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Hardware Developments to Determine the Transfer Function of a 1-Second Fluxgate Magnetometer

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ABSTRACT

With the introduction of the INTERMAGNET standard for 1-second magnetic data and the development of new fluxgate magnetometers to meet this standard, it has become increasingly necessary to ascertain the transfer function of magnetometer systems.

Here we describe a black box test device developed by the British Geological Survey (BGS), which is based on a principle devised by the Institut Royal Météorologique (IRM), used to determine the timing accuracy, amplitude and phase response of a fluxgate magnetometer. This device was used to evaluate two commonly used systems deployed within INTERMAGNET observatories; the DTU FGE for 1-minute data and the 1-second standard Lemi-025. Here we also describe tests carried out to determine the noise characteristics of these magnetometers.

The test methodologies and results are presented, alongside previously presented timing measurements for comparison and validation of the test device.

Keywords: Magnetometer, Transfer-function, Timing, 1s- standard.

INTRODUCTION

Now that the specifications for INTERMAGNET 1-second data have been defined and manufacturers are releasing products that claim to meet this standard, it has become increasingly important for INTERMAGNET Observatories (IMOs) to independently ascertain the transfer function of their instrumentation and to not solely rely on the manufacturer's claims.

To aid IMOs in this, BGS has designed and constructed a simple to use calibration device that can be used by non-technical staff and without the need for any specialist external equipment. The device is designed to be used in conjunction with a Helmholtz coil and to make use of the linear least squares parameter estimation method developed by IRM (*Rasson, 2008, 2009*) by outputting an accurately time-stamped periodic signal, or by outputting a time-stamped step signal, a Fast Fourier Transform (FFT) tool can be used to analyse the impulse response of the system.

DEVICE SPECIFICATIONS

To accurately test the timing characteristics of a 1-second standard fluxgate magnetometer the absolute time accuracy relative to UTC of any used calibration device must be of an order of magnitude above the 10ms time-stamp accuracy laid down by the INTERMAGNET 1-second standard. To achieve such accuracy the device designed by BGS utilises the 1 Pulse-Per-Second (1PPS) TTL output from a Garmin 18LVC GPS receiver in conjunction with a PIC18F45K20 8-bit embedded microcontroller to give a measured timing-accuracy of less than 1μs for any output signal.

The external Helmholtz coil with inductance (~2 mH) and resistance (~74 ohms) is designed to easily fit over any fluxgate magnetometer sensor without perturbing the setup and has a measured time-constant of less than 30μs with a -3dB point of 5.9kHz with a scale value of 448nT/mA. The combined time-delay and time-constant of the calibration device and Helmholtz coil is easily an order of magnitude above the 1ms requirement of a 1-second magnetometer calibration test system.

The embedded microcontroller controls all functions of the calibration device: it reads in and stores the NMEA string from the GPS in a temporary buffer; it constantly monitors for the 1PPS and derives its timing accuracy from this; it controls a 20x4 Hitachi LCD to display time/date and user input information; it drives the output signal to the coil with an adjustable amplitude between 15mV & 500mV, corresponding to an applied field of between 90nT & 3000nT; it inputs user parameters by means of push-button switches.

The device has an internal 12V battery, whose voltage is displayed on the LCD and can also be run from a 12Vdc external power supply. A green LED indicates the presence of the 1PPS and flashes every second when the GPS is acquired. A blue LED indicates the on/off state of the output voltage.

The calibration device can be used to either output a periodic square wave with period, amplitude, start date/time and number of cycles selected by the user, or can be used in step-function mode, where the user can select the amplitude and start & finish date/time.

Figure 1. Calibration Device

Whilst in output mode, the device will constantly check for the presence of the 1PPs and, if lost will terminate the test run, displaying an error message with the number of test cycles completed (in periodic mode), or the finish time in step mode.

The time, date and acquisition status of the GPS are constantly displayed on the LCD and an error message is displayed if the GPS is disconnected or if no valid GPS signal has been acquired.

