between the USB powered set-up and complete battery operation, using a 12V Pb accumulator, was about 1.5% of the output peak-to-peak noise voltage. The USB-powered set-up performed less well. This value is quite low, and the more convenient USB-powered mode is used during calibrations.

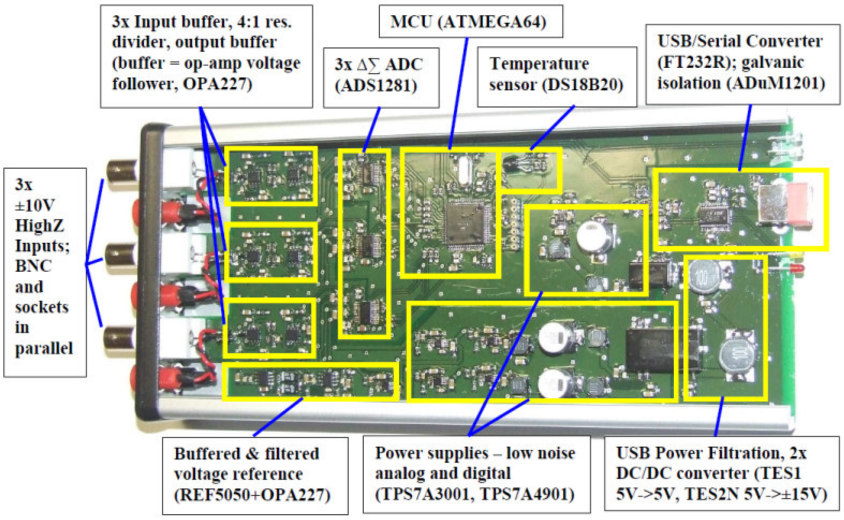

Fig. 3.7 Three-channel DAQ unit with simultaneous sampling and USB interface

3.4. *Vectorially Compensated Tri-axial Vector Fluxgate Magnetometer*

This magnetometer was designed and developed in order to have the possibility to compare the properties and calibration results of the vectorially compensated design with more widely-used tri-axial individual measured field compensation. Several available and published structures were studied prior to the development [24], [15], [27]. The idea is to build standard, but smaller, ring-core fluxgate sensors (see Fig. 3.8) into the vector compensation module that will be easier to manufacture and assemble, and cheaper than e.g. a spherical compensation shell [24]. Vector-compensated design should provide two main advantages: low non-orthogonality, due to the precise geometry of the compensation coils, and the elimination of cross-field errors, since the sensors operate in a virtually zeroed magnetic field. This means that the device is highly linear. This is important for evaluating the preciseness of the calibration procedure, i.e. the fit quality with respect to other conditions, e.g. magnetic contamination. The non-linearity could otherwise hide these effects.

Fig. 3.8 From left to right: BNP-2 ring support and Vitrovac 6025X ribbon; the ring with glued core and excitation winding; placed in the pick-up coil support; finished sensor with pick-up coil.

The vector magnetic field compensation system consists of three sets of four serially-connected coils in a modified Merritt configuration. Various coil systems used for creating a homogeneous magnetic field were described in [31]. The Merritt configuration is easiest to implement. Unfortunately mechanical constraints (manufacturability of the support) do not allow the design of all three axes with optimal geometrical proportions. ANSYS - Magnetostatic finite element modeling software was used to optimize the coil support design for maximum space volume with minimal non-homogeneity. Fig. 3.9,10 show the flux density in the support volume, and pink color indicates the range from 46000 nT to 50000 nT, i.e. ±4.1 % of the nominal field – 48700 nT).

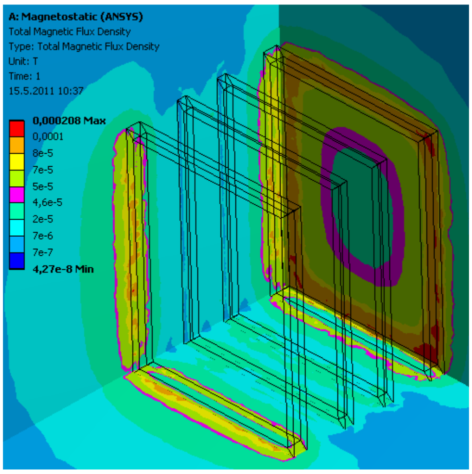

Fig. 3.9 Z-axis compensation coils model

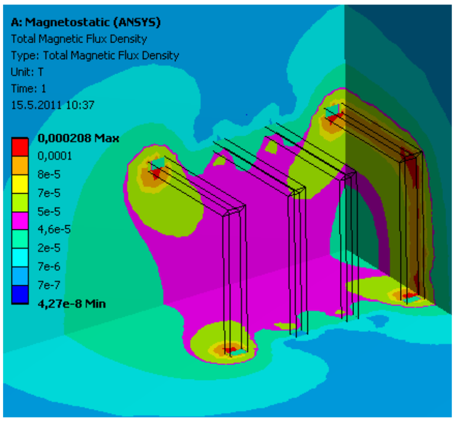

Fig. 3.10 Cut through the sensor body; pink color shows the volume with ±4 % in-homogeneity (46 to 50 µT)

