Nanometrics
Sensor Calibration

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Nanometrics Systems Engineering

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Revision 5

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1 Introduction:

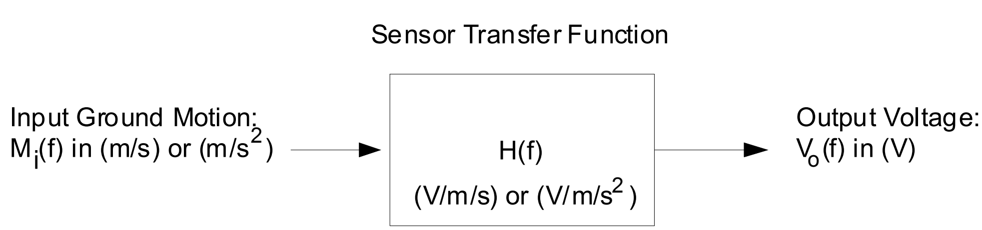
The objective of this document is to explain and demonstrate the calibration procedure of seismic sensors with a particular focus on Nanometrics 24-bit digitizers and the corresponding software tools.

1.1 Background:

In the context of seismology, calibration refers to the procedure that is used to verify or derive the frequency response and the sensitivity of a seismic sensor. Seismic sensors, seismometers (velocity) or accelerometers (acceleration), are transducers that convert ground motion into an electric signal. However, in order to relate the output voltage of a sensor to the actual ground motion that triggered it, knowledge of the sensor transfer function and sensitivity is required. This knowledge allows us to reconstitute and analyze the amplitude and frequency of the monitored ground motion seismic signal.

Typically, calibration serves two main purposes. First, it is used to derive the frequency response of a sensor when this information is missing. In most cases, however, the transfer function of the sensor is known as it is usually provided by the manufacturer. The second and most important motive behind calibration consists of periodically checking the operation of the sensor, and detecting any changes to its known sensitivity and transfer function with temperature and time.

In general terms, the calibration process consists of applying to the sensor a known input signal and observing the corresponding output in order to determine the relationship between the two. Depending on the nature of the input signal and the procedure involved, there exist two types of calibration methods, mechanical calibration and electrical calibration. An overview of these two methods is presented below.



$$M_i(f) = V_o(f) \,.\, H(f)$$

Figure 1: The seismometer transfer function

1.2 Mechanical Calibration:

Mechanical calibration, which is also called absolute or direct calibration, involves exciting the sensor with a known mechanical motion. These tests are usually conducted using mechanical instruments such as shake, displacement or tilt tables, as well as any kind of device that can practically apply a known velocity or displacement to the sensor. These tests constitute absolute as opposed to relative calibration methods, as they are not dependent on any knowledge of the sensor parameters. On the other hand, this advantage is outweighed by the inconveniences associated with the cost, practicality and reliability of such tools, in addition to the fact that the sensors are often installed in underground vaults that are extremely difficult to reach. When performed in the lab, this method fails to detect installation-dependent effects such as the resonances caused by pier coupling.

1.3 Electrical Calibration:

Electrical calibration is an alternative to the mechanical calibration method introduced above. This method consists of exciting the sensor, through its calibration coil, with a known electric signal.

The motor constant of the calibration coil should be listed in the sensor manual. The motor constant is a critical parameter in electrical calibration that defines the transfer function between the voltage across the calibration coil, or the current through it, and the resulting acceleration of the mass. This dependence of electrical calibration on the known value of the motor constant explains why this method is also called relative or indirect calibration.

The most important advantage of electrical over mechanical calibration resides in the fact that electric signals are very easy to generate and measure using more accurate and more cost efficient instruments, as compared to their mechanical counterparts. Conventionally, it is electric calibration that is used periodically to calibrate sensors and perform a routine check on their functionality. Mechanical calibration is prohibitively difficult, and although essential, it is seldom recommended to the user.

1.3.1 Types of Electrical Calibration:

There exist many types of electrical calibration depending on the nature of the excitation electric signal. The most commonly used electric signals are pulses, step functions, random binary signals, white noise and sinewaves of different frequencies. A detailed description of these types can be found in the seismology literature; the following paragraphs, nevertheless, present a brief overview.

Pulses and step functions can be used to extract the parameters of the second order system, namely, the natural frequency and the damping ratio. These parameters are, then, utilized to construct the transfer function.

Alternatively, broadband signals such as pseudorandom binary signals and white Gaussian noise could also be used. In this case, both the input and the corresponding output waveforms should be simultaneously digitized; therefore, two digital channels are required. Their frequency domain spectrum is derived through the Fast Fourier Transform (FFT) algorithm. The sensor transfer function is derived from the relation between the input and output signal Fourier transforms.

1.3.2 Electrical Sinewave Calibration:

The present document describes the sinewave electrical calibration procedure using Nanometrics 24-bit digitizers. The advantages associated with sinewave calibration include simplicity and efficiency. In sinewave calibration no pre-processing or post-processing of the input and output signals is required. Instead, only the amplitude and frequency of these signals need to be known.

In this method, the value of the amplitude response at a specific frequency point is determined by the ratio of output-to-input signal amplitudes. When only the midband sensitivity is required, the test is repeated at 2 or more frequency points selected in the midband frequency range.
On the other hand, when the whole transfer function is to be determined, the test should be repeated at a larger number of frequency points chosen not only in midband but also in the 3 dB and cut-off regions. The larger the number of frequency points the higher the accuracy of the derived amplitude response curve. Selecting 4 points per decade should usually yield a reasonably accurate response plot. One could opt, for instance, for a larger number of points around the corner frequency region, if this is a particular area of interest. In a similar fashion, the phase response can also be constructed by observing the change in the delay between the input and output signals at each calibration frequency point.

An example of the amplitude Bode plot that could be generated using sinewave calibration is shown in the following figure. The example illustrates the frequency points used in the calibration, as well as the passband and the cut-off regions of the sensor.

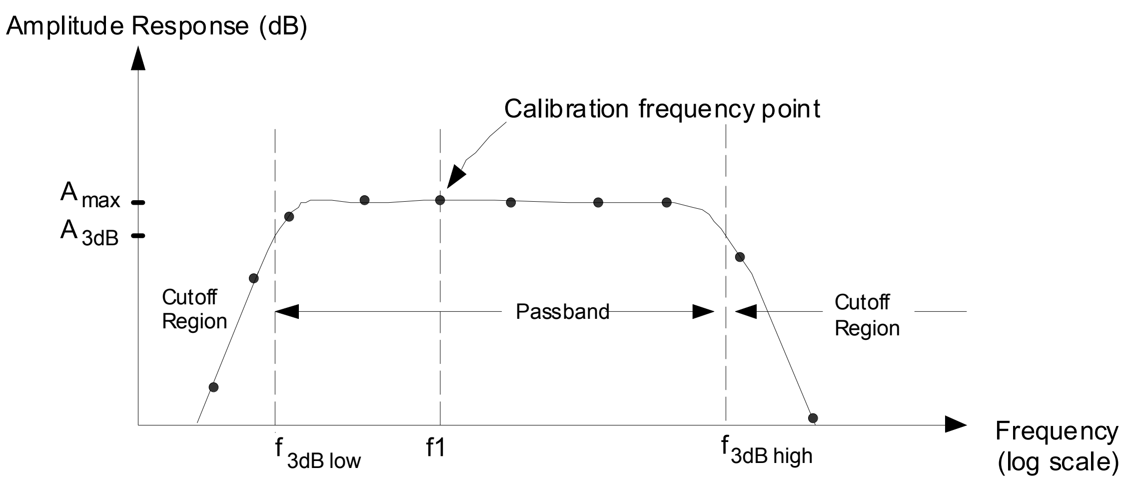


Figure 2: Example of an amplitude Bode plot derived with sinewave calibration

The figure shown below shows an example of an input calibration sinewave signal, and its corresponding time domain steady state output response. The only expected difference should be the amplitude change and the phase shift that reflect the amplitude and phase responses of the sensor at that particular frequency.

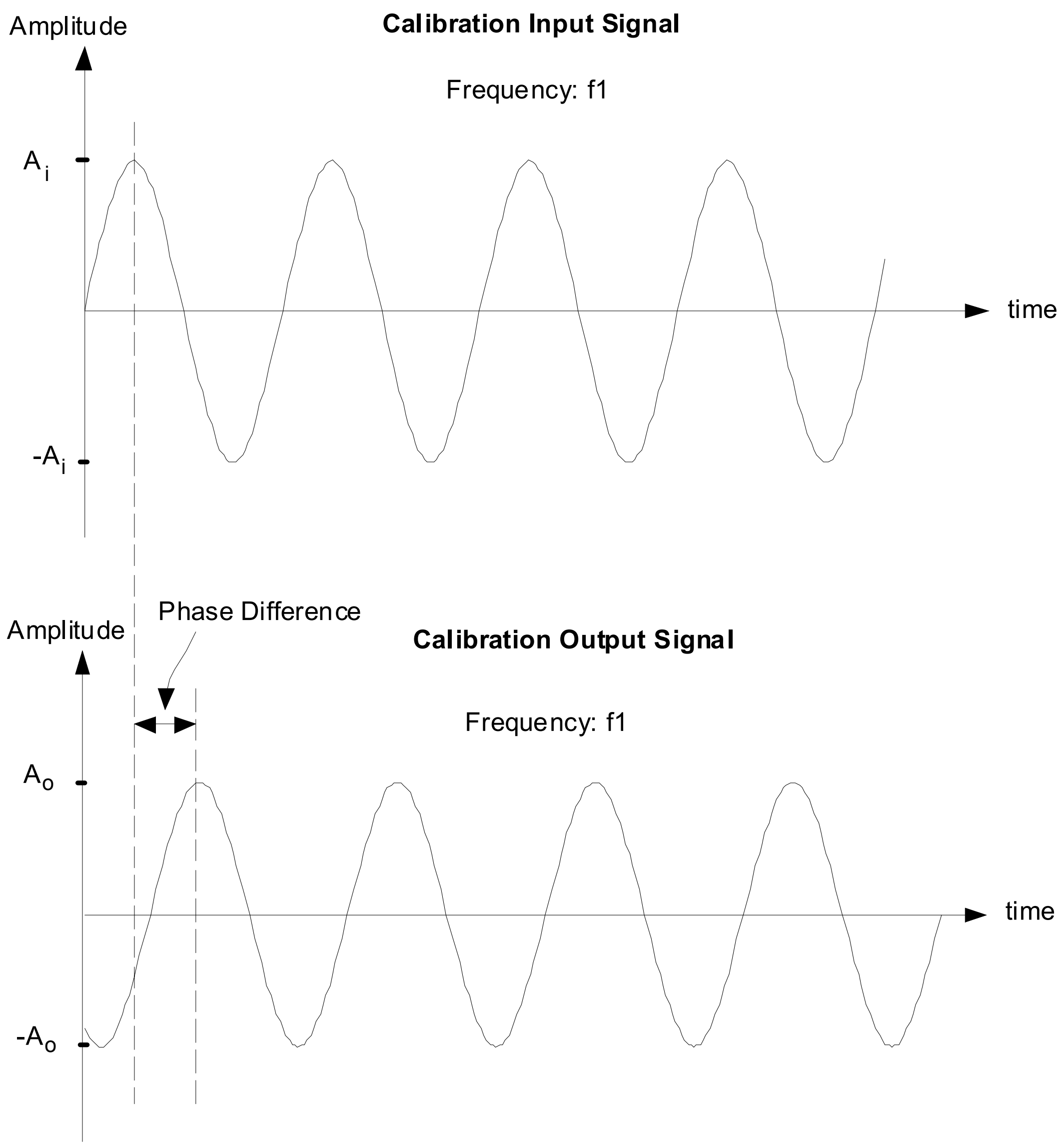


Figure 3: Example of input and output calibration signals

2 The Nanometrics Calibration System:

This part describes the stages of the Nanometrics calibration system. For more details, please, refer to the relevant Nanometrics manuals.

