DESCRIPTION:

The MLNT-3D was developed in cooperation with the Paul Scherrer Institute in Switzerland and the University of Malta. It denotes a miniaturized 3-axis low-noise and high-resolution magnetic field-to-voltage digital transducer with a hybrid 3-axis Hall probe type S or an integrated 3-axis Hall probe C.

The hybrid Hall probe integrates three high-resolution Hall sensors (Bx, By, Bz) arranged along the X-axis, and a temperature sensor. The probe provides a good angular accuracy (orthogonality error < 2°) of the measurement axes.

The Hall probe is connected with an electronic box (Module E in Fig. 1). The Module E provides biasing for the Hall probe and the application of the improved spinning-current technique, which very effectively cancels offset, low frequency noise and the planar Hall effect. The additional conditioning of the Hall probe output signals in the electronic box includes Hall signal amplification, high linearization, compensation of the temperature variations, and limitation of the frequency bandwidth.

The digital part of the transducer electronics provides the possibility of automatic data acquisition via a USB serial interface by a computer of all three digital voltages (Vx, Vy, Vz), proportional with each of the measured components (Bx, By, Bz, respectively) of a magnetic flux density, and a voltage proportional with the temperature of the Probe. An encoder with EnDat Interface can be connected to accurately synchronize the probe position and measured magnetic field values.

The Module E has miniaturized dimensions of 145mm x 45mm x 45mm.

The application includes high-precision magnetic characterization of the insertion devices.

KEY FEATURES:

→ Very robust Hall Probe. The Hall sensors are glued onto a reference ceramic plate suitable for an appropriate fixing of the Probe.
→ Hybrid 3-axis (Bx, By, Bz) Hall Probe, with three Hall sensors arranged along the X-axis.
→ Measurement range up to +/-2T
→ Measurement of DC & AC magnetic fields (up to 500Hz).
→ DC magnetic resolution 0.8 uT.
→ Broadband noise 2 uT.
→ 24-bit A/D Convertor
→ External Trigger (Synchronization between probe position and measurement)
→ Very high linearity.
→ Very low planar Hall voltage.
→ A temperature sensor on the probe for the temperature compensation.
→ Miniaturized electronic box (145mmx45mmx45mm).

TYPICAL APPLICATIONS:

→ Mapping magnetic fields
→ Characterization of the undulator systems
→ Application in laboratories and in production lines
→ Quality control and monitoring of magnet systems (generators, motors, etc.)
→ Miniaturized electronic box can be placed inside of the undulator.
→ Together with the 3-axis Hall probe, the miniaturized electronic box can be placed between the undulator and its outer shell.
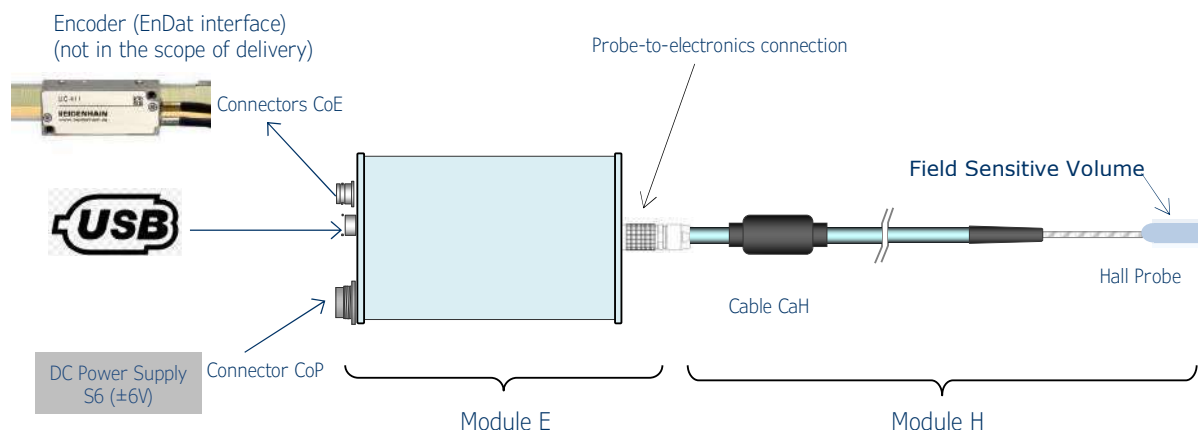