The sensor was scalar calibrated with the use of a non-magnetic calibration platform. The calibration results are presented in the summary of the parameters below. This first prototype generally provided excellent results, and the design seems to be very promising for further development.

Tab. 3.1 Summary of parameters

Parameter	Value	Unit
Measurement range	±65 000	[nT]
Sensitivity – design plan	100	[kV/T]
Sensitivity X-axis (real vs. design 100 kV/T)	1.0028	[-]
Sensitivity Y-axis (real vs. design 100 kV/T)	0.9915	[-]
Sensitivity Z-axis (real vs. design 100 kV/T)	1.0539	[-]
Offset X-axis	3.94	[nT]
Offset Y-axis	-33.46	[nT]
Offset Z-axis	-17.04	[nT]
Non-orthogonality α	-0.3343	[°]
Non-orthogonality β	0.2205	[°]
Non-orthogonality γ	0.0239	[°]
Noise (Power spectral density @ 1Hz)	~35	[pT/√Hz]
Offset Temperature dependence	-0.8 up to 4*	[nT/degC]
Transfer function linearity	<±15ppm**	[ppm]
Signal bandwidth	50	[Hz]
Power consumption (total)	1.69	[W]
Sensor head dimensions	50x40x40	[mm]
Sensor head mass	130	[g]

*this parameter requires a very long measurement time, and should be measured more precisely in the future
**value from a linearity measurement, scalar calibration indicates values better than <±5ppm

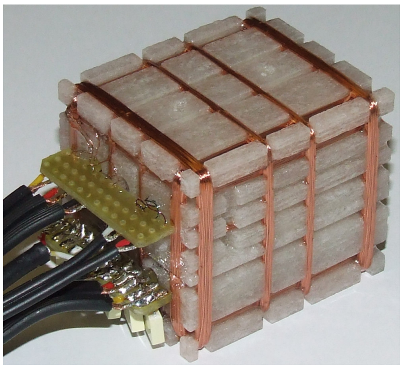

Fig. 3.11 Complete sensor with wire terminals, tuning capacitors and cabling. Everything is fixed together with two-component epoxy glue.

4. RESULTS

The sensors listed below were calibrated using the non-magnetic calibration platform. Some of the sensors were made available only for a short time, and the calibration had to be performed in an unsuitable environment with a non-homogeneous magnetic field, and the results are not very good. The calibrated magnetometers are listed in Tab. 4.1, calibration of the accelerometers is also possible and a list of calibrated device together with results can be found in the thesis full-text.

Tab. 4.1 Magnetometers

1.	Billingsley Aerospace & Defence; TFM100 Ringcore fluxgate magnetometer
2.	Billingsley Aerospace & Defence; TFM65 Vacquier fluxgate magnetometer
3.	Stefan Mayer Instruments; FL3-100 Fluxgate magnetometer
4.	Applied Physics Systems; APS534 Fluxgate magnetometer
5.	InnaLabs; M3 AHRS unit (accelerometer, gyroscope and magnetometer)
6.	MicroStrain; 3DM-GX2 AHRS unit (accelerometer, gyroscope and magnetometer)
7.	Honeywell; HMR2300 AMR Magnetometer
8.	Honeywell; HMR3000 AMR Magnetometer
9.	Czech Technical University in Prague – Compass module, PCB fluxgate magn.
10.	Czech Technical University in Prague – Vectorially compensated fluxgate magnetometer

It is essential to select an appropriate measurement site for the data collection for the scalar calibration algorithm. The selection criterion is stability and homogeneity of the local magnetic field. The best results so far were obtained at the Karlova Ves site.

Karlova Ves – "Cervena louka", 49°59'30.87"N, 13°49'44.36"E (A-site)

This site is a small meadow accessible by car, without any buildings or structures of any type, and no power network is available. The big advantages of this location are the good magnetic field homogeneity and the relatively short traveling time, less than one hour from Prague. See Fig. 4.1.