2.1 *Overview of a Typical System:*

A basic understanding of the typical seismograph system including the sensor and the digitizer is crucial to performing a reliable calibration. Both Nanometrics digitizers, HRD-24 and Trident, have built-in calibration circuits that are designed to drive the sensor calibration coil. The following figure shows the different stages of the Nanometrics calibration system.

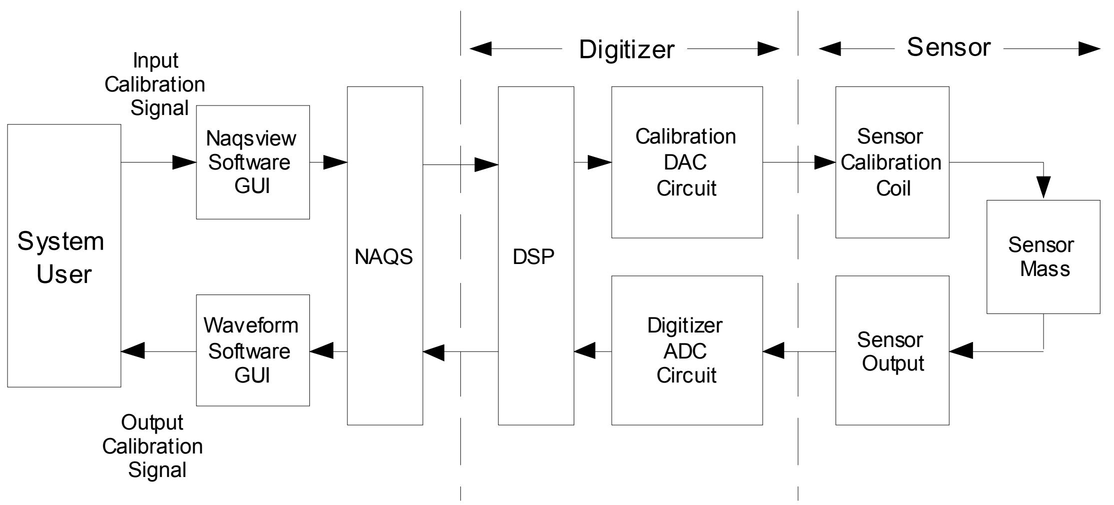


Figure 4: A typical calibration system

The block diagram shown in Figure 4 can be simplified to emphasize the main stages and transfer functions of the Nanometrics calibration system. This simplified model is shown in Figure 5; it will be adopted as the generic model for the remainder of the analysis.

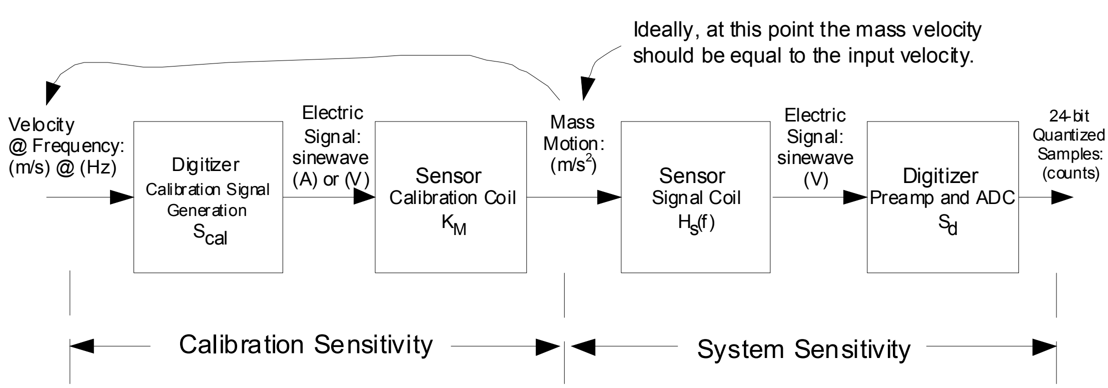


Figure 5: The main stages of the Nanometrics calibration system

The key conclusion here is that the model can only measure $K_M.H_S(f)$ as opposed to $H_S(f)$. The value of $H_S(f)$ is, therefore, derived relatively to the known value of K_M. This dependence on K_M illustrates the difference between relative and absolute calibration.

2.2 Signal Generation:

This block consists of all the digital logic and subsequent analog circuits that transform the ground motion user command, in velocity and frequency units, into the actual electric sinewave signal sent to the sensor calibration coil.

The block includes the following Nanometrics software and hardware components:

- NaqsView graphical user interface (GUI) and calibration software
- Naqs.stn system file with the calibration coil motor constant and the coil resistance parameters
- NaqsServer data acquisition software
- Nanometrics digitizer calibration DSP block, digital-to-analog converter (DAC) and op-amps

The input to the block is a velocity amplitude and frequency command entered by the user through the NaqsView GUI. NaqsView performs the following tasks:

- NaqsView converts the velocity amplitude input (m/s) into acceleration amplitude (m/s^2); this task requires using the value of the input calibration frequency.

- NaqsView also extracts the value of the calibration coil motor constant and the coil resistance from a system file, Naqs.stn, included in the NMX user directory. The software uses these values to compute the amplitude of the electric sinewave signal that is required to generate that acceleration or velocity at the sensor mass.

After the sinewave amplitude has been determined by NaqsView, it is sent in an NMX control packet to the digitizer DSP, along with the calibration duration and the frequency. This is done through the NaqsServer data acquisition software. The DSP issues the control signals required to prompt the digitizer op-amps to generate the appropriate amplitude and frequency sinewave electric signal. The calibration op-amp circuits of the HRD and the Trident are not identical; they will be described and compared below.

The diagram shown below in figure 8 illustrates the sequence of events that occur during the generation of the input calibration signal.

2.3 Calibration Circuits (HRD-24 vs. Trident):

Nanometrics products include two types of 24-bit digitizers, the HRD-24 and the Trident. Both digitizers include a calibration circuit that generates the electrical signal required to perform sinewave sensor calibration. Knowledge of these internal circuits and their input impedances is essential in order to model the calibration circuit and predict its response. The sensor calibration circuit consists, typically, of a coil with an input impedance or coil resistance, Rc, and a motor generator constant, A_m. The coil inductance, denoted L_c, is negligible at passband frequencies. The connection of the HRD-24 and Trident to the sensor calibration coil will be described and modeled as follows.

2.3.1 The HRD-24 Calibration Circuit:

The HRD-24 digitizer calibration circuit consists of an operational amplifier and a 500 Ω input resistance. The corresponding circuit diagram is shown below:

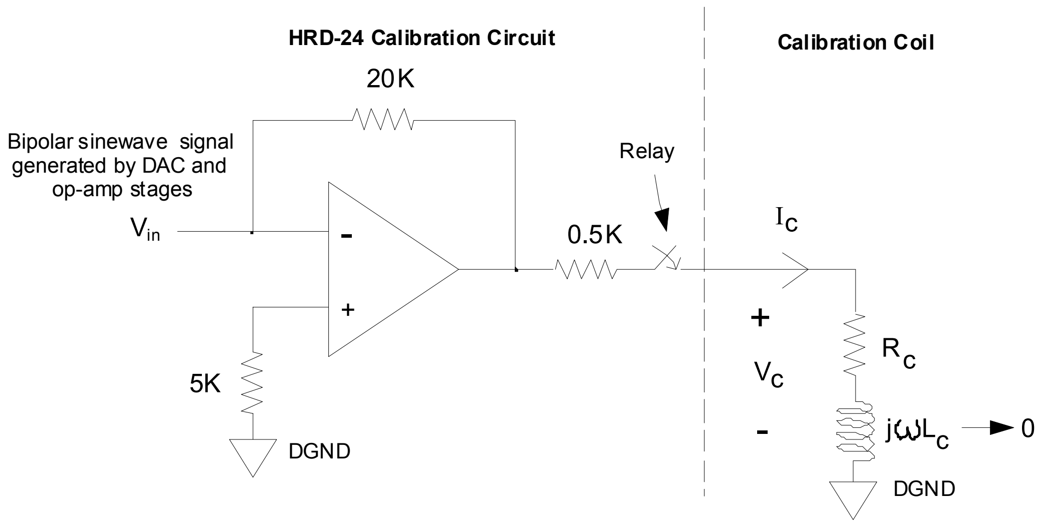


Figure 10: HRD-24 calibration circuit diagram

The above diagram illustrates the calibration circuit for a single channel. The input voltage to the op-amp, V_{in}, is generated by the DSP stage followed by a digital-to-analog converter DAC stage. As explained above, the Nanometrics system translates the calibration velocity amplitude entered by the user into a corresponding voltage sinusoidal signal of amplitude V_C. The computation procedure of V_C takes into account the transfer functions modeled above. The sensor mass is excited by the current I_C generated by V_C through the calibration coil. At steady-state the excited sensor mass is expected to be oscillating at the frequency and velocity specified by the user.

The op-amp driving the calibration circuit operates in voltage mode and can be modeled as a bipolar sinusoidal voltage source. The corresponding equivalent circuit model is shown in the next figure, which also illustrates the case of a 3-channel calibration. Nanometrics digitizers allow the option to calibrate up to 3 coils simultaneously. The output voltage of the op-amp remains constant independently of the number of channels used. A higher number of channels, however, draw proportionally larger currents from the op-amp. Therefore, due to the limited current capability of the op-amp, the maximum attainable calibration signal amplitude is decreased. The value of this maximum signal in velocity units is displayed by NaqsView.

Note: The maximum output voltage, V_{Cmax}, is +/- 5V max.