Figure 1. **Typical measurement setup with the SENIS digital magnetic-field-to-voltage transducer with hybrid 3-axis Hall probe (module H) and electronics (miniaturized module E, 145mm x 45mm x 45mm).**

Figure 2. **Photo of a 3-axis magnetic field transducer with a hybrid Hall Probe type "S". (The probe S can be fixed in a probe holder PHS-H, available at SENIS.)**

MODULE H: SPECIFICATIONS

The SENIS 03S Hall probe is a very thin 3-Axis Hall probe system that gives an analogue voltage output for each of the three components of the measured magnetic flux density and for the probe temperature. The probe contains the three high-resolution Hall elements and a temperature sensor.

The sensors are embedded in the probe package and are connected to the cable. The probe package is made of a ceramic material and serves as a reference plate, suitable for appropriate positioning of probe.
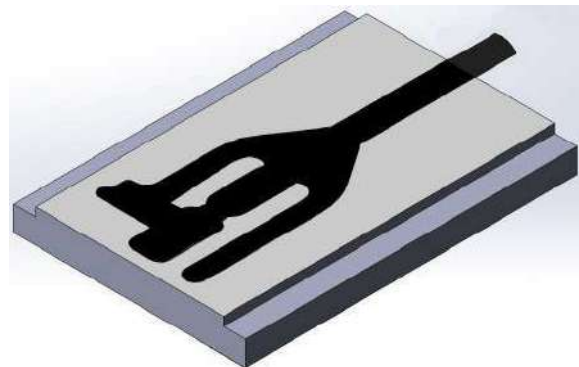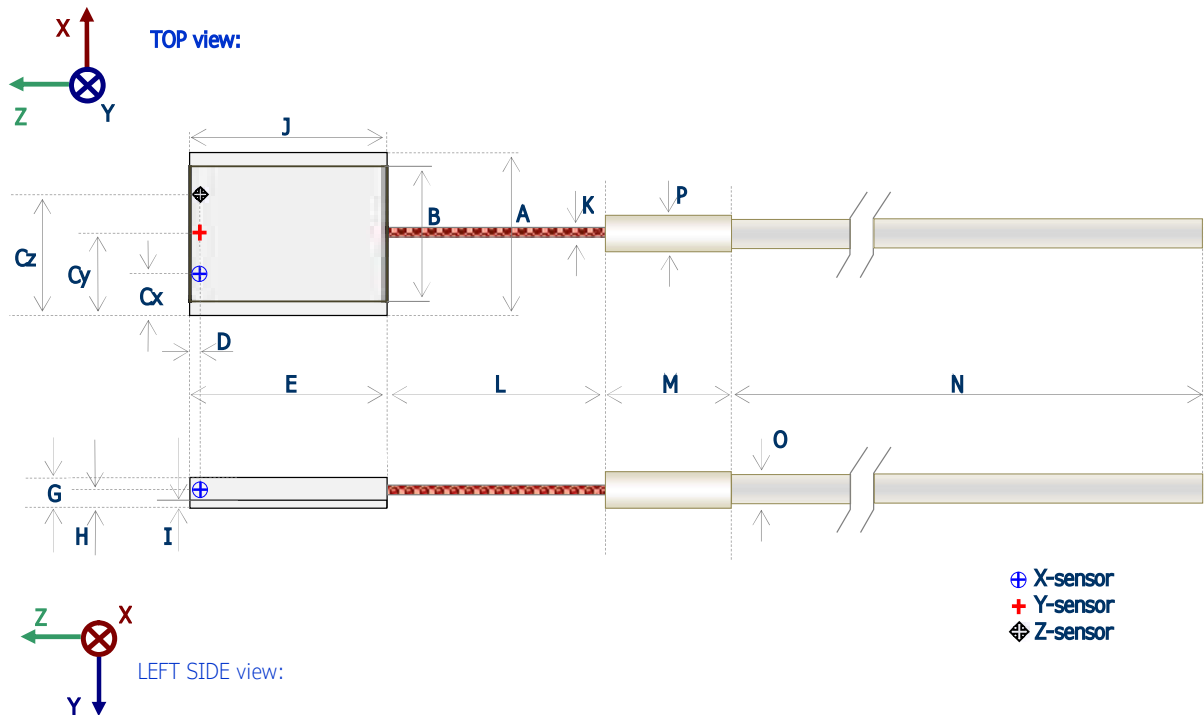

Figure 3. **Hall probe type 03S**

Key features of the H3A–03S Hall probe system:

→ Low noise (allowing high-resolution measurements)
→ Measurement of X, Y and Z magnetic field components with a high angular accuracy and high spatial resolution
→ Virtually no planar Hall effect
→ Negligible inductive loops
→ The probe provides a temperature signal for an efficient compensation of temperature effects
→ CaH cable connection to the transducer's electronic module via a LEMO connector.