TIMING TESTS

To validate correct operation of the device, tests were carried out on two commonly used fluxgate magnetometers in IMOs (the DTU FGE-K and the Lemi-025), using two differing techniques; FFT analysis of the system impulse (*Shanahan, 2009*) and least squares parameter estimation of a periodic signal (*Rasson, 2008, 2009*).

A 24-bit Earthdata PS6-24 seismic digitiser, sampling at 200Hz was used in conjunction with the calibration device in step response mode with an applied step size of 100nT to determine the phase and amplitude response of the FGE-K fluxgate magnetometer by using the impulse response method. The FGE-K was tested with and without the RC low pass filter (LPF) on the output stage.
Figures 2 & 3 show the phase and amplitude response, which compare favourably with the results carried out by Shanahan using a FGE-J fluxgate electronics and Guralp DM24 digitiser, again showing that with the removal of the RC filter the group-delay remains constant and linear within the pass band range.

Note the presence of 50Hz mains signal in the response, highlighting the need for adequate anti-aliasing filtering to ensure that this signal is not folded back into the pass band range.

The impulse method was not used to analyse the Lemi-025 as the magnetometer acquisition system digitises the signal and outputs at too low a sample rate (10Hz & 1Hz).

In total four time series tests were carried out on the DTU FGE-K and Lemi-025 magnetometers as per the Rasson method at periods of 4, 8, 16 & 32 seconds to determine the timing and amplitude responses, with the results presented in Figures 4 & 5 and Table 1.

Results for the FGE-K fluxgate correlated with those of the impulse test shown in Figures 2 & 3. The Lemi-025 tests indicate that the group-delay and amplitude response for all tested time periods meets the INTERMAGNET 1-second standard (10ms and -3dB).

NOISE TESTS

To quantify the instrument noise of the two fluxgate magnetometers, each type was tested in turn in a near zero magnetic field for four hours within a custom built mu-metal shield with a specified external signal attenuation of 114dB, shown in Figure 6.

Each magnetometer was configured to output at 1 sample per second. The Lemi-025 was tested as the complete delivered unit, with its own custom built 24-bit digitiser. The ADC used for testing the FGE-K fluxgate noise was an Earthdata 24-bit digitiser designed for seismic applications. The ADC is a delta-sigma modulator with a dynamic range of over 150dB, primary sample rate of 192 kHz and consists of a Finite Impulse Response (FIR) digital filter with an out-of-band attenuation of 120dB.

The Noise Power Spectral Density (NPSD) is calculated using the Welch-Periodogram method used by Shanahan (2009). A total of 14, 2048 point sections were averaged with Bartlett windowing applied. The Discrete Fourier Transform (DFT) was then produced using the FFT algorithm with the negative frequencies folded into the spectrum to obtain the total noise power.

The NPSD results for the FGE-K fluxgate compare favourably with the parallel method tests on a FGE-J conducted by Shanahan (*2008*), showing a total RMS noise (up to the Nyquist rate of 0.5Hz) of 0.04nT. The difference in roll-off rates up to the Nyquist shows the differing filter