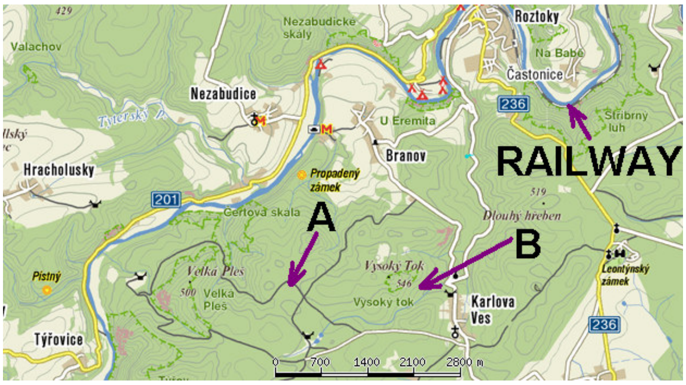

Fig. 4.1 CHKO Krivoklatsko nature reserve, close to Karlova Ves, showing two places, A and B, where measurements were performed.

The data acquisition process is the first and most important part of scalar calibration. We need to acquire with the DUT tri-axial vector sensor something between 20-1000 samples which uniformly cover the surface of a sphere equal in radius to the Earth's magnetic field magnitude. This means that there are values taken from the whole available field range for all the three axes and for both polarities. Small numbers of samples mean fast data acquisition, reducing the risk of offsets drifting with time or temperature, but we obtain less detailed information on linearity and also less confidence about the results. A large number of measured samples makes the measurement extremely long and slow, which is very ineffective if there is some problem during data acquisition. Offset time-temperature drift during a long calibration run can also cause problems. For the calibration mentioned below, 161 samples were taken in the course of each calibration. It takes approximately 16 minutes to collect the samples with the tri-axial non-magnetic calibration system. The distribution of the points was derived from equations mentioned in [7]. The order is optimized in such a way that the DAQ process is as fast as possible, and there is only one turn in one direction. The change in rotation direction is to prevent twisting off the DUT connecting cable.

Fig. 4.2 shows the data plotted as it was acquired. We see that the X and Z axes are covered more uniformly than the Y axis – this is due to the positioning procedure, and would be difficult to change. If necessary, the position of the DUT in the holder can be changed and the results compared. Fig. 4.3 shows the data plotted in a 3D graph, which should cover the spherical surface uniformly.

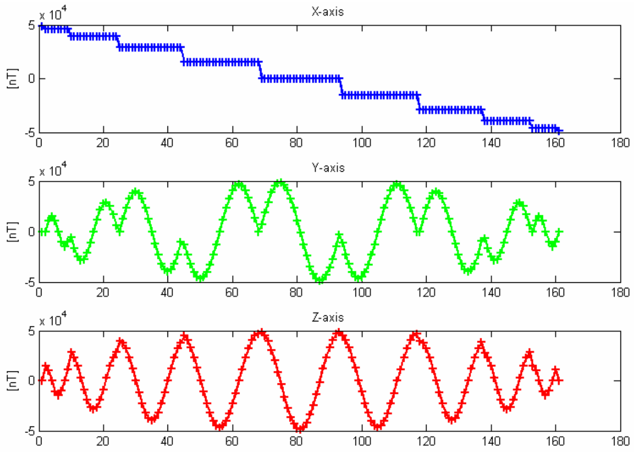

Fig. 4.2 X,Y and Z vector field values taken at each data point. The shape is given by the initial device fixation on the platform, and also by the order of positions, which are typically programmed in such a way that the time to reach them all is minimal, and it is possible to make only one turn in one direction due to the DUT connecting harness.

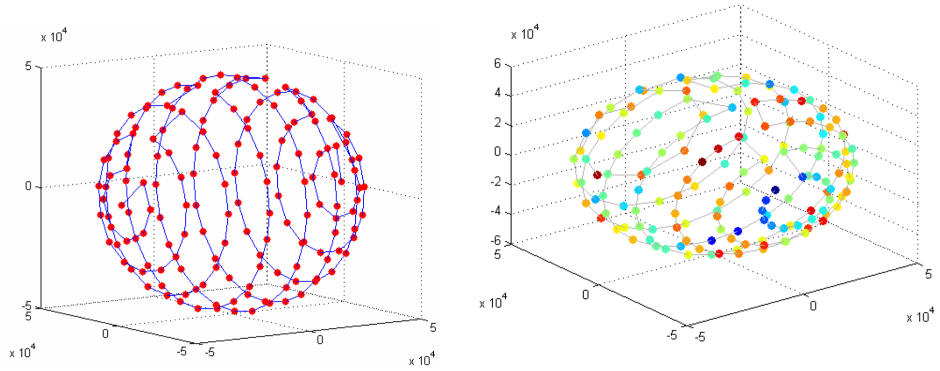

Fig. 4.3 The picture on the left shows the distribution of ideal uniform data on the “sphere surface”. The picture on the right has the calibration residual parameter plotted at each point in a standard color palette, blue lowest value, red highest value – real data, slightly non-uniform due to the bad initial position.

