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The FGE Magnetometer and the INTERMAGNET 1 Second Standard

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ABSTRACT

During the years 2012-2014, the Danish Space Center, DTU Space, has developed, tested, and implemented new features of the well known 3-axis FGE Fluxgate Magnetometer. Measurements show that the FGE is suitable for the new INTERMAGNET one second standard thanks to its good linearity and stability, even though the noise in the high frequency band is too large. With a good data acquisition system, such as the Magrec-4B/ObsDaq from Mingeo, it is possible by filtering correctly to keep the time stamp below the 10 ms limit.

Key words: FGE magnetometer, Fluxgate sensors, INTERMAGNET, Linearity, Group delay.

INTRODUCTION

The new INTERMAGNET standard for 1 second data (*Turbitt, 2013*) demands magnetometers with good linearity, high stability and low noise, and fast dataloggers with accurate timing and sharp filtering.
The FGE magnetometer has proven over the last decades to have very good stability and new lab tests show a very good linear frequency response up to 20 Hz.

We have used the Hungarian Magrec-4B datalogger system with ObsDaq v.5.5 A/D converter (ADC) from Mingeo for the tests, since this system can correct delays separately on each channel and can apply the digital filter developed within the PLASMON project. This filter fulfills the new demands for the frequency response: the filter is linear from DC to 0.2 Hz and has more than 60 dB attentuation at 0.5 Hz and above. With the Magrec-4B and ObsDaq ADC, operating at 128 Hz sampling rate and using GPS time synchronization together with proper delay correction for a magnetometer channels, the time stamp accuracy relative to UTC is better than 10 ms.

A new feature for the FGE is the development of an electronic board for differential output of the three components X, Y and Z, which makes it possible to upgrade older FGE systems to use fast seismic dataloggers or similar instruments (like Magrec-4B/ObsDaq datalogger system) in parallel with the old datalogger systems. This gives better noise characteristics, frequency response and timing accuracy.

THE NEW INTERMAGNET ONE SECOND STANDARD

INTERMAGNET has made a new standard for 1 second data describing the demands for magnetometers, data acquisition system, calibrations and observatory practice. These specifications need to be fulfilled to accept data as 1 second data.
These demands can be divided in different groups:

- Linearity: The magnetometer shall be linear in the pass band DC to 0.2 Hz with maximum gain/attenuation of 3 dB and constant phase response less than +/- 10 ms.
- Stability: The demands for stability is the same as the old standard for 1 minute data: Maximum component scaling and linearity error: 0.25 % and maximum component orthogonality error: 2 mrad
- Timing: Data logger system shall have time stamp accuracy better than 10 ms (with GPS time for example) and the data resolution shall be 1 pT which demands a high resolution (24 bit) AD converter.
- Filter: The low pass filter shall be very sharp (starting at 0.2 Hz) and attenuate with minimum 50 dB at 0.5 Hz, which demands a very good digital filter.
- Noise: The pass band noise level for DC – 8 mHz is the same as for 1 minute data: <100 pT RMS. But since the power in the signal for higher frequencies up to 0.2 Hz is very small, the noise level in the band of 8 mHz - 0.2 Hz shall be smaller: ≤10 pT/√Hz at 0.1 Hz.
- Also the maximum offset error between absolute observations should be less than +/- 2.5 nT.

FREQUENCY TESTS OF THE FGE

The transfer function of the magnetometer (both sensor and electronics) can be measured in several different ways. Three parameters are interesting due to the INTERMAGNET demands: linearity, delay and phase. We have chosen two different tests to measure these parameters: a multiple frequency test (MFT) where each frequency is analyzed, and a square wave test with Fourier analysis.