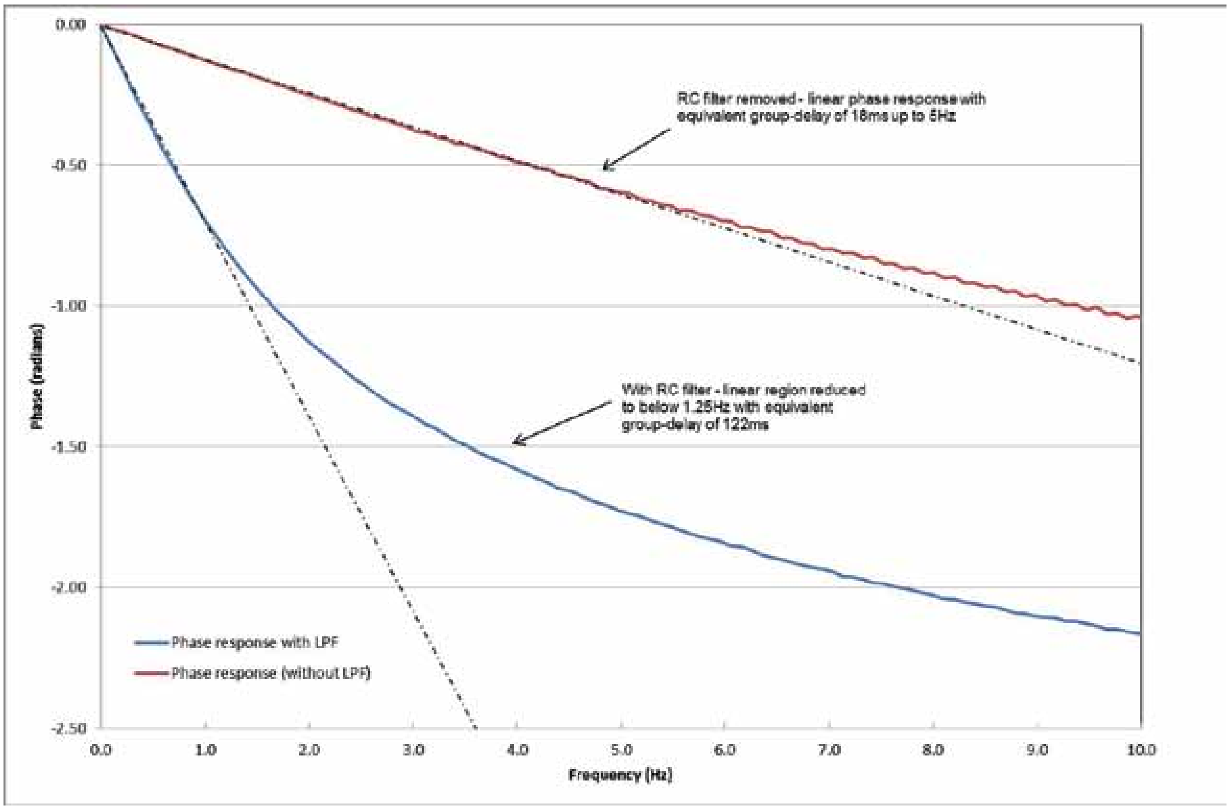

Figure 2. Phase Response of DTU Fluxgate With and Without Output Filter

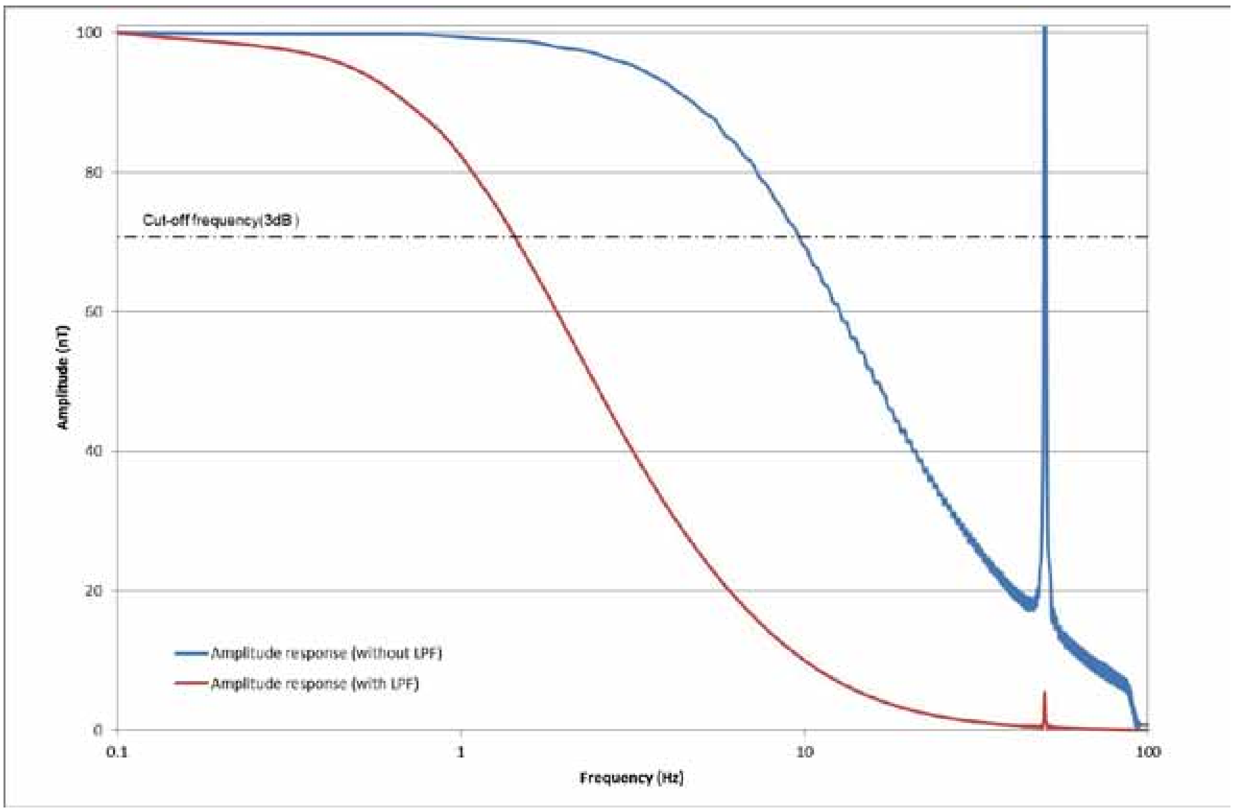

Figure 3. Amplitude Response of DTU Fluxgate With and Without Output Filter