The results are presented in the form of a set of MATLAB graphs. The data presented here comes from the calibration of the vectorially compensated vector fluxgate magnetometer, see section 3.4. Nine calibration coefficients (three offsets, three sensitivities and three non-orthogonalities) derived from the data are noted at the end. Fig. 4.4 shows, from top to bottom, the vector magnitude calculated from the raw input vector data, shown in blue color. The same graph then contains the vector magnitude calculated from the measured vector data with corrections applied, shown in red color. We can see that the calibration has a big positive impact on the vector magnitude variation. The next graph shows the residuals; a residual is a difference calculated for each datapoint – the calculated calibrated vector magnitude is subtracted from the reference vector magnitude, which is measured by a scalar magnetometer. The aim of the algorithm is to minimize the residuals (sum of squares). The last graph shows a “data weighting” vector. In fact, for better visualization it is 1-w; a zero value being the best quality and “1” is the worst quality data. The meaning and usage of the weighing vector “w” is described in greater detail in Theoretical background section of the thesis.

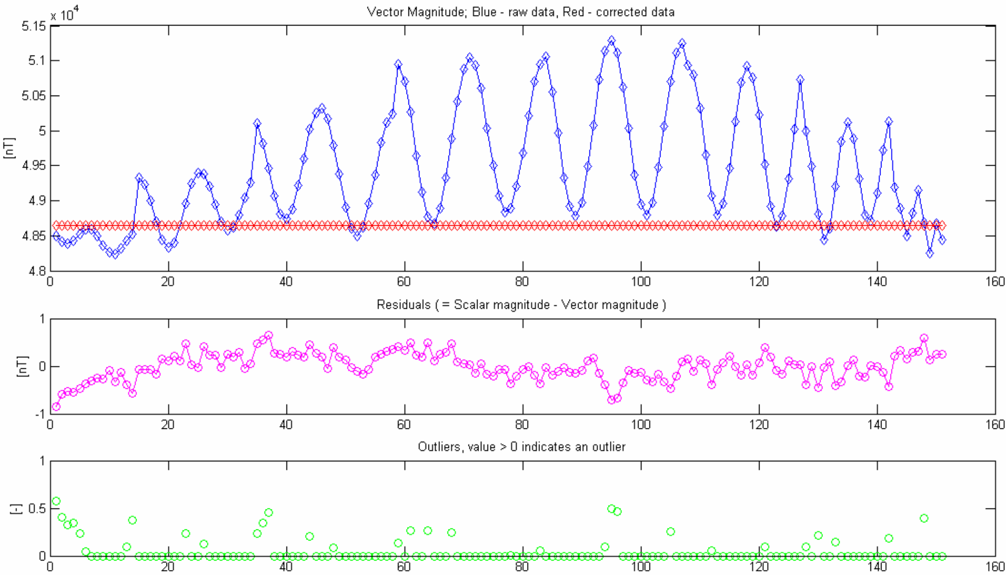

Fig. 4.4 MATLAB plot showing, from top to bottom, the uncalibrated vector magnitude (blue), the calibrated vector magnitude (red), the calibration residuals (pink) and some information about the quality of the data for each data point. The best is zero value, green.

This graph shows that the vector magnitude variation without calibration is 3100 nTpp. The calibration reduces the variation by three orders, down to <±1 nT. The weighting vector contains some “low quality” points, but it always will – they are represented on a relative scale. If we were to remove those points and run the calibration again, we would again get some indication of low quality points, but with a lower corresponding absolute value.

Knowledge of each datapoint position allows us to construct a 2D graph which presents the layout of the residuals. The position of each residual is known, because it is an input parameter for the positioning system. The 2D graph is actually a spherical surface unreeled into rectangular shape. The x-axis corresponds to roll 0-360 deg, and the y-axis corresponds to pitch -90 to 90 deg. The MATLAB plot function approximates the values between the acquired samples, and thus a continual graph can be shown. Ideally, no systematic relation should be visible in the graph – the distribution of the residual values should be random, see [7] for such a map. In practice, this is hard to achieve – we would need a sensor that is perfectly linear and has very low cross-field error and, in addition, calibration equipment that does not influence the calibration by creating a non-homogeneity in the sensor area.

