International comparisons to establish the traceability in the global network of geomagnetic observatories to SI units

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Abstract

The international comparisons in the field of earth-level dc magnetic flux density measurements with participation of six National Metrology Institutes (NMIs) and four geomagnetic observatories (GMOs) have been carried out in 2013 and 2014 under the auspices of the Regional Metrology Organization Asia Pacific Metrology Programme (APMP). The obtained expanded uncertainty (k=2) of weighted mean value of correction values does not exceed 0.1 nT in the range of 20 to 100 μT, which was one of the main aims of this comparison.
VNIIM (D.I. Mendeleyev Institute for Metrology) was the pilot laboratory for this comparison registered in the Key Comparisons Data Base (KCDB) under index APMP.EM-S14.
Index Terms— transfer standard, magnetic flux density, uncertainty, atomic magnetic resonance, nuclear magnetic resonance.

1. Introduction

The ultimate goal of this comparison is to establish the traceability and increase the accuracy in measurements of parameters of the Earth magnetic field through applying the achievements of the state-of-the-art metrology in the field of magnetic measurements. The importance of this task stems from the role the low level magnetic measurements play in research, including those that directly benefit the human life and the use of natural resources.

A number of national metrology institutes (NMIs) have established independent standards of magnetic flux density (MFD) traceable to their respective realizations of SI units. However, the main source of precise data on the magnetic field of the planet - the global network of geomagnetic observatories, having hundreds years continuous measurements history, are presently not traceable to NMIs and are outside of the global measurement and conformance infrastructure.

This comparison was open to NMIs with independent realization of the MFD unit and to geomagnetic observatories with high level MFD measurement capabilities.

The following NMIs participated in the comparison: VNIIM (Russia), NPL (UK), PTB (Germany), CMI (Czech Republic), KRISS (S. Korea), NIM (China). The geomagnetic community was represented by the following GMOs: Royal Meteorological Institute (Belgium), Institute of Geophysics (Czech Republic), National Measurement Institute Geoscience (Australia), Zentralanstalt für Meteorologie und Geodynamik (Austria).

The measurement procedure provided for the use of a transportable quantum standard magnetometer (transfer standard - TS) delivered unattended to the participants by the pilot laboratory with calibration by the latter at the beginning, in the middle and after the comparison to monitor its stability.

2. Objectives of the comparison

The objective of the comparison was to compare and to harmonize the values of the MFD unit (T) reproduced by national standards and by the equipment of the participating geomagnetic observatories.

It was expected that, as a result of the comparison, the total uncertainty (coverage factor k = 2) of the conditional value of the unit will be decreased to a level of 0.1 nT.

The range of the MFD values for participants was selected from capabilities of each laboratory within the range of 20 to 100 μT covering the average MFD value of the Earth field at the location of each laboratory.

The reference value of MFD was established in each point as the weighted mean value on the basis of the results of measurement uncertainty estimation obtained by each participant.

3. The transfer standard

The transfer standard prepared by the pilot laboratory represented a commercial portable quantum magnetometer based on the proton magnetic resonance method combined with the Overhauser effect.

Proton magnetometers are the basic instrument for MFD measurements on a global network of geomagnetic observatories.

The relation between the proton precession frequency f_p and magnetic flux density B is, theoretically, perfectly linear and independent of the ambient temperature, humidity and atmospheric pressure: $B = 2\pi f_p / \gamma'_p$.

Gyromagnetic ratio of the protons, γ'_p, is one of the important fundamental physical constants and its value recommended by the Committee on Data for Science and Technology (CODATA 2010) is: $\gamma'_p = 2.675\ 153\ 268(66) \times 10^8\ s^{-1}\ T^{-1}\ (2.5 \times 10^{-8})$.

Magnetometers based on Nuclear Magnetic Resonance (NMR), specifically proton magnetometers, are theoretically considered "absolute" instruments because they are based on a fundamental conversion constant. In practice, however, they have systematic (type-B) uncertainties that can be hundreds of times higher than the uncertainty of the γ'_p determination. Such limitations are due to low signal-to-noise ratios, NMR signal phase shifts through signal damping, magnetization of the sensor parts, NMR frequency measurements, etc.

These errors are an individual property of every proton magnetometer and it may be compensated by applying a correction factor obtained through calibration against the standard of MFD, provided that the stability of the correction factor is experimentally proven.

Such a procedure resting upon the use of the Russian primary standard of the MFD unit described in [1] and [2] was followed at VNIIM for the travelling standard used for this comparison.

