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AN OVERVIEW OF COMMERCIALLY AVAILABLE TESLAMETERS

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Abstract – The Hall-effect based Teslameters (also called Gaussmeters) are the mostly applied instruments for measuring DC and AC magnetic flux densities in modern science and industry. This paper gives an overview of commercially available Teslameters at the high-end performance level. The Teslameters have been evaluated by following characteristics that are published by suppliers: probe dimensions, magnetic field sensitive volume, accuracy, magnetic resolution, measurement range, frequency bandwidth, temperature coefficient sensitivity, and price/performance ratio.
The Teslameter that best matches the measurement needs in various application fields incorporates a 3-axis integrated Hall probe, analog electronics based on the spinning-current technique, an analog-to-digital converter, an embedded computer, and a touch-screen display. The 3-axis Hall probe is a single silicon chip integrating both horizontal and vertical Hall magnetic sensors and a temperature sensor. The spinning-current eliminates most of the Hall probe offset, low-frequency noise, and the planar Hall voltage. The errors due to the Hall sensor non-linearity and the variations in the probe and electronics temperatures are eliminated by a calibration procedure. The errors due to the angular imperfections of the Hall probe are eliminated by a calibration of the sensitivity tensor of the probe. This Teslameter can measure magnetic field vectors from about 100nT to 30T, with the spatial resolution of 100 µm, magnetic resolution ±2ppm of the range, the accuracy 0.002% of the range, a temperature coefficient less than 5ppm/°C, and angular errors less than 0.1°.

Keywords: Teslameter, Gaussmeter, Magnetic measurement, Hall probe

1. INTRODUCTION

A teslameter, also called gaussmeter, is an instrument for measuring magnetic flux density. Usually, a teslameter consists of a magnetic field probe and an electronic module. The probe converts the measured magnetic field into an electrical signal. Most teslameter probes used in modern science and industry are based on the Hall-effect [1] - the probe contains a Hall-effect device [2]. The electronic module supports the operation of the probe, processes the signal of the probe, and provides the interface with the user. Modern teslameters are digital, meaning that the signal processing includes analogue-to-digital conversion and digital signal conditioning, and the user interface includes a digital display. A digital teslameter with a magnetic field probe based on a Hall-effect device is often called in short – a Hall teslameter.

Hall teslameters are used for measuring magnetic flux densities in the magnetic field range from a few µT to about 30T, the frequency range from DC to several tens of kHz, and the temperature range from a few degrees K to about 200°C (although most of commercially available teslameters are intended for much narrower temperature range around the room temperature). The best published characteristics of modern Hall teslameters include the magnetic resolution as high as 0.1ppm and the magnetic field measurement accuracy of up to 50ppm of the measurement range. However, the measurement accuracy of a teslameter is usually strongly deteriorated by temperature variations, at AC measurement conditions, and by non-homogeneity of the measured magnetic fields. Accurate measurement of inhomogeneous magnetic field is steadily getting more important and challenging because of the long trend of miniaturization of technical systems. For example, this is so in the field of mapping of small magnets used in conjunction with magnetic sensors [3] – [5], or in the measurement of the magnetic field of the undulators of the electron light sources [6].

The measurement accuracy of nonhomogeneous magnetic fields is additional deteriorated if the following conditions are not sufficiently met [7]:

- Small sensitive volume of the probe, which allows for high spatial resolution of the magnetic measurement;
- Measurement of all three components of a magnetic field simultaneously at the same spot;
- Small overall dimensions of the probe, so that it can be inserted into a small space;
- Accurate spatial positioning of the probe with respect to a coordinate system;
- Accurate angular positioning of the probe with respect to a coordinate system;
- Parallelism of the sensitivity vector(s) of the probe with the axes of the coordinate system;
- No planar Hall effect

Each magnetic measurement task requires a specific combination of the characteristics of a teslameter. Unfortunately, it is often not easy to select the most appropriate teslameter for a given application. The difficulties stem from the fact that vendors sometimes apply different terminology for the same characteristics, do not publish precise conditions of the validity of the quoted data, or simply neglect to publish some important characteristics.

