ExpoM - ELF Measurement Procedures: Tips and Recommendations to get the most out of your measurements

1 Interferences from the geomagnetic field

One of the strongest natural sources of magnetic fields is the geomagnetic field, i.e. the static field of the earth that is used by magnetic compasses for navigation. Depending on the geographic location, its magnitude at the Earth's surface ranges from about 25 to 65 µT. In Europe, the average geomagnetic field strength is about 50 µT. Inside buildings and other structures containing steel and iron parts the field can be lower. In most practical situations, the static geomagnetic field is at least one order of magnitude stronger than the fields generated by man-made sources. Frequency selective measurements allow to separate the two contributions.

However, when a measurement device is physically moved through the static field, the sensors measure a different field strength depending on their current orientation with respect to the static field. Therefore, the sensors register a variation in the magnetic field strength, which is measured as any other magnetic field. The quicker the movement of the device, the more difficult it gets to discern movement induced variations from time-varying magnetic fields from other sources. In practice, these movement induced artifacts appear as contributions of up to several microtesla at the low end of the frequency scale. The influence of these artifacts decreases towards higher frequencies. Frequencies above a few 100 Hz are only affected to a low extent.

1.1 Recognizing movement induced artifacts

The presence of movement induced artifacts can be recognized by looking at specific characteristics in the in the time domain and spectrum representation of the measurement. Power lines, transformers and other power installations operate at a fixed frequency of 50 or 60 Hz. The magnetic field generated by these sources can therefore be recognized by very regular oscillations in the time domain signal (Figure 1). In the spectrum, these oscillations manifest themselves as a distinct spike at the corresponding frequency (Figure 1, right picture).

Movement induced magnetic field variations on the other hand are relatively slow and exhibit no clear periodicity in the time domain signal. This results in a spectrum whose power is strongly confined towards the lowest part of the frequency spectrum (Figure 2). In addition, the spectrum is rather continuous and does not show any distinct peaks.

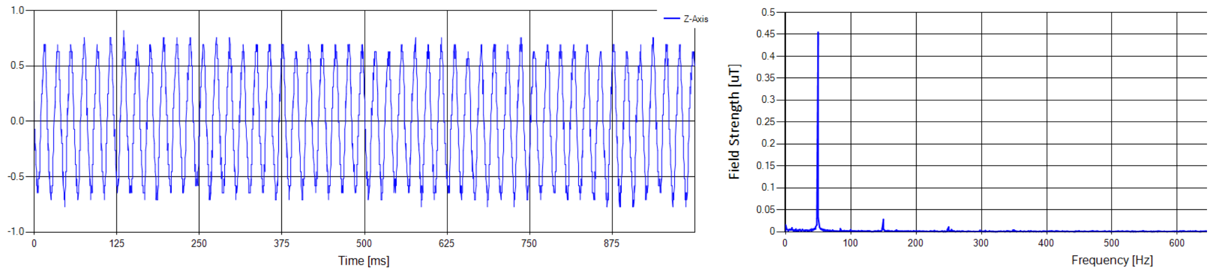

Figure 1: Time domain (left) and spectral view (right) of a measurement with a distinct 50 Hz magnetic field component

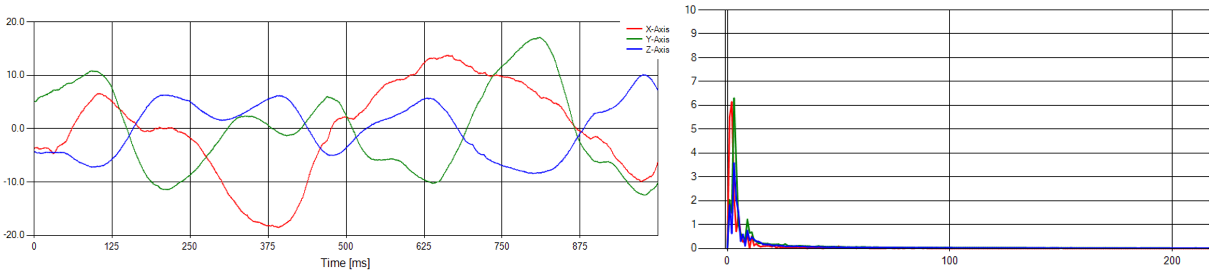

Figure 2: Time domain (left) and spectral view (right) of a measurement with movement induced artifact

1.2 Movement detection using ExpoM-ELF built-in IMU

In order to facilitate the detection of measurements affected by movement artifacts, ExpoM-ELF features a built-in Inertial Measurement Unit (IMU) including an acceleration sensor and gyroscope. Movement induced artifacts in a homogeneous field only occur if the device is rotated within the static field. Translation movement do not have any effect. Therefore, only the gyroscope data (i.e. rate of rotation) of the device is of interest for this topic.

