

New INTERMAGNET Fluxgate Magnetometer

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Abstract

The peculiarities of a candidate INTERMAGNET compatible 1-second magnetometer design are considered and analyzed. A new magnetometer functional diagram, which combines analogue and digital processing, is proposed. The first results of the magnetometer prototype tests are presented and discussed.

1. Introduction

The major part of ground-based magnetometer systems provides digital data as 1-minute means today. They cover, therefore, a spectrum narrower than that provided by the 20 mm/h photographic recordings of the past. This is somewhat in contradiction with the needs of present scientific applications, which require having broadband data, i.e. data with increasingly fast temporal resolution.

To address this shortcoming, INTERMAGNET decided at its Dourbes meeting in 2003 to create a new recording standard based on a 1 second means data acquisition. The first requirements for such a geomagnetic data acquisition system were compiled during an INTERMAGNET survey investigating the needs of the scientific community using geomagnetic time series data (Love 2005). The main consensus of the survey is as follows: geomagnetic data acquired at 1 Hz sampling should have 0.01 nT resolution at least, be filtered by a digital filter and be centered onto the UTC second within 0.01 s.

This large increase in the operational frequency range met some important difficulties, the most serious of which are discussed and addressed below.

2. Requirements to the New 1 s INTERMAGNET Magnetometer

Presently, with even relatively noisy instruments, e.g. with 100 pT/sqrt(Hz) @ 1 Hz, the noise level does not prevent to reach a signal-noise ratio better than 1 in the full operational frequency range when averaging for 1-minute data.

The necessity to measure quicker magnetic fluctuations requires using instruments with much lower noise level – 1 pT/sqrt(Hz) @ 1 Hz and below. As a rule the induction sensors are used for these purposes. But some progress in design of flux-gate sensors gives us expectation to use it also for measurement of magnetic fluctuations within the so called “dead band” at 0.1–1 Hz frequency. So, the new 1-second INTERMAGNET compatible magnetometer should provide an extremely low noise level as compared to other flux-gate instruments.

The decrease of the noise level and preserving the same upper limits of the measured fluctuations automatically require bigger dynamic range of the instrument. The coarse calculations show that even using the internationally accepted 10 pT resolution and the range of measurement ± 5000 nT, the necessary dynamic range is equal to 120 dB. For providing such value, at least a 20-bit ADC should be used.

The other problem which arises is to provide a sufficient level of immunity to manmade (industrial) noise, especially as produced by power lines. Really, in comparison with the 1-minute magnetometer the 1-second one is sixty times closer to 50/60 Hz mains harmonics and the probability of aliasing to the passband is much higher. Moreover, against a background of the lower noise of the instrument the mains interference will be more considerable. The quite realistic estimation of the level of magnetic fields produced by power lines is $A_{50} = (1 - 100)$ nT_{rms}. In order to estimate the necessary suppression factor K of this type of noise two criteria could be used: spectral density cleanliness and wideband signal-noise ratio. In both cases the 50 Hz products could be compared with the magnetometer noise as well as with the geomagnetic variations. Let us approximate spectral density of geomagnetic fluctuations b_g and magnetometer noises b_n by the following expressions:

$$b_g = b_{g0} \cdot \frac{f_0^3}{f \cdot (f + f_1)^2}, \quad (1)$$

$$b_n = b_{n0} \cdot \left(1 + \frac{f_{n0}}{f}\right), \quad (2)$$

where b_{g0} = geomagnetic fluctuations spectral density value at frequency f_0 ; f_1 = corner frequency of the geomagnetic variations (below this frequency the slope of the spectrum decreases to 3 dB/octave); b_{n0} = the magnetometer noise spectral density value at the so-called plateau; f_{n0} = corner frequency, below which magnetometer noises increase.

The wideband signal-noise ratio criterion in the given frequency band can be described by the expression:

$$\frac{B}{A_{50}/K} \geq 1 \Rightarrow K \geq \frac{A_{50}}{B}, \quad (3)$$

where B = level of the signal in the band from $f_{\min}$ to $f_{\max}$. The spectral density cleanliness criterion is given by the expression:

$$\frac{\sqrt{b(f)}}{A_{50}/(K \cdot f_{\min}^{1/2})} \geq 1 \Rightarrow K \geq \frac{A_{50}}{\sqrt{b(f) \cdot f_{\min}}}. \quad (4)$$

The estimations of the suppression factor were calculated taking into account the following values of the parameters: $f_{n0} = f_0 = 1$ Hz; $\sqrt{b_{n0}} = \sqrt{b_{g0}} = 1$ pT·Hz^{-1/2}; $f_{\max} = 0.5$ Hz; $f_1 = 0.0002$ Hz; $A_{50} = 1$ nT. They are presented in Table 1. From this table it follows that the necessary suppression factor of 50-Hz signal could reach 120 dB and more.

