

FINAL REPORT
Bilateral Comparison of DC Magnetic Flux Density Between
NML-SIRIM and KRISS
(P1-APMP.EM-S13)

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1 Introduction

This report describes a bilateral comparison of the magnetic flux density (MFD) between Korea Research Institute of Standards and Science (KRISS) and National Metrology Laboratory, SIRIM (NML-SIRIM) of Malaysia, registered in the KCDB as P1-APMP.EM-S13. This bilateral comparison was piloted by KRISS. KRISS participated in CCEM Key Comparison CCEM.M.-K1, thus providing the link between NML-SIRIM results and CCEM.M.-K1. This report includes the measurement results from the participants and information about their calibration methods.

The MFD measurements are based on the newest gyromagnetic ratio of the shielded protons γ'_p value recommended by CODATA in 2010[1], and the experimental determination of the ratio ($\gamma_{4\text{He}}/\gamma'_p$) of ⁴He atoms to protons [2] as eq.(1):

$$B = (2\pi/\gamma_{4\text{He}}) \cdot f_{4\text{He}} \quad \text{and} \quad B = K \cdot I \quad (1)$$

where $f_{4\text{He}}$, B and I are ⁴He AMR frequency, MFD and current, respectively, K – conversion constant of coils.

The below values of physical fundamental constant were adopted as the conversion factor for standard Cs-⁴He AMR magnetometer.

$$B = (2\pi/\gamma_{4\text{He}}) f_{4\text{He}}; \gamma_{4\text{He}}/2\pi = 28.023\,801 \text{ Hz/nT}, u_c = 4 \times 10^{-8}$$
$$\gamma'_p = 2.675\,153\,268 \times 10^{-8} \text{ s}^{-1}\text{T}^{-1}, u_c = 2.5 \times 10^{-8} [1]$$
$$(\gamma_{4\text{He}}/\gamma'_p) = 658.200\,555, u_c = 3 \times 10^{-8} [2]$$

2 The Transfer Standard

The transfer standard is a Helmholtz coil prepared by NML-SIRIM. The transfer standard is capable of carrying a maximum permitted current I_c of 3 A, producing a field in its centre with a magnetic flux density B_o of about 20 mT. The field in the Helmholtz coil is homogeneous in the centre spherical region of 20 mm diameter. The transfer standard was transported by a courier company.

3 Calibration Methods

A description of the calibration methods and the reporting of results of each laboratory are given below.

3.1 KRISS

The transfer standard was calibrated by using low magnetic field standard system in nonmagnetic laboratory. It consists of a Cs-He Atomic Magnetic Resonance (AMR) standard magnetometer, current sources and measuring set and apparatus for compensation of the Earth magnetic field (EMF) as shown in Figure 1. Nonmagnetic environment includes a wooden house for main experimental working space, and two auxiliary buildings. One of auxiliary buildings, also being non-magnetic, is an observatory to measure time-varying component of EMF. The other one is a service building for supplementary equipments such as temperature control system. The temperature in main working place is kept within $25 \pm 1^\circ\text{C}$ by utilizing air conditioner in service building and the nonmagnetic air ducts, settled underground[3].

The Helmholtz coils for compensating EMF are composed of two coil systems (main and auxiliary), each of which has three orthogonal coils. The pairs of main and auxiliary coil windings for each component have identical coil constants, are connected serially. The DC component of EMF at working space is easily compensated by the applied opposite MFD. To compensate the AC EMF, Cs AMR field-controller is connected to E-W feedback Helmholtz coil windings. This system automatically cancels out the EMF variations.

The main current to generate a standard MFD in the Helmholtz coil is supplied by the Keithley 220 source from 10 mA to 50 mA. Cs-He AMR which plays role as a magnetometer is employed for the standard of the MFD generation.