If the IMU is activated in the device settings, the rate of rotation of the ExpoM-ELF device is recorded and stored together with the magnetic field data. It can later be viewed in the single measurement section of ExpoM-ELF utility (see Figure 3). In the example below, a comparison between a stationary measurement (gyroscope sensor noise of less than 0.5 degrees per second) and a measurement while moving the device (leading to an instantaneous rotation rate of up to almost 100 degrees per second) is shown.

Please note that the IMU data can only be recorded for measurement performed in the LF band.

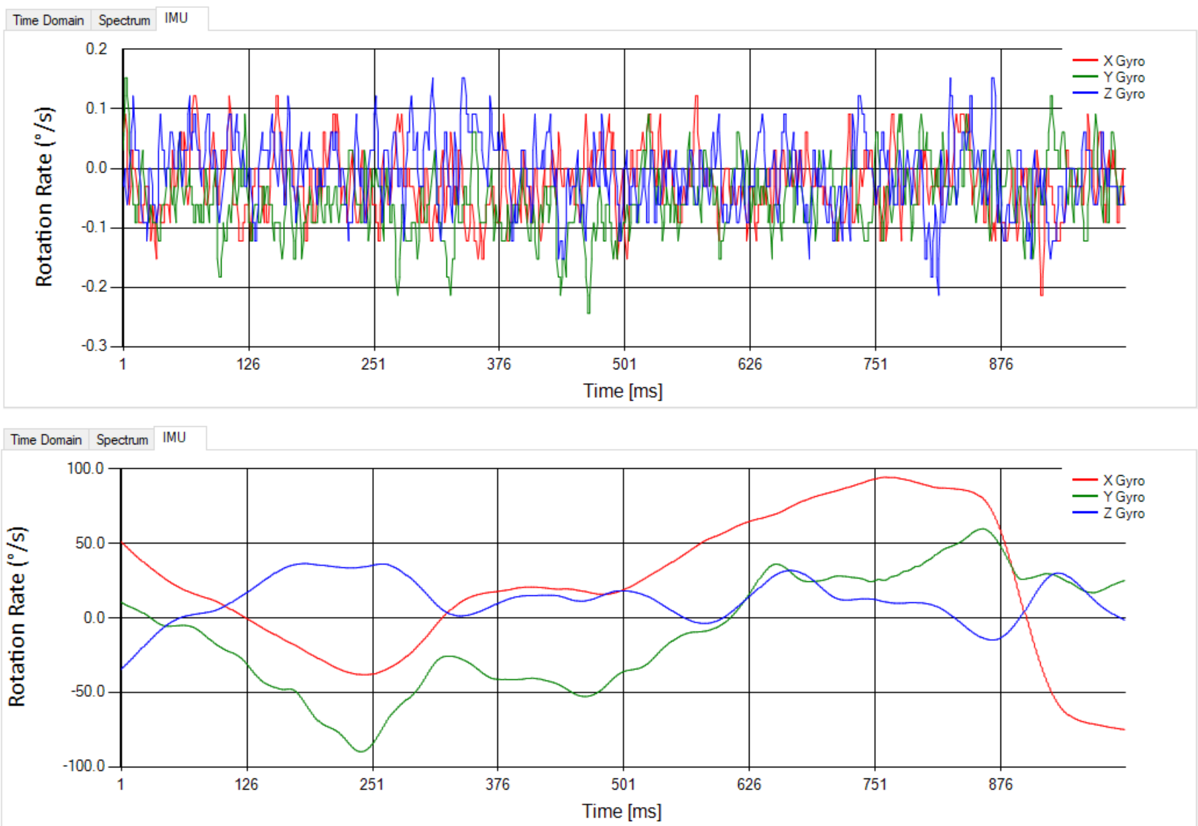

Figure 3: ExpoM-ELF Utility: IMU tab in the single measurement view. The two plots show an example of a stationary measurement (top) and a measurement while carrying and moving the device (bottom).