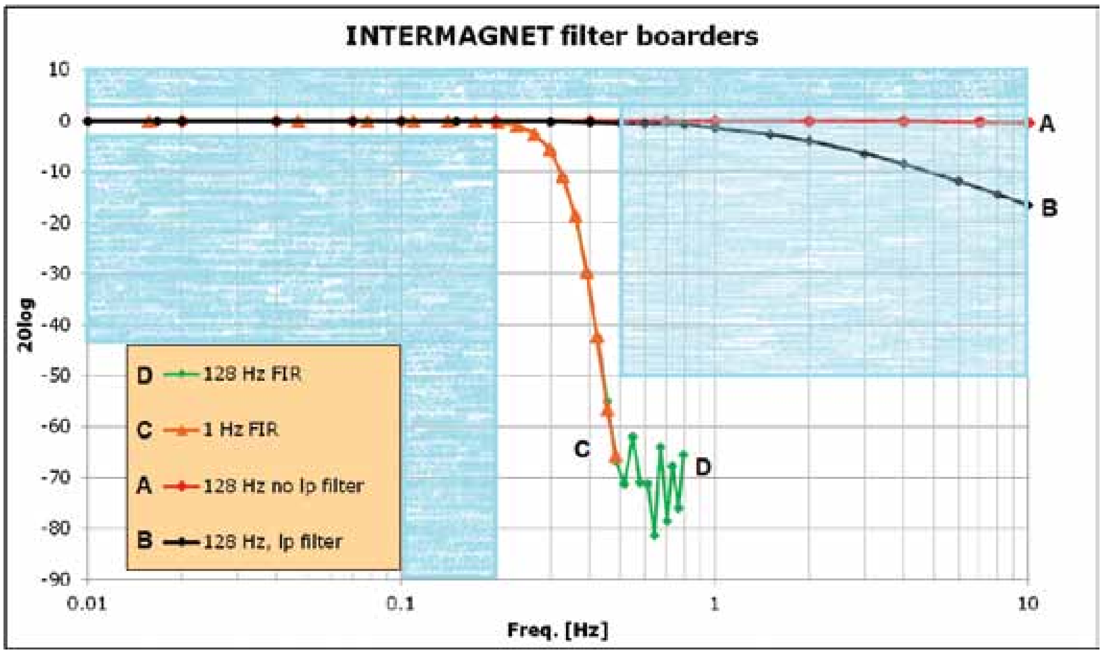

Figure 1. Magnitude plot of INTERMAGNET filter demands. Blue shaded borders mark out the very narrow band between 0.2Hz and 0.5Hz where the INTERMAGNET filter has to attenuate with 50 dB. The four curves show the FGE response with different filtering: A: FGE analog output without any filter, B: FGE analog output with normal 1 Hz lowpass filter, C: FGE analog output with PLASMON FIR filter (1 Hz data filtered from 128 Hz data), D: FGE analog output with PLASMON FIR filter (128 Hz data)

MULTIPLE FREQUENCY TEST (MFT)

In the MFT setup we have placed 3 normal fluxgate sensors in a zero field cylinder with 7 layers of u-metal to cancel out the natural geomagnetic field and noise, such as 50 Hz. In the cylinder the sensors are placed in a coil so we can add different magnetic signals to the sensors from a waveform generator. This generator is controlled by a computer that also collects the data.

A FGE magnetometer electronics measures the signal from two (X and Y) of the three fluxgate sensors, while the third channel (Z) is used for measuring the reference signal from the waveform generator. All three signals are acquired through a newly developed differential output board (DiffOut) and a 24 bit ObsDaq ADC with 128 samples/s rate, and data are stored in the computer. Since the third channel is used as reference there is no need for any synchronization between waveform generator, ADC and computer. The ADC and computer were previously tested with same signal on all 3 channels to verify that all 3 channels are sampled simultaneously. (The ADC used for the tests works without an input multiplexer, as it has three independent analog inputs sampling in parallel).

In each test a number of cosine frequencies between 8.3 mHz (120 s) and 60 Hz with various amplitude and cycles are programmed and executed. For each frequency, the recorded signals are analyzed using a Levenberg-Marquardt-leveling algorithm, the amplitude of the sinusoidal signals are measured for all 3 channels, and the delays between the two sensor channels and the reference channel are measured. From the delays, the phases between X, Y and reference Z are calculated.

Unlike the square wave test mentioned later, this test focuses on certain frequency bands, such as 0.1 Hz – 1 Hz, and analyze it in detail using a large number of frequencies.

Square wave test

The other test used to quantify the magnetometer transfer function is a square wave test.