In spite of these difficulties, in this paper, we will try to compare the published characteristics of the commercially available teslameters. The global teslameter market is currently served by about 50 vendors with more than 100 types of teslameters [8]. We will concentrate in this study on the high-end segment of the market, with the highest-performance teslameters for the magnetic measurement range from about 1uT to 30T at about room temperature. Since the high-performance teslameters are commonly available as desktop versions only, most of hand-held teslameters were not evaluated in the study. Out of the reviewed tesalemeters, 9 models are functioning with 3-axis Hall probes, and four of them incorporate the integrated Hall probes on a single chip. The other 3-axis Hall probes are hybrid probes that consist of 3 discrete Hall sensors positioned in the way that each of them measures the one component of the magnetic field.

The comparison of the teslameters is organized in the following way: we first compile and compare the best published values of the most important characteristics; then, based on these data, we try to identify the teslameter type with the best combination of the characteristics, which best meets the needs for accurate magnetic measurement in modern science and industry.

2. COMPARISON OF TESLAMETERS CHARACTERISTICS

In each of the following tables we list three to five teslameters with the best following characteristics: 1) probe dimensions, size of the magnetic field sensitive volume, and probe angular errors; 2) magnetic resolution; 3) magnetic field measurement accuracy; 4) measurement range; 5) frequency bandwidth and 6) temperature coefficient of sensitivity.

2.1. Probe dimensions, magnetic field sensitive volume and probe angular error

For measuring non-homogenous magnetic fields the following characteristics are crucial: small overall dimension of the probe, measuring all three components of the magnetic field at the same spot (i.e. small magnetic field sensitive volume (MFSV) of the probe); and small angular errors of the probe (orthogonality error of the Hall devices within the probe). In the Table 1. are presented the three teslameters that best meet the required needs.

Table 1. Comparison of probe dimensions, magnetic field sensitive volume and angular errors of the probe

Published probe characteristics	Provider
• Fully integrated 3-Axis Hall probe; • Various and customizable dimensions (Width x Thickness), e.g.: Probe C: 4.0mm x 0.9 mm Probe K: 2.0mm x 0.5mm **Thinnest probe: 0.25mm** • MFSV distance from the tip of the probe: 0.15mm • MFSV: 0.1 x 0.1 x 0.1mm^3 • Orthogonality error (calibrated): 0.1°	SENIS AG [9]
• Hybrid 3-axis Hall probe; • Probe dimensions (WxTh): 5mm x 2mm • FSV distance from the tip of the probe: 3mm • MFSV: 0.1 x 0.1 x 0.1 mm^3 • Orthogonality error (calibrated)	COLIY [10]
• Applies SENIS Hall probes, among others [11]	METROLAB [12]

Many vendors of teslameters do not quote exact dimensions of the magnetic sensitive volume nor the angular error of their Hall probes. The SENIS integrated 3-axis Hall probe is described in Reference [13]

2.2. Comparison of the magnetic field measurement accuracy

The magnetic field measurement accuracy of the teslameter is defined as the maximum difference between the actual measured magnetic flux density and that given by the teslameter. Usually, the accuracy is expressed in percentage of the measurement range. In Table 2. we list five teslameters with the best magnetic field measurement accuracy.

Table 2. Comparison of the magnetic field measurement accuracy

Published magnetic field accuracy DC-accuracy of range	Provider
0.002% Integrated 3-axis Hall probe	SENIS [9]
0.005% Single channel 0.5% 3-channel	Projekt Elektronik [14]
0.05% Single channel 0.1% 3-channel	Lake Shore [15]
0.01% Single channel only	Group3 [16]
0.1% 3-channel	FW Bell [17]

2.3. Comparison of the magnetic resolution

Resolution of the teslameter is the smallest detectable change of the magnetic flux density that can be revealed by the teslameter. The resolution is limited by the noise and depends on the frequency band of interest. Vendors usually quote both DC resolution and AC resolution, but they rarely specify the related bandwidth. Though, one vendor [9] expresses DC resolution by quoting “Offset fluctuation & drift” over the period of time 10s (or 100s) with the sampling rate 20/s - which corresponds to the frequency range from 0.1Hz (or 0.01Hz) to 10Hz. Table 3. gives a comparison of the five teslameters with the best magnetic resolution.