2 Choosing the best FFT window

The spectrum of the magnetic field measurements displayed in the ExpoM - ELF Utility is computed from the time domain measurements using the Fast Fourier Transform (FFT). The output of the FFT represents the spectrum of the signal in form of a series of amplitudes at equally spaced frequency points (FFT resolution). The FFT achieves the best results when the frequency components in the measured signal are located at an integer multiple of the FFT resolution. If this criterion is not met, The FFT operation may lead to unexpected results. In this section, the most important effects are explained in order to make sure that the user is able to choose the most suitable settings for the visualization of the recorded data.

2.1 FFT windowing

FFT windowing functions can be used during the FFT operation to optimize specific properties of the resulting spectrum. The two principal characteristics that have to be trade off against each other are frequency resolution and amplitude accuracy.

ExpoM-ELF Utility offers three windowing options: The Rectangular window (i.e. no window), the flat top window, and the Blackman-Harris window. The basic characteristics of the tree windows are compared in Table 1:

Parameter	**Rectangular Window**	**Flat Top Window**	**Blackman-Harris Window**
FFT bin width (Hz)	1 / measurement period		
Frequency Resolution (3dB bandwidth)	1.0 x FFT bin width	3.771 x FFT bin width	2.005 x FFT bin width
Equivalent noise bandwidth (ENBW)	1.0	3.771	2.005
Scalloping loss (worst-case amplitude error)	-3.9 dB (36%)	< 0.1 dB (<1%)	-0.8 dB (9%)
Spectral leakage (see 2.3)	Bad	Very good	Very good
Sensitivity (noise floor)	Very good	fair	good

Table 1: Properties of the FFT windowing options available in ExpoM-ELF Utility.

2.2 Scalloping Loss

The rectangular window has a higher frequency selectivity than the flattop and Blackman-Harris window. It is therefore preferable for weak and narrowband signals that fall in the center of the FFT frequency bins. The 3dB bandwidth of the flattop window is almost 4 FFT bins wide.

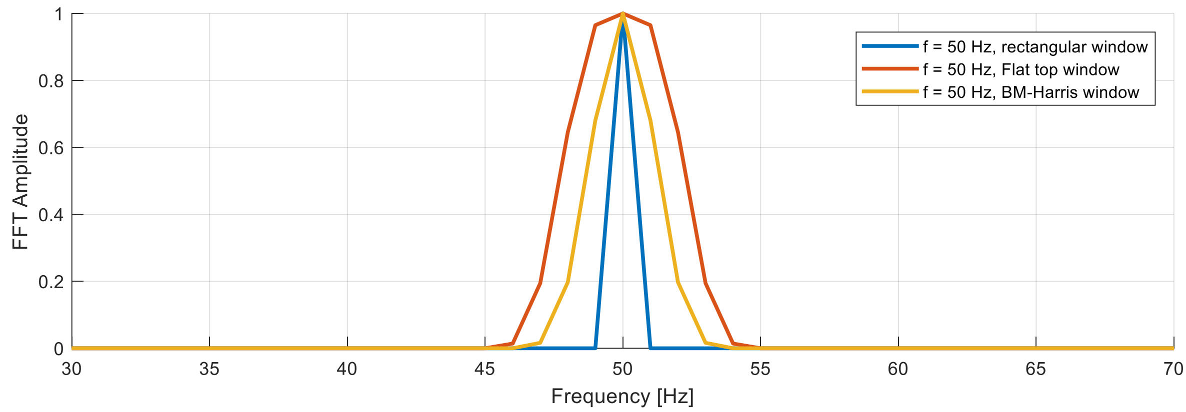

Figure 4: 4096-point FFT of a sinusoidal input at 50.0 Hz. The frequency falls exactly in the center of the FFT bin.

However, the high resolution of the rectangular window comes at the cost of a phenomenon referred to as scalloping loss. If the frequency of the measured signal lies in-between two FFT frequency bins, the signal power is spread among several adjacent FFT bins (spectral leakage). This is shown in the example in Figure 5. As a result, the reported peak signal amplitude in the center bin is too low. The worst-case error occurs for frequencies that fall exactly between two FFT bins. The Blackman-Harris window is also affected by scalloping loss but to a much lower extent. It therefore represents a compromise between frequency resolution and amplitude accuracy.

The flattop window on the other hand is specifically designed to address this issue and exhibits virtually no scalloping loss at all.