The comparison of the two standard helium-cesium atomic resonance magnetometers of the primary standard of VNIIM with the transfer standard was carried out using a precision comparator of DC MFD measuring instruments. The standard DC MFD comparator consists of three-component two-meter new type standard coils (TCC) of uniform constant magnetic field, a quantum programmable MFD stabilizer-controller and precision system for compensation of three orthogonal EMF components.

Corrections of the transfer standard have been determined over the entire measurement range from 20 up to 100 μT, which allowed comparison measurements to be conducted with a B-type uncertainty better than 0,05 nT (coverage factor k = 2) and type A (random) uncertainty close to 0,01 nT.

4. Representation of reporting results and measurement uncertainty

Each participant presented the measured differences between the MFD readings of the travelling standard and those of the standard of his laboratory in each measured point of the range along with the estimated uncertainty.

The following parameters were taken into account in estimating the measurement uncertainty:

1. Coefficient of MFD conversion into magnetic resonance frequency of magnetometers (adopted values of gyromagnetic ratios).

2. Magnetization of magnetic-resonance sensors
3. Non-uniformity of the reproduced MFD
4. Stability of the reproduced MFD.

Finally, each participant presented values of difference between the results of MFD measurements by the transported standard and the standard of the laboratory in each point of the range along with the estimation of the total uncertainty.

In all cases the measurement uncertainty was calculated in accordance with the *Guide for expression of measurement uncertainty* for the coverage factor k = 2.

5. Results of the Comparison

Results of the data processing for the comparison under project APMP.EM-S14 are given in Tables 1 and 2.

Table 1. Weight-average value of measurement results

Measured MFD Bm, µT	20	30	40	50	60	70	80	90	100
Number of participants	6	6	6	9	7	6	6	5	5
Y, nT *	-0,18	-0,13	-0,14	-0,20	-0,16	-0,16	-0,16	-0,14	-0,12
stdY, nT**	0,06	0,06	0,06	0,05	0,06	0,06	0,06	0,07	0,07

* $Y = \Sigma[X(i)/(1/U_x(i)^2]/\Sigma[1/U_x(i)^2]$ is a weight-average value of measurement results; correction to the National Result is calculated as CorrNS =Y - (NS – TS).

** $stdY = 1/\Sigma[1/U_x(i)^2]$ is a standard deviation of Y.

. Table 2. Data correction to measurements results of NS

NIM, GO	Sources and systems for MFD reproduction	NIM and GO standard magnetome-ters	Measured MFD value, Bm, µT	U_i*(k=2) , nT **	Difference***: TS – NS , **,nT	Weighting factor **WFi	Correction to NS (add with the sign) depending from Bm, nT
VNIIM	AMR based coils comparator	AMR He^4-Cs magnetometer	20; 30; 40; 50; 60; 70; 80; 90; 100	0,15	0,12	0,69;0,69;0,66; 0,45;0,62;0,68 0,70;0,84;0,77	-0,07; 0; 0,01; -0,06; -0,06; -0,05;-0,04; 0,02; 0
NPL	NMR based coils comparator	NMR magnetometer	20; 30; 40; 50; 60; 70; 80; 90; 100	4; 6; 8; 10; 12; 14; 16; 18; 20	-1,5;- 1,9;- 2,5; -3,0;- 3,3;- 3,8; -4,6;- 5,5;- 6,7	< 0,01	-1,7; -2,0; -2,6; -3,2; -3,5; -4,0; -4,8; -5,6; -6,8
GO, Belgium	AMR based coils comparator	AMR K^{39} magnetometer	20; 30; 40; 50, 60;70; 78	0,26	0,47;0,05;0,04; 0,09;0,07;0,16; 0,22	0,23;0,23;0,22; 0,15;0,21;0,23; 0,23	0,31;-0,07; -0,09;-0,08; -0,08; 0.03;0,04; - -
PTB	NMR based coils comparator	NMR-FP PTB magnetometer	20, 30, 40, 50, 60, 70, 80, 90, 100	1,6; 1,3;1,4; 1,3; 1,4; 1,3; 1,3; 1,1; 0,7	-0,39;-0,56; -0,60;-0,38; -0,45;-0,12 -0,04;-0,03; -0,16	0,01;0,10;0,05 0,02;0,02;0,02 0; 0; 0,04	-0,59; -0,72; -0,73;-0,58; -0,60; -0,27; -0,20; -0,17; -0,32
CMI	EMF	Overhauser magnetometer GSM-19	48,6	0,36	0,17	0,08	- - - -0,02; - - - - -
GO, Czech	EMF	Overhauser magnetometer GSM-19G	48,6	0,36	0,47	0,08	- - - 0,28; - - - - -
KRISS	AMR based coils comparator	AMR He^4-Cs magnetometer	20; 30; 40; 50; 60; 70; 80; 90; 100	1,0	-0,8; -0,8;-0,8; -0,7; -0,7; -0,6; -0,5; -0,4; -0,5	0,02;0,02;0,01; 0,01;0,01;0,02; 0,02;0,02;0,02	-0,99; -0,99; -0,93-0,88; -0,88; -0,77 -0,66; -0,54; -0,62
NIM	NMR based Coils comparator	NMR magnetometer	20; 30; 40; 50; 60; 70; 80; 90; 99	0.52;0.46; 0.37;0.35; 0.44;0.53; 0,62;0.72; 0.77	0.11; 0.75; 0.64;0,79;0,78; 0,91;0,87;0,88; 0,84	0,06;0,07;0,10; 0,11;0,07;0,06; 0,04;0,03;0,03	-0,09; 0,68; 0,47; 0,61; 0,62; 0,73; 0,74; 0,76; 0,68
GO, Austral.		Overhauser	58	0,44	0,42	0,07	- - -