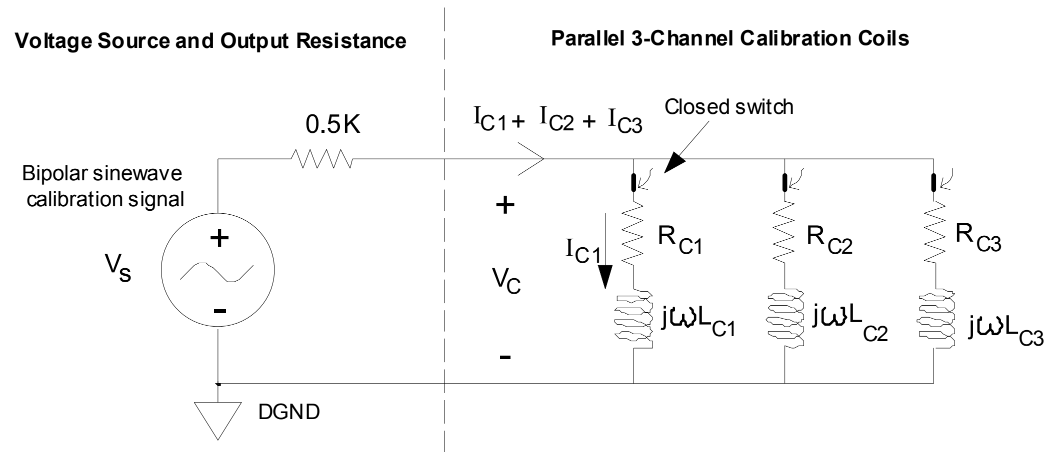


Figure 11: HRD-24 3-channel calibration equivalent circuit

2.3.2 The Trident Calibration Circuit:

The Trident digitizer calibration circuit, unlike the HRD-24, can be operated in the voltage or the current mode. In other words, the HRD-24 calibration circuit is always equivalent to a voltage source whereas the Trident calibration circuit can be configured as a voltage or as a current source. The desired circuit mode is specified by the user in the Libra GUI. Electronic switches controlled by the DSP calibration engine are programmed to result in the desired circuit configuration. The circuits corresponding to both modes are described below.

It is important to note that only one mode, whether voltage or current, is sufficient to perform the calibration of a sensor. The reason behind this is the fact that the calibration coil motor constant can be converted from current to voltage units through Ohm's law when the value of the calibration coil resistance is known. However, in some cases the calibration coil resistance is unknown, which favors the adoption of one mode versus the other.

Even when the calibration coil resistance is unknown, the voltage mode would still be sufficient to perform calibration. This is because the value of this resistance can be derived by connecting the coil terminals to a constant voltage source with a known external output resistance. Circuit theory allows the user to derive the unknown value by measuring the voltage drop across the external resistance. In summary, the current mode is not a necessity; nevertheless, it is a useful option that could facilitate the calibration procedure when the calibration coil resistance is unknown.

Note: Trident voltage and current modes require a different sensor-to-digitizer cable design reflecting the different pin assignment. In voltage mode, the sensor calibration pins are connected to cal+ and analog ground on the digitizer connector, respectively. In current mode, the sensor calibration pins should be connected to the digitizer pins cal+ and cal-.

Warning: The current mode works ONLY if the calibration signal return path goes through the precision shunt resistor at port CAL- (Figure14). This is typically the case of passive sensors. In the case of active sensors, CAL- is used for calibration enable control signals and the calibration signal returns through the analog ground path; therefore, current calibration CANNOT be used.

2.3.2.1 Trident Voltage Mode:

This mode is nearly identical to the HRD-24 voltage mode described above. For the purpose of calibration, the only differences worth noting are the op-amp circuit configuration and the value of the output resistance. In fact, the different op-amp configuration affects only the transfer function of the op-amp circuit, not the equivalent voltage source model shown below in the second figure. The output resistance of the calibration circuit is 0 Ω for the Trident and 500 Ω for the HRD-24. This is the only difference reflected in the equivalent circuit shown below.

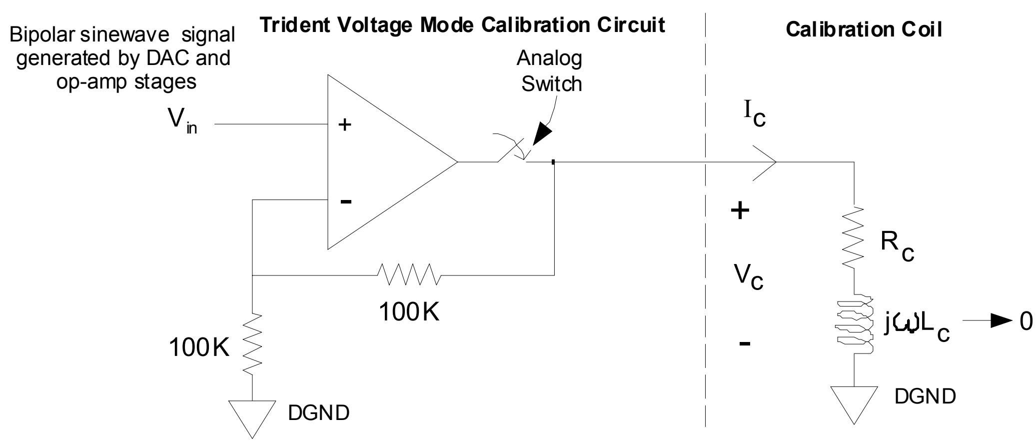


Figure 12: Trident voltage mode calibration circuit diagram

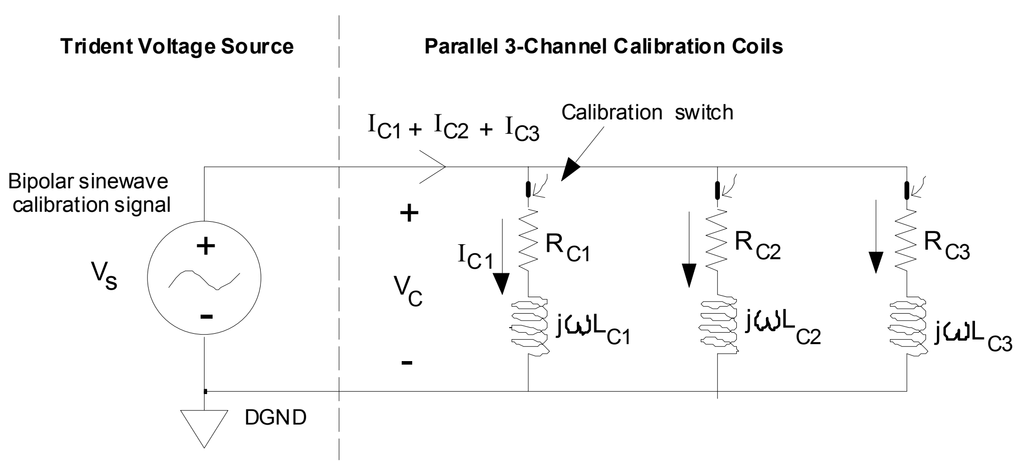


Figure 13: Trident voltage mode 3-channel equivalent circuit

Note: The maximum output voltage, V_{Cmax}, is +/- 5V max.

2.3.2.2 Trident Current Mode:

The current mode option is only available with the Trident digitizer. The Libra GUI software allows the Trident user to choose between voltage and current mode calibrations. Typically, when the calibration coil motor constant is in current units, the current mode is used; and when it is in voltage units, the voltage mode is used. However, this should not be taken as a rule of thumb; the sensor and the cable designs constitute other crucial considerations. The Trident current mode calibration circuit diagram and its corresponding equivalent model are given below.

Note: The maximum output current, I_{Cmax}, is +/- 10mA max.

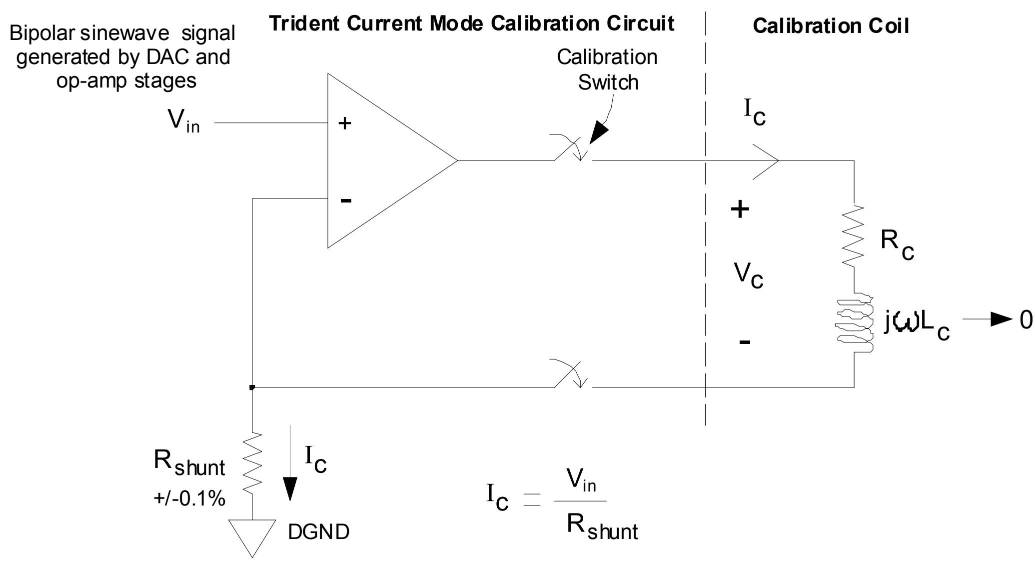


Figure 14: Trident current mode calibration circuit diagram

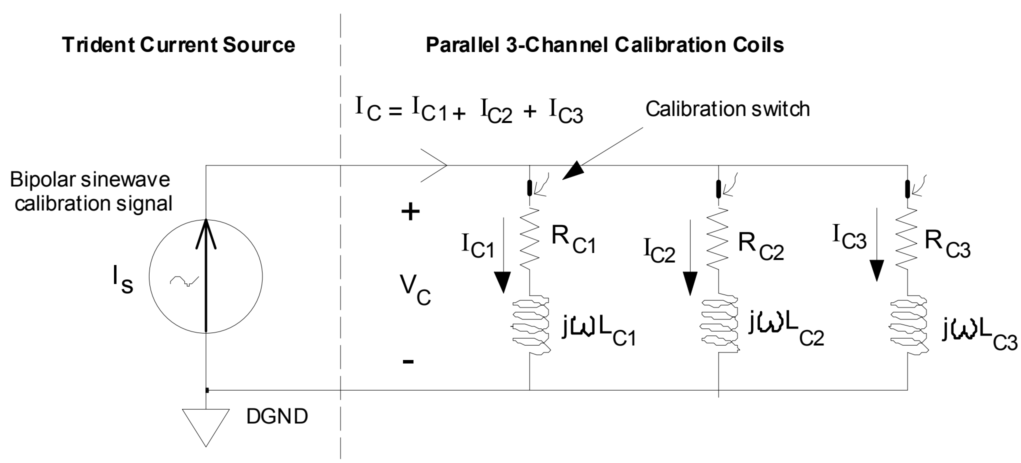


Figure 15: Trident current mode 3-channel equivalent circuit

2.4 *Sensor Calibration Coil:*

The sensor calibration coil is the second stage of the simplified model introduced above.

The input to the calibration coil system is the electric signal generated by the first stage, and the output is a force that is exerted on the sensor mass. According to Lenz's law, the force exerted on the mass is proportional to the current through the coil. At steady-state, a sinewave with frequency f_1 and amplitude A_1 is expected to cause the mass to oscillate at the same frequency, but at an amplitude in (m/s^2) proportional to the current in the coil.

