# P1-APMP.EM-S9
# on supplementary comparison

# VNIIM/KRISS Bilateral Comparison of DC Magnetic Flux Density by Means of a Transfer Standard Coil

# FINAL REPORT

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# 1. Introduction

The purpose of these bilateral comparisons is the conformance of the base unit of magnetic measurements - a DC magnetic flux density and its ratio to a current, reproduced in VNIIM and KRISS - at institutes where adequate conditions for precise measurements in low magnetic fields are provided and the appropriate equipment for to attain a high level of accuracy is available.

Special conditions are required to ensure the best uncertainty levels of the measurements, and these were fulfilled for this comparison. These conditions are resumed in the presence of the following factors: Non-magnetic laboratory located far from sources of human-produced magnetic interference, automatic system of deep compensation of the Earth's magnetic field, and quantum measuring instrument for precision conversion of a highly uniform magnetic flux density is reproduced by transfer Standard Coil to AC frequency. As a result of this bilateral comparison, total standard uncertainties of tesla/ampere(T/A) measurements of (1-2) $\times 10^{-6}$ were expected.

This comparison may form a basis for follow-on multilateral APMP comparison of DC magnetic flux density standards.

# 2. Participants and schedule

## 2.1 Participants

D. I. Mendeleyev Institute for Metrology(VNIIM)
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(Pilot laboratory)

Korea Research Institute of Standards and Science(KRISS)
Daejeon, Republic of Korea

## 2.2 Quantity

DC Magnetic Flux Density by Means of a Transfer Standard Coil

## 2.3 Comparison schedule

Table 1. Comparison schedule.

| Year | Date of Measurement | Laboratory | Country or Economy |
|---|---|---|---|
| 2010 | 22 June – 24 June | KRISS(Solenoid No.3) | Korea (Rep. of) |
| | 23 June – 24 June | KRISS(Transfer std. coil, VNIIM No.1) | Korea (Rep. of) |
| | 6 July – 7 July | VNIIM(Transfer std. coil, VNIIM No.1) | Russia |

## 3. The traveling standard

The transportable T/A and Tesla standard ЭСТВ №01, was developed and fabricated by VNIIM on the basis of the quartz Garret solenoid [1] designed to produce a known magnetic flux density (MFD) and a known ratio of magnetic flux density to DC current. A single layer two-pitch solenoid of the Garret type with a winding installed in a screw groove cut on the surface of a cylindrical quartz carcass has a length of about 400 mm and a diameter of 130 mm. The travelling standard is capable of carrying a maximum current in solenoid winding $I_C$ of 1.05 A, which produces a field in its centre with a MFD $B_0$ of about 1 mT. The field in the solenoid is homogeneous within $2\times10^{-6}$ in the central spherical region of 30 mm diameter, which is sufficient to enable a narrow atomic magnetic resonance(AMR) line width for precision MFD measurements up to 1 mT[2].

A copper thermo resistor of the value $R_t \approx 125\ \Omega$ attached to the internal surface of a solenoid quartz carcass for use as a coil temperature reference. By varying the room temperature, the temperature coefficient of the coil conversion coefficient (coil constant) $K_B^{R_{t0}} = B_0/I_s$ with respect to the change of $R_t$ was measured at VNIIM using an He-Cs AMR standard magnetometer, and comparisons with the primary standard solenoid VNIIM which value of a constant is determined on the dimension of a solenoid winding.

Results of long-term VNIIM researches of stability of a travelling standard (solenoid ЭСТВ№ 01) from a current and the temperature dependence of a coil constant $K_B$ are represented as(1):

$$K_B^{R_t} = 9.539846\,[1 + 8.2\times10^{-7}\,(125.0\ \Omega - R_t)] \times10^{-4}\ \text{T/A} \tag{1}$$

Estimation of total standard uncertainty ($k$=1) is $u_c = 5\times10^{-7}$.