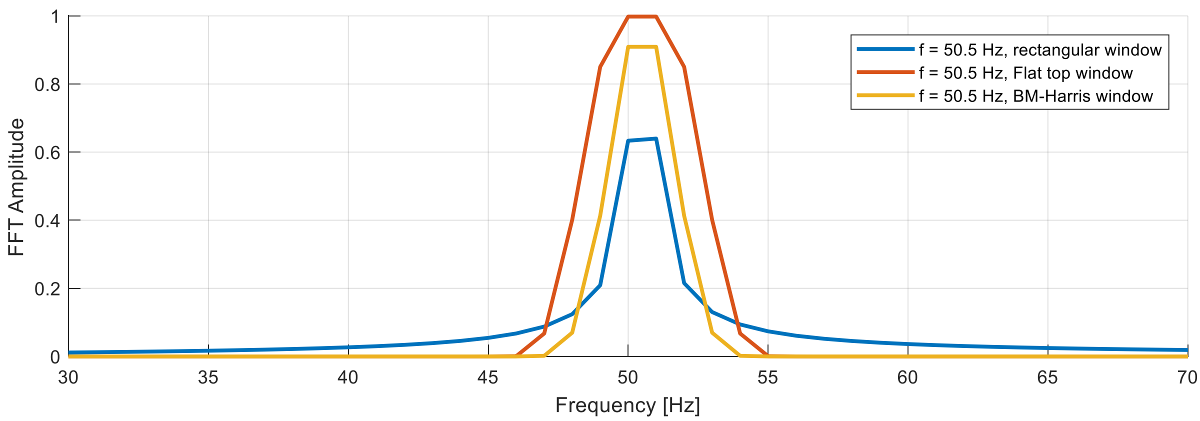

Figure 5: 4096-point FFT of a sinusoidal input at 50.5 Hz. The frequency lies exactly between the 50 Hz and the 51 Hz bin. This represents the worst-case scalloping loss and spectral spreading for the rectangular window. The flattop window is unaffected by this issue.

2.3 Spectral Leakage

As a result of the scalloping loss, the rectangular window exhibits an effect referred to as spectral leakage. The power of frequency components that fall between two FFT bins is not only shared between the two adjacent FFT bins, but is spread over a wider range of bins. This effect can therefore lead to a significant decrease of the sensitivity at all other frequencies. This effect is most clearly visible on a logarithmic scale. Please note that spectral leakage also occurs with most movement induced artifacts. In case of personal measurements when the device is carried by a (moving) person it is therefore strongly recommended to analyze the spectrum using either the flat top or the Blackman-Harris window.

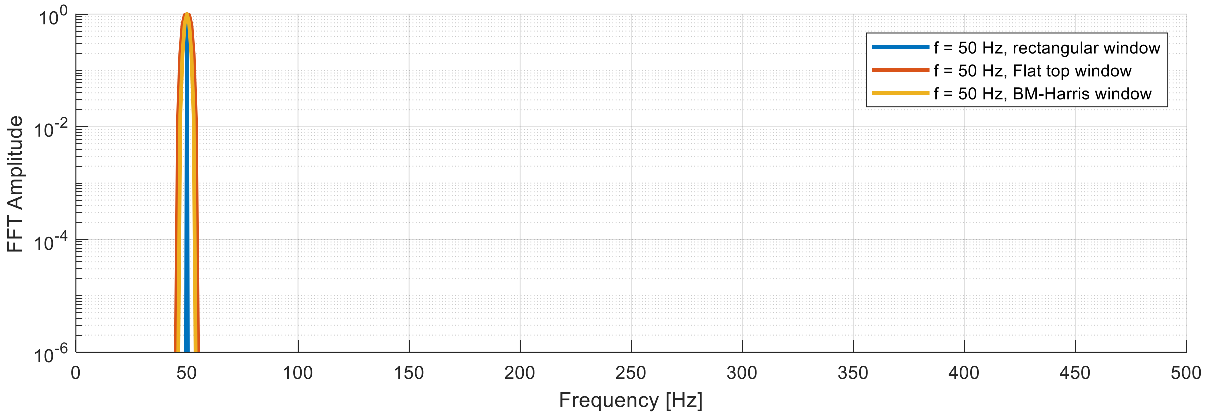

Figure 6: 4096-point FFT of a sinusoidal input at 50.0 Hz without spectral leakage (logarithmic scale).