Table 3. Comparison of the magnetic resolution

Published magnetic resolution	Provider
0.1uT	SENIS [9]
0.1uT	Group3 [16]
0.1uT	Projekt Elektronik [14]
0.1mT NOTE: for the range of 30uT, the resolution of 0.1nT available	FW Bell [17]
0.1mT NOTE: for the range of 3.5uT, the resolution of 2nT available	Lake Shore [15]

2.4. Comparison of the measurement range and frequency bandwidth

Hall-effect-based teslameters are applied for measuring DC and AC magnetic flux densities in the range from about 1uT to about 30T. The frequency bandwidth characterizes how well a magnetometer tracks rapid changes in magnetic field. Some vendors do not specify whether or not there is inductive pick-up in the connections of their Hall probes at the upper part of the broad frequency range they quote, which makes the comparison difficult.

Table 4. Comparison of the measurement ranges

Published measurement range	Published frequency bandwidth (per axis)	Provider
1uT-30T	DC-75kHz	SENIS [9]
1uT-30T	DC-50kHz	FW Bell [17]
1uT-30T	DC-20kHz	Lake Shore [15]
0.3T-3T	DC-3kHz	Group3 [16]
20mT-2T	DC-1kHz	Projekt Elektronik [14]

2.5. Comparison of the temperature coefficient of sensitivity

Thermal stability of the Teslameter is the dependence of the measurement on temperature. It is given as a temperature coefficient of sensitivity in ppm per degree Celsius.

Table 5. Comparison of the temperature coefficient sensitivity

Published temperature coefficient sensitivity	Provider
3ppm	Projekt Elektronik [14]
5ppm	SENIS [9]
10ppm	Group3 [16]
30ppm	Lake Shore [15]
200ppm	FW Bell [17]

2.6. Summary of the teslameters' performances and prices

By comparing the teslameters by the above characteristics we found that there are two providers offering 3-axis Hall probes with very small magnetic field sensitive volume and small probe angular errors. Two providers guarantee very high DC-accuracy of the measurement range. Three providers offer high magnetic resolution for their Hall-effect based 3-axis teslameters. The temperature coefficient of sensitivity is better than 30ppm in three cases.

Last but not least is the price/performance ratio of the evaluated teslameters. Whereas 1-axis high-end teslameters range from 3k$-6k$, the 2-axis are between 5k$-10k$, and the 3-axis teslameters are in the price segment of 14k$-20k$.

3. THE TESLAMETER WITH THE BEST COMBINATION OF PERFORMANCES

In four out of five tables, the teslameter of Senis [9] appears at the top of the list. In summary, this new teslameter can measure magnetic field vectors of a magnitude from about 1µT to 30T, with an angular error less than 0.1°, spatial resolution 100 µm, magnetic resolution ±2ppm of the range, with an accuracy of 0.002% of the range, and a temperature coefficient less than 5ppm/°C. We present below some details of this teslameter [18].

3.1. Novel Integrated Three-axis Hall probe

Accurate measurement of highly non-homogenous magnetic fields requires small and compact sensitive volume of the Hall probe and measuring all three components of a magnetic field simultaneously at the same spot. An early version of the Senis integrated 3-axis Hall probe [13] fulfilled well these requirements, but the residual flicker noise of this probe limited the measurement accuracy to about 0.1%. SENIS recently developed a new integrated 3-axis Hall probe with much better performance.