Fig. 4.5 shows little dependence in the y-axis. We can distinguish four alternating horizontal bands: negative, positive, negative and positive. This is probably caused by some residual magnetic gradient present in the sensor area, a gradient induced by ferromagnetic materials in the structure of the positioning platform.

Note: ten data-points were removed from the beginning of this measured dataset because of improper initial positioning of the pitch frame. The first ten points were too concentrated at one pole, and there was also a possibility of a small error due to the presence of the operator for a short time very close to the platform for a visual

check of the positioning process. In consequence there is a “missing belt” of values of the residuals in Fig. 4.5.

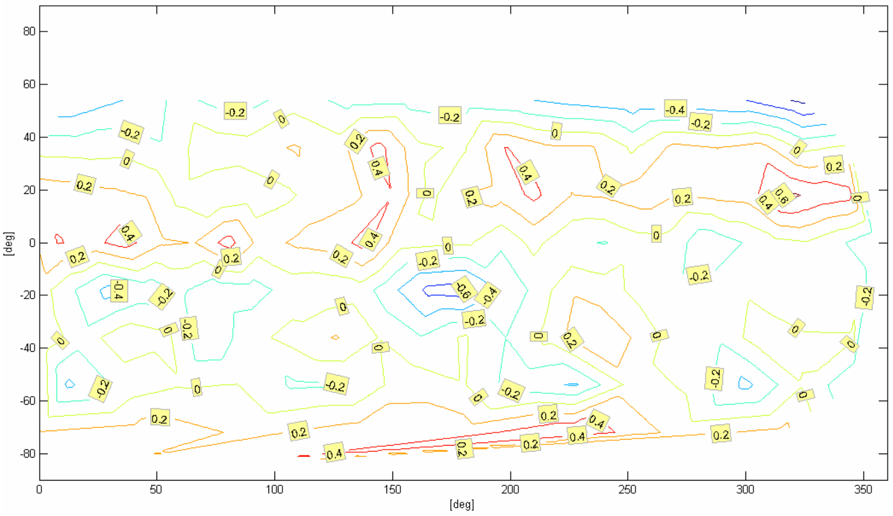

Fig. 4.5 Map of scalar residuals (difference between the scalar and calibrated vector magnitude value)

The sensitivity values indicate that there is a 5% maximum mismatch on the Z-axis between the design value (100 kV/T) and the real value. The offsets are quite small. Any value below 100 nT can be considered good. It is the sum of the fluxgate sensor offset and all op-amps offsets in the signal path, where 100 nT corresponds to 10 mV in output voltage. The non-orthogonalities should be mainly due to the orthogonality error of the compensation coil system [22]. Any value below 0.5 deg can be considered good, but ideally the values should be below 0.1 deg. The calibration misfit indicates the quality of the calibration fit. Values as small as 0.05 nT_{RMS} can be achieved (for data, see [22]), but this would require special conditions, see the Conclusions. “Data points used” indicates how many datapoints were finally used in the calibration algorithm. Any value >90 % is good.

The way to describe the quality of the fit is by comparing the residuals with the full scale range. For the measurement analyzed above, it is: maximal residual value 0.6582 nT, minimal residual value -0.84739 nT, which gives ~±0.753 $nT_{P\text{-}P}$. The full scale range is 2*48645 nT (97290 $nT_{P\text{-}P}$), and the ratio is approximately **±0.0008 % (±8 ppm).**

Tab. 4.2 Summary of calibration results for magnetometers

Device	**S_X** [-]	**S_Y** [-]	**S_Z** [-]	**O_X** [eu]	**O_Y** [eu]	**O_Z** [eu]
TFM100G2	0.9994	0.9993	1.0003	-58.60	148.73	-106.2
TFM65VQS	0.9974	1.0037	1.0032	-39.30	183.33	240.9
FL3-100	0.9982	0.9968	0.9971	90.94	51.57	53.66
CTU Compass	0.8903	0.9106	0.8864	76.85	84.30	-23.10
CTU Vec.Comp.	1.0028	0.9914	1.0538	3.94	-33.46	-17.04
HMR2300	1.0322	1.0236	1.0338	705.2	-336.4	828.2
HMR3000	1.0864	1.0088	0.9646	-1774	1296	-527.3
InnaLabs M3	1.0080	1.0115	1.0424	-2963	-508.9	-716.1