Table 2. Coil constant from a current and the temperature dependence.

| **Date** | ***I* (A)** | **$R_t$ (Ω)** | **$K_B$ (x$10^{-4}$ T/A)** |
|---|---|---|---|
| 22.05.09 | 0.6 | 123.5 | 9.5398578 |
| 21.08.09 | 0.6 | 123.8 | 9.5398558 |
| 13.05.10 | 0.6 | 124.7 | 9.5398466 |
| 14.05.10 | 0.6 | 124.8 | 9.5398494 |
| 21.05.09 | 1.0 | 125.4 | 9.5398425 |
| 20.08.09 | 1.0 | 126.7 | 9.5398341 |
| 17.05.10 | 0.6 | 126.7 | 9.5398312 |
| 14.05.10 | 1.0 | 128.0 | 9.5398221 |

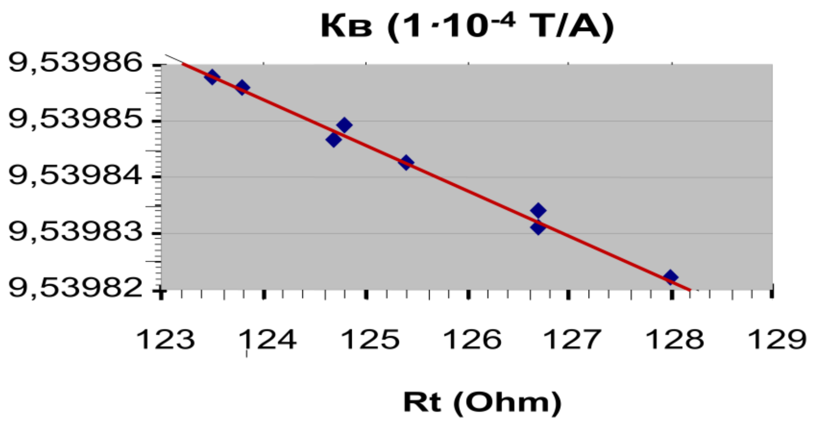


Figure 1. Measurement of solenoid temperature coefficient.

# 4. Measurement method

## 4.1 Measurements and reproduction of the magnetic flux density

Measurements and reproduction of a MFD field of a solenoids were carried out at KRISS and VNIIM in space with full compensation of a Earth magnetic field (EMF) and its variations. The measuring systems for the EMF compensation consist of a large volume, three-component coil system (TCS) with active control of coil currents by precision DC current sources and external optically pumped atomic magnetic resonance converter.

Compensation of the EMF variations is controlled in the TCS system by means of a converter placed inside an auxiliary conjugated coil system ("two-volume system").

Transfer standard coil constant T/A in its geometrical center is derived from the results of direct measurements by standard He-Cs magnetometer of the MFD $B_S$ generated by a solenoid at the applied DC current $I$ in the solenoid winding.

Measurements were carried out at two opposite directions of the current in the winding of the solenoid to remove the effect of the uncompensated part of the Earth magnetic field. Solenoid constant $K_B$ is determined as(2):

$$K_B = B_S / I, \qquad K_B = \frac{B_{K1} + B_{K2}}{I} \tag{2}$$

where $B_{K1}$ and $B_{K2}$ are the values of MFD measured by a standard magnetometer at two opposite directions of current.

All results of MFD measurements are based on the newest gyromagnetic ratio of the shielded protons $\gamma'_P$ value recommended by CODATA in 2010[3], and the experimental determination of the ratio ($\gamma_{4He} / \gamma'_P$) of $^4$He atoms to protons [4] as(3):

$$B_{KR} = (2\pi/\gamma_{4He}) \cdot f_{4He} \quad \text{and} \quad B_{KR} = K^B{}_{VN} \cdot I_{KR} \qquad (3)$$

where $f_{4He}$, $B_{KR}$ and $I_{KR}$ are $^4$He AMR frequency, MFD and current, respectively, measured by KRISS, $K^B{}_{VN}$ – conversion constant of VNIIM solenoid measured by VNIIM.

### 4.2 Comparison of the conversion constants of VNIIM and KRISS solenoids

The conversion constants of each solenoid (VNIIM and KRISS) were measured with identical current in their windings. The ratio of the coil constants of the KRISS solenoids ($K^B{}_{KR}$) and VNIIM ($K^B{}_{VN}$) is defined as(4):

$$[K_B{}^{KR} / K_B{}^{VN}] = [B_{KR}/B_{VN}] \qquad (4)$$

where $B_{KR}$ and $B_{VN}$ are measured values of MFD in VNIIM and KRISS solenoids.
Type *B* uncertainty(systematic) of current measurements in this case is excluded. One series of measurements is carried out in N pairs of single measurements of MFD $K_B{}^{KR}$ and $K_B{}^{VN}$, $B_K$ and current $I$. Each pair of measurements is performed at two opposite directions of the current $I$. On the basis of the results of these measurements the average value of results of measurements and their uncertainty were calculated.

