FLUX-GATE MAGNETOMETER NOISE: THEORETIC AND EXPERIMENTAL STUDY

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ABSTRACT

The problem of calculation and measurement of flux-gate magnetometers magnetic noise (MN) is analyzed. The theoretical approach to MN estimation is given and semi-empirical relations allowing MN calculation in all operation frequency band are deduced. It is shown that the MN density increment in the direction of extremely low frequency can be approximated by $1/f^{\alpha}$ function where $\alpha \approx 3/4$, but exact α value is not important for MN calculation for periods up to 1 year. The experimental study of flux-gate magnetometer noise in wide frequency band is made and its results are discussed.

1. INTRODUCTION

The flux-gate magnetometers (FGM) are the most widespread instruments for weak magnetic field measurements. The magnetic noise (MN) - fluctuations, arising by periodic magnetization of flux-gate sensor (FGS) core - are in principle unremovable and determine sensitivity threshold of modern FGM. Another sources of short-term errors, including electric fluctuations in electronic part, may have influence on output noise of high sensitivity FGM mostly in non-professional constructions and are not taken into account here.

Certainly, big impression at all skillful in the magnetometry makes few words said by the way in [1] about «zero offset stability is better than ±0,1 nT over a temperature range of ±60°C and for periods exceeding one year, based on our current Voyager data; the stability of the AMPTE/CCE MFE was <1 nT per axis over the 4.5 year lifetime. The inherently low-noise circuit design, coupled with careful layout of the critical analog circuitry, produced system noise levels ($\sim 10^{-7}$ nT^2 Hz^{-1})». Unfortunately, the attempts failed to find other paper of any of the authors of this work with more detailed explanations of with what testing facilities and in which conditions were obtained these figures and whether these results were confirmed by independent investigators.

But the aim of this paper is not to discuss these results. First theoretic approximation allowing to estimate expected flux-gate magnetometer (FGM) MN will be given and then the attempts to confirm these results will be described.

2. MAGNETIC NOISE FREQUENCY DEPENDENCE

The problems of MN calculation and measurement require special approach both in theoretic analysis and practical implementation. In the result of intensive investigations following semi-empirical equations were proposed for the calculation of MN density b(f) and its root-mean-square value ΔB_{sq}:

$$b(f) = b_0 \, [1+(f_0/f)^{\alpha}] , \tag{1}$$

$$\Delta B_{sq} = \{ \int_{f_{min}}^{f_{max}} b(f) \, d f \}^{1/2} = \{ b_0 \, [f_{max} - f_{min} + f_0^{\alpha} \, (f_{max}^{1-\alpha} - f_{min}^{1-\alpha})/1-\alpha]\}^{1/2}, \tag{2}$$

where f_{max} and f_{min} - correspondingly maximum and minimum frequencies of operation frequency band of FGM, b_0 - noise density constant.

The shape of MN frequency spectrum is determined by the corner frequency f_0 and coefficient α. In early FGM developments the corner frequency f_0 was about some hundreds of Hz. Further, especially because ring-core and race-track FGS were developed, the value of f_0 in the majority of the cases was reduced up to ~1 Hz. By its character MN is similar to flicker noise, for which $\alpha=1$ is usually taken. However our detailed research of MN frequency spectrum for different materials and designs in frequency band up to 1 mHz showed that the value of α for FGM has to be accepted in limits of 0.75...0.8.

Let us emphasize again that in known works the α value was more often accepted to be equal to 1 and even more than 1. This apparently small difference gives principally other results as to the MN power calculation. Really, for $\alpha=1$ equation (2) is transferred to

$$B_{sq} = b_0[f_{max}-f_{min}+f_0 \ln (f_{max}/f_{min})], \tag{2a}$$

what means that the more observation time increases the more noise deviations are approaching to infinity.

But it is not observed in practice - even during one year of observation (what corresponds to $f_{min} \cong 3 \cdot 10^{-8}$ Hz) the zero level of FGM changes in rather narrow limits. This is because of logarithmic increasing of B_{sq} value while b(f) is growing hyperbolically when $f_{min} \rightarrow 0$. That is why even the increasing of b(f) by many orders leads only to moderate growth of B_{sq}.

In order to explain this let us proceed as follows. B_{sq} value is determined on the interval from f_{min} to f_{max}. Its growth when f_{min} is decreased (or, what is the same, observation period T_{max} is increased) is convenient to estimate in relative units. Let us take as comparison base the noise signal with constant density $b(f)=b(f_0)$=const and corresponding B_{sq} value designate as $B_{sq}(T_0)$= = $B_{sq}(1s)$ when f_0 = 1 Hz .

The $B_{sq}(T_{max}) / B_{sq}(1\ s)$ ratio is presented on Fig.1, upper plot for $\alpha = 1$, lower one for $\alpha = 0.8$.