The calibration coil motor constant is the parameter that defines the factor of proportionality between the current and the force. This parameter is usually provided by the manufacturer in the sensor data sheet. It is, typically, expressed in $[A/(m/s^2)]$ or $[V/(m/s^2)]$ where the coil resistance is used to convert between these two units. Sometimes the motor constant is also expressed in units of (N/A), in which case the mass in (Kg) is used to convert to the desired $[A/(m/s^2)]$ or $[V/(m/s^2)]$ units.

2.5 *Sensor Transfer Function:*

This is the third block in the model defined above. It is important to remember at this point that the calibration procedure is attempting to model the transfer function of this particular system. The first two cascaded stages generate a sinusoidal relative acceleration in (m/s^2) that constitutes the input signal to the signal coil. The output, on the other hand, is an electric signal that represents the response of the sensor to the excitation input signal.

Most sensors are linear systems with a flat amplitude response with respect to acceleration or velocity. The response of the sensor to the sinusoidal excitation signal should, therefore, also be sinusoidal with the same frequency, but with an amplitude and phase that reflect the amplitude and phase responses of the sensor at that particular frequency.

It is important to specify the main difference between the calibrations of velocity as compared to acceleration sensors. A velocity sensor or seismometer is characterized by a flat passband amplitude response with respect to velocity. An accelerometer, on the other hand, exhibits a flat passband amplitude response with respect to acceleration. NaqsView allows the user to specify the amplitude of the input signal in velocity (m/s). As a result, when plotting the response curve of an accelerometer, it is always important to remember to convert the amplitude response from velocity to acceleration through differentiation. Otherwise, the derived amplitude response curve will be in units of velocity and will not, therefore, exhibit the expected flat pattern in the passband region.

When expressed in units of velocity, the passband amplitude response of an accelerometer exhibits a 20dB/decade slope that reflects the angular velocity of the input sinusoidal signal. This is illustrated in figure 7 below, which shows a typical response curve of an accelerometer expressed in both acceleration and velocity units.

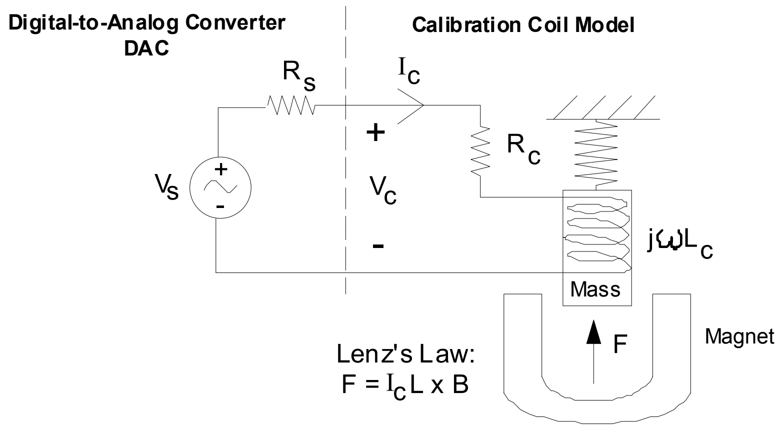


Figure 6: A typical sensor calibration coil

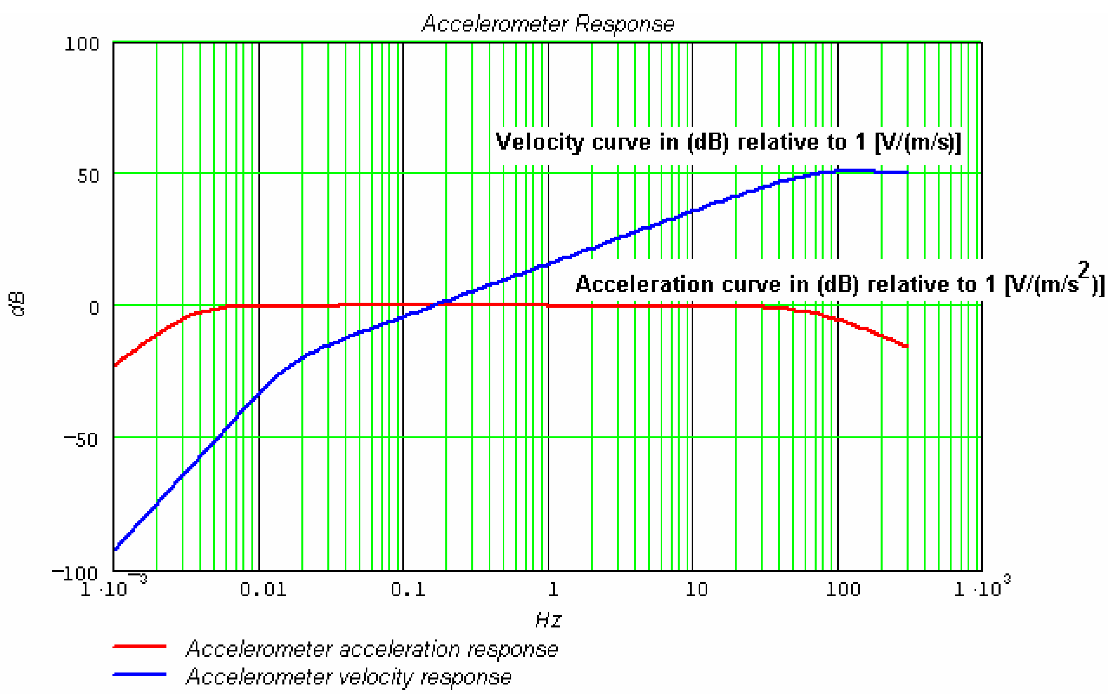


Figure 7: Accelerometer normalized velocity and acceleration response curves

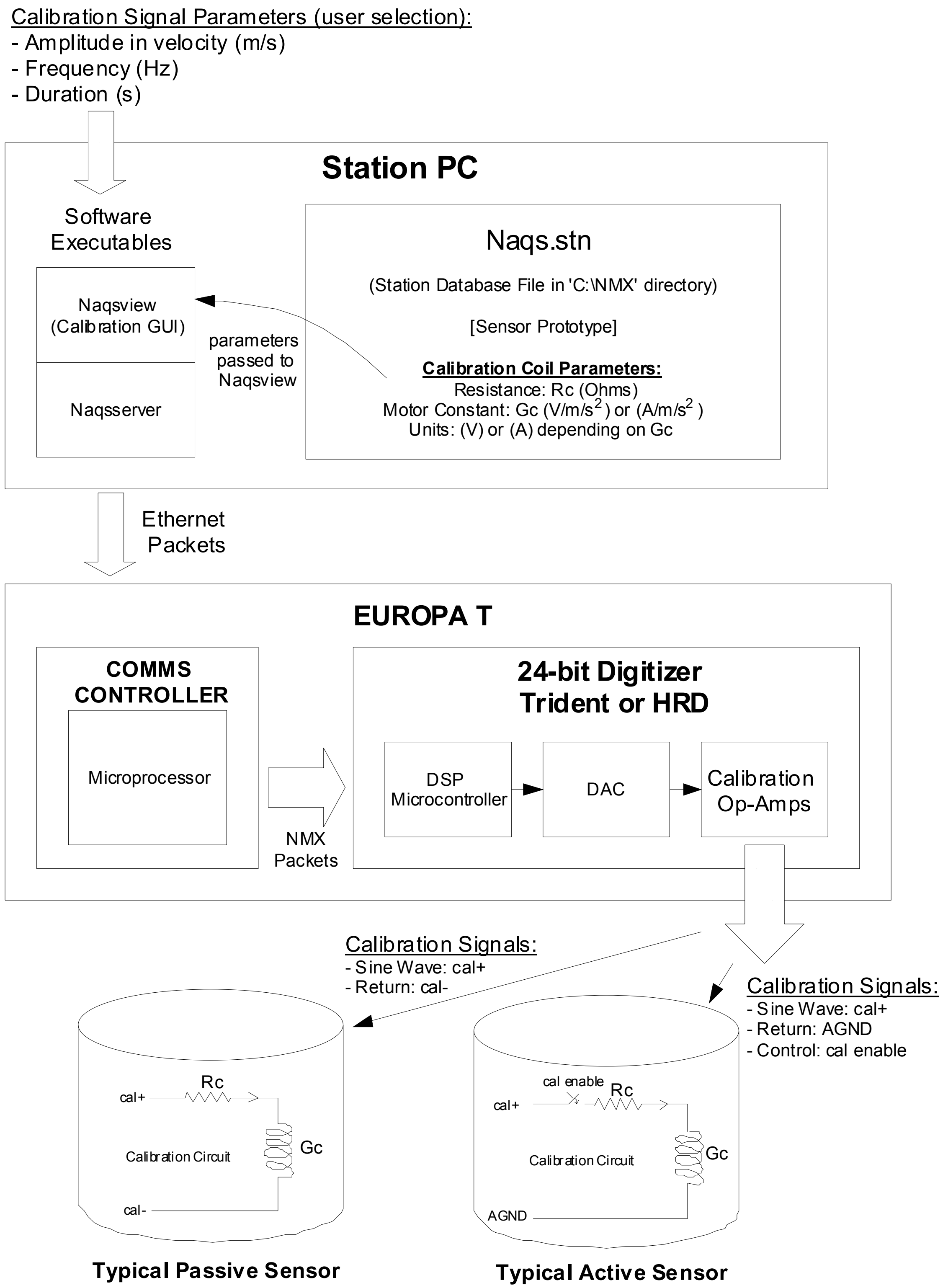


Figure 8: The signal generation process

2.6 Digitizer:

The system formed by the digitizer preamplifier and analog-to-digital converter constitutes the final stage of the calibration model. The role of this stage is to sample and quantize the output signal of the sensor under calibration.

The digitizer sensitivity is an important factor that should be taken into consideration at this level. This sensitivity specifies the number of quantized levels (counts) allocated to map an input voltage level of 1 (μV); it is expressed in (counts/μV). It is reasonable to assume that the amplitude response of the digitizer up to 80% of the Nyquist frequency is flat and equal to the digitizer sensitivity. In other words, the sampling frequency should be set to at least 2.5 times the calibration frequency in order to ensure that the signal is located in the flat midband region of the digitizer response curve. Such a sampling frequency, however, yields only 2.5 samples per calibration period. In order to be able to observe graphically the output samples and measure the amplitude of the expected sinewave signal, a minimum of 5 samples per calibration period is required. Therefore, **the sampling frequency must be 5 times the calibration frequency**.

