



BSI Standards Publication

Nanomanufacturing — Key control characteristics

Part 9-1: Traceable spatially resolved nano-scale stray magnetic field measurements — Magnetic force microscopy

National foreword

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TECHNICAL SPECIFICATION



**Nanomanufacturing – Key control characteristics –
Part 9-1: Traceable spatially resolved nano-scale stray magnetic field
measurements – Magnetic force microscopy**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**NANOMANUFACTURING –
KEY CONTROL CHARACTERISTICS –****Part 9-1: Traceable spatially resolved nano-scale stray magnetic
field measurements – Magnetic force microscopy**

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Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts of the IEC TS 62607 series, published under the general title *Nanomanufacturing – Key control characteristics*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

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- amended.

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INTRODUCTION

Measurements of magnetic fields that are homogeneous over macroscopic volumes can be made traceable to the SI standards, and traceable calibration chains from the national metrology institutes to the end users are well-established.

However, many important industrial applications such as magneto-resistive position, angle, or motion control rely on precision sensing of spatially varying magnetic fields. Such spatially varying magnetic fields can, for example, be generated by a magnetic bit pattern of a magnetic encoder scale. Today, magnetic encoder bit patterns have typically a lateral periodicity above 100 μm . Based on stray field interpolation, such encoders are applied, for example, for precision positioning systems with sub-micrometre resolution. However, such precision positioning requires reliable local field measurements which are not yet underpinned by any suitable standards.

Today, local magnetic stray field measurements with resolutions from above 50 μm down to below 500 nm can be realized by scanning magnetic field detection (SMF) methods with different field sensors such as Hall sensors, magneto-resistive (MR) sensors and magnetically coated tips on an oscillating cantilever (magnetic force microscopy (MFM)), or with imaging techniques like Kerr and magneto-optical indicator film (MOIF) microscopy. Achievable spatial resolution and typical scanning area are compared in Figure 1.

MFM provides a significantly higher resolution than other SMF techniques and MOIF (see Figure 1) and can therefore be considered as the standard tool for nano-scale investigations of the local magnetic properties of magnetic nanostructures, thin films and devices [1]¹. However, despite its wide use, MFM measurements per se only deliver purely qualitative stray field images that cannot be applied for quantitative data analysis. This results from the fact that the measured signal strongly depends on the properties of the magnetic tip, the mechanical properties of the cantilever and the sensitivity of the detection device. Hence a calibration that includes the characterization of the magnetic tip and the microscope is needed if the MFM method is to be used to provide values of key control characteristics (KCCs) which are ultimately traceable to national calibration standards.

This document aims to provide industry end users, instrument manufactures and calibration laboratories with a description of traceable calibration procedures based on reference materials with well-defined local stray field distributions. This document includes the description of suitable reference samples, the evaluation of MFM key parameters required for the method, and the determination of the instrument calibration function (ICF). Due to the finite dimension of the tip, a spatial broadening of the MFM signal is unavoidable. Mathematically this broadening can be described by the convolution of the ICF and the real magnetic field structure of the sample to be measured. Vice versa, a quantitative analysis of the measured data is achieved by a deconvolution of the MFM measurement data using the ICF. The description of this process is the key part of this document.

¹ Numbers in square brackets refer to the Bibliography.

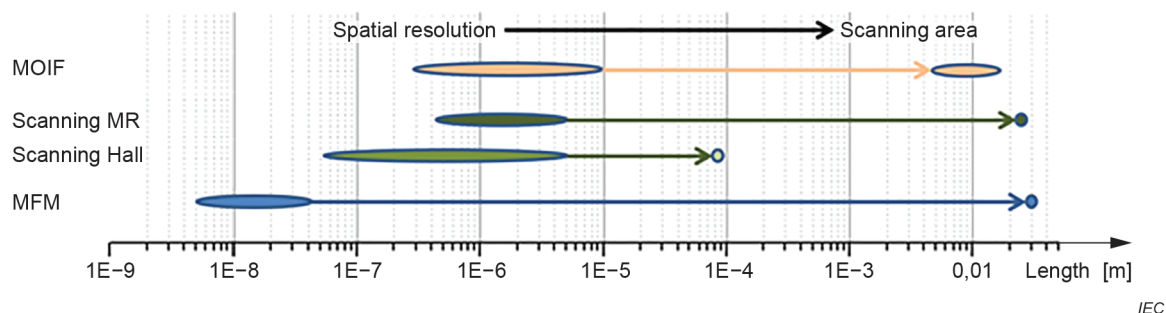


Figure 1 – Spatial resolution of magnetic stray field characterization techniques and their possible maximum scan area