Hall probe and Cable - dimensions and tolerances:

Probe dimensions [mm]				Cable dimensions [mm]	
A	10.00 ± 0.05	E	10.00 ± 0.05	K	1.0 ± 0.1
B	9.00 ± 0.05	F		L	100 ± 5
Cx	3.00 ± 0.05	G	1.40 ± 0.05	M	20 ± 1
Cy	5.00 ± 0.05	H	0.70 ± 0.05	N	10'000 ± 50
Cz	7.00 ± 0.05	I	0.38 ± 0.05	O	2.2 ± 0.2
D	2.00 ± 0.05	J	10.00 ± 0.05	P	2.8 ± 0.2

Figure 4. **Dimensions of the H-Module H3A-03S10F (all measures are displayed in mm). The RED cross denotes the Y-sensor, the BLUE circled-cross denotes the X-sensor, and the GREY beveled cross denotes the Z-sensor.**

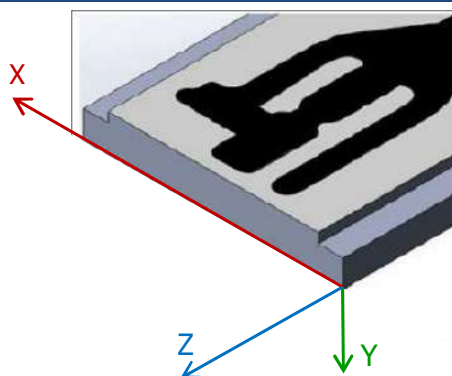NOTE: Different cable lengths are available upon a request.

Figure 5.   **Reference Cartesian coordinate system of the SENIS Hall probe 03S**

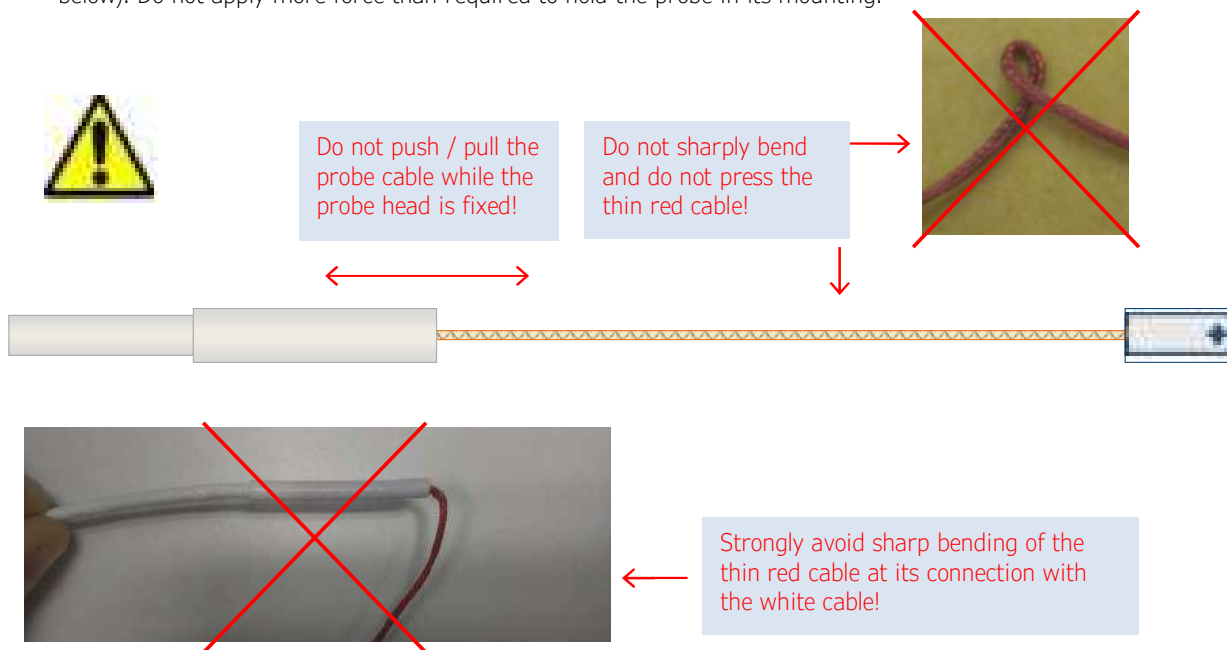| Parameter	X (mm)	Y (mm)	Z (mm)
Dimensions:			
Magnetic field sensitive volume (MFSV)	1 x 150 x 150 µm	150 x 1 x 150 µm	150 x 150 x 1µm
Position of the FSV centre of Z-sensor	7.0	-0.70	-2.0
Position of the FSV centre of Y-sensor	5.0	-0.70	-2.0
Position of the FSV centre of X-sensor	3.0	-0.70	-2.0
Total probe external dimensions	10	1.4	10
Positioning accuracy:			
Mutual angular accuracy of axes	Better than 2° (mutual orthogonality)		
Angular accuracy of axes with respect to the reference surface	< ±2°, determined during calibration		
General properties:			
Cable	Shielded, without outer PVC jacket		