A square wave signal with the base frequency f_{sq} can be described as a serial of sinusoidal waves with odd harmonic frequencies (1, 3, 5, ..) based on f_{sq}:

$$x_{sq}(t) = \frac{4}{\pi}\left(\frac{1}{1}\sin(2\pi f_{sq} t) + \frac{1}{3}\sin(6\pi f_{sq} t) + \frac{1}{5}\sin(10\pi f_{sq} t) + \ldots\right)$$

This means that if a square wave signal goes through a 'black box', it is possible to find the transfer function of this black box by analyzing the output signal via the FFT. Both gain and phase can be calculated for each frequency, but sample timing has to be very precise to get the right phase. If the amplitudes of the harmonic frequencies are normalized by multiplying with $2k$-1 (1, 3, 5,.) then the gain transfer function of the magnetometer can be found.

Geological Survey of Canada has made a test system for magnetometers called 'GPS Interface Mark 7, variable pulse generator' (*Olfert, 2013*).

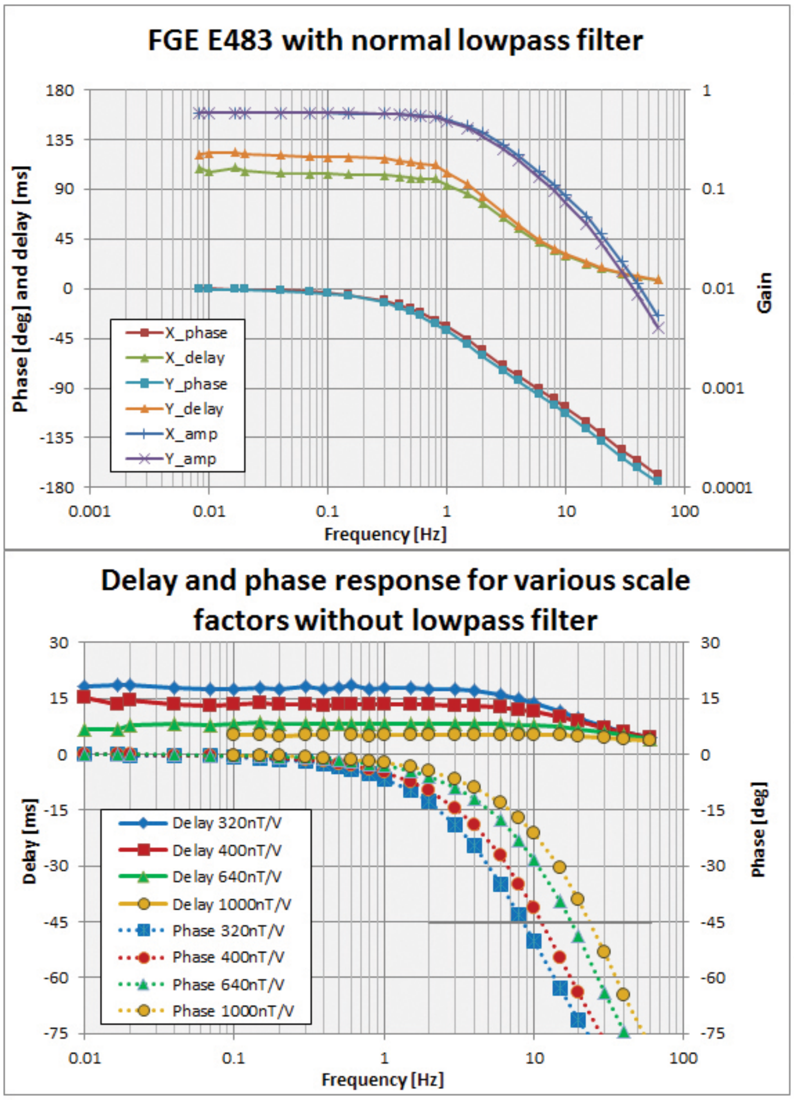

Figure 2. Transfer function of a normal FGE with lowpass filter (upper plot), and delay and phase for various scale factors without lowpass filter (lower plot), all measured with MFT-test.

This system gives a square wave magnetic signal through a coil to a magnetometer at a small distance. It can be used at geomagnetic observatories to test magnetometers without disturbing the magnetometer setup, since the coil is placed close to the sensor without touching it. If the coil is placed in the right angle (45 degrees) close to a 3 axis magnetometer, it is possible to obtain a similar response for all 3 axes at the same time.

The data acquired will be a 'square wave like' signal without the highest frequencies depending on the magnetometers transfer function.