The MFM technique as described in this document has a resolution down to about 10 nm to 20 nm (depending on the signal-to-noise ratio of the instrument), which is at least one order of magnitude superior to other common characterization techniques for spatially varying magnetic fields. MFM systems operated at ambient conditions typically can achieve a resolution of around 50 nm [1]. With optimized tips, a resolution down to below 20 nm is possible [2]. The highest resolution in MFM is achieved in vacuum. With very precise tip–sample distance control [3] and high-resolution tips [4], a resolution down to 10 nm could be demonstrated.

While the MFM technique has the best precision and accuracy of the test methods (see Figure 1), as a scanning technique it is comparatively slow, requires specific ambient conditions such as stable temperatures and can only be used for samples which are flat and smooth on a micrometre scale (depending on the scanning unit). For routine statistical process control (SPC) of the manufacturing process, it may not be suitable in many use cases. Therefore, it is anticipated that the MFM technique needs to be complemented, for example, by:

- the magneto-optical indicator film technique (MOIF), which, as an imaging process, allows high throughput;
- scanning Hall or MR test methods, which can easily be calibrated in homogeneous external fields. In CMOS technique, arrays of parallel Hall sensors can be prepared and thus a high throughput can be achieved in a scanning process.

Wherever possible, existing relevant scanning probe microscopy (SPM) standards are referred to, especially those developed by ISO/TC 201 like ISO 18115-2 [5] and ISO 11952 [6].

In summary, this document provides a traceable method for nanometre-resolution measurements of magnetic field patterns, which is the basis for precise control of fabrication processes and final product qualification. The key control characteristics for those products are very product specific (see, for example, IEC TS 62622:2012 [7]).

NANOMANUFACTURING – KEY CONTROL CHARACTERISTICS –

Part 9-1: Traceable spatially resolved nano-scale stray magnetic field measurements – Magnetic force microscopy

1 Scope

This part of IEC 62607 establishes a standardized method to characterize spatially varying magnetic fields with a spatial resolution down to 10 nm for flat magnetic specimens by magnetic force microscopy (MFM). MFM primarily detects the stray field component perpendicular to the sample surface. The resolution is achieved by the calibration of the MFM tip using magnetically nanostructured reference materials.

The objective of this document is to define and describe:

- reference materials for traceable high resolution magnetic stray field measurements;
- the calibration procedures to determine the instrument calibration function (ICF) and, if required, MFM key parameters entering the deconvolution process;
- the deconvolution process which allows to calculate quantitative stray field data from the measured MFM data using the ICF;
- the evaluation of the measurement uncertainty, including the prevention of potential artefacts which can occur during the measurement leading to a misinterpretation of the results.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1 General terms

3.1.1

key control characteristic **KCC**

key performance indicator

measurement process characteristic which can affect compliance with regulations and quality, reliability or subsequent application of the measurement result

Note 1 to entry: The measurement of a key control characteristic is described in a standardized measurement procedure with known accuracy and precision.

Note 2 to entry: It is possible to define more than one measurement method for a key control characteristic, if the correlation of the results is well-defined and known.

Note 3 to entry: In IATF 16949 [8] the term "special characteristic" is used for a KCC. The term key control characteristic is preferred since it signals directly the relevance of the parameter for the quality of the final product.