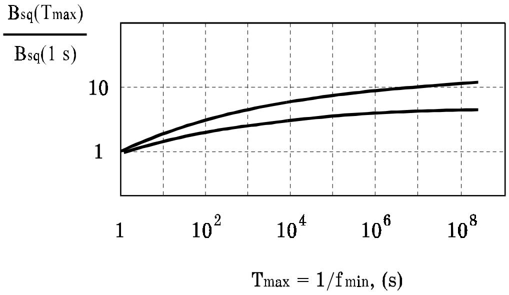

Fig.1. Magnetic noise peak growth with $f_{min} \to 0$

It is interesting to stress that for the observation time equal to 1 day (~86400 s) MN density for $\alpha = 1$ also augments in 86400 times, but B_{sq} is only 8 times higher (Fig.1, upper curve) relatively to uniformly distributed $b(f)=b(f_0)$ density. Correspondingly for 1 year period for which $b(f_{min})/ b(f_0) \approx 3.1\cdot10^7$ B_{sq} augments only in 11 times.

It is seen that for periods from 1 day to 1 year the ratio between B_{sq} values for α=0.8 and α=1 is ~2.2...2.5, what is essential but not coincides with «infinite» growth of b(f).

It follows also from equation (2a) and Fig. 1 that even for 1 year period the calculated value of peak-to-peak MN deflection for typical FGM with $b_0^{1/2} \cong 10$ pT/Hz$^{1/2}$ is in good enough agreement with experimental data obtained in practice - 1...2 nT. Thus, extremely low-frequency MN process obeys to the laws as usual infra-low-frequency ones and expressions (1,2) may be used in the frequency band approaching zero too.

3. EXPERIMENTAL MAGNETIC NOISE STUDY

The frequency band of FGM application or the period of studied signals is usually from some fractions of second up to some years. When MN is discussed, the FGM users mostly name the magnetic noise as the noise in the upper part of the frequency band, whereas MN in the lower part is called «drift». As we showed, both MN and drift are physically the same noise parameters, but in different time domains. In order to have the full impression about temporal noise dependence of the FGM following temporal band share is proposed:

0,1 s - 100 s - flicker noise (f-band);
1 m - 100 m - short-term noise (s-band);
1 h - 30 days - mean-term noise (m-band);
1 day - 365 days - long-term noise (l-band).

Such division of time bands is not arbitrary. It is connected with different possible application area of FGMs. So, f-band noise allows to estimate the FGM applicability for magnetic pulsation study. Also the methodology of noise investigations in this band differs from this in other bands. S-band noise is interesting for the application of FGM for mineral deposits prospecting. M-band is the time periods used for magnetotelluric investigations. And last but not least l-band noise is very important for observatory practice and it determines especially the necessary periodicity of absolute measurements. In all these bands the FGM noise was tested.

The special laboratory equipment developed and installed in LCISR allows to make detailed noise power tests in f-band. The typical time dependence for LEMI-004 FGM noise power spectrum is shown on Fig. 2.

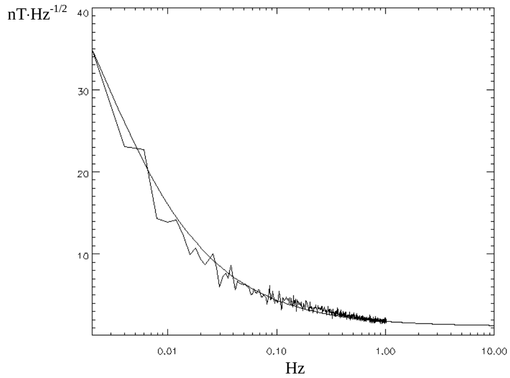

Fig. 2. FGM f-band noise.

Very low value of corner frequency f_c and good noise uniformity at higher frequencies are clearly seen. These tests particularly prove that this magnetometer excellently suits for magnetic pulsation study, the frequencies of which are within f-band.

For the tests in other bands a two-poles low-pass filter was installed at FGM outputs. Both the s-band and m-band noises were tested at Belsk Observatory (Poland), the basic magnetometer of which is of torsion type (PSM). This type magnetometers are especially good in mentioned temporal bands because of inherently low level of suspended magnet own oscillations if the temperature of the environment is strictly stabilized. In Belsk Observatory the temperature in reference magnetometer hut is maintained in the limits within ±0,1 centigrade.

Fig. 3 illustrates the results of s-band tests. The resolution of registration unit was 30 pT/bit only and sampling was made once per second without averaging. Then the LEMI-004 s-band noise was estimated as the difference between output signals of X, Y, Z channels of LEMI and PSM. Special measures were taken in order to eliminate the time shift influence between the samplings of reference and tested magnetometers channels. The 10-minutes intervals were randomly chosen for tests in the day time when the activity of Earth's magnetic field was relatively low. It is well seen that the s-band noise is mainly within ±1 digit or about 50 pT.