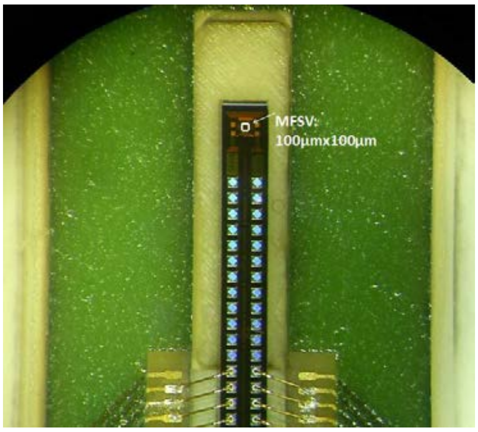

Fig.1. SENIS 3D Hall Probe. Spacial Resolution:100µmx100µm
The Probe is packaged in alumina ceramics. Probe dimensions (WxThxL) in mm: 6.0x1.6x14.5

The new Senis 3-axis Hall probe incorporates several horizontal and vertical Hall devices, monolithically integrated on a single silicon CMOS chip. Both horizontal and vertical Hall devices feature high magnetic sensitivity (higher than 0.04V/VT) and low flicker noise (the corner frequency lower than 2kHz) [19]. For each measurement axis, eight equal parallel-connected Hall devices are used. This allows reducing the noise equivalent magnetic field spectral density of the thermal noise of each group of Hall devices to about 40nT/√Hz. All 24 Hall devices occupy an area of only 100µm x 100µm.

A temperature sensor, which is also integrated on the Hall probe chip, enables an efficient temperature compensation of the influences of the probe temperature.

The electronic module drives the Hall devices in the probe according to an optimized spinning-current method. The resulting modulation-demodulation process of the Hall voltages elimintes the offset and the flicker noise of both the Hall devices and the amplifiers of the Hall signal; and it also eliminates the planar Hall voltage. After analog-to-digital conversion of the “clean” and amplified Hall signals with up to 22 significant bits, the Hall signals are further processed by an embedded computer. The digital processing includes filtering, linearization, and corrections of temperature dependence. The cancellation of the temperature influence is based on a novel calibration procedure that takes into account both the temperature of the probe and the temperature of the electronics module. The calibration process also includes the precise measurement of the nine components of the sensitivity tensor of the probe [20], which allows the elimination of the errors that might be caused by the angular tolerances of the Hall probe. The interface with the user is provided by a touch-screen display.

3.2. Latest measurement results of the novel teslameter

First measurement results of the novel teslameter have been published [7]. Here we present the latest characterization results regarding magnetic resolution, measurement accuracy, temperature compensation and orthogonality error – see Figures 2 – 5 and Table 6.

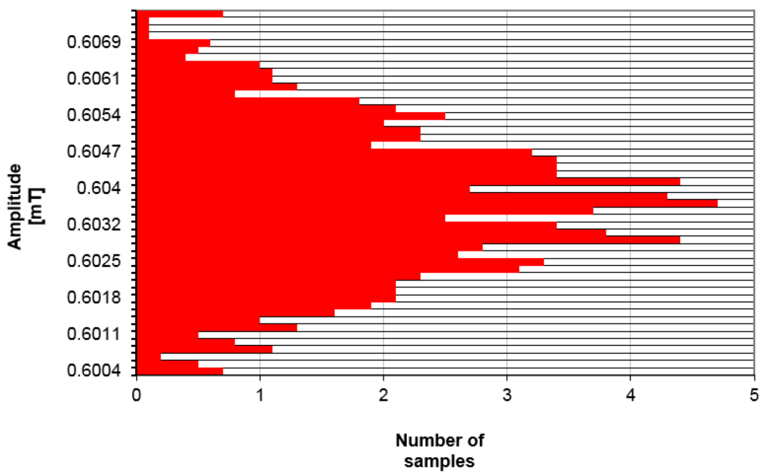

Fig. 2. Histogram of the noise-equivalent magnetic field of the 3MH5 SENIS’ Teslameter with the low-noise hybrid Hall probe, in the magnetic measurement range 2T and the frequency range from 0.1Hz to 10Hz. The calculated standard deviation is 1.2μT and the six sigma peak-to-peak noise is 7.2 μT, which corresponds to the width of the histogram. At DC measurements (integration time 1 second) the teslameter has the peak-to-peak resolution of about 1ppm of the measurement range.