Table 1
Estimations of the necessary 50-Hz suppression factor

$f_{\min}$, Hz	SNR		Spectral density cleanliness	
	K1, dB (Magn. noise)	K2, dB (Geomagn. variat.)	K3, dB (Magn. noise)	K4, dB (Geomagn. variat.)
10^{-1}	131	99	60 ... 65	0 ... 61
10^{-2}	123	53	60 ... 75	0 ... 71
10^{-3}	119	9	60 ... 85	0 ... 81
10^{-4}	116	0	60 ... 95	2 ... 91
10^{-5}	114	0	60 ... 105	20 ... 101
10^{-6}	112	0	60 ... 115	40 ... 111

3. The particularities of the magnetometer design

So, the new magnetometer should provide fast frequency response on the one hand, and deep suppression of the mains harmonics on the other hand. In order to fulfil these mutually contradictory requirements we propose the following magnetometer structure (Fig. 1).

The frequency response of the magnetometer itself corresponds to a first order low pass filter. For suppressing 50/60 Hz interferences, the output signal of the magnetometer is fed to an analogue second-order notch filter, which is connected to the input ADC. Optionally an anti-aliasing low-pass filter could be added at the ADC input. ADC output data is going through the linear phase digital low-pass filter and the flow of 10 Hz data is formed. These data enter the PC, where further operations are performed. By applying a 10-Hz data Gaussian low-pass digital filter similar to the INTERMAGNET 1-minute one, the final 1-second data are produced and recorded.

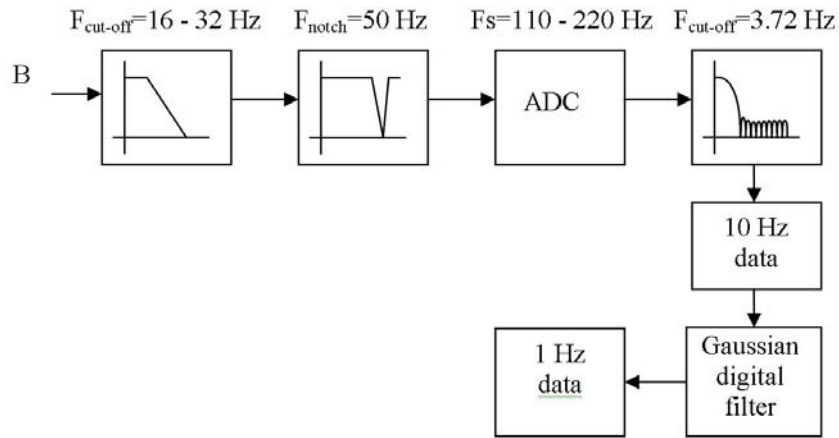


Fig. 1. The new INTERMAGNET compatible magnetometer functional diagram.

The cut-off frequency of the magnetometer analogue channel is selected in the band between 16-32 Hz, which allows preserving the condition of a small (5-10 ms) and linear phase delay in the frequency band from DC to 10 Hz. Such a value of the cut-off frequency simultaneously provides practically negligible attenuation of the measured signals at frequencies below 1 Hz.

The Q-factor of the 50 Hz notch-filter should be relatively high in order to minimize phase delay and amplitude attenuation in the operational frequency range. The calculations show that using a second-order notch-filter with $Q > 10$, the additional phase delay will be no more than 0.4 ms at frequencies up to 10 Hz, and the passband amplitude attenuation may be neglected.

The low-pass digital filter was chosen taking into account the following considerations: linear phase delay, maximal bandpass flatness, zero of amplitude-frequency response at the frequencies 10, 50 and 60 Hz, deep suppression of the signal above 10 Hz. All these requirements are successfully fulfilled by the finite-impulse response filter based on the so-called flat-topped window, which is presented in Fig. 2.

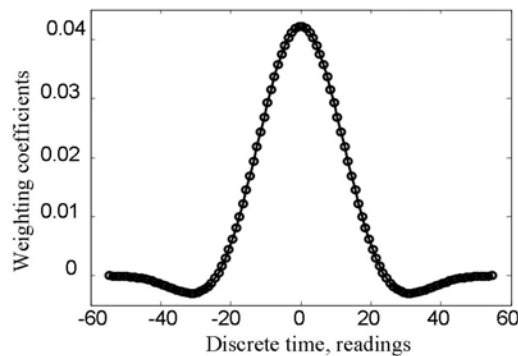


Fig. 2. The flat-topped time window.