Device	**α** [°]	**β** [°]	**γ** [°]	**Misfit [nT]**	**Loc.**
TFM100G2	-0.1692	-0.0954	0.18703	**1.09**	4
TFM65VQS	0.04756	-0.2777	0.04112	**0.81**	4
FL3-100	-0.1016	-0.6719	-0.2542	**3.65**	2
CTU Compass	2.360	3.068	1.524	**96.15**	2
CTU Vec.Comp.	-0.3342	0.2204	0.0238	**0.28**	4
HMR2300	1.499	-9.076	-0.021	**105.1**	2
HMR3000	0.068	-0.519	-0.158	**69.70**	2
InnaLabs M3	-3.737	-1.368	-2.860	**63.92**	1

Loc. – measurement location, see chapter 5.2.

Sensitivity listed relative to design value (typically 100 kV/T), Offset in Engineering Units, which are usually almost equal to nT (sensitivity ~1)

5. CONCLUSION

The main goal of this doctoral thesis was to evaluate the practical usability of a technically-improved scalar calibration procedure. In order to achieve this goal, innovative, very complex mechanical, electrical equipment and software have been developed and tested. We will now summarize the achievements with reference to the goals stated in the introductory chapter. The detailed technical parameters of each device and system were listed in the text of the thesis, and will not be repeated here. However, some possible improvements and proposals for further research will be introduced.

The main original results of this dissertation thesis

- design and development of a novel automated non-magnetic calibration platform for scalar calibration of magnetometers and accelerometers, development of auxiliary electronic and software systems, bi-axial and tri-axial versions of the platform were developed
- testing of the scalar calibration procedure with the above mentioned system using a wide range of commercial and custom sensors (magnetometers and accelerometers)
- design, development and testing of a high precise data acquisition module, preparation for a construction of a magnetometer with a digital output
- novel construction of a tri-axial vector fluxgate magnetometer with a vector compensation of a measured magnetic field

The results versus the aims stated

1) *The feasibility of a computer-controllable non-magnetic positioning system*

This work was carried out in two steps. The first bi-axial non-magnetic platform was successfully developed from scratch at the Danish Technical University, during a six-month internship at DTU SPACE. Selection of components and materials proved to be a real challenge, because of the very strict requirements on the magnetic cleanliness of the whole system. Later, at the Czech Technical University in Prague, the tri-axial platform was redesigned. In this case it was possible to concentrate on further technical improvements of the system, because the basic construction components, materials and ideas were identical to, or very similar to, the bi-axial platform. Due to time constraints, only a little experience of the practical operation of the bi-axial platform was gained in Denmark. Many function issues emerged during the calibration campaign carried out with the tri-axial system. These will be mentioned later in the section on suggestions for future improvements. The calibration results presented in this thesis indicate that there is some potential for improving the system, mainly from the point of view of magnetic cleanliness. Nevertheless, the current version has provided very competitive results, comparable with those achieved at dedicated magnetic calibration facilities.

2) *Develop and manufacture all the necessary accessories (control unit, DAQ unit)*

This step consisted mainly of engineering work related to electrical circuit design. In case of the control unit, the most critical point was the development of custom non-magnetic incremental optical sensors for sensing the angular position of the frames. The DAQ module is a state-of-the-art structure using the latest, most-precise available components. The achieved parameters are directly comparable with top-level commercial products, and the circuitry that has been developed and tested can be further used in our future plan to produce a magnetometer with a digital output.

3) *Develop and/or modify the firmware and software*

A large amount of supporting software was programmed in the scope of the thesis. Most of it was written with the use of the National Instruments CVI or LabView development environments, e.g. platform control, DAQ control, linearity measurements, and the dedicated DAQ for specific DUT instruments. Several programs in C-language were developed for single-chip microcontrollers. The most demanding task was to understand, modify and implement the calibration algorithms. The MATLAB implementation of the Gauss least-squares estimator has been published, but it has been slightly modified in order to understand the code and evaluate the effect of the approximations that are used. The linear algorithm, has also been published, but without the source codes. The algorithm has been coded in MATLAB. The quality of the implementation was slightly influenced by the complexity of the algorithm and the mathematical apparatus that was used (not all features presented in **[7**] were correctly implemented). Nevertheless, the results obtained from the algorithms were quite similar, which increases the reliability of the calibration parameters, and the tests indicate that their precision does not limit the precision of the calibration procedure and calibration system.