Recommended accessories:

- Probe Holder PHS-H
- Zero Gauss chamber ZG-5035

Installation manual for the 03S probe:

Although the 03S probe is very robust with respect to its size, it should be handled with special care.

Considering that we deal with a high-precision device of very small dimensions, following precautions should help to avoid damage to the probe during installation and handling, and ensure that the device's accurate calibration remains preserved:

- The Hall Probe is sensitive to Electrostatic Discharge (ESD). Be sure to ground yourself and follow proper procedure when handling the Hall probe.

- The mounting of the Probe should be carried out by application of very low pressure to its head and particularly on the thin cable.

- Do not apply more force than required to hold the probe in its place. Damage to either the ceramics package of the Hall sensor or thin wiring could destroy the Probe.

- Repeatable strong bending of the thin cable should be avoided:

- If the probe head is clamped, the user needs to make sure that the environment surface in contact with the reference plane of the probe is flat and covers as much of the probe reference surface as possible (see image below). Do not apply more force than required to hold the probe in its mounting.

Do not push / pull the probe cable while the probe head is fixed!

Do not sharply bend and do not press the thin red cable!

Strongly avoid sharp bending of the thin red cable at its connection with the white cable!

- In order to prevent rupture of the thin probe wiring, the user should fix and secure the probe cable in the proximity of the head. The thin wires of the flexible section of the probe can be folded only with a special care. Any repetition sharp bending must be strongly avoided.

- Do not expose the thin cable to the sharp edges.

MAGNETIC AND ELECTRICAL SPECIFICATIONS:

NOTE: Unless otherwise noted, the given specifications apply for all measurement channels at room temperature (20-25°C) and after a device warm-up time of at least 30 minutes.