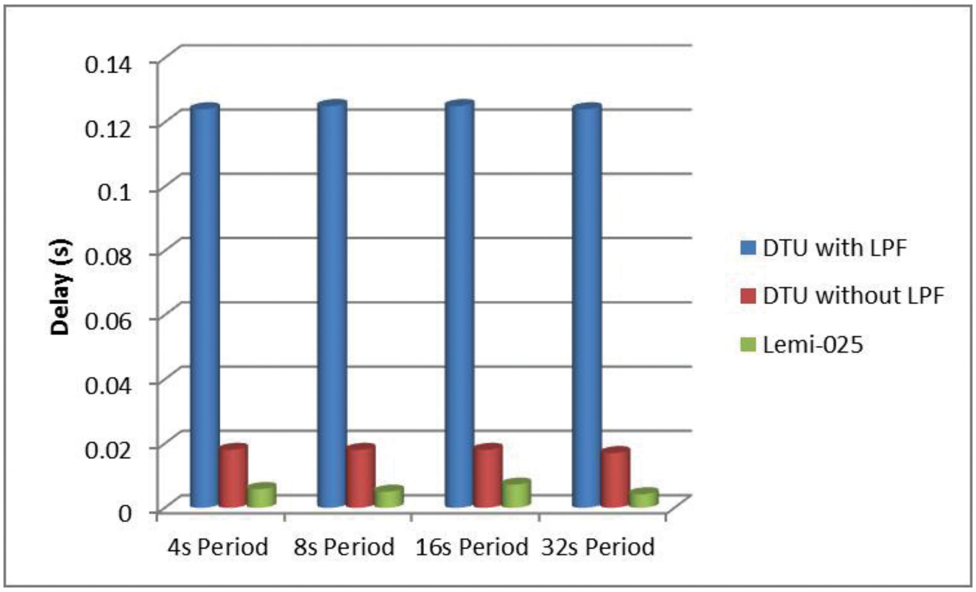

Figure 4. Timing delay of series tests

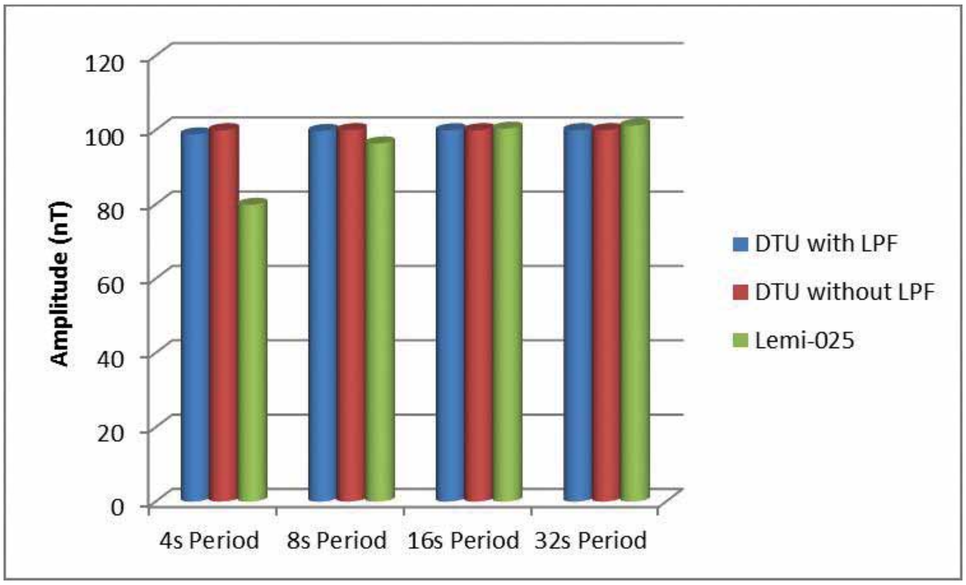

Figure 5. Amplitude Response of series tests

Period (s)	Lemi-025		DTU (with RC filter)		DTU (without RC filter)	
	Delay (s)	Amp. (%)	Delay (s)	Amp. (%)	Delay (s)	Amp. (%)
4	0.006	79.86	0.124	98.81	0.018	99.95
8	0.005	96.35	0.125	99.74	0.018	99.97
16	0.007	100.36	0.125	99.94	0.018	99.96
32	0.004	101.19	0.124	99.96	0.017	99.98