4) *Develop a fluxgate magnetometer with vector compensation of the measured magnetic field*

A huge effort was invested in developing this magnetometer. At the beginning, a lack of theoretical knowledge and experience was evident. Fortunately, plenty has been written on this topic. However, the aim was to develop something different, offering advantages over previously-published designs, above all, compactness, ease of manufacture, and lower cost. The measurement and calibration results are very promising, if we take into account that this was a first prototype of a device of this kind at CTU in Prague. In fact, the sensor was very useful for understanding the results of the scalar calibration procedure. If we had not had the device, it would not have been obvious whether the non-linearity visible in the calibration residual maps had come from the non-linearity the DUT’s transfer function, or whether it had been caused by insufficient magnetic cleanliness of the “non-magnetic” platform. In fact, magnetic cleanliness had been the cause of the problem. The sensor is now being developed further in the scope of a commercial project, and has been proposed for application in the ESA tender for a “Service Oriented Spacecraft Magnetometer Set”.

5) *Evaluate the construction and calibration results*

The most convenient method for evaluating the results is to compare them with published values. The non-magnetic calibration platform is probably unique worldwide, and it is not possible to compare the technical parameters. Only the scalar calibration results can be compared. The problem is that this includes other components of the system: the DAQ unit, scalar magnetometer synchronization and precision, and the DUT parameters. **The lowest calibration misfit value that was achieved is 0.27 $\mathrm{nT_{RMS}}$ and it is for the vectorially compensated fluxgate magnetometer.** The state-of-the-art values for a similar* sensor are 0.15 $\mathrm{nT_{RMS}}$ for the CSC sensor for the CHAMP mission [1], and 0.05 $\mathrm{nT_{RMS}}$ for the CSC sensor for the Oersted mission.

However, even the 0.27 $\mathrm{nT_{RMS}}$ value corresponds to a ±8 ppm peak-to-peak misfit from the full-scale value, which is a very good result.

*a sensor with almost 30 years of continual development history, which has flown in several space missions.

The calibration uncertainty that has been achieved (**total uncertainty of u = 2.34 nT,** k=1), is very competitive and there is still a possibility of further improvement, by removing the sources of magnetic field gradient. This could significantly reduce the uncertainty of the calibration parameters for DUT instruments with a digital output.

Proposals for further improvements and research

Practical operation with the system and the calibration results have led to some ideas on potential future improvements. A key factor that has a direct influence on the calibration results is the magnetic cleanliness of the platform. There is still some residual contamination in the motor and sensor area, which is not easy to remove. An option might be to make the frame of the platform from a lighter material, e.g. fiber-glass-laminate, which would enable its dimensions to be increased without exceeding the available motor torque. Larger dimensions mean better field homogeneity in the center of the platform.

A second key factor is the temperature stability of the DUT during calibrations. Currently, there is no protection from environmental effects, e.g. sunlight and wind. If the calibration is made in an outdoor environment, for reasons of field homogeneity, there can be serious problems. One solution, which would also bring another benefit, could be the application of some kind of non-magnetic thermostatic box. Flexible and lightweight design from thermally insulating fabric and super-isolation foils, perhaps with embedded resistive heating, could solve this problem. The benefit could be in measurements of the temperature dependences of the DUT (offset, scale and orthogonality temperature drifts). Another issue is the possibility of some improvements in the mechanical conception, e.g. a DUT harness, which would eliminate cable jams.

This phase of the work was concentrated on the scalar calibration procedure, which does not deal with the external reference frame alignment calibration. This issue should be also addressed in the next phase.

The development of a vectorially compensated fluxgate magnetometer is still in progress. The main issue is the availability of a suitable low noise magnetic material for the cores, and improvements in its fixation and mechanical assembly.

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Development and testing of a compact fluxgate sensor with a vector compensation of measured magnetic field (extension of a conference proceedings paper with latest results and new development plans)
Scalar calibration of vector magnetometers and accelerometers with an automatic non-magnetic calibration platform (extension of a conference proceedings paper with latest results and proposals for system improvement)

Contribution percentage of the author: all authors have equal contribution

* Renaudin, V., Afzal, M.H., Lachapelle, G: Complete triaxis magnetometer calibration in the magnetic domain; Journal of Sensors 2010, art. no. 967245
Lai, Y.-C., Jan, S.-S., Hsiao, F.-B.: Development of a low-cost attitude and heading reference system using a three-axis rotating platform; Sensors 10 (4), pp. 2472-2491