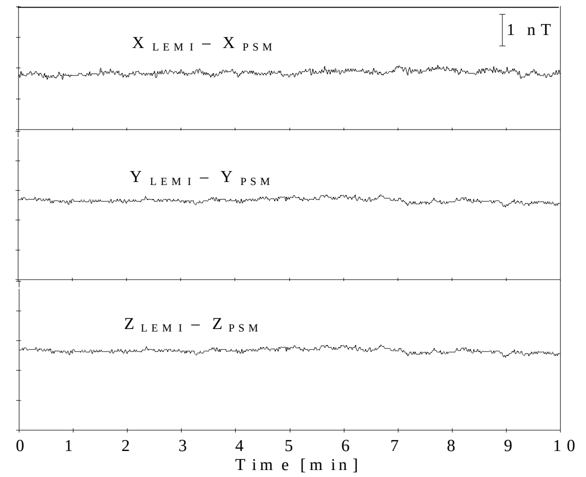

Fig. 3. FGM s-band noise

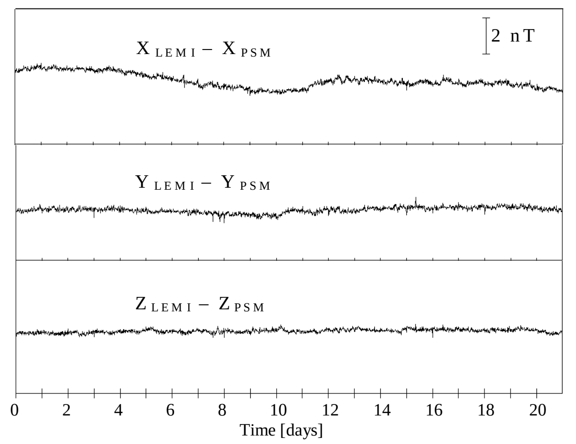

Fig. 4. FGM m-band noise.

The same methodology was used for m-band noise estimation. First the 30-seconds averaging of 1-second samples for each channel was made in the registration unit and then 2-minutes mean was constructed as one point at Fig. 4. The m-band noise for Z-component can be estimated as very good - about 0,3 nT/month. For X and Y components these numbers are about 1.2 nT/month and 0.5 nT/month respectively. But to this it is necessary to make following objections.

First, the tested LEMI-004 was placed outside of reference hut and no special pier and thermal stabilization was used.

Second, for the applied methodology of noise investigation very important is to have as good as possible alignment of sensor components of both reference and tested magnetometers. For Z-component it is possible to have always good alignment, but for X and Y axes to get the alignment error less than 30’ is very difficult. As a result, in the plot for X-components difference we have a trend correlated with Y-component of magnetic field variations and in the plot for Y-components difference - correlated with X-component of the field.

The most complicated is the l-band noise investigation

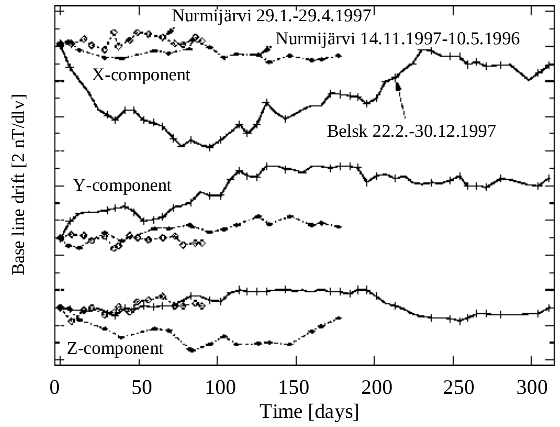

Fig.5. FGM l-band noise.

and not only because it needs very long time. In this time domain absolute measurements only can be the reference for noise calculation. In order to be as much sure in the obtained data as possible these tests were made with different specimens of LEMI-004 magnetometers in Belsk and Nurmijarvi (Finland) Observatories. The results are presented on figure 5 and the marks on the plots correspond to the times of absolute measurements made by Observatory staffs.

Analyzing the results of l-band tests the objections to the precedent results also have to be taken into account. Even without them it is possible to conclude that for all 3 randomly chosen tested magnetometers the l-band noise was within INTERMAGNET standard requirements, i.e., no more than ± 5 nT/year. For the best of them this value was 2-3 times less.

4. CONCLUSION

The present study of flux-gate magnetometer magnetic noise allows to explain some practically observed problems with FGM MN estimation. The given semi-empirical dependence for FGM MN was in good agreement with the results of experimental MN study in wide frequency band.

One important term - noise density constant b_0 - was not analyzed in the paper, but it is necessary to know that this term is essential for B_{sq} r.m.s. value determination at corner frequency f_0. For lower frequencies as expressions (1) and (2) predict the noise increment will be the same for all properly constructed FGMs. That is why to reduce b_0 is the same as to improve FGM parameters. Some practical advices for this are also given in [2].

REFERENCES

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[2] R. Berkman, V. Korepanov and B. Bondaruk. «Advanced flux-gate magnetometers with low drift», in Proceedings of XIV IMEKO World Congress, Tampere, Finland, Vol. IVA, pp. 121-126, 1997.