It is possible to analyze data in the frequency domain up to half the sample frequency, so with a normal sample rate of 1 Hz, data can be analyzed up to 0.5 Hz.

It is normally necessary to sample at least 512 seconds of data to obtain a robust result. This is shown in Figure 1 where curve C is data sampled with 1 Hz and the signal is a 64 second long square wave. Curve D is the same square wave signal sampled at 128 Hz, but the data analyzed is the FIR filtered 128 Hz data.

MEASUREMENTS ON THE FGE MAGNETOMETER

Several sets of fluxgate sensors and FGE electronics with different scale factors and filters have been tested in the laboratory at DTU Space using the two test methods.

Most FGE magnetometer electronics produced over the last 20 years have a first order lowpass filter with a cutoff frequency $f0$ = 1.6 Hz (*Pedersen, 2013*), so this has been tested carefully on several different old and new FGE electronics. Since the actual cutoff frequency is determined by the lowpass filter capacitor whose tolerance is 20, $f0$ can change ±20% from its nominal value. A normal test of 2

Table 1. Group delay and cutoff frequencies versus Scale factor

Scale Factor [nT/V]	Delay [ms]	f0 [Hz]
320	18	8
400	14	11
640	9	17
1000	5	25

Table 2. Change in sensor constants over years

	Years between calibrations	Sensor constants changes between calibrations		
FGE no		X o/oo	Y o/oo	Z o/oo
S0100	19	-0.4	0.2	0.1
S0101	20	2.0	-1.8	2.3
S0110	19	0.1	0.0	6.3
S0130	17	-0.2	0.6	-0.1
S0176	14	9.2	-0.1	1.3
S0228	8	0.5	0.3	0.4
S0260	9	4.0	3.6	0.0
S0288	3	0.1	0.0	0.0
S0291	6	-0.6	0.3	-0.9
S0291	1	0.3	0.4	0.0
S0335	3	-0.2	-0.1	0.0
S0336	6	-1.1	-1.1	-0.1
S0373	3	-0.2	-0.2	0.0

Table 3. Change in orthogonality between calibrations

	Years between calibrations	Orthogonality changes between calibrations		
FGE no		X-Y mrad	Z-X mrad	Z-Y mrad
S0100	19	0.1	-2.4	1.9
S0101	20	-0.3	0.1	-3.2
S0110	19	-0.1	3.5	4.9
S0130	17	-0.5	-0.1	0.9
S0176	14	-0.6	-0.2	-0.4
S0228	8	0.4	-0.1	-2.2
S0260	9	0.3	0.3	-0.1
S0288	3	-0.4	0.2	-0.7
S0291	6	0.6	-0.4	0.2
S0291	1	0.1	0.0	0.1
S0335	3	0.2	1.3	0.9
S0336	6	0.5	-0.5	-0.3
S0373	3	0.0	0.0	0.0

or 3 channels in a FGE with lowpass filters mounted can therefore give results with a large spread of delays.

The upper plot of Figure 2 shows the results for 2 channels of the 3 measured parameters in the MFT-test: the amplitude (gain), the phase and the delay. The green and orange curves show that the group delay of X and Y are constant at around 100 ms and 115 ms up to 1 Hz. The cutoff frequency of the lowpass filter is found to be around 1.5 Hz (where the phase is -45 degrees).

Since the group delay can vary 20-30 ms between the 3 channels with lowpass filters, it will be necessary to measure the delay in each channel in each FGE electronic. The measured delay should be taken into account when producing 1 second data conforming the INTERMAGNET standard.

If the lowpass filter is removed from the electronics, then the delay is mainly controlled by the magnetometers gain in the feedback loop. This is actually the scale factor of the magnetometer which normally is set to a value between 320 nT/V and 1000 nT/V. A high scale factor results in a higher cutoff frequency and smaller delay.

The lower plot in Figure 2 shows the result of MFT tests of 4 FGE's with different scale factors all without lowpass filters. The -45 deg points of phase response curves indicate *f0* cutoff frequencies between 8 Hz and 25 Hz, while the delay plots shows group delays between 18 ms and 5 ms. These results are summarized in Table 1.