Parameter	Value	Remarks
Maximum measurement range ($\pm B_{FS}$)	± 2 T (± 20 kG)	No saturation of the outputs
Linear range of magnetic flux density ($\pm B_{LR}$)	± 2 T (± 20 kG)	Fully calibrated measurement range
Total measuring accuracy (@ B < $\pm B_{LR}$)	$\pm 0.01\%$	See note 1
Sensitivity to DC magnetic field (S)	2 V/T	
Tolerance of sensitivity (S_{err}) @ B < $\pm B_{LR}$	0.05%	See notes 3 and 4
Nonlinearity (NL) @ B < $\pm B_{LR}$	0.015%	See note 4
Temperature Coefficient of Sensitivity	< ± 25 ppm/°C (± 0.0025 %/°C)	@ Temperature range 25°C $\pm$ 5°C
Long-term instability of Sensitivity	< 0.5% over 10 years	
Offset (@ B = 0T)	< ± 2 mV (1 mT)	@ Temperature range 25°C $\pm$ 5°C
Temperature Coefficient of the Offset	< ± 4 µV/°C (2 µT/°C)	
Offset fluctuation and drift (from 0.1 to 10Hz, i.e. Δt=0.05s, t=100s)	< 9.4 µV$_{PP}$ (4.7 µT$_{PP}$)	Peak-to-peak values; See note 6
Output noise:		
Noise Spectral Density @ f > 1Hz (NSD$_1$)	0.36 µT/Hz^{0,5}	Region of 1/f – noise
Corner frequency (f_C)	10 Hz	Where 1/f noise = white noise
Noise Spectral Density @ f > 10Hz (NSD$_W$)	0.12 µV/Hz^{0,5} (0.06 µT/Hz^{0,5})	Region of white noise
Broad-band noise from 10Hz to Bw, V_{nRMS}	< 3 µV (1.56 µT)	Standard deviation value; see note 7
Resolution		See notes 6 - 10
Typical frequency response:		
Frequency bandwidth (Bw)	500 Hz	Sensitivity attenuation is -3dB; Note 11
Temperature output of the probe:		
Analogue temperature sensor	Pt100	
Temperature sensor accuracy	1°C	
Temperature output of the electronic box:		
Digital temperature sensor	12 bit	
Temperature sensor accuracy	0.1°C	
Digital:		
Microcontroller clock	200 MHz	
Encoder	RS485 interface	Heidenhain absolute encoder
Encoder protocol	EnDat 2.2	
Output File Format	R32	32 bits floating point format

Start/Stop	0,+5V	Start and Stop signals for acquisition
Error	0,+5V	Error signal
Busy	0,+5V	Busy signal
Buffer Memory	128 MB	
Synchronisation time	8.4us	Time between Hall signal and Encoder
Trigger Frequency	Max 8kHz	Programmable measurement speed
ADC #bits	24 bits/22 ENOB	
ADC Conversion Time	>10 us	

Magnetic flux density (B) units (T-tesla, G-gauss) conversion:

1 T = 10 kG   1 mT = 10 G   1 µT = 10 mG

MODULE E: MECHANICAL and ELECTRICAL SPECIFICATIONS:

Figure 6. 3-channel digital electronic module LMNT-3D with the dimensions 145mm x 45mm x 45mm.

Module E, type B (for 3-axis magnetic field transducers)	High mechanical strength, electrically shielded aluminium case 45 W x 145 L x 45 H mm (see Fig. 6) weight 0.3kg	
Connector CoE (TE M12 FMLE PNLREAR 8P)	V+ GND ENDAT_DATA_P ENDAT_DATA_N ENDAT_CLOCK_P ENDAT_CLOCK_N	Pin 2, 8 Pin 1,5 Pin 3 Pin 4 Pin 7 Pin 6
Hall probe connector CoH	LEMO - EGG.2B.319.CLL - socket, panel, 19 way (mating Plug: FGG.2B.319.CLAD92Z)	Front side
DC Power Connector CoP (MOLEX ULTRAFIT 4CKT), rear side	Power input: +6V Power input: -6V Power common: GND	Pin 1 Pin 2 Pin 3, Pin 4
DC power	Voltages:	±6V nominal, ±2%
	Current:	0.35 A @ +6 V 0.07 A @ -6 V

SD CARD slot
(HIROSE SMT MICORSD CON), rear side

USB 2.0
(MINI TYPE B SMT), rear side

Environmental parameters:

Operating Temperature	+5°C to +45°C	Optimal temp. range: +15°C to +35°C
Storage Temperature	-20°C to +85°C	

ADDITIONAL CALIBRATION OPTIONS:

DC Calibration Table (Vout vs. Bnmr)

The DC Calibration Table (Vout vs. Bnmr) of the transducer can be ordered as an option. The calibration table is an Excel-file, providing the actual values of the transducer output voltage for the test DC magnetic flux densities measured by a reference NMR Teslameter. The standard calibration table covers the linear range of magnetic flux density $\pm B_{LR}$ in the steps of $B_{LR}/10$. Different calibration tables are available upon request. By the utilisation of the calibration table, the accuracy of DC and low-frequency magnetic measurement can be increased up to the limit given by the resolution (see Notes 1 and 6 - 10).

AC Calibration - Frequency Response characterization

Another option is the AC Calibration Table (Amplitude & Phase vs. Frequency) of the frequency response. This is an Excel file, providing the actual values of the transducer transfer function (complex sensitivity and Bode plots) for a reference AC magnetic flux density. The standard frequency response calibration table covers the transducer bandwidth, from DC to Bw, in the steps of $Bw/10$. Different calibration tables are also available upon request. Utilisation of the frequency calibration table allows an accuracy increase of the AC magnetic measurements almost up to the limit given by the resolution (see Notes 1 and 6 - 11).