The frequency and phase response of the digital filter at sampling frequency $F_s = 220$ Hz are presented in Fig. 3. As it is clearly seen, the filter frequency response has multiple zeros at every multiple of 2 Hz starting from 10 Hz and the maximal level of the minor lobes is less than -81 dB. The cut-off frequency at level -3 dB is equal to 3.72 Hz and the gain errors at the frequencies of 0.5 and 1 Hz are equal to $+0.03$ and -0.103% , correspondingly. The relatively big phase delay is highly linear and stable due to the quartz-stabilized ADC sampling frequency and can easily be corrected for by shifting the data time scale by the corresponding value of 256 ms. The parameters of the magnetometer frequency response are presented in Table 2.

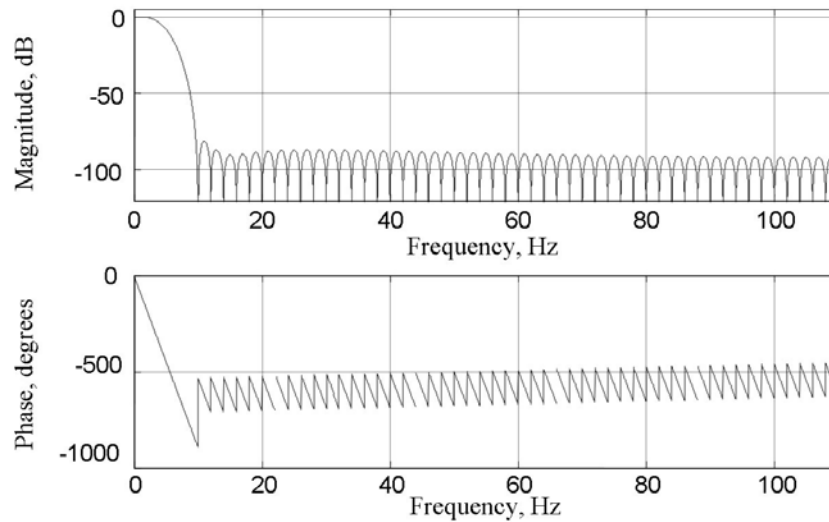


Fig. 3. The frequency response of the digital filter.

Table 2

Total frequency response

Frequency	0.001	0.1	0.5	1.0
Attenuation	0.0%	0.0004%	-0.002%	-0.23%
Phase	-0.093°	-9.22°	-46.1°	-92.2°
Delay	256.12 ms	256.12 ms	256.12 ms	256.12 ms

4. The Results of Tests of New Magnetometer Prototype

The first attempt to realize the proposed functional diagram of the magnetometer was carried out. The prototype was constructed using a magnetometer based on the traditional analogue design and an existing data acquisition system (CAM-unit), which is produced by LC ISR for collecting data from search coil sensors (LC ISR, 2005).

The CAM-unit contains three GPS synchronised 24-bits ADC's, which provide simultaneous analogue-to-digital conversions of all three magnetometer output channels with a sampling frequency of $F_s = 256$ Hz. These data were transferred to the PC, where the on-line digital filtration procedure was performed. The filtered data is then decimated to 16 Hz and stored in the PC hard disk. The functional diagram of the prototype sufficiently corresponds to what is described above (see Fig. 1). To this end, an existing 4-order low-pass filter embedded into the CAM-unit was left in operation. The cut-off frequency of this filter is to 100 Hz which still gave about 6.5 ms of an additional phase delay for signals in the passband.

The prototype was tested at the Dourbes Geomagnetic Observatory of the Royal Meteorological Institute of Belgium. The results of the tests are described below. The frequency and phase response of the analogue part of the instrument (measured at the test point just at ADC input) is presented in Fig. 4.

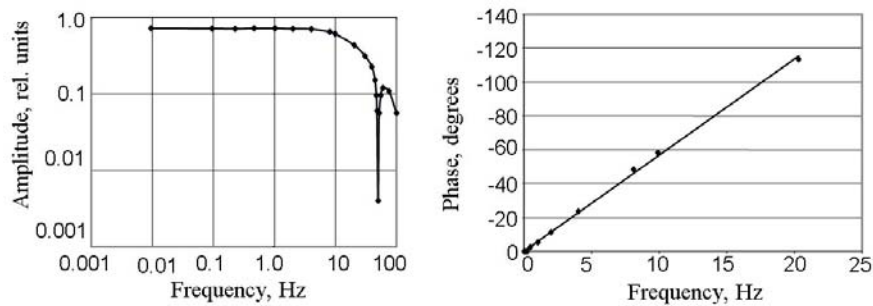


Fig. 4. The frequency and phase response of the analogue channels of the prototype.