## 5. Comparison results

Results of measurements in KRISS of VNIIM solenoid conversion coefficient and magnetic flux density**.**

### 5.1 Input data for applied standards of electric and magnetic units and constants.

- Transported standard quartz solenoid VNIIM– ЭСТВ №1
  $K_B{}^{Rt} = 9.539846\ [1 + 8.2\times10^{-7}\ (125.0\ \Omega - R_t)] \times 10^{-4}$ T/A, $u_c = 5\times10^{-7} (k=1)$

- Standard quartz solenoid KRISS - №3
  $K_B = 12.310614\ [1 - 1.65\times10^{-6}(50.0\ \Omega - R_t)] \times 10^{-4}$ T/A, $u_c = 2\times10^{-7}$

- Standard He-Cs magnetometer KRISS #1 (SM)

$B_{SM} = (2\pi/\gamma_{4He}) f_{4He}$; $2\pi/\gamma_{4He} = 28.023802$ Hz/nT, $u_c = 4\times10^{-8}$
$\gamma'_P = 2.675153268\times10^{-8}$ $s^{-1}T^{-1}$, $u_c = 2.5\times10^{-8}$ [3]
$(\gamma_{4He}/\gamma'_P) = 658.200555$, $u_c = 3\times10^{-8}$ [4]

- Voltage standard, Fluke, type 7004, #41037

$E_0 = 1.018\ 052\ 7$ V, $u_{E0} = 2\times10^{-7}$

- Resistance 10 Ω, Tettex, type 3275, #3012749, $t_{oil} = 25.04^{o}C$
$R_{10} = 10.000005$ Ω, $u_{R0} = 3.5\times10^{-7}$

- Multimeter, Fluke, type 8508A, # 3012749, $u_{Mo} = 4\times10^{-7}$

- Current reproduced in windings of solenoids

$I_{KR} = [(E_0 - 0.0180000)/R_{10}] = [(1.0180527 - 0.0180000)/10.000005] = 0.10000522$ A
$u_{I(KR)} = (u^2_{E0} + u^2_{R0} + u^2_{M0})^{1/2} = 6\times10^{-7}$

## 5.2 Measurement results

Table 3. The results of measurement of MFD and coil constant.

| Date | Solenoid, ЭСТВ №1, VNIIM | | | | | | $u_A$ ($k=1$) |
|---|---|---|---|---|---|---|---|
| | $B_S$(nT) | $u_A(B_S)$, ($v_i$=5) $1\times10^{-6}$ | $K_{Bt}$ ($10^{-4}$, T/A) | $R_{ti}$(Ω) | $\Delta K_{Bt} = K_{B0}-K_{Bi}$ (nT/A) | $K_{B0}$ ($10^{-4}$T/A Rt=125.00 Ω | |
| 23.06. 2010 | 95403.58 | 0.8 | 9.539862 | 125.70 | 0.05 | 9.539867 | |
| 23.06. 2010 | 95403.48 | 0.3 | 9.539852 | 125.72 | 0.05 | 9.539857 | |
| 24. 06. 2010 | 95403.48 | 0.5 | 9.539852 | 125.84 | 0.06 | 9.539857 | |
| 24. 06. 2010 | 95403.52 | 0.5 | 9.539856 | 125.60 | 0.07 | 9.539859 | |
| Average | 95403.52 | 0.2 | 9.539856 | 125.72 /125.00 | 0.06 | 9.539860 | $u_A=2\times10^{-7}$ |

Total standard uncertainty ($k$=1) of the measured value of the $B_{VN\_KR}$ magnetic flux density unit is $u_c=4.7\times10^{-7}$. MFD reproduced VNIIM solenoid using KRISS current and measured by KRISS standard He-Cs AMR magnetometer is given(5):

$$B_{KRISS} = (95403.52 \pm 0.05)\ \text{nT} \tag{5}$$

Uncertainty budgets of measurements by KRISS of the VNIIM magnetic flux density using KRISS current (Table 4).