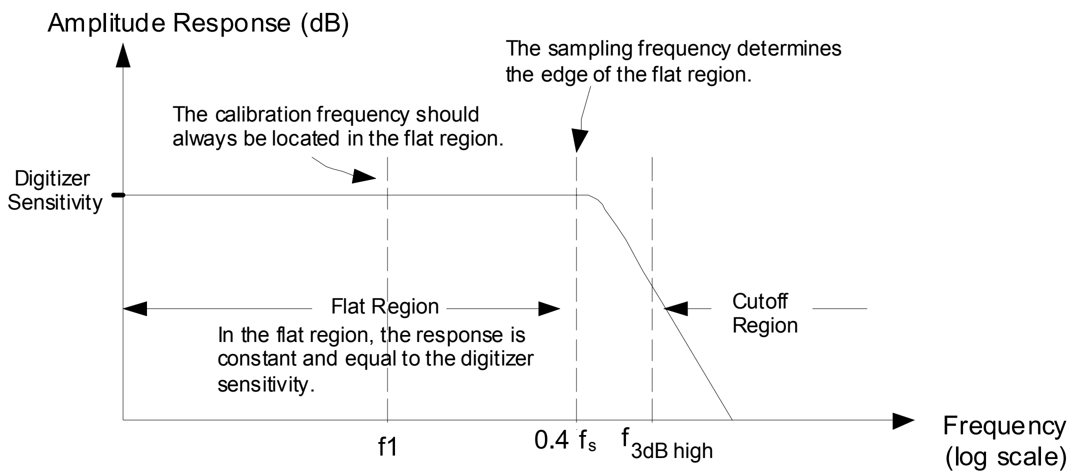


Figure 9: The digitizer sensitivity

2.7 Time Domain Waveform Viewer:

The quantized levels in units of (counts) are, then, displayed graphically in the time domain through the Nanometrics Waveform time series real-time viewer. This software allows the user to observe and measure the amplitude of the sensor output sinewave. Waveform also displays the RMS level of the signal in (counts).

3 Calibration Limitations:

This part describes the practical limitations encountered in sensor calibration. These limitations will be introduced then illustrated graphically in Figure 16.

3.1 Lowest Calibration Amplitude:

There exists a lower threshold for the calibration amplitude below which the signal would be buried in noise. In fact, the calibration signal amplitude should be large enough to generate a mass motion that is higher than the input equivalent system noise. Relatively small calibration signals result in low signal-to-noise ratios and, therefore, inaccurate measurements. This lowest amplitude threshold is illustrated graphically by the input equivalent noise floor of the system.

3.2 Sensor Clip Level:

The highest possible calibration amplitude is limited by the clip level of the sensor. Large enough calibration amplitude can drive the sensor into saturation and clip the output signal. In the passband region, the sensor response and the clip level are both flat with respect to velocity. In the cut-off regions, however, the first electrical stage of the sensor, including the coil and the feedback loop, attenuates the signal, increasing, therefore, the clip level. In other words, the clip level is a constant voltage level when referred to the output; however, when it is referred to the sensor input, its shape as a function of frequency becomes a mirror image of the sensor amplitude response. This is illustrated in the figure given below.

3.3 Lowest Calibration Frequency:

The lowest achievable calibration frequency is limited by the time allocated by the user to perform the calibration. The abrupt connection of the sensor calibration coil to the digitizer calibration electric circuit creates a step response superimposed on the calibration signal. This step response constitutes a transient component that becomes infinitesimal as time elapses and the system approaches its steady-state. The smaller the lower corner frequency of the sensor response, the longer the time needed for the system to reach steady-state. Quantitatively, the time required for the system to reach steady-state can be estimated as illustrated in the following example.

Example:

The lower corner frequency of a sensor is always given in the datasheet. This parameter is required in order to perform the calculation.

- Lower corner frequency: $T_{corner} = 100$ s (usually given in seconds)

- Calibration frequency: $f_{cal} = 0.005$ Hz

- Time constant: $\tau = T_{corner}$
  $\tau = 100$ s

It is reasonable to assume that the sensor reaches steady-state after 5 time constants have elapsed.

- Time for steady-state: $t_{SS} = 5.\tau$
  $t_{SS} = 500$ s

Around 5 additional cycles are needed after steady-state has occurred in order to measure the amplitude accurately. This results in the total required calibration time.

Total calibration time: $t_{total} = t_{SS} + 5.(1/f_{cal})$
$t_{total} = 1500$ s

Clearly, at lower frequencies the calibration procedure can take a very long time.

3.4 Highest Calibration Frequency:

The highest possible calibration frequency is limited by both the digitizer sampling rate and the maximum attainable calibration signal amplitude.

Practically, when the calibration signal is to be displayed using Waveform, it can be observed that a minimum of 5 samples per cycle is needed in order to view a coherent measurable sinusoidal signal. **The sampling frequency should, therefore, be set to 5 times the maximum required calibration frequency**. This is higher than the sampling theorem requirement. For example, at a sampling frequency of 100 samples per second, the maximum achievable calibration frequency is 20 Hz.

The digitizer calibration signal clip level constitutes the other limiting factor for the highest attainable calibration frequency. In fact, it is important to remember that according to Lenz's law, the mass motion in acceleration is proportional to the amplitude of the calibration signal current. This implies that at a certain constant calibration signal amplitude, the mass motion in acceleration is flat with respect to frequency in the passband region. The corresponding mass motion in velocity, on the other hand, is a decreasing function of frequency. Velocity sensors have a flat response with respect to velocity; consequently, as frequency increases their output to the decaying input velocity signal will end up vanishing below the noise floor. This is illustrated in the Figure 16.

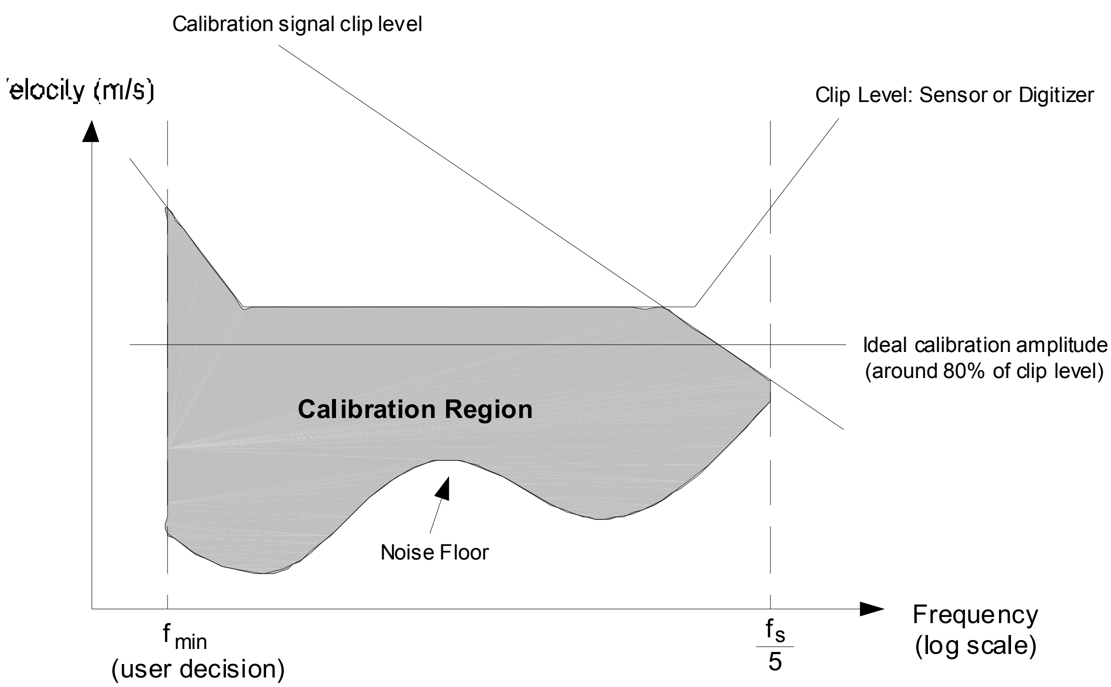


Figure 16: The calibration practical limitations

4 Step-by-Step Calibration Procedure:

This procedure describes a simple method to perform amplitude calibration using the Nanometrics system.

1 - Verify the system calibration parameters:

Note: This step has to be performed only once, before the first calibration.

The parameters that should be checked are the calibration units, the calibration coil resistance, the calibration coil constant, the calibration enable and the calibration relay settings. These parameters, which are described in detail in the NaqsServer software manual, should correspond to the sensor being calibrated.

These parameters are stored in the 'Naqs.stn' system file located in the NMX user directory. If the user is confident of the content of this file, this step can be skipped. Otherwise, this step should be performed very carefully as errors will affect the functionality of the system. This text file can be edited using any text editor tool like Notepad in the Windows operating system.

2 - Select the calibration frequency range:

The calibration frequency range should cover the passband region of the sensor plus an additional one half of a decade on each side. For example, for a short period sensor with a passband frequency range of 0.5 to 16Hz, the calibration range would be 0.1 to 80Hz.

The user, nevertheless, can opt for a different range, depending on the calibration objective or the particular areas of interest. For instance, when only the sensitivity of the sensor has to be verified, a single midband point can be chosen for calibration. Sometimes the sampling rate should be increased in order to do high frequency calibration.

3 - Select the calibration frequency points:

The number of frequency points per decade of frequency range depends on the targeted accuracy and reliability of the calibration procedure. The larger the number the higher the accuracy, but the larger the amount of time and effort required to perform the calibration. **A conservative choice would be 1 frequency point per decade in the passband, 1 point on each corner, 4 points below the lower corner and 4 points above the higher corner.** Opting for more than 10 points per decade would normally be a waste of effort and time.

4 - Start the Nanometrics calibration software tools:

The required Nanometrics software tools should be installed before beginning the calibration procedure. These tools include, NaqsServer NaqsView and Waveform Viewer. NaqsServer is the data acquisition system and should be started first. NaqsView has the graphical user interface, GUI, which allows access to the sensor calibration input commands. Finally, Waveform Viewer displays graphically the time domain quantized samples stored in the data server i.e. NaqsServer. Please, refer to the Nanometrics manuals on how to use these tools.

Note : STEPS 5, 6, 7, 8 CONSIST OF SPECIFYING THE CALIBRATION SETTINGS IN NAQSVIEW:

5 - Choose between voltage and current mode: (Trident users)

The current mode calibration option is only available for Trident users. The difference between the current and the voltage modes was explained above.

6 - Specify the calibration signal frequency in (Hz):

The frequency of the calibration signal in (Hz) is specified and entered in NaqsView. This and the following steps should be repeated until stepping through all the calibration frequency points selected above. The midband sensitivity and the expected passband response are usually known beforehand. Therefore, it is recommended to start, first, with a midband frequency point in order to avoid calibrating at a marginal frequency that falls in the cut-off regions of either the sensor or the digitizer. This way it can be verified early in the procedure that the system is responding correctly to calibration before stepping through the rest of the frequency points.

7 - Specify the calibration signal amplitude in (µm/s):

In order to maximize the signal-to-noise ratio and hence the accuracy of the measurements while avoiding the clip region, it is recommended to use a conservative calibration amplitude of around 80% of the sensor full scale.

8 - Specify the calibration signal duration (s):

The calibration signal duration is another setting that should be specified and entered in NaqsView before every frequency point calibration.

An example of how to compute the value of this parameter was given above in the calibration limitations section of the document.

9 - Calibrate and derive the system amplitude response:

The calibration is initiated through the control buttons on the NaqsView GUI. The time domain system output is observed through the Waveform GUI. A sinewave with the same frequency as the calibration signal is expected to be seen.

At steady-state, i.e. after 5 time constants have elapsed, the output signal amplitude should be measured as displayed in Waveform in units of (counts). The amplitude response of the system at the calibration frequency, f_i, is the ratio of the output signal amplitude in (counts) to the calibration velocity amplitude in (m/s).

