

## DC MAGNETIC FLUX DENSITY STANDARDS IN THE RANGE OF EARTH MAGNETIC FIELD

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**Abstract:** We have carried out precision magnetic measurements utilizing a magnetic-resonance technique, aiming for improving the magnetic-field standard below 100  $\mu\text{T}$ . The standard for measuring dc magnetic flux density is intended to cover the range from 10  $\mu\text{T}$  to 100  $\mu\text{T}$ , with an uncertainty ( $k = 2$ ) ranging from 4  $\mu\text{T/T}$  to 10  $\mu\text{T/T}$ .

Keywords: magnetic flux density, magnetic resonance

### 1. INTRODUCTION

The  $^4\text{He}$  magnetic-resonance magnetometry can be used to represent the magnetic-field standard in a low-field region. In a magnetic field ( $B$ ), the angular resonance frequency ( $\omega_H$ ) for  $^4\text{He}$  is as follow:

$$\omega_H = \gamma_{4\text{He}} \cdot B, \quad (1)$$

where  $\gamma_{4\text{He}}$  is the  $^4\text{He}$  gyromagnetic ratio. Previously, the value of  $\gamma_{4\text{He}}$  was measured at KRISS in collaboration with VNIIM as  $1760.78819 \times 10^8 \text{ s}^{-1}\text{T}^{-1}$  with an uncertainty of  $0.18 \times 10^{-6}$  using atomic magnetic resonance (AMR) for Cs- $^4\text{He}$  [1]. The Cs- $^4\text{He}$  AMR technique is based on optical-pumping polarization by means of metastable exchanges with polarized atoms of cesium. The Cs- $^4\text{He}$  AMR has various advantages for a low-field range in comparison with proton nuclear magnetic resonance (NMR). For instance, the AMR frequency is hundreds of times higher than NMR frequency, and the optical method used in AMR-signal monitoring is much sensitive, which give rise to higher relative accuracy in the measurement. [2]. The measurement standard of KRISS includes a nonmagnetic facilities, an Cs- $^4\text{He}$  AMR magnetometer, 3-axis Helmholtz coils, and an automatic system for compensating for Earth's magnetic field(EMF). The standard serves to calibrate the dc magnetometers, teslameters, magnetic flux-density coils and to support experiments related to research involving magnetic fields below 100  $\mu\text{T}$ .

### 2. NONMAGNETIC FACILITIES

Nonmagnetic environment includes a nonmagnetic laboratory building for arranging main experimental working space, and two auxiliary buildings. One of them (observatory), also nonmagnetic, is intended for arranging a

system for automatic compensation of a Earth magnetic field (EMF), and in the second - service building, the most magnetic part of the measuring equipment and temperature control system settled down. These buildings are separated from each other to eliminate magnetic interaction of the equipment placed in them [3][4].

There are no artifacts such as another buildings, roads, and electrical power substations within a radius of 100 m from the nonmagnetic laboratory building. To reduce the vibration of the main working space, there is a sub-foundation, independent from the building foundation, which is made from sand, marble gravel, and white cement. The floor is located 2 m above the ground to remove the magnetic mirror effect in the soil from the solenoid field. The temperature in main working place is kept within  $25 \pm 1 \text{ }^\circ\text{C}$  by air conditioner controller in service building 50 m away and the nonmagnetic air ducts, settled underground.

The magnetic susceptibilities of soil and rocks after grounding are about  $1.5 \times 10^{-5}$  and  $2.3 \times 10^{-5} \text{ A}\cdot\text{m}^2/\text{kg}$ , respectively, as measured by a superconductivity SQUID or magnetic balance susceptometer. The susceptibilities of construction materials are on the order of  $10^{-6} \text{ A}\cdot\text{m}^2/\text{kg}$  or below. Brass hardware for of the frames, shingles for roofing is on the order of  $10^{-5} \text{ A}\cdot\text{m}^2/\text{kg}$  [3][4].