The scale factors, range and linearity of the transfer function and noise measurements were carried out using the special facility – the K^{39} full field stabilizer (Fig. 5a), which produces a given magnetic field with high stability and low noise level. It was found that the measurement range of the instrument is equal to ± 3000 nT and linearity of the transfer function is better than 100 ppm for all magnetometer components. The tested magnetometer noise of Z-component in the stabilized field of 44000 nT is presented in Fig. 5b. The standard deviation during a 1-minute record is 0.013 nT. The noise spectra calculated using long time records are presented in Fig. 6. The noise level measured in the full field stabilizer is close to the one measured in the magnetic shield at LC ISR. Some small difference could be explained by the extra noise of stabilizer products at frequencies 0.2 Hz, 0.4 Hz, 0.8 Hz etc.

Such a low noise prototype allowed us to measure geomagnetic variations starting from 0.3 Hz and below, which is in good agreement with Nyquist bandwidth of 1-second sampled data. The executed analysis showed that this design concept allows us still to raise temporal resolution of such a magnetometer till 0.1 second while maintaining the severe INTERMAGNET requirements as to phase shift and filtration parameters. The only improvement which is still necessary is to lower the magnetometer noise below 1 pT.

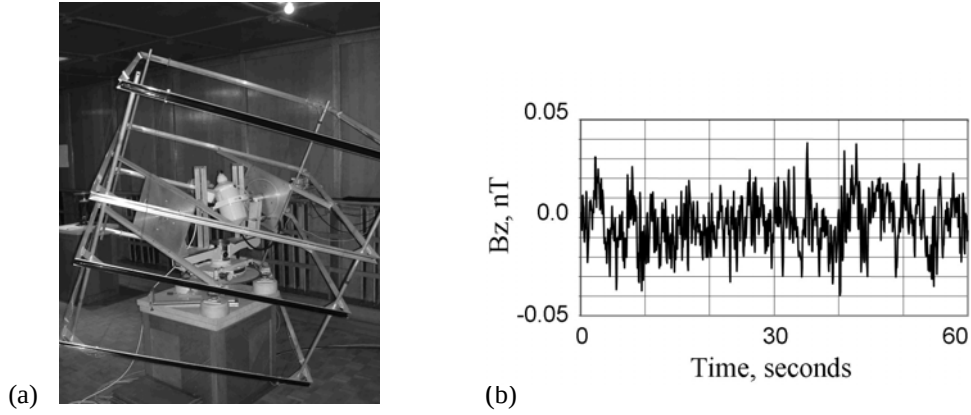


Fig. 5. The K^{39} full field stabilizer and the prototype noise in the stabilized 44000 nT field.

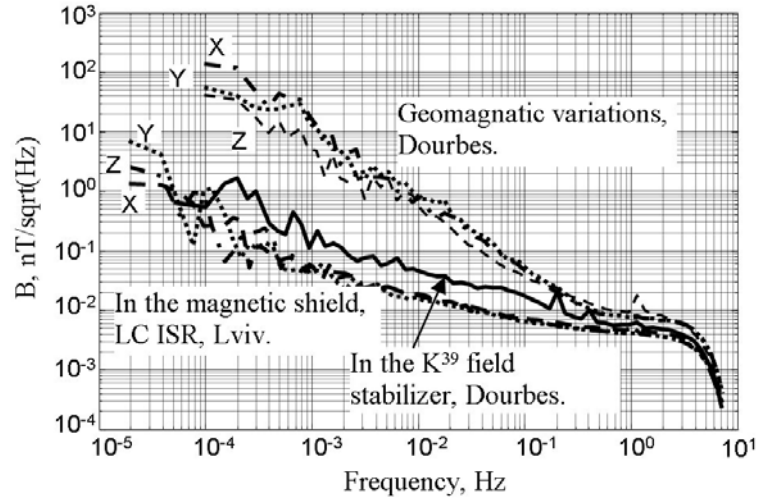


Fig. 6. The spectra of the magnetometer prototype noise and of the geomagnetic variations.

5. Conclusion

The particularities for a candidate INTERMAGNET 1-second magnetometer are considered and analyzed. In order to fulfil the conflicting requirements for its frequency response, a new magnetometer functional diagram, which combines analogue and digital filters, is proposed. Using this approach a prototype was designed, built and successfully tested. The results of the tests demonstrate the possibility to satisfy the specifications regarding the timing accuracy (< 0.01 s error), data resolution (< 0.01 nT) and noise level. The proposed magnetometer could even be used at a 0.1-second sampling, if the minimization of flux-gate sensors noise is provided to the required level. However, it was also shown that the digital filter realized for the magnetometer prototype using an external PC with a corresponding executable is unreliable because of possible errors in the data transmission channel, computer and magnetome-

ter. For the next step it is planned to implement the proposed filtration algorithm into the magnetometer hardware using an high-speed microprocessor. The parameters of such magnetometer and results of its tests will be presented to the observatory community within one year.

References

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- LC ISR, 2005, *Satellite synchronized ULF induction magnetometer set*, <http://www.isr.lviv.ua/LEMI30.htm>, 133 kB.

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