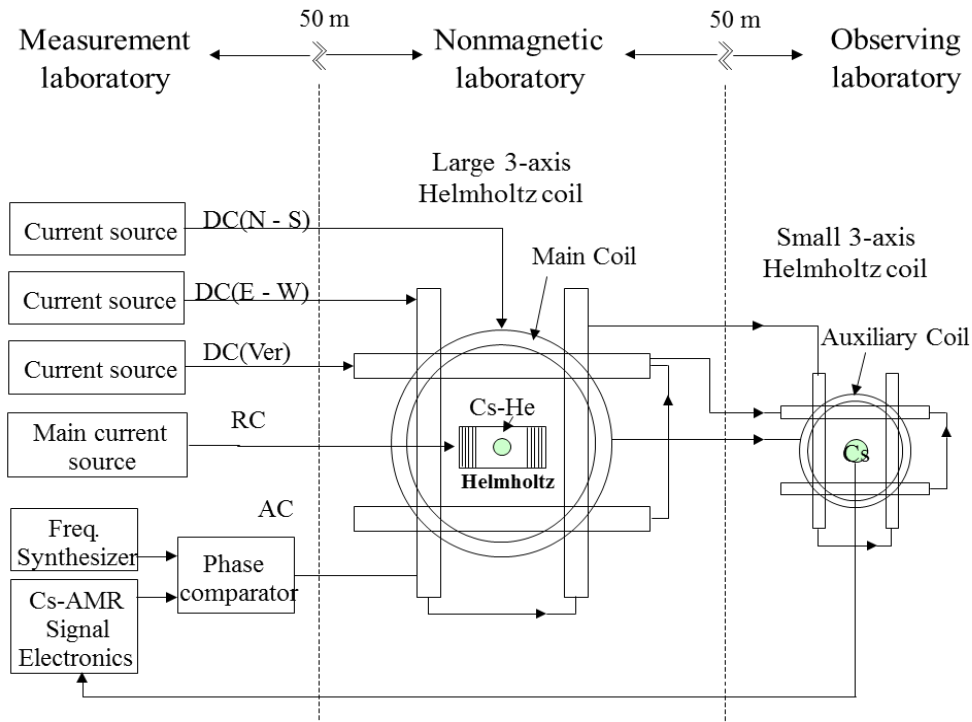


Fig. 1. Block diagram of low magnetic field standard system at KRISS

The equipment used at KRISS for measuring the transfer standard coil includes the following:

- (a) Low magnetic field standard system in nonmagnetic laboratory
- (b) Cs-He AMR magnetometer (WTM-01Z, S/N: 509001)
- (c) Fluxgate Magnetometer (Bartington, Mag-03H, S/N: 49)
- (d) DVM (HP 3458A, S/N: 2823A05164)
- (e) Current source (Keithley 220)
- (f) Standard resistor (Tettex 3274/KT, S/N: 140761)

3.2 NML-SIRIM

At NML-SIRIM, the transfer standard was measured using Hall probe magnetometer in the normal environment with an axis of the coil is oriented to the east-west direction to minimize the geomagnetic effect. The measurement set-up appears in Fig. 2.

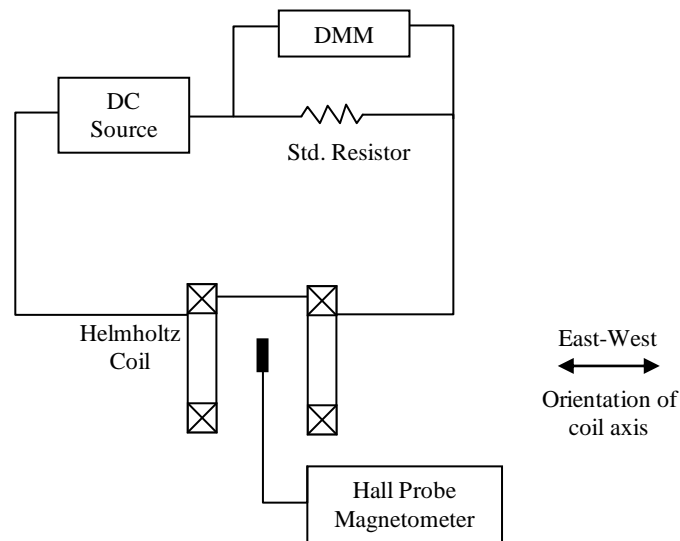


Fig. 2. Measurement set-up at NML-SIRIM

The equipment used at NML-SIRIM for measuring the transfer standard coil includes the following:

- (a) Hall Probe Magnetometer (FH-27, S/N: 100137)
- (b) DVM (HP34401A, S/N: 3146A33838)
- (c) Current source (HP 6225A, S/N: 3258A-09974)
- (d) Standard resistor (YEW 2792, S/N: 66VW3036)

4 Results

Table 1 presents the coil constant values as reported, mean value of the coil constant and uncertainties of the mean as quoted by both laboratories. Fig. 3 shows the coil constant reported by both laboratories plotted against the period when the measurements were carried out.

**Table 1. Results of coils constant determination
(Uncertainty: Extended uncertainty with $k=2$)**

Institute	Date	Reported Coil Constant, K (mT/A)	Mean, K (mT/A)	Uncertainty, U (mT/A)
NML-SIRIM	18-Jun-2012	6.396	6.397	0.012
	19-Jun-2012	6.398		
	21-Jun-2012	6.397		
	20-Nov-2012	6.394		
	21-Nov-2012	6.397		
	22-Nov-2012	6.397		
KRISS	15-Aug-2012	6.3957	6.3959	0.0039
	19-Aug-2012	6.3959		
	20-Aug-2012	6.3961		

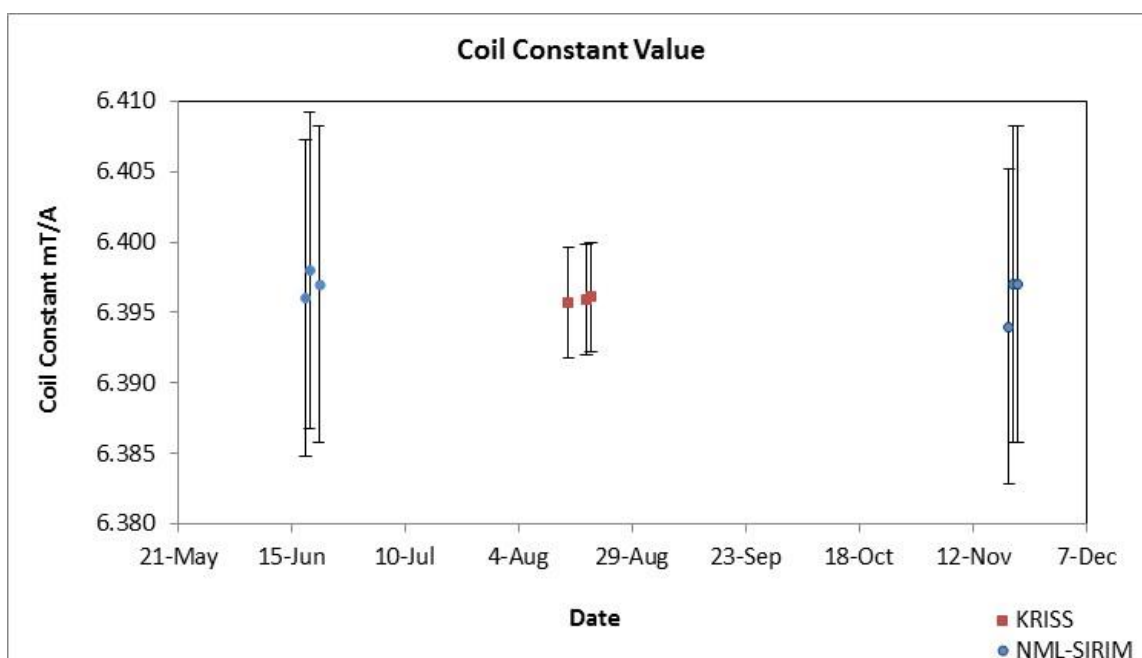


Fig.3 Coil constant value reported by KRIS and NML-SIRIM

The estimated uncertainties assigned by each laboratory to its measurements are in Table 2 and 3. Standard uncertainties are abbreviated as Std. Unc and degrees of freedom as DOF.