- Calibration signal amplitude in (m/s): $A_i(f_i)$ (m/s)

- Output signal amplitude in (count): $A_O(f_i)$ (count)

- System amplitude response in [count/(m/s)]: $H_{system}(f_i) = \dfrac{A_O(f_i)}{A_i(f_i)}$

10 - Compute the sensor amplitude response:

The sensor amplitude response in [V/(m/s)] can be derived from the system amplitude response computed above. This step should be ignored when the system as opposed to the sensor amplitude response is required. However, in most cases the calibration targets the derivation of the sensor response. The sensor response at this particular calibration frequency can be derived by dividing the system response by the known digitizer sensitivity. It is important to remember that the digitizer response is flat in the calibration region defined above, from DC to one fifth of the sampling rate. **The DC removal option of the Nanometrics digitizers should be disabled during calibration**. The sensor amplitude response at the calibration frequency is computed as follows:

- Sensor amplitude response in [V/(m/s)]: $$H_S(f_i) = \frac{H_{system}(f_i)}{S_d}$$

$H_{system}(f_i)$ is the system response in [count/(m/s)] derived above, and S_d is the digitizer sensitivity in (count/volt).

- Sensor amplitude response in (dB): $$H_S(f_i)_{dB} = 20.\log(H_S(f_i))$$

The figure shown below illustrates the calculations involved in deriving the sensor amplitude response at the calibration frequency point f_i.

11 - Step to the next frequency point and repeat the calibration:

The calibration procedure steps 6 through 11 should be repeated at each of the frequency points selected above. Stepping through all these points should provide the user with the required data to plot the sensor frequency response illustrated in figure 17.

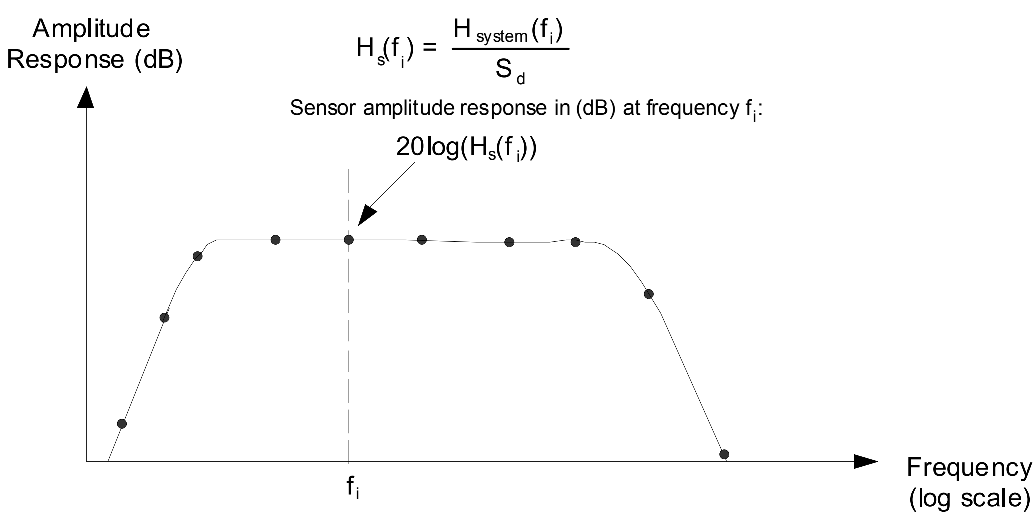


Figure 17: The derivation of the sensor amplitude frequency response

5 Digitizer Relative Calibration (Advanced Method):

In this method, the sensor calibration is performed relatively to the digitizer transfer functions. This part of the document describes the advantages and disadvantages of this method, as well as the adjustments and steps required to perform it.

5.1 Overview:

The digitizer transfer functions include the calibration signal circuit, as well as the digitizer preamplifier and 24-bit analog-to-digital converter. In this context, uncertainty in the calibration input signal and inaccuracy in the digitizer sensitivity constitute potential sources of digitizer induced error.

The advantages of this method include eliminating such potential errors. This will improve the accuracy and reliability of the calibration procedure. Another advantage is the fact that knowledge of the calibration input signal and digitizer sensitivity is not necessary.

The disadvantages, on the other hand, include, first, the added complexity and the need for a calibration loop-back plug. Furthermore, this method requires a constant voltage as opposed to a constant current source. This is due to the difference between the sensor calibration coil resistance and that of the loop-back plug. In other words, a constant current source will generate two different voltages at the input of the digitizer depending on whether it is driving the calibration plug or the sensor calibration coil. Therefore, only voltage mode calibration can be used with Tridents.

5.2 Loop-Back Plug:

This plug is used to digitize the input calibration signal. This signal is fed back into one of the digitizer channels as illustrated in the figures shown below. Also illustrated is the pin assignment for a 1-channel plug. In the case of a 3-channel loop-back plug, the input calibration signal should be connected to the 3 digitizer channels, respectively. This is done by replicating the channel 1 connections 2 more times, for channels 2 and 3, respectively.

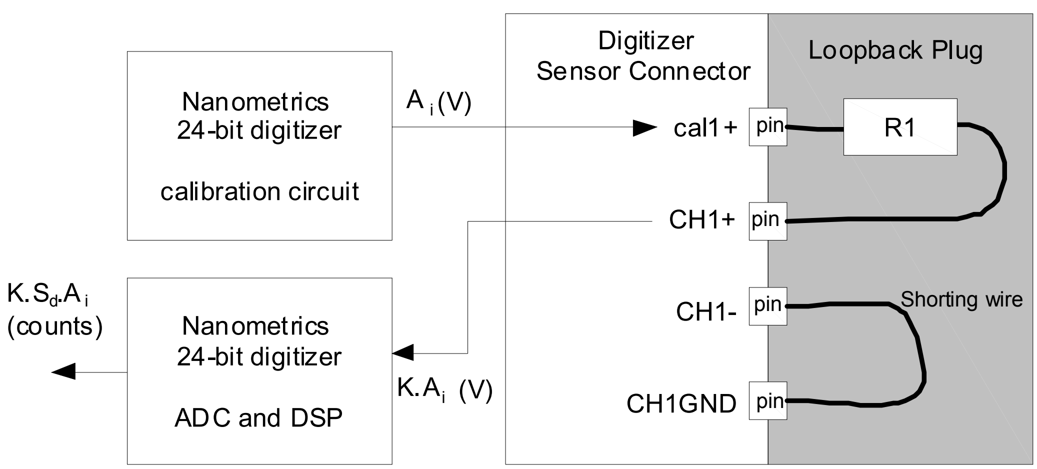


Figure 18: The loop-back plug pin assignment

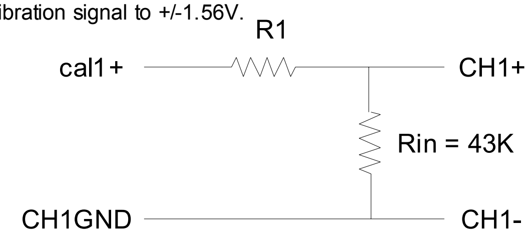


Figure 19: The loop-back plug electrical model

The value of the gain is derived from the following equation: $K = \frac{Rin}{Rin + R1}$

5.2.1 Trident Loop-Back Plug:

As shown in the figure above, Trident users need to include a resistor R1 in the loop back plug. Unlike the HRD-24, the Trident common mode rejection circuit saturates if driven with a single-ended input signal larger than the allowed maximum of +/- 1.56 V. As a result, the series resistor R1 and the Trident shunt 43 KΩ input resistance will form a voltage divider with gain K. This voltage divider gain, K, should ideally be set around 0.25 in order to limit the +/- 5 V capability of the calibration op-amps to the +/- 1.56 V range tolerated by the Trident channel. The Trident input shunt resistance is typically 43 KΩ; therefore, the corresponding series resistance required to implement a gain of 0.25 is 129 KΩ.

5.2.2 HRD-24 Loop-Back Plug:

The users of the HRD-24 do not need to use the voltage divider and consequently the resistor R1. The HRD-24 design allows for single-ended input signals higher than +/- 5 V. The sensor amplitude response is derived using the same equation with a gain, K, equal to 1.

5.3 Deriving the Transfer Function:

The transfer function of the sensor as a function of the other calibration parameters is determined in this part. In the case where the input signal is fed back to the digitizer channel, as shown in Figure 20, the following relationship is derived:

$$A_{O1} = A_i K.S_d \qquad (1)$$

In the case where the input signal is driving the sensor calibration coil, as shown in Figure 21, the following equation is derived:

$$A_{O2} = \frac{A_i.H_S(f_i).S_d}{2.\pi.f_i.K_M} \qquad (2)$$

Equations (1) and (2) lead to the expression defining the transfer function of the sensor at a certain frequency point f_i:

$$H_S(f_i) = \frac{2.\pi.f_i.K_M.K.A_{O2}}{A_{O1}} \quad (3)$$

The parameters used in the above equation and their units are the following:

- A_i: Calibration input signal (V)
- A_{O1}: Digitized calibration loop-back signal (count)
- A_{O2}: Digitized calibration sensor output signal (count)
- K: Voltage divider gain (for HRD-24, R1 is not used, K = 1)
- K_M: Calibration coil motor constant [V/(m/s^2)]
- S_d: Digitizer sensitivity (count/V)
- f_i: Calibration frequency point (Hz)
- $H_s(f_i)$: Sensor amplitude response [V/(m/s)]

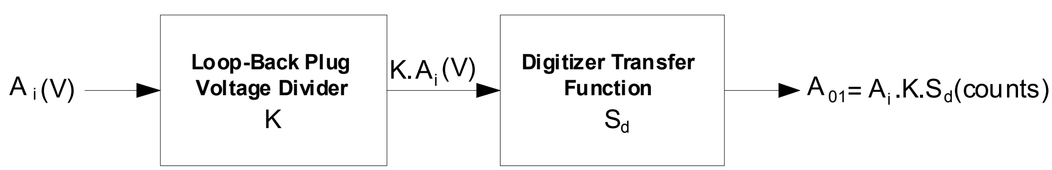


Figure 20: The transfer functions in loop-back operation

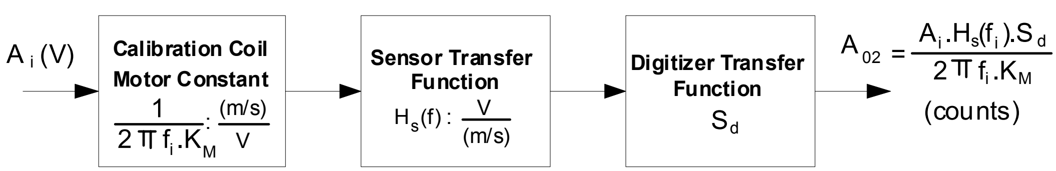


Figure 21: The transfer functions in sensor calibration operation

5.4 Step-by-Step Advanced Calibration Procedure:

This part describes the practical steps defining the digitizer relative calibration procedure.

1 – 8 – Follow the similar steps 1 to 8 described in section 4

The first 8 steps are all identical to steps 1 to 8 described above in section 4. The only exception being that step 5 no longer allows the Trident user to choose between current and voltage calibration mode. This method is only performed in voltage mode.