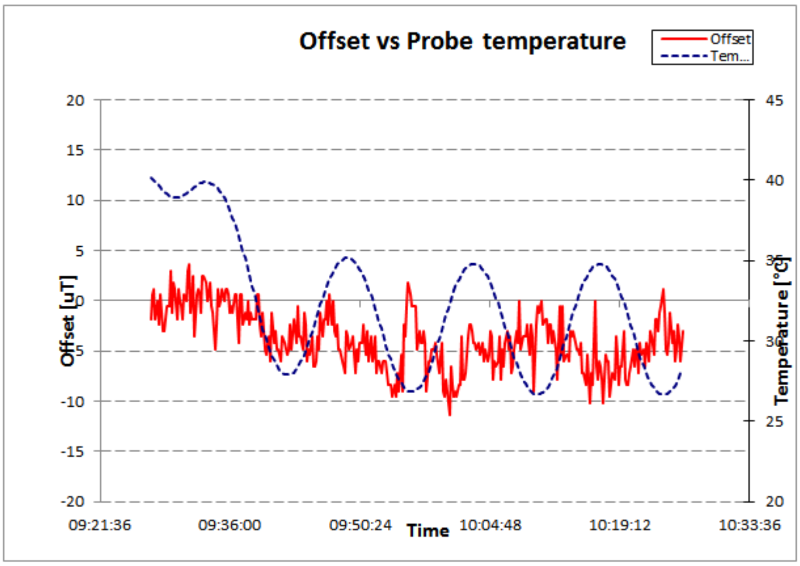

Fig. 3. Illustrating offset stability of the 3MH5 SENIS’ Teslameter. Solid red line: offset, left scale; Dashed blue line: probe temperature, right scale. The figure shows that, at room temperature, the offset fluctuations are not correlated with temperature.

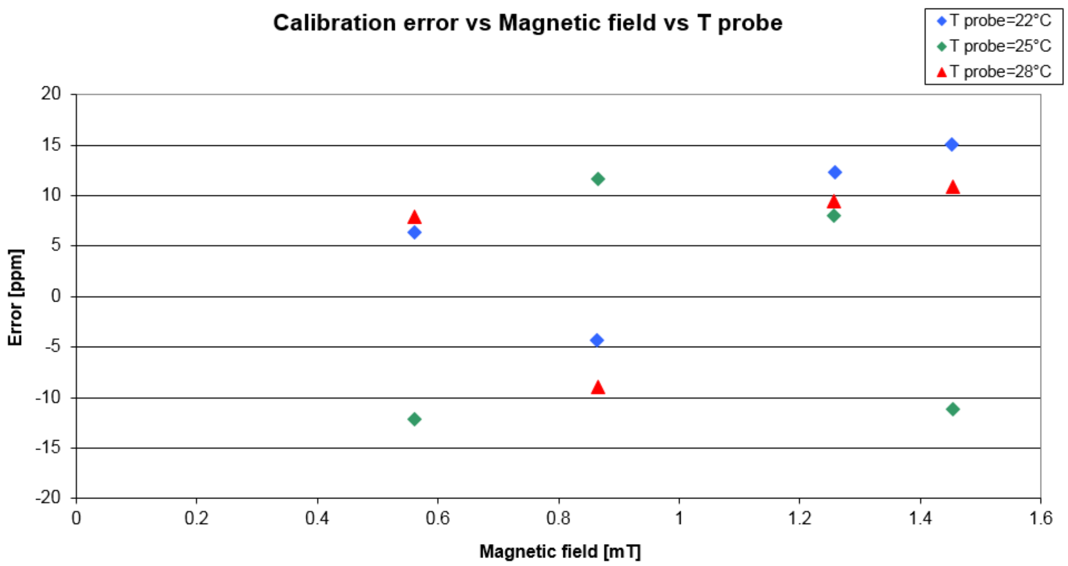

Fig. 4. The measurement error of the 3MH5 SENIS' Teslameter in the measurement range 2T. If the room temperature varies within +/- 3°C around 22°C, the measurement error is within +/-15ppm (parts per million) of the measured value.