Table 2. KRISS uncertainty budgets

Uncertainty Source	Type	Distribution	Std. Unc	DOF
Cs-He AMR magnetometer	B	Rectangular	0.6 nT	∞
Transfer coil non-uniformity	B	Rectangular	1.7 μ T	∞
Current source instability	B	Rectangular	0.96 μ T	∞
Earth magnetic field variation	B	Rectangular	2.0 nT	∞
Repeatability	A	Normal	0.12 μ T	7
$U = 3.9 \mu\text{T} (k = 2)$				

Table 3. NML-SIRIM uncertainty budgets

Uncertainty Source	Type	Distribution	Std. Unc	DOF
Current source instability	B	Rectangular	0.5 μ T	∞
Non-uniformity of coil	B	Rectangular	4.5 μ T	∞
Probe positioning error	B	Rectangular	2.3 μ T	∞
Calibration of FH-27 magnetometer	B	Rectangular	1.5 μ T	∞
Resolution of FH-27 magnetometer	B	Rectangular	0.3 μ T	∞
Drift of FH-27 Magnetometer	B	Rectangular	1.2 μ T	∞
Repeatability	A	Normal	1.4 μ T	9
$U = 11.2 \mu\text{T} (k = 2)$				

5 Summary and Conclusion

The result presented by NML-SIRM, shows good agreement with the pilot laboratory KRISS.

5.1 Summary

The mean value of the coil constant and the uncertainty of the mean reported by both laboratories were used in the calculation of the DOE. The degree of equivalence (DOE) between NML-SIRM and KRISS is summarized as follows,

$$D = K_{\text{NML-SIRM}} - K_{\text{KRISS}} = 1.1 \mu\text{T/A}, U(D) = 11.9 \mu\text{T/A} \text{ (approximately 95\%, } k = 2)$$

5.2 Link to the CCEM KC

The reported DOE of KRISS with respect to the CCEM KC (CCEM.M.K1) reference value are as follows [4].

$$d_{\text{KRISS}} = -15.7 \text{ nT/A}, U(d_{\text{KRISS}}) = 4 \text{ nT/A}$$

The DOE of NML-SIRM with respect to the BIPM KCRV is given by the following equation

$$d_{\text{NML-SIRM}} = D - d_{\text{KRISS}}$$

The uncertainty is given by

$$u^2(d_{\text{NML-SIRM}}) = u^2(D) + u^2(d_{\text{KRISS}})$$

Therefore the $d_{\text{NML-SIRM}}$ value and the expanded uncertainty ($k = 2$) are as follows:

$$d_{\text{NML-SIRM}} = 1.1 \mu\text{T/A}, U(d_{\text{NML-SIRM}}) = 11.9 \mu\text{T/A}$$

5 References

- [1] Peter J. Mohr, Barry N. Taylor, and David B. Newell, “CODATA recommended values of the fundamental physical constants: 2010”, Rev. Mod. Phys., 84, Oct. 2012.
- [2] V. Ya. Shifrin, P. G. Park, V. N. Khorev, C. H. Choi, and C. S. Kim, "A new low-field determination of the proton gyromagnetic ratio in water", IEEE Trans. Instrum. Meas., 47(3), 638-643 (1998).
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- [4] Kurt Weyand, *Final Report, CCEM Key Comparison CCEM.M.K1, Magnetic Flux Density by Means of Transfer Standard Coil*, Metrologia, Vol. 42, March 2005.