The SENIS 3-Axis Ultra-low noise Hall transducer H3A-03S10F-B02T0K5K is applicable in the B-frequency range from DC to 500Hz (-3dB point of sensitivity attenuation, where B being the density of the measured magnetic flux). In addition to the Hall voltage, at high B–frequencies also inductive signals are generated at the connection probe-thin cable. Moreover, the probe, the cable and the electronics in the E-module behave as a low-pass filter. As a result, the transducer has the "complex" sensitivity of the form:

$$S = S_H + jS_I$$

Here:

- S_H represents sensitivity for the output signal in phase with the magnetic flux density (that is the real part of the transfer function);
- S_I is the sensitivity with the 90° phase shift with respect to the magnetic flux density (i.e. the imaginary part of the transfer function).

Calibration data can be ordered for S_H and S_I for all three axes X, Y and Z (as an option). This allows the customer to deduce accurate values of the measured magnetic flux density at even high frequencies by an appropriate mathematical treatment of the transducer output voltage V_{out}.

NOTES:

1) The **accuracy** of the transducer is defined as the maximum difference between the actual measured magnetic flux density and that given by the transducer. In other words, the term accuracy expresses the maximum measurement error. After zeroing the offset at the nominal temperature, the worst case relative measurement error of the transducer is given by the following expression:

$$\text{Max. Relative Error: } M.R.E. = S_{err} + NL + 100 \times Res / B_{LR} \quad [\text{unit: \% of } B_{LR}] \qquad \text{Eq. [1]}$$

Here, S_{err} is the tolerance of the sensitivity (relative error in percents of S), NL is the maximal relative nonlinearity error (see note 4), Res is the absolute resolution (Notes 6-10) and B_{LR} is the linear range of magnetic flux density.

2) The output of the measurement channel has two terminals and the output signal is the (differential) voltage between these two terminals. However, each output terminal can be used also as a single-ended output relative to common signal. In this case the sensitivity is approx. 1/2 of that of the differential output (*Remark: The single-ended output is not calibrated*).

3) The **sensitivity** is given as the nominal slope of an ideal linear function $V_{out} = f(B)$, i.e.

$$V_{out} = S \times B \qquad \text{Eq. [2]}$$

where V_{out}, S and B represent transducer output voltage, sensitivity and the measured magnetic flux density, respectively.

4) The **nonlinearity** is the deviation of the function $B_{measured} = f(B_{actual})$ from the best linear fit of this function. Usually, the maximum of this deviation is expressed in terms of percentage of the full-scale input. Accordingly, the nonlinearity error is calculated as follows:

$$NL = 100 \times \left[\frac{V_{out} - V_{off}}{S'} - B \right]_{max} / B_{LR} \quad (\text{for } -B_{LR} < B < B_{LR}) \qquad \text{Eq. [3]}$$

Notation:

B = Actual testing DC magnetic flux density given by a reference NMR Teslameter

$V_{out}(B)$– V_{off} = Corresponding measured transducer output voltage after zeroing the Offset

S' = Slope of the best linear fit of the function $f(B) = V_{out}(B) - V_{off}$ (i.e. the actual sensitivity)

B_{LR} = Linear range of magnetic flux density

Tolerance of sensitivity can be calculated as follows:

$$S_{err} = 100 \times |S' - S| / S \qquad \text{Eq. [4]}$$

5) The **planar Hall voltage** is the voltage at the output of a Hall transducer produced by a magnetic flux density vector co-planar with the Hall plate. The planar Hall voltage is approximately proportional to the square of the measured magnetic flux density. Therefore, for example:

$$\left. \frac{V_{planar}}{V_{normal}} \right|_{@ B=B_0} = 4 \times \left. \frac{V_{planar}}{V_{normal}} \right|_{@ B=B_0/2} \qquad \text{Eq. [5]}$$

Here, V_{normal} denotes the normal Hall voltage, i.e. the transducer output voltage when the magnetic field is perpendicular to the Hall plate.