Response / No response and reviews

8. SUMMARY

The topic of this thesis is a design, development, and testing of a complex equipment for scalar calibration of vectorial sensors of magnetic field. The scalar calibration procedure is an alternative calibration method for calibration of tri-axial vector magnetometers which can be used if the vector coil system for traditional calibration procedure is not available or is not accurate enough. The scalar calibration method has some advantages but also limitations. Specific equipment has been developed in order to improve its potential and possibilities. The main instrument is a completely non-magnetic computer controllable platform for mechanical positioning of the Device Under Test (i.e. fluxgate or AMR magnetometer). Bi-axial version of the platform was developed during a six-month internship at the DTU SPACE, Denmark. This platform has been further developed and extended at the Czech Technical University in Prague in order to suit local requirements. Third axis of freedom has been added in order to allow full testing of an electronic compass module with electronic tilt error compensation. USB based data acquisition module for high precise simultaneous measurement of the DUT output voltage was also developed. Its small dimensions and bus powered mode are excellent for often transports to distant measurement sites. Novel construction of a vectorially compensated tri-axial fluxgate sensor of magnetic field was developed in order to understand what limits the accuracy of the calibration procedure. The sensor provided very good results – the quality of the calibration fit was the best among all devices that were calibrated using this system, including state-of-the-art commercial magnetometers. The instrument is being further developed in the scope of other projects. The best calibration result has a precision of ±8ppm and absolute accuracy is in the range of 50ppm. These values are comparable to the precision of the calibration sites that uses the vector coil system to calibrate the magnetometers. There is a good potential to improve both the values, proposals for changes in the system has been stated.

9. RÉSUMÉ

Tématem této disertační práce je specifický druh kalibrace vektorových senzorů magnetického pole, případně zrychlení. Magnetometry nacházejí v dnešní době uplatnění v mnoha oblastech průmyslu a vědy. Na senzory jsou kladeny stále náročnější požadavky, aby bylo možné dosáhnout maximální přesnosti měření je nutné tyto přístroje kalibrovat.

Pro kalibraci vektorových senzorů magnetického pole se používají nejčastěji dvě metody. První metoda využívá známého vektoru magnetického pole generovaného pomocí soustavy tří navzájem kolmých cívek, přičemž kalibrovaný senzor je v klidu v definované pozici. Druhá metoda (tzv. skalární kalibrace) využívá konstantní a homogenní zemské magnetické pole, které se nechá působit na kalibrovaný senzor. Senzorem se postupně mechanicky rotuje tak, aby magnetické pole působilo rovnoměrně na všechny osy citlivosti.

Skalární kalibrace je velmi vhodná pro orientační měření a testování ve vývojové fázi a pro ověření parametrů před odjezdem do certifikované laboratoře, kde se pro kalibraci použije typicky první zmíněná metoda. Nevýhodou skalární kalibrace je náročnost na obsluhu a čas. Během šesti-měsíční stáže na DTU Space byl vyvinut unikátní automatický dvouosý plně nemagnetický polohovací systém, který umožňuje rychlé a opakovatelné provedení procedury skalární kalibrace.

Po návratu na ČVUT byl systém rozšířen o třetí osu volnosti. Vznikl tak unikátní systém umožňující navíc kalibraci a testování elektronického kompasu s elektronickou kompenzací náklonu. Celý systém se skládá z kompletně nemagnetické polohovací plošiny, potřebné řídící elektroniky a software a matematických kalibračních algoritmů. V disertační práci je prezentován také vývoj USB modulu pro simultánní a vysoce přesné měření výstupního napětí kalibrovaného senzoru.

Vyvinutý kalibrační systém byl testován s dostupnými komerčními magnetometry se známými zaručenými parametry. Po odstranění několika problémů nebylo jasné, jestli je dosažená přesnost kalibrace limitována měřeným senzorem nebo kalibračním systémem samotným. Pro ověření byl vyvinut tříosý fluxgate senzor magnetického pole s vektorovou kompenzací měřeného pole. Tyto senzory se vyznačují extrémně vysokou linearitou (<1ppm) a stabilitou parametrů. Senzor je dále vyvíjen v rámci projektu TAČR a byl navržen pro aplikaci v tendru evropské kosmické agentury – SOSMAG. Se senzorem bylo při kalibraci pomocí vyvinutého systému pro skalární kalibraci dosaženo vynikajících výsledků, přesnost kalibračního fitu je v řádu ±8ppm. Výsledky odhalily problémy, které budou řešeny při budoucím vývoji systému.