PERFORMANCE OF THE FGE MAGNETOMETER

The FGE magnetometer has shown its stability over many years use. More than 300 instruments have been setup round the world during the last 30 years, and only 13 of them have needed to be repaired and recalibrated in the last 10 years. The data from these recalibrations shown in Table 2 reveals that the sensor sensitivity changes only a few thousandths between calibrations even after 10 years. Also the orthogonality between the 3 sensors in the marble cube (Table 3) is very stable and the measured changes are only parts of a mrad.

Noise level of the FGE was measured with sensors inside a zero field cylinder. The measured one second data exhibited around 35 pT_{RMS} noise on average. In the 8 mHz - 0.2 Hz band this means about 80 pT/√Hz average noise level density that exceeds the INTERMAGNET specified noise limit at 0.1 Hz. The noise spectrum is not totally homogenous within this range, the amplitude slightly decreases as frequency increases, especially from DC 0.008 Hz to 0.1 Hz, so at 0.1 Hz the noise density can be slightly lower than the average density, but still above the limit.

Despite of the higher noise it is however still possible to deliver 1 second data to INTERMAGNET, since noise is often not the critical issue and it can easily be seen in data.

DATA ACQUISITION SYSTEMS

For INTERMAGNET minute data the sample timing and resolution is not as important as for INTERMAGNET 1 second data. To produce minute data, it is typical to use a slow 16-bit ADC such as the ADAM-4017.

In the new 1 second standard the timing, the resolution and the filtering have become a big issue, and therefore we have tested and used a newer datalogger system from Mingeo in Hungary: Magrec-4B (*Merenyi, 2014*) with a 24-bit ADC called ObsDaq v.5.5 (*Merenyi, 2013*). This is a fast datalogger system supporting a sample rate of 128 Hz or more, so there is no problem with aliasing from 50/60 Hz signals. The datalogger can apply different filtering, including a 2 step FIR filter originally developed for the PLASMON project (*Heilig, 2012*). This filter fulfills the demands from INTERMAGNET, so it was used in most of our tests. In Figure 1 it can be seen how this FIR filter cuts off between 0.2 Hz and 0.5 Hz.

The ObsDaq ADC supports two sampling modes: free-run mode and triggered mode. In triggered mode the sampling is kept synchronized to an external timing signal, for example to a GPS-PPS signal, resulting in very high time stamping accuracy (better than 0.1ms). However, in all of our tests, we used the free-run mode. In this mode the A/D sampling is not synchronized to any external clock and there is some time sliding due to errors of ObsDaq internal clock. At 128 Hz sampling rate, the times of free-run mode samples are slowly fluctuating relative to UTC seconds with up to ± 3.9 ms. Magrec-4B can determine UTC time labels with ±1 ms accuracy for these samples, using its GPS. Depending on the filter calculation method, this ± 3.9 ms fluctuation will result in ± 3.9 ms timing errors in1 Hz data, or it can be corrected by the filter. Even in the first case, the total time stamping error stays below ±5 ms.

With the Maglin software for the Magrec datalogger it is possible to test the delay of each channel, using a GPS controlled square wave signal, like the Canadian system. It is possible to measure delay within ± 2 ms, and these delay values can be stored and used in the datalogger correcting for the delay.

THE NEW DIFFERENTIAL OUTPUT BOARD DIFFOUT

The FGE magnetometers were originally designed with single ended analogue output for the 3 magnetic channels and for the two temperature sensors. This configuration has been adequate until now, but new fast and precise data loggers like seismic acquisition systems often need differential signals.

DTU Space therefore has developed a small electronic board (*Pedersen, 2014*) that can be built into the FGE box and provides differential output of X, Y and Z. Each channel uses high quality amplifiers and arrays of matched resistors to get very good performance:

- Low temperature coefficients below 0.01 nT/Kelvin.
- Linear to much higher than 1 kHz.
- User selected high accuracy gain of 1, ½ or ¼. (Attenuation factor of 1, 2 or 4)