	EMF	**magnetometer GSM-90**					**- 0,26 - - - -**
GO, Austria,	**EMF**	**Overhauser magnetometer GSM-19**	**48,4**	**0,9**	**-0,13**	**0,11**	**- - - -0,32 - - - - -**

***** U_i is the expanding uncertainty estimation for measured values Bm reported by participants.** Parameters which concern to the measured MFD values Bm.
*** NS is MFD measured by the NMI or GO magnetometer, and TS is MFD measured by the transported standard.
WFi is a weighting factor: $WFi = [1/U^2_i]\cdot[\sum 1/U^2_i]^{-1}$; $\sum$WFi =1.

EMF is Earth magnetic field Data processing of comparisons is executed on the basis application of weighting factor according to BIPM recommendations: Cox M G “The evaluation of key comparison data” 2002 *Metrologia* 39 589-95

As it follows from the presented results of the comparisons, the received expanded uncertainty (k=2) of weight-average value of correction values does not exceed 0,1 nT in the range of 20 – 100 µT, that was the basic purpose of this comparisons.

6. Conclusion

This first international comparison of MFD standards in geomagnetic range with participation of six NMIs and four GMOs has established a metrological procedure within the global measurement and conformational infrastructure that has made it possible to assure the traceability in the measurement of the Earth magnetic field carried out in geomagnetic observatories.

As a result of the comparison, the following measurement parameters were determined from calculation of the weighting factor of the measurement uncertainties reported by the participants:

- differences between the MFD measured by national standard magnetometers and the transfer standard;
- weighted mean MFD and the expanded uncertainty;
- corrections for all ten standards and their expanded uncertainty.

The expanded uncertainties obtained for the weighted mean quantities do not exceed 0.1 nT in the range from 20 to 100 µT, which was one of the main aims of this comparison.

A key aim of this comparison was to establish a metrological service system for the network of geomagnetic observatories. Application in the practical work corrections to measurements GO allow to lower uncertainty of measurements more than in 5 times to a level less than 0,1 nT.

Comparisons for certification quantum magnetometers of all geomagnetic observatories network can be organized using experience of this project APMP.EM-S14 and by an example of the other measurements fields, for example in the field of electric measurements having long traditions in metrology service.

Organizers of the project expect proposals from IAGA and geomagnetic observatories concerning their wish to participate in the expanded programme to gradually increase coverage to the complete network.

References

1. V.Ya.Shifrin, E.B.Alexandrov, T.I.Chikvadze, V.N.Kalabin, N.N.Yakobson, V.N.Khorev and P.G.Park, MAGNETIC FLUX DENSITY STANDARD FOR GEOMAGNETOMETERS» METROLOGIA, 37(3), 2000
2. V. Ya. Shifrin, V. N. Khorev, V. N. Kalabin, S. L. Voronov, A. E. Shilov, “ State primary standard for the units of magnetic induction, magnetic flux, magnetic moment, and magnetic induction gradient”, “Measurement Techniques”, October 2012, Volume 55, Issue 7, pp 739-744

3. V.Ya.Shifrin, V.N. Khorev, V.N. Kalabin and P.G.Park, "Experimental estimation of accuracy of modern scalar quantum magnetometers in measurements of the Earth magnetic field", Physics of the Earth and Planetary Interiors, 166, 2008, 146-152
4. Recommendation of COOMET R/GM/19:2008.
5. Bureau International des Poids et Mesures (BIPM) 1999 Mutual recognition of national standards and of calibration and measurement certificates issued by national metrology institutes *BIPM Publication* (Sevres: BIPM)