6) This is the *"6-sigma"* peak-to-peak span of offset fluctuations with sampling time Δt=0.05s and total measurement time t=100s. The measurement conditions correspond to the frequency bandwidth from 0.01Hz to 10Hz. The *"6-sigma"* means that in average 0.27% of the measurement time offset will exceed the given peak-to-peak span. The corresponding root mean square (RMS) noise equals 1/6 of "Offset fluctuation & drift".

7) Total output RMS noise voltage (of all frequencies) of the transducer. The corresponding peak-to-peak noise is about 6 times the RMS noise. See also Notes 8 and 9.

8) Maximal signal bandwidth of the transducer, determined by a built-in low-pass filter with a cut-off frequency f_T. In order to decrease noise or avoid aliasing, the frequency bandwidth may be limited by passing the transducer output signal trough an external filter (see Notes 9 and 10).

9) **Resolution** of the transducer is the smallest detectable change of the magnetic flux density that can be revealed by the output signal. The resolution is limited by the noise of the transducer and depends on the frequency band of interest.

   The **DC resolution** is given by the specification "Offset fluctuation & drift" (see also Note 6).

   The worst-case (**AC resolution**) is given by the specification "Broad-band noise" (see also Note 7).

   The resolution of a measurement can be increased by limiting the frequency bandwidth of the transducer. This can be done by passing the transducer output signal trough a hardware filter or by averaging the measured values.

   Caution: filtering produces a phase shift, and averaging a time delay!

   The RMS noise voltage (i.e. resolution) of the transducer in a frequency band from f_L to f_H can be estimated as follows:

$$V_{N\_RMS} = \sqrt{NSD_{1f}^2 \times 1Hz \times \ln\left(\frac{f_H}{f_L}\right) + 1.22 \times NSD_W^2 \times f_H}$$ Eq. [6]

   Notation:

   - NSD_{1f} is the *1/f* noise voltage spectral density (RMS) at f=1Hz;
   - NSD_w is the RMS white noise voltage spectral density;
   - f_L is the low, and f_H is the high-frequency limit of the bandwidth of interest;
   - the numerical factor *1.22* is determined by a second-order low-pass filter.

   For a DC measurement: f_L=*1/measurement time*.

   The high-frequency limit cannot be higher than the cut-off frequency of the built-in filter *Bw:* $f_H \leq Bw$.

   If the low-frequency limit f_L is higher than the corner frequency f_C, then the first term in Eq. (6) can be neglected. Otherwise, if the high-frequency limit f_H is lower than the corner frequency f_C, than the second term in Eq. (6) can be neglected. The corresponding peak-to-peak noise voltage can be calculated according to the *"6-sigma"* rule, i. e. $V_{nP-P-B} \approx 6 \times V_{nRMS-B}$.

10) According to the sampling theorem, the sampling frequency must be at least two times higher than the highest frequency of the measured magnetic signal. Let us denote this signal sampling frequency by f_{samS}. However, in order to obtain the best signal-to-noise ratio, it is useful to allow for over-sampling (this way we avoid aliasing of high-frequency noise). Accordingly, for best resolution, the recommended physical sampling frequency of the transducer output voltage is $f_{samP} > 5 \times Bw$ (or $f_{samP} > 5 \times f_H$), if an additional low-pass filter is used (see Note 8). The number of samples can be reduced by averaging every N subsequent samples, where $N \leq f_{samP} / f_{samS}$.

11) Senis low-pass filter and differential-to-single-ended transformer are designed to preserve maximal signal quality when connected to the electronic module E. They don't contribute any additional noise when they are properly connected. The low-pass filter can be used in different frequency ranges depending on the customer specific application resp. expected signal frequency. Approximately, the transducer transfer function is similar to that of a second-order Butterworth low-pass filter, with the bandwidth from DC to *Bw*. The filter

attenuation is -40 dB/dec (-12 dB/oct). The AC Calibration Table (frequency response characterization) is available as an option.

12) The switching "noise" is a periodic signal at f_{sw}=16.67kHz and the related harmonics. It is due to the switching transients produced by the so-called spinning current process in the Hall elements. When performing A/D conversion of the transducer output signal, the sampling rate should be well above 2 x f_{sw} in order to avoid aliasing of the switching noise. The switching noise can be efficiently suppressed by averaging the transducer signal over a time period N x 1/f_{sw}, with N being an integer number.