### 3. AUTOMATIC COMPENSATION OF THE EARTH MAGNETIC FIELD AND REPRODUCED MAGNETIC FIELD

In free space unshielded large volume reproducing system of the low permanent magnetic field(MF) is necessary for use in such areas of a magnetic measurements as: the calibration of the magnetometers, measurement of the MF of the different technical products, materials, testing the ecological and medical effects, etc[2]. Different from the most of previous designs[5][6] for the EMF compensation, this equipment allows not only to compensate automatically EMF but also to reproduce precisely a stable MF[7].

The dc EMF working spaces in the nonmagnetic building are compensated by the opposite MF, currents passing through the large 3-axis Helmholtz coil. Also time- EMF variations are monitored at the observatory by the Cs-AMR magnetometer which is located in the center of another small 3-axis Helmholtz coil having an identical coil constant with that of large one in each direction. In addition to large

windings for dc EMF, each pair has an extra one of feedback coil for the compensation of a time-varying EMF.

The diameters of large 3-axis Helmholtz coils are 196 cm, 174 cm, and 150 cm in the vertical, east-west and north-south directions, respectively. And those of small one are nearly half of the large one. The frames of Helmholtz coil were made of glued pieces of wood. The enameled copper wire of 1 mm diameter was wound to be closely packed with each other.

A block-diagram of the EMF compensation and MF reproduction system is shown in Fig. 1. This equipment was installed at described above nonmagnetic buildings and away from the artificial MF noise sources[2]. The device consists of couple of the uniform field coil system - the large one and the small one-with three serially connected orthogonal components, two current sources for compensation of the permanent EMF-components and main current source for reproducing the MF.

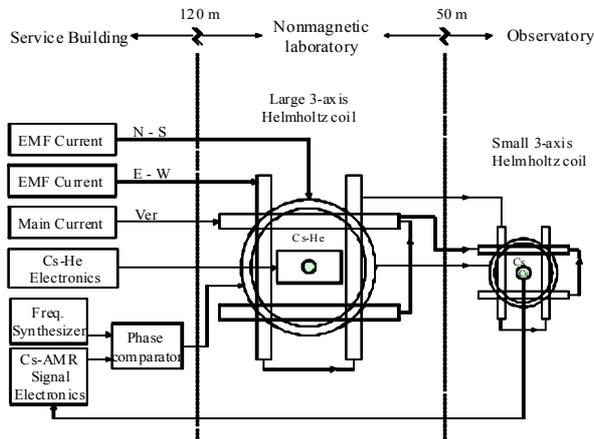


Fig. 1. Apparatus for the automatic compensation of the Earth magnetic field and reproduced magnetic field.

Small differences of coil constants between the large and the small one are trimmed by the connection of shunt resistors. The EMF variations and the current instability are compensated by using the Cs-AMR controller, the sensor of which is placed in the center of the small coil system. The Cs-<sup>4</sup>He magnetometer is applied for MF measurements inside large coil working volume.

The residual MF drift in the working place of the coils is determined by the differences of the next parameters of the two coil systems: coil constants, coils axis direction, local field variations and temperature drift. Effects of the first two drift sources decreased after alignment of the coil constants and their axis directions within 0.01 % and 1 deg. respectively. It reduces EMF variations effect due to both two reasons about  $1 \times 10^4$  times[8].

The third source of the MF instability depends on the local magnetic noise situation and the amplitude is about 0.05 nT in our case. The difference of the temperature drifts is in principle due to the large volume of the coil system (1.5 m × 1.5 m × 1.5 m) and the temperature dependence of the coil constant. This temperature coefficient depending on the coil

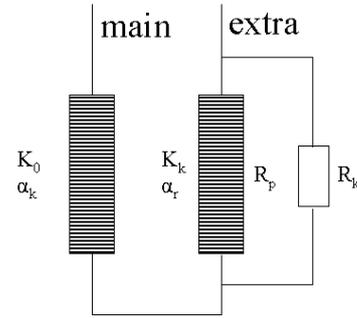


Fig. 2. Main and extra coils for temperature-compensation.

frame material ( $\alpha_t$ ) is from  $2 \times 10^{-5}$  to  $2 \times 10^{-4}$  1/°C. For example, for the 50 mT reproducing MF, 1°C-temperature variation, and  $\alpha_t = 3 \times 10^{-5}$  1/°C, it results in 1.5 nT drift.