Table 1. Time series test results

Figure 6. Interior view of mu-metal shield pictured without lid

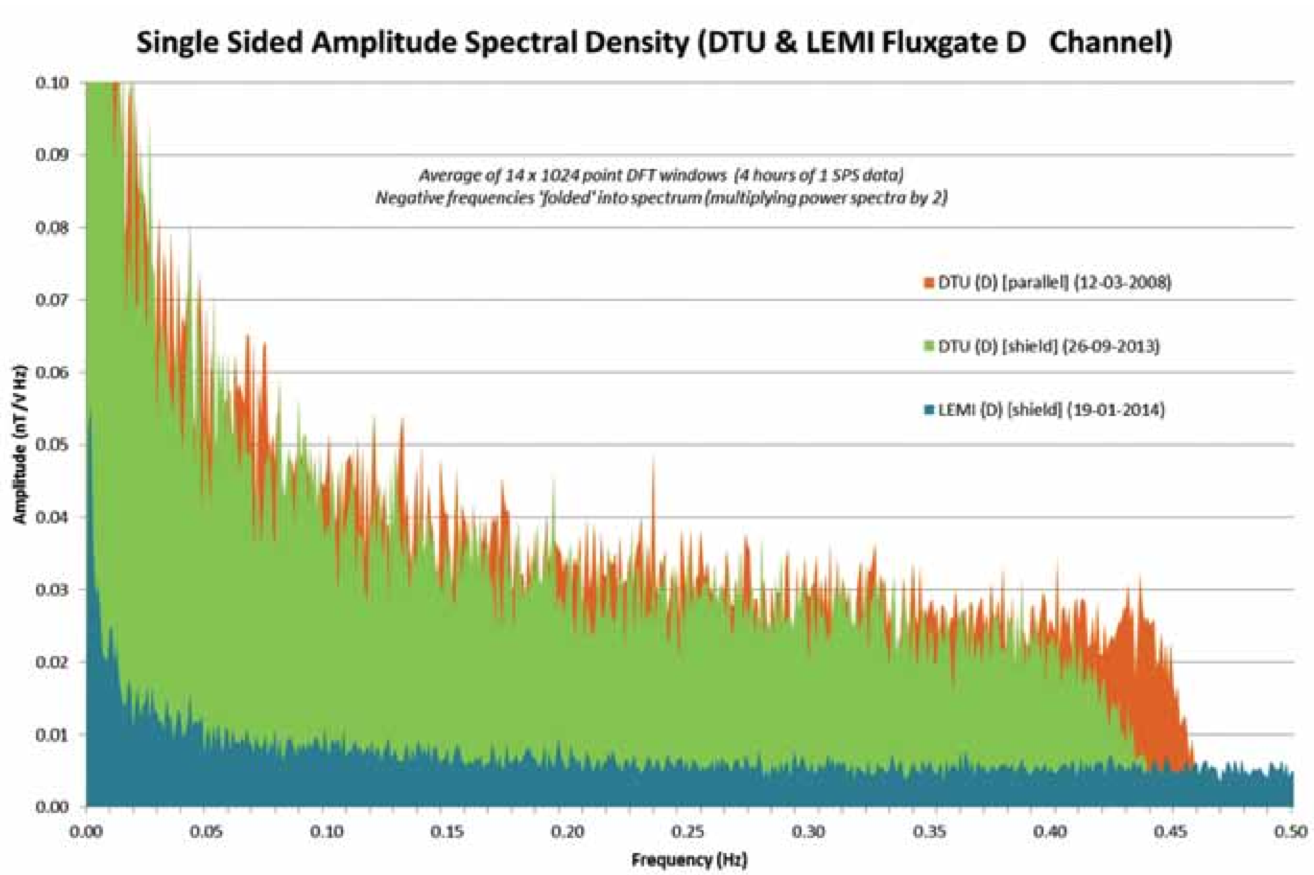

Figure 7. Noise Power Spectral Density

responses of the Guralp and Earthdata digitisers.

The results indicate that the Lemi-025 meets the noise requirements of the 1-second standard with a noise level of 9pT/√Hz at 0.1Hz.

CONCLUSIONS

The hardware we have developed has proved to be an effective testing device to determine the timing characteristics of any fluxgate magnetometer. The device has demonstrated to be easy to use and has delivered comparable and reliable results using two differing testing methods.

The results confirm that with the removal of the RC low-pass filter the DTU FGE-K's group-delay remains constant and linear at a value of 18ms throughout the 1-second standard pass band. With a high enough sample rate on the recording digitiser this group-delay value can be easily time-shifted to meet the - INTERMAGNET time-stamp accuracy standard for one-second data.

The DTU FGE-K meets the 1-second standard amplitude requirements in the pass-band and with additional filtering can be made to satisfy the amplitude requirements of the stop-band. However, as previously determined by Shanahan (*2009*) the DTU FGE, with a noise level of 40pT/√Hz at 0.1Hz does not meet the noise requirements of the INTERMAGNET standard for one-second data.

The Lemi-025 tests show that the unit meets the timing requirements laid down in the INTERMAGNET time-stamp accuracy standard for one-second data, with a group delay for all test periods well below that of the stipulated 10ms. The amplitude results indicate that the Lemi performs well within the pass-band range. However, more tests need to be carried out to fully quantify the unit's performance within the stop-band.

The noise test of the Lemi-025 are promising and indicate that the Lemi meets the INTERMAGNET 1-second noise standard. However, these tests do not measure the long-term stability of the magnetometer and further tests need to be carried out to quantify the long-term characteristics of the Lemi-025.

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