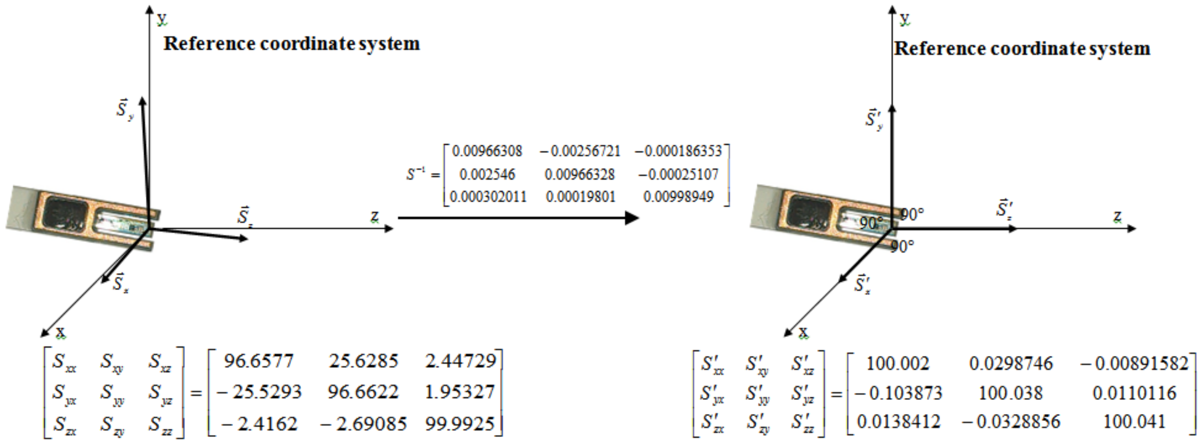

Fig. 5. Illustrating the correction of the angular errors of a 3-axis integrated Hall probe [20]. In order to demonstrate the efficiency of the calibration method, the probe was rotated with respect to the z-axis for about 15°. Left: the "raw" sensitivity matrix (before calibration); Middle: the inversed "raw" sensitivity matrix; Right: The corrected sensitivity matrix, which is an almost identity matrix, with negligible off-diagonal terms. The related angular errors are shown in Table 6.

Table 6. Angular errors of the 3-axis integrated Hall probe with the sensitivity matrices shown in Fig. 5. Notation: x_r - Roll of x sensor; x_t - Tilt of x sensor; y_p - Pitch of y sensor; y_r - Roll of y sensor; z_p - Pitch of z sensor; z_t - Tilt of z sensor. In spite of the deliberately produced big initial error x_r and y_r, after the calibration of the probe, all angular errors are reduced to less than 0.1°.

	x_r	x_t	y_p	y_r	z_p	z_t
Before calibration	14.85°	1.45°	1.16°	-14.79°	-1.54°	-1.38°
After calibration	0.017°	-0.005°	0.006°	-0.059°	0.018°	0.008°

4. CONCLUSIONS

We compared the published performance of the best, mostly 3-axis, Hall-effect teslameters that are commercially available on the global market. The comparison was based on the following characteristics: probe dimensions, magnetic field sensitive volume, probe angular errors, magnetic resolution, magnetic field measurement accuracy, magnetic measurement range, frequency bandwidth, and temperature coefficient of sensitivity. The novel SENIS 3-axis teslameter with integrated Hall probe seems to match best the demanding measurement needs in various applications in modern science and industry.

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