Table 4. Uncertainty budgets.

| Items of uncertainty | Type of estimations | Distribution | Standard uncertainty | Degree of freedom |
|---|---|---|---|---|
| Standard He-Cs magnetometer KRISS | B | Normal | $3\times10^{-7}$ | ∞ |
| Variations of an external field and current | A | Normal | $2\times10^{-7}$ | 3 |
| MFD non-uniformity | B | Normal | $3\times10^{-7}$ | ∞ |
| Total standard uncertainty | $u_c = 4.7\times10^{-7}$ | | | |

Magnetic flux density calculated through value of a solenoid VNIIM conversion coefficients $K_{VN}$ and value of a current $I_{KR}$ in its winding, reproduced in KRISS, by the values of used volt and resistance standards, is equal to(6):

$$B_{VN\_KR} = K_{VN}\times I_{KR} = (953984.6 - 0.06)\ \text{nT/A} \times 0.10000522\ \text{A} = (95403.40 \pm 0.09)\ \text{nT}, \qquad (6)$$

where 0.06 nT/A is correction to $K_{VN}$ for solenoid temperature.
Uncertainty of the KRISS current: $u_{I(KR)} = (u^2_{E0} + u^2_{R0} + u^2_{M0})^{1/2} = 6\times10^{-7}$ and VNIIM solenoid $u_{VN\_SOL} = 5\times10^{-7}$, $u_{VN\_KR} = 7.8\times10^{-7}$. Total standard uncertainty of the reproduced value of the $B_{VN\_KR}$ magnetic flux density is $9.3\times10^{-7}$ or 0.09 nT.
The relative difference $\partial B$ reproduced at VNIIM and measured at KRISS MFD values is received (7):

$$\partial B = [(B_{VNIIM\_KRISS} - B_{KRISS}) / B_{KRISS}] = 0.8\times10^{-6}\ (0.08\ \text{nT}) \qquad (7)$$

Experimental data of VNIIM/KRISS comparison of the MFD unit have shown an agreement with a total standard uncertainty of $1.2\times10^{-6}$.

### 5.3 Results of KRISS solenoid conversion coefficient measurements

Table 5. Conversion coefficient of solenoid.

| Date | Solenoid №3, KRISS | | | | | | |
|---|---|---|---|---|---|---|---|
| | $B_S$ n(nT) | $u_A(B_S)$ ($v_i$=5), | $K_{Bt}$, $10^{-4}$ T/A | $R_{ti}$, Ω | $\Delta K_{Bt} = K_{B0} - K_{Bi}$, nT/A | $K_{B0}$, $10^{-4}$ T/A | $u_A(k=1)$ |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | $1\times10^{-6}$ | *R*ti, Ω | | | *R*t=50.00 Ω | |
| 22.06. 2010 | 123112.72 | 0.6 | 12.310631 | 50.34 | 0.07 | 12.310638 | |
| 22.06. 2010 | 123112.60 | 0.7 | 12.310619 | 50.25 | 0.05 | 12.310624 | |
| 23.06. 2010 | 123112.58 | 0.4 | 12.310617 | 50.23 | 0.05 | 12.310622 | |
| 24.06. 2010 | 123112.70 | 0.6 | 12.310629 | 50.28 | 0.06 | 12.310635 | |
| Average | 123112.65 | 0.2 | 12.310624 | 50.00 | 0.06 | 12.310630 | $u_A=2\times10^{-7}$ |

Total standard uncertainty ($k$=1) of the measurements at value of the KRISS and VNIIM solenoids constants is $7.6\times10^{-7}$ (Table 6). Measured in KRISS ratio VNIIM/KRISS solenoids conversion coefficients with use the KRISS standard helium-cesium magnetometer and 100 mA current reproducing system is the following(8):

$$(K_{KR}/K_{VN})_{comp10} = (123106.08/95398.41) = 1.29044096 \tag{8}$$

Budget of uncertainty of measurements at the values of the KRISS and VNIIM solenoids constants (Table 6).

Table 6. Uncertainty budgets of solenoids constants.

| Items of uncertainty | Type of estimations | Distribution | Standard uncertainty | Degree of freedom |
|---|---|---|---|---|
| Standard He-Cs magnetometer | B | Normal | $3\times10^{-7}$ | ∞ |
| Current VNIIM | B | Normal | $6\times10^{-7}$ | ∞ |
| Variations of an external field and current | A | Normal | $2\times10^{-7}$ | 3 |
| MFD Non-uniformity | B | Normal | $3\times10^{-7}$ | ∞ |
| Total standard uncertainty | | $u_c = 7.6\times10^{-7}$ | | |

Total standard uncertainty ($k$=1) of the VNIIM/KRISS coils constant ratio is $u_c = 4.7\times10^{-7}$ (uncertainty in the reproduction of the current is excluded). The value of the KRISS solenoid constant calculated on the basis of the measured ratio of two solenoids constants and the constant of VNIIM solenoid is(9):

$$K_{KR(comp10)} = K_{VN}\times(K_{KR}/K_{VN})_{comp10} = 1231060.2 \text{ nT/A } (R_t = 50.00\ \Omega) \tag{9}$$

with total standard uncertainties of $9.4\times10^{-7}$.