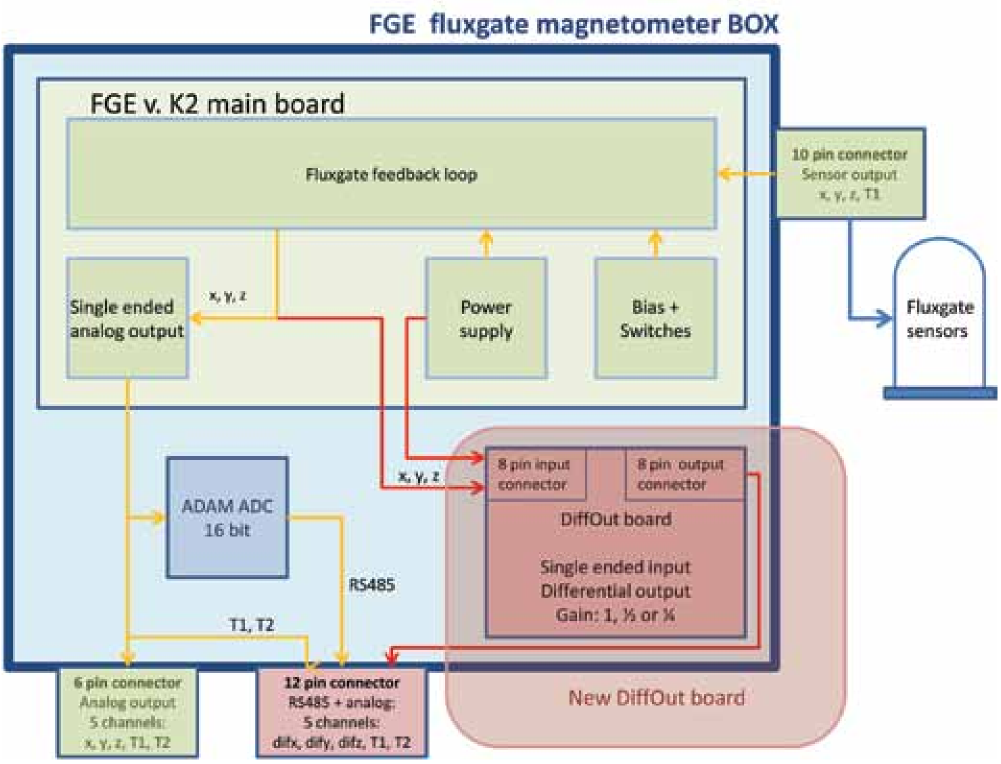

Figure 3. DiffOut board in the FGE box.

- 2 user selectable options for filtering: 1st order lowpass filter or no filter.
- It can run in parallel with the original single ended output.

The DiffOut board is mechanically mounted in the FGE box and connected to power (+/- 15 V) and to ground on the FGE board. The input of X, Y and Z are connected on the FGE board just before the single ended output amplifier, so the signals are the same but without the lowpass filter. The 3 differential outputs and the ground can be connected to a 12 pin connector on the box, as seen in Figure 3.

In this way the 3 magnetic channels can be measured in two independent ways without affecting each other.

CONCLUSIONS

Except for the noise at 0.1 Hz, the FGE magnetometer can fulfill all the instrument demands of the new INTERMAGNET standard for 1 second data:

- Linear from 8 mHz to 1.5 Hz with the original lowpass filter.
- Linear up to 8-25 Hz without filter depending on scale factor.
- Orthogonality between sensors are better than 2 mrad and can be less than 1 mrad.
- Scaling and linearity are better than 0.25%.
- Group delay is stable up to 1 Hz or more.
- Long term stability is very good.

Since the FGE magnetometer is the main instrument in many geomagnetic observatories round the world, and it is not typical or popular to make any changes in a long time running proven system, an important question arises: how the original FGE can be upgraded for the new INTERMAGNET one second standard? Our answers are the following:

- Use better data acquisition systems with faster and higher resolution AD converters, GPS timing control and digital filtering.
- Use parallel acquisition with old and new dataloggers to compare data for a period.
- Determine the group delay of the magnetometer and use this information to correct the timing of the one second data.

The FGE electronics has been sold mostly in two versions: without digital output (only single ended analog output) or with digital output, where a 16 bit ADC is build into the box. Almost all FGE's have the 1st order lowpass filter included.

If parallel acquisition is desired, it is recommended to install the DiffOut board to obtain the 3 channels out in parallel without interfering between the original and new datalogger. With the DiffOut board bypassing the lowpass filter, the delay is low and well known.

If the original output with lowpass filter is used, beware of the big group delay. This should either be measured and taken into account for each channel in the software or should be eliminated by removing the filter capacitors on the FGE main electronic board. Then the group delay can be found in table 1, and it will only vary a few ms.

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