9 - Digitize the calibration input signal

The calibration input signal should, first, be digitized and measured in (counts). The signal is fed back into the digitizer channel by connecting the loop-back plug described above into the digitizer sensor connector. Once the plug is installed a calibration session is initiated at the time, amplitude and frequency specified in the previous steps, and the steady-state amplitude of the calibration signal is measured in (counts) as observed through the Waveform GUI. The measured value corresponds to the parameter A_{O1} in equations (1) and (3).

10 - Calibrate the sensor

The loop-back plug is now removed and the sensor is connected to the digitizer. The sensor is, then, calibrated with the same calibration signal defined above and used in step 9. The resulting sensor output signal is observed using the Waveform GUI and measured in (counts) after it reaches its steady-state. Please, refer to the analysis presented above for more information on steady-state. The measured signal amplitude corresponds to the parameter A_{O2} defined in equations (2) and (3).

11 – Compute the response

The sensor amplitude response, $H_S(f_i)$, at the calibration frequency is derived using equation (3) defined above. This equation requires also knowledge of K, the loop-back plug gain; and K_M, the sensor calibration coil motor constant converted to the appropriate units.

12 - Step to the next frequency point and repeat calibration

The calibration procedure steps 6 through 11 should be repeated at each of the selected frequency points. Stepping through all these points should provide sufficient data to plot the sensor frequency response illustrated in Figure 17.

5.5 *Adjustments for Accelerometer Calibration:*

Equations (2) and (3) derived above correspond to seismometers i.e. velocity meters. In the case of accelerometers, the sensor transfer function is expressed in units of acceleration as illustrated in Figure 22. This entails a slight modification to these equations consisting of removing the 2πf factor.

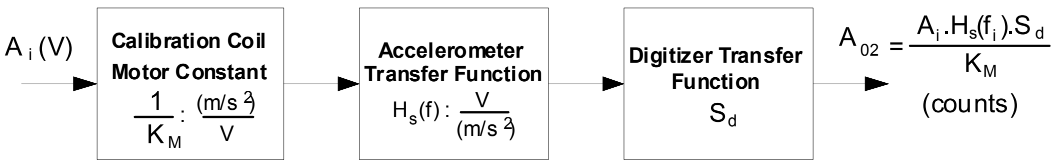


Figure 22: The accelerometer transfer functions

The appropriate forms for equations (2) and (3) in the case of accelerometers are the following, respectively:

$$A_{O2} = \frac{A_i.H_S(f_i).S_d}{K_M} \qquad (4)$$

Equations (1) and (4) lead to the expression defining the transfer function of the accelerometer at a certain frequency point f_i:

$$H_S(f_i) = \frac{K_M.K.A_{O2}}{A_{O1}} \quad (5)$$

The units of the parameters used in this equation are all similar to those used above in the case of seismometers, with the exception of $H_s(f_i)$ which in this case is expressed in [V/(m/s^2)].

6 Other Calibration Considerations:

This part includes an overview on some other potential calibration issues, like unit conversion and accelerometers.

6.1 Conversion of the Calibration Coil Motor Constant:

The calibration coil motor constant can be expressed in several different units. It is important to convert this parameter to the appropriate units when computing the sensor response. The following are 2 typical examples illustrating this conversion into the units used in this document [V/(m/s^2)].

Example 1: STS-2 Low-Power Seismometer: Calibration coil motor constant is given in (g/mA).

The required parameters in their appropriate units are:

- Calibration Coil Motor Constant (sensor manual): $K_{MA} = 0.002(g/mA)$
- Calibration Coil Resistance (sensor manual): $R_{coil} = 30.0\Omega$
- Gravitational Acceleration: $g = 9.8(m/s^2)$

The calibration coil motor constant in [V/(m/s^2)] is computed as follows:

$$K_M = \frac{R_{coil}}{K_{MA}.g.10^3}$$

$$K_M = 1.531.[V/(m/s^2)]$$

Example 2: Geotech GS-13 Seismometer: Calibration coil motor constant is given in (N/A).

The required parameters in their appropriate units are:

- Calibration Coil Motor Constant (sensor manual): $K_{MA} = 4.516(N/A)$
- Mass (sensor manual): $M = 5Kg$
- Calibration Coil Resistance (sensor manual): $R_{coil} = 28.5\Omega$
- Gravitational Acceleration: $g = 9.8(m/s^2)$

The calibration coil motor constant in [V/(m/s^2)] is computed as follows:

$$K_M = \frac{M.R_{coil}}{K_{MA}}$$

$$K_M = 31.55.[V/(m/s^2)]$$

6.2 Calibration Accuracy and Precision:

The calibration accuracy is the error between the measured and the actual sensor response. This is an important issue that should be considered in sensor calibration. The accuracy of a calibration operation depends, typically, on the following factors:

- The accuracy of the calibration signal generator
- The accuracy of the digitizer sensitivity
- The accuracy of the sensor motor constant
- The voltage divider effects of cable and loop-back plug resistance

Adopting the advanced calibration method described in section 5 should eliminate the sources of error associated with the digitizer sensitivity and the input calibration signal. This should improve the accuracy of the calibration significantly. It is difficult to define an absolute threshold for accuracy as this depends on many considerations such as the application, the digitizer and the sensor type. However, a 5% accuracy is both achievable by the methods described here and adequate for most applications.

The precision, on the other hand, is the spread or the standard deviation of the measured results around their mean. The calibration precision depends on the following:

- The background seismic noise
- The digitizer noise
- The sensor noise

Precision is improved by increasing the signal-to-noise ratio. This is done by using a large calibration input signal as described above, and attempting to minimize the noise levels.

7 References:

Hutt, Charles R., *Standards for Seismometer Testing: A Progress Report*. U.S. Geological Survey, Albuquerque Seismological Laboratory, Albuquerque, NM, USA, 1990.

Kuo, Benjamin C., *Automatic Control Systems.* Prentice Hall, New Jersey, USA, 1995.

Nilsson, J.W. and Riedel, S.A., *Electric Circuits – Fifth Edition.* Addison Wesley Publishing Company, USA, 1996.

Oppenheim, A. V. and Willsky, A. S., *Signals and Systems.* Prentice Hall, New Jersey, USA, 1983.

Ott, Henry W., *Noise Reduction Techniques in Electronic Systems – Second Edition*. John Wiley and Sons, Inc., New York, USA, 1988.

Wielandt, Erhard, *Seismic Sensors and their Calibration*, http://www.geophys.uni-stuttgart.de/seismometry/man_html/index.html, 2001.

8 Appendix A: Trident and the High Gain STS-2

This section covers the particular issues encountered in a Trident and a High Gain STS-2 calibration.

The Problem:

The smallest calibration signal that could be generated by the Trident digital-to-analog (DAC) converter is large enough to saturate the Trident ADC. In other words, small calibration amplitudes result in a signal which is buried in noise, whereas large calibration amplitudes saturate the Trident ADC and possibly the STS-2 itself due to the high output response of the High Gain STS-2. An amplitude range where these problems could be avoided does not exist.

The Solution:

The solution is to allow the calibration op-amp to generate a signal that is higher than its noise floor, while avoiding saturation. This is implemented by creating a voltage divider that attenuates the calibration signal before it reaches the sensor calibration coil. Accordingly, a resistor was added inside the cable to the calibration loop. The resistor value was computed in the objective of matching the calibration DAC dynamic range to that of the ADC while taking into consideration all the relevant transfer functions in the cascade. Please, note that as a result of these changes, the STS-2 High Gain seismometer can ONLY be calibrated in VOLTAGE mode.

The Implementation Procedure:

The following is a description of the solution procedure:

1). Cable Modification: The cable is modified by placing a standard 0.1%, 20KΩ resistor in series with the CCOM pin, which is the calibration return pin of the sensor. For noise considerations, this resistor should be placed in the sensor connector.

2). Cal Coil Resistance: In the STS-2 [Sensor] section of the Naqs.stn, this should be set at 20030 Ohms for the purpose of consistency. Only the HRD uses this value. In the case of the Trident, the value of this resistance has no impact at all on the calibration.

3). Cal Coil Motor Constant: This constant should be adjusted in the Naqs.stn file to account for the voltage divider formed by the 20KΩ series resistance. The new value is 1023.52 [$V/(m/s^2)$]. The following example shows how to compute this value.

The following values are found in the STS-2 manual:

- Motor Constant: $K_{MG} = 0.002$ g /mA, where g = 9.8 (m/s^2)
- Calibration Coil Resistance: $R_{cal} = 30\ \Omega$

The motor constant is converted to Amps/(m/s^2) as follows:

$$K_{MA} = 10^{-3} / K_{MG} = 10^{-3} /(0.002 \times 9.8) = 0.051\ [A/(m/s^2)]$$

The motor constant is converted to [Volts/(m/s^2)] by multiplying by the calibration coil resistance:

$$K_{MV} = R_{cal} \times K_{MA} = 0.0051 \times 30 = 1.53 \ [V/(m/s^2)]$$

The final step is to adjust the calibration coil motor constant to account for the voltage divider. In other words the value we are computing should include the effect of the attenuation through the voltage divider. As a result, we should expect a value that is much larger because a higher voltage level is now required to generate 1 (m/s^2) of acceleration. Using this adjusted value in the Naqs.stn file ensures that the software is accounting for the attenuation.

It is important to note that since a voltage divider is used for the attenuation, the Trident calibration should, therefore, only be performed in VOLTAGE mode. In current mode the voltage divider will not attenuate the signal and the problem will not be solved. Furthermore, the STS-2 presents a slightly different case from the typical voltage mode circuit presented above. This is because the STS-2 calibration signal return path is through the cal- Trident pins as opposed to the ground pins. This will result in placing the R_{shunt} resistance - shown in the description of the current mode above – in series with the STS-2 calibration coil and the 20KΩ attenuation resistance. The diagram shown below illustrates the resulting circuit:

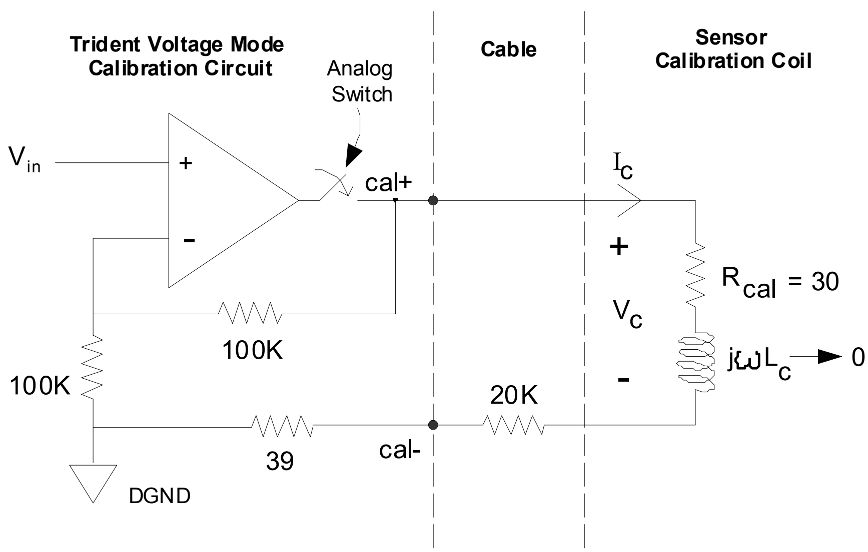


Figure 23: The STS-2 adjusted calibration loop

The motor constant is adjusted to account for the voltage divider effect:

$$K_M = K_{MV} \times (30 + 39 + 20000) / 30 = 1023.52 \ [V/(m/s^2)]$$

The adjusted value, K_M, is entered in the Naqs.stn file. Please, note that this value is only correct for a single channel calibration. Multiple channel calibration results in changing the value of this constant by a factor approximately equal to the number of channels. The problem associated with multiple channel calibration is discussed in a separate section below.