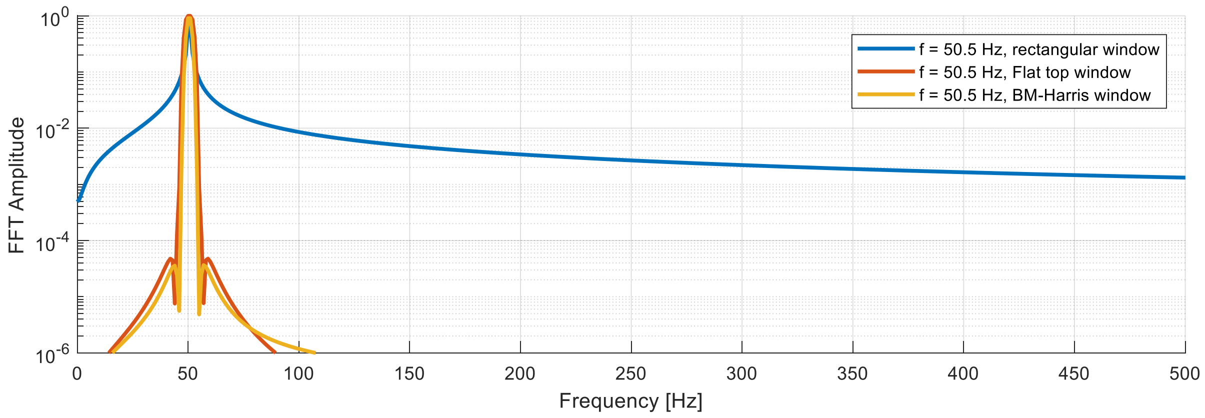

Figure 7: 4096-point FFT of a sinusoidal signal at 50.5 Hz. The spectral leakage of the rectangular window leads to decreased sensitivity at all other frequencies.

3 Recommendations

We can conclude that the best choice of the FFT window depends on the type of magnetic field sources of interest. The flat top window provides the most consistent results in terms of amplitude accuracy independent from the shape of the measured signal. This comes however at the cost of a lower sensitivity and a lower spectral resolution. If the source of magnetic field is known to be at an integer multiple of ExpoM-ELFs frequency resolution (i.e. 50.0 Hz, 134.0 Hz etc.), scalloping losses and spectral leakage can be expected to have a negligible effect on the spectrum. In this case, the rectangular window providing a more detailed and lower noise floor may be the better option. For personal measurements with high potential for movement induced artifacts, the flat top and the Blackman-Harris window provide more consistent results due to their much lower spectral leakage.

Table 2 shows the recommended FFT window for selected use cases of ExpoM-ELF.

Situation	**Rectangular Window**	**Flat Top Window**
Stationary measurements on power lines (50/60 Hz)	**OK**	***OK*** *(less sensitive)*
Stationary measurements including railway power (16.6 Hz)	*reduced amplitude accuracy*	**OK**
Personal Exposure measurements (with movement)	*not recommended*	**OK**
Very low amplitude measurements	**OK**	*(higher noise floor)*
Overview frequency scans	**OK**	***OK*** *(lower resolution)*

Table 2: FFT window recommendations for selected use cases of ExpoM-ELF.

3.1 Spectral power measurements

3.1.1 Wideband measurements

To compute the wideband power within a certain bandwidth of the FFT, the power of the FFT bins within the desired band must be added. To compensate for the effect of the windowing function, the result must be divided by the corresponding Equivalent noise bandwidth (ENBW) of the window:

$$P(BW) = \frac{1}{ENBW} \sum_{BW} FFTbin[i]^2$$

The resulting RMS field strength can then be computed by taking the square root of this result:

$$B_{RMS} = \sqrt{P(BW)}$$

This method assumes that the desired bandwidth is several times wider than the ENBW of the applied windowing function (see Table 1).

3.1.2 Signal amplitude of sinusoidal (narrowband) signals

If the input signal is known to be a sinusoidal signal, it is sufficient to consider just the FFT bin with the highest amplitude without any summing or scaling. Both the flattop and the rectangular window will directly report the correct signal amplitude in the FFT bin closest to the actual signal frequency, except for scalloping losses.

For frequencies lying exactly between two FFT bins, the flattop window will report the same (and correct) amplitude in both the upper and lower adjacent FFT bin (see Figure 5).