To minimize this effect the temperature-compensation method[9] based on the using the extra temperature dependent coil winding with the adjustable temperature coefficient was realized(Fig. 2). The temperature compensation condition as shown in equation(2):

$$\alpha_k \cdot K_0 = \alpha_t \cdot K_k \left( \frac{R_p \cdot R_k}{R_p + R_k} \right) \quad (2)$$

where  $K_0$ ,  $K_k$  and  $\alpha_k$ ,  $\alpha_t$ - coil constants and the temperature coefficients for the main and extra windings of the coils,  $R_p$ ,  $R_k$  resistance of the extra winding. In this experiment the temperature-depending drift decreased more than 30 times by this method.

Fig. 3 and Fig. 4 show the ordinary stability of the reproduced MF. Fig. 3 represents the initial EMF variations and variation of the field that was reproduced by the above described system for 1 hour. Fig. 4 show the stability of the reproduced MF in 50  $\mu$ T for 2 hours.

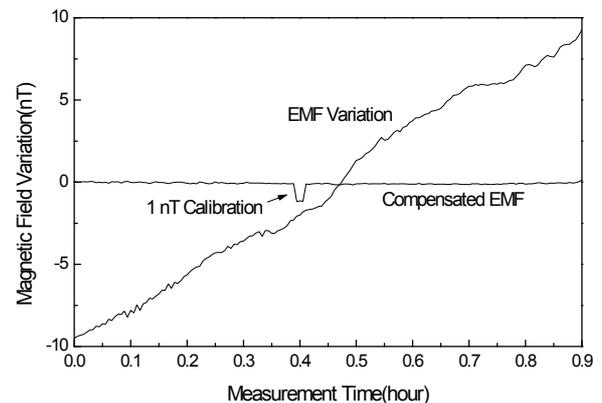


Fig. 3. Variation of the EMF and reproduced MF.

The reproduced field standard deviation was the 0.02 nT for (1- 60) s interval and drift was the 0.1 nT for 1 hour while the initial EMF variations was 20 nT.

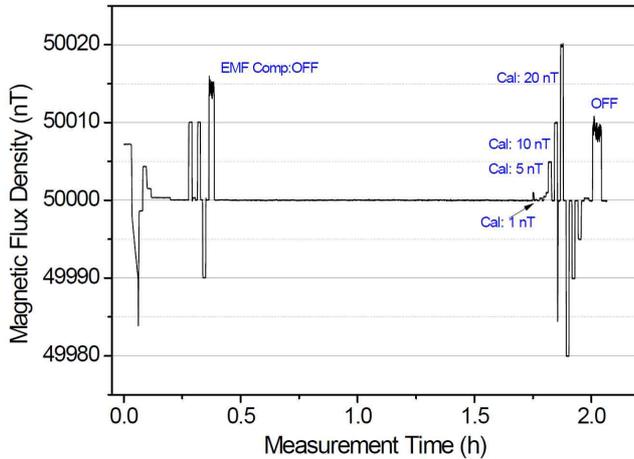


Fig. 4. The reproduced MF in 50  $\mu\text{T}$ .

#### 4. CONCLUSION

The AMR-based MF reproduction and the compensation system for EMF are themselves of interest for metrology applications in electromagnetic instruments. Using the  $\gamma'_p$  measuring complex we developed allowed us to reduce the uncertainty in the reproduction of the tesla at KRISS by about 100 times below 100  $\mu\text{T}$  in the range of EMF. It also allowed us to create a new primary standard for the magnetic flux-density unit, which can be used for calibration of industrial-standard magnetometer.

The stable, uniform MFD is maintained in the range 10  $\mu\text{T}$  to 100  $\mu\text{T}$ , with an uncertainty ( $k = 2$ ) ranging from 4  $\mu\text{T}/\text{T}$  to 10  $\mu\text{T}/\text{T}$ .

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