Presented KRISS preliminary value of the solenoid constant is(10):

$$K_B = 123106.14\ [1 - 1.65\times10^{-6}(50.0 - R_t)]\ \ \text{nT/A}\ \ (u_c=2\times10^{-6}) \qquad (10)$$

to be in agreement with the above result of comparisons (difference is $1.1\times10^{-6}$) but has 2 times bigger uncertainty of measurements.

The relative difference in MFD values $\partial B$ reproduced by VNIIM in KRISS and measured at KRISS is equal to $1.2\times10^{-6}$. It shows the agreement of the results of measurements to estimation a component of their uncertainty.

## 5.4 Measurements conversion coefficient of VNIIM solenoid at VNIIM after measurements at KRISS

Input data for applied standards of electric and magnetic units and constants.

- Transported standard quartz solenoid VNIIM– ЭСТВ №1
  $K_B^{Rt} = 9.539846\ [1 + 8.2\times10^{-7}\ (125.0\ \Omega - R_t)]\ \times10^{-4}$ T/A, $u_c = 5\times10^{-7}$
- Standard helium-cesium magnetometer VNIIM ЭТ-1 (SM), $u_c = 3\cdot10^{-7}$
  $B_{SM} = (2\pi/\gamma_{4He})\, f_{4He}$; $2\pi/\gamma_{4He} = 28.023802$ Hz/nT ($u_c = 3\times10^{-8}$)
  $\gamma'_P = 2.675153268\times10^{-8}\ s^{-1}T^{-1}$ $(2.5\times10^{-8})$[3], $(\gamma_{4He}/\gamma'_P) = 658.200555(3\times10^{-8})$[4]

- Voltage standard – Fluke, type 732B, # 7590806, $E_0$=1.01812628 V, $u_{EO} = 1\times10^{-7}$

- Resistance 1 Ω, type M3024, # 1, $t_{oil}$= 25.04°C
  $R_0$(1 A) = 0.99998804 Ω, $u_{R0} = 0.5\times10^{-7}$

- Multimeter, Agilent, type 3458A, # MY 45044017, $u_{M0} = 2.5\times10^{-7}$

- Current reproduced in windings of solenoids
  $I_{VN} = [(E_0 - 0.0180000)/R_0\ ] = [(1.01812628 - 0.0180000)/0.99998804\ ] = 1.0001382$ A
  $u_{I(VN)} = (u^2_{E0} + u^2_{R0} + u^2_{M0})^{1/2} = 2.7\times10^{-7}$

Results of measurements of the VNIIM solenoid conversion coefficient (Table 7) and magnetic flux density using VNIIM standard magnetometer. Budget of uncertainty in measurements of the VNIIM solenoid magnetic flux density (Table 8). Budget of uncertainty of measurements at value of the VNIIM solenoid constant (Table 9).

Table 7. Measurement of VNIIM solenoid conversion coefficient.

| Date | Solenoid, ЭСТВ №1, VNIIM | | | | | | $u_A$ ($k$=1) |
|---|---|---|---|---|---|---|---|
| | $B_S$ (nT) | $u_A(B_S)$, ($v_i$=5) $1\times10^{-6}$ | $K_{Bt}$ ($10^{-4}$, T/A) | $B_S$ (nT) | $u_A(B_S)$, ($v_i$=5) $1\times10^{-6}$ | $K_{B0}$ ($10^{-4}$ T/A $R$t=125.00 Ω) | $B_S$ (nT) |
| 06.07.2010 | 954115.30 | 0.2 | 06.07.2010 | 954115.30 | 0.2 | 06.07.2010 | 954115.30 |
| 06.07.2010 | 954115.18 | 0.04 | 06.07.2010 | 954115.18 | 0.04 | 06.07.2010 | 954115.18 |
| 06.07.2010 | 954115.37 | 0.1 | 06.07.2010 | 954115.37 | 0.1 | 06.07.2010 | 954115.37 |
| 06.07.2010 | 954115.48 | 0.07 | 06.07.2010 | 954115.48 | 0.07 | 06.07.2010 | 954115.48 |
| 07.07.2010 | 954116.02 | 0.1 | 07.07.2010 | 954116.02 | 0.1 | 07.07.2010 | 954116.02 |
| Average | 954115.47 | | Average | 954115.47 | | Average | 954115.47 |