The following example illustrates the adjustments to the [Sensor] section of the Naqs.stn file:

```
[ Sensor ]                    // Predefined sensor - all fields mandatory
TypeName = STS-2              // Name of this prototype - may be same as model
Model = STS-2                 // Sensor model name
SensitivityUnits = M/S        // Units of ground motion:  M, M/S or M/S**2
Sensitivity = 20.0e+9         // Counts per unit of ground motion
SensitivityFreq = 1.0         // Frequency at which sensitivity is correct
CalibrationUnits = VOLTS      // Calibration input units:  VOLTS or AMPS
CalCoilResistance = 20030     // Calibration coil resistance in ohms
CalCoilConstant = 1023.52     // Calibration units per m/s/s
CalEnable = 2                 // Digital enable signal for calibration
CalRelay  = 0                 // Analog relay for calibration (0 = use channel number)
MassCenterEnable = 1          // Digital enable signal for mass centering
MassCenterDuration = 8        // Duration of the mass center signal in seconds
CalSource = Trident           // Source of the calibration signal (HRD or TRIDENT)
```

4). Trident Configuration: The Control section should be changed using the ConfigUI as follows:

- High Voltage Level: High 12V
- Calibration Mode: Voltage (active low)
- Line 1: LOW
- Line 2: HIGH (Please, review note below)
- Line 3: LOW

NOTE: It was observed that some STS-2 host boxes had a reversed polarity for their control line. As a result, if the calibration fails with the above configuration, please, switch Line 2 to LOW and repeat.

The Calibration of Multiple Channels:

It is important to note the problem associated with the simultaneous calibration of multiple channels. As will be explained in more detail below, the Trident and STS-2 system allows the user to calibrate 1, 2 or 3 channels simultaneously. The solution procedure presented above produces correct calibration responses only in the case of a single channel calibration. The reason behind this problem is the fact that in a simultaneous calibration of multiple channels, the calibration circuit will have multiple coils placed in parallel. This results in changing the calibration coil resistance value, which will now be divided by the number of channels being calibrated. For example, in a 3-channel calibration the coils U, V and W will be placed in parallel; as a result, the coil resistance will change from 30Ω to 10Ω. In turn, this changes the gain of the voltage divider and, therefore, the computed value of the motor constant K_M. In conclusion, calibrating simultaneously multiple coils results in a reduced channel response error. The following example illustrates the change in the value of the motor constant that occurs as a result of a 3-channel calibration.

The motor constant, K_{MV}, computed above is adjusted to account for the voltage divider effect and the 3 coils parallel combination as follows:

$$K_{M3} = K_{MV} \times [\ (30/3) + 39 + 20000\ ] / (30/3) = 3067.50\ [V/(m/s^2)]$$

This implies that an approximate 1/3 loss in the calibration response is expected during a 3-channel calibration.

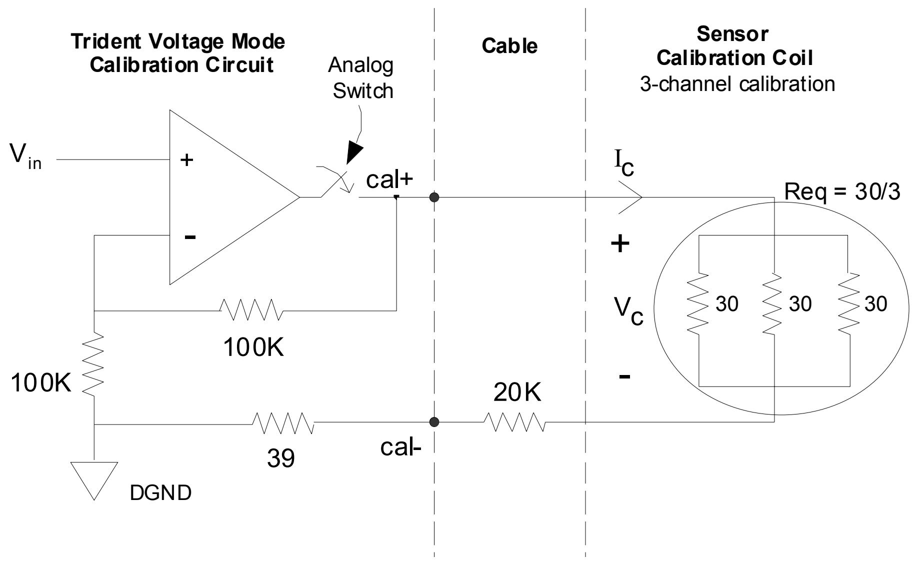


Figure 24: Multiple channel calibration.

The Calibration Channels:

The calibration channels in Naqsview refer to the following sensor components:

- Channel 1 or Z calibrates the U component on the STS-2.
- Channel 2 or N calibrates the V component on the STS-2.
- Channel 3 or E calibrates the W component on the STS-2.

Please, note that this notation is misleading. This is because whereas ZNE refer to UVW in the Naqsview calibration section, they do refer to ZYX in the digitizer channel definition. The assignment of digitizer channels 1, 2 and 3 to Z, N and E is done in the channel definition of the Naqs.stn file. On the other hand, the cable connects physically the digitizer calibration signals cal1, cal2 and cal3 to U, V and W, respectively.

The Transformation Matrix:

The calibration of any of the sensor U, V or W components will create a response in channels Z, N and E of the digitizer which is defined in amplitude by the transformation function given in the STS-2 manual. This is misleading because whereas ZNE refer respectively to UVW in the sensor calibration section of Naqsview, the same ZNE channels should be regarded as ZYX, respectively, in the digitizer defined channels. The cable physically connects the digitizer channels 1, 2 and 3 to the sensor outputs Z, Y and X, respectively.

For example, calibrating channel 1 which is confusingly labeled as Z in the Naqsview window will, in fact, send a calibration signal to the U component of the sensor. In turn, the amplitude response will be observed on all of the Z, Y and X i.e. the Z, N and E digitizer channels according to the coefficients defined in the transformation matrix. The transformation matrix between XYZ and UVW is shown in the STS-2 manual.

The Error Analysis:

The procedure described above introduces a negligible source of error to the calibration results. The use of a 0.1% standard resistor to create the voltage divider ensures that the error is kept to a minimum level. It was, however, observed that the calibration results sometimes deviated from the expected value by around 14%. This deviation is mainly due to the error introduced by the use of the nominal as opposed to the actual value of the STS-2 calibration motor constant. The actual value is not provided by the STS-2 manufacturer. The Trident calibration DAC represents another source of error; however, such an error is inherent to the calibration of all sensor types, and is not particular to the case of the High Gain STS-2.

The HRD Case:

The HRD requires the same adjustments in order to correct for the High Gain STS-2 calibration problem. The only difference is that because the HRD only supports voltage calibration, the 39Ω resistance is inexistent and should not be accounted for in the voltage divider. Moreover, as mentioned above, the value of the calibration coil resistance in the Naqs.stn file is used by the HRD; therefore, it should be entered correctly as shown in the example below.

The motor constant is adjusted as follows to account for the voltage divider effect:

$$K_M = K_{MV} \text{ x } (30 + 20000) / 30 = 1021.53 \text{ [V/(m/s}^2\text{)]}$$

Please, note that this value of the motor constant is correct only in the case of a single channel calibration. The problems of multiple channel calibration were explained above.

The following illustrates the adjustments to the [Sensor] section of the Naqs.stn file for HRDs:

```
[ Sensor ]                     // Predefined sensor - all fields mandatory
TypeName = STS-2               // Name of this prototype - may be same as model
Model = STS-2                  // Sensor model name
SensitivityUnits = M/S         // Units of ground motion:  M, M/S or M/S**2
Sensitivity = 20.0e+9          // Counts per unit of ground motion
SensitivityFreq = 1.0          // Frequency at which sensitivity is correct
CalibrationUnits = VOLTS       // Calibration input units:  VOLTS or AMPS
CalCoilResistance = 20030      // Calibration coil resistance in ohms
CalCoilConstant = 1021.53      // Calibration units per m/s/s
CalEnable = 2                  // Digital enable signal for calibration
CalRelay  = 0                  // Analog relay for calibration (0 = use channel number)
MassCenterEnable = 1           // Digital enable signal for mass centering
MassCenterDuration = 8         // Duration of the mass center signal in seconds
CalSource = HRD                // Source of the calibration signal (HRD or TRIDENT)
```

The Digitizer to High Gain STS-2 Cable:

The pin assignment of the Trident to High Gain STS-2 cable is given in the following table. The same cable is used in the case of Europa HRD and Europa Trident digitizers:

From STS-2 High Gain			To Digitizer		
Conn.	**Pin**	**Name**	**Conn.**	**Pin**	**Name**
P1	B	Z+	P2	U	CH1+
P1	G	Z-	P2	C	CH1-
P1				B	CH1_GND
P1	F	GNDS	P2	B	CH1_GND
P1	C	Y+	P2	A	CH2+
P1	H	Y-	P2	S	CH2-
P1				T	CH2_GND
P1	D	X+	P2	a	CH3+
P1	J	X-	P2	P	CH3-
P1				R	CH3_GND
P1	Q	UCAL	P2	N	CAL1+
P1	M	CCOM	R1	1	CAL1-
R1	2	CCOM	P2	Z	CAL 1-
P1		SHELL	P2		SHELL
P1	N	VCAL	P2	M	CAL2+
P1	P	WCAL	P2	L	CAL3+
P1		SHELL	P2		SHELL
P1	T	UPOS/U+	P2	K	MPOS1
P1	V	VPOS/V+	P2	X	MPOS2
P1		SHELL	P2		SHELL
P1	U	WPOS/W+	P2	J	MPOS3
P1		SHELL	P2		SHELL
P1	E	AUTZ	P2	H	CALEN1
P1	K	CALSW	P2	W	CALEN2
P1		SHELL	P2		SHELL
P1	R	PERSW	P2	G	CALEN3
P1	S	RET	P2	V	DGND
P1		SHELL	P2		SHELL
P1	W	+VIN	P2	F	BATTERY
P1	X	-VIN	P2	D	BAT_RET
P1		SHELL	P2		SHELL
P1		SHELL	P2		SHELL
P2	Z	CAL1-	P2	c	CAL2-
P2	c	CAL2-	P2	Y	CAL3-
P1	L	SIGSW	P1	K	CALSW