Table 8. Uncertainty budgets of VNIIM solenoid magnetic flux density.

| Items of uncertainty | Type of estimations | Distribution | Standard uncertainty | Degree of freedom |
|---|---|---|---|---|
| Standard He-Cs magnetometer | B | Normal | $3\times10^{-7}$ | ∞ |
| Variations of an external field and current | A | Normal | $0.5\times10^{-7}$ | 4 |
| MFD non-uniformity | B | Normal | $3\times10^{-7}$ | ∞ |
| Total standard uncertainty | | $u_c = 4.2\times10^{-7}$ | | |

Table 9. Uncertainty budgets of VNIIM solenoid constant.

| Items of uncertainty | Type of estimations | Distribution | Standard uncertainty | Degree of freedom |
|---|---|---|---|---|
| Standard He-Cs magnetometer | B | Normal | $3\times10^{-7}$ | ∞ |
| Current VNIIM | B | Normal | $2.7\times10^{-7}$ | ∞ |
| Variations of an external field and current | A | Normal | $2\times10^{-7}$ | 3 |
| MFD | B | Normal | $3\times10^{-7}$ | ∞ |

| | | | | |
|---|---|---|---|---|
| nonuniformity | | | | |
| Total standard uncertainty | $u_c = 5.4\times10^{-7}$ | | | |

Averaged values of solenoid magnetic flux density and conversion coefficient measured by standard magnetometer are 954115.47 nT and $9.5398463 \times10^{-4}$ T/A, respectively. The total standard uncertainties are $4.2\times10^{-7}$ and $5.4\times10^{-7}$.

The calculated value of the VNIIM magnetic flux density using VNIIM solenoid and current is(11):

$$B_{VN} = K_{VN}\cdot I_{VN} = [953984.60 - 1.07]\ \text{nT/A} \times 1.0001382\ \text{A} = 954115.37\ \text{nT} \quad (11)$$

The total standard uncertainty of $B_{VN}$ value is $5.7\times10^{-6}$. The relative difference $\partial B$ reproduced by VNIIM solenoid and current and measured by standard magnetometer values was determined to be(12):

$$\partial B = [(B_{KB,\,I} - B_{4He})/B] = 1.0\times10^{-7}\ (0.10\ \text{nT}) \quad (12)$$

The experimental data of VNIIM/KRISS comparison of the MFD unit have shown an agreement with a total standard uncertainty of $1.0\times10^{-6}$ .

## 6. Conclusion

The above reported results have shown a good agreement of experimental comparison data with an estimation of the uncertainty components of applied standards. The coordinated values of the MFD unit and its ratios to DC current at the level of standard uncertainty (1-1.2) $\times10^{-6}$ ($k$=1) on the basis of gyromagnetic ratio of the shielded protons $\gamma'_P$ value, recommended by CODATA in 2006, the experimental determination of the ratio ($\gamma_{4He}/\gamma'_P$) of $^4$He atoms to protons and standards of a current of two institutes are received.

In contrast to the key comparison of CCEM.M.-K1(2000) the results in this report not only comparisons of unit T/A, but also T, reproduced by two institutes contain. The difference between the units T/A reproduced by VNIIM and KRISS in this comparisons, is lowered from $8\times10^{-6}$ to $1\times10^{-6}$, while VNIIM result in KC of 2000, was the closest ($8\times10^{-7}$) coincided with average weighed value T/A according to these multilateral comparisons. The received results give a basis for carrying out multilateral comparisons of standard quantum magnetometers of metrological institutes in the framework of APMP with participation of geomagnetic observatories, which require an establishment of the unified standard of the MFD unit.

The results of this comparison show the possibility of decreasing the uncertainty of the MFD unit determination at direct comparisons of standard quantum magnetometers, that assumes an exception of uncertainty of reproduction and measurement of the solenoids conversion constant and current.

## 7. References

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