3.2 General terms related to magnetic stray field characterization

3.2.1

magnetic-force microscopy

MFM

atomic force microscopy mode employing a probe assembly that monitors both atomic forces and magnetic interactions between the probe tip and a surface

[SOURCE: ISO 18115-2:2013, 3.15]

3.2.2

magneto-optical indicator film technique

MOIF technique

method of mapping the magnetic field above a sample surface by a thin magneto-optical indicator film

Note 1 to entry: The magnetic fields induce a perpendicular magnetization component in the active layer of the detector, which is recorded with the Faraday effect.

3.2.3

dynamic mode scanning force microscopy

scanning magnetic force microscopy mode in which the relative positions of the probe tip and sample vary in a sinusoidal manner in time at each point in the image

Note 1 to entry: The sinusoidal oscillation is usually in the form of a vibration in the z-direction and is often driven at a frequency close to, and sometimes equal to, the cantilever resonance frequency.

Note 2 to entry: The signal measured can be the amplitude, the phase shift, or the resonance frequency shift of the cantilever.

[SOURCE: ISO 18115-2:2013, 3.6, modified – The source uses the term "dynamic-mode AFM" instead of "dynamic mode scanning force microscopy" and the term "AFM mode" instead of "scanning magnetic force microscopy mode"]

3.2.4

intermittent contact mode

mode of scanning the probe where the probe is operated with a sinusoidal z-displacement modulation such that the probe tip makes contact with the sample for a fraction of the sinusoidal cycle

[SOURCE: ISO 18115-2:2013, 5.73]

3.2.5

non-contact magnetic-force microscopy

NC-MFM

dynamic mode scanning force microscopy (3.2.3) in which the probe tip is operated at such a distance from the surface that it samples the weak attractive van der Waals or other forces

3.2.6

scanning magnetic field microscopy

SMF microscopy

method of measuring and mapping the magnetic field from a sample surface by mechanically scanning a probe above the sample surface

Note 1 to entry: This generic term encompasses *scanning Hall probe magnetometry* (3.2.7) and *scanning MR magnetometry* (3.2.8).

3.2.7

scanning Hall probe magnetometry

SHM

scanning magnetic field microscopy (3.2.6) mode in which a Hall probe is used as the scanning sensor to measure and map the magnetic field from a sample surface by acquiring a Hall voltage

[SOURCE: ISO 18115-2:2013, 3.23, modified – The phrase "scanning magnetic field microscopy" is used instead of "SPM" and the phrase "by acquiring a Hall voltage" is added]

3.2.8

scanning MR magnetometry

SMR magnetometry

scanning magnetic field microscopy (3.2.6) mode in which a magneto-resistive sensor probe on a cantilever is scanned over a magnetic sample surface to measure the *magnetic field distribution* (3.3.1) by acquiring a magneto-resistive voltage

[SOURCE: ISO 18115-2:2013, 3.25, modified – The phrase "scanning magnetic field microscopy" is used instead of "SPM" and the phrase "magnetic field distribution" is used instead of "two-dimensional magnetic images"]

3.3 Terms related to the measurement method described in this document

3.3.1

magnetic field distribution

spatially resolved magnetic field data array in the x-y-plane with the x-, y-direction in the sample plane and the z-direction along the sample surface normal with a spatial resolution dx , dy at a distance d above the surface of a test specimen

3.3.2

raw data distribution

spatially resolved MFM raw data array with the x-, y-direction in the sample plane and the z-direction along the sample surface normal at a distance d above the surface of a test specimen

3.3.3

magnetic force

force acting between magnetic volumes

Note 1 to entry: In SPM, the magnetic dipoles are usually incorporated as ferromagnetic material in the probe tip and it is the magnetic field of the sample that is measured.

[SOURCE: ISO 18115-2:2013, 5.8, modified – The phrase "magnetic volumes" is used instead of "magnetic dipoles in a magnetic field"]

3.3.4

magnetically coated probe tip

probe which is coated with a thin magnetic layer on the tip side of the cantilever

Note 1 to entry: The magnetic layer creates a magnetic volume that interacts with the sample magnetic field and thus probes it.

3.3.5

constant height mode

mode of scanning the probe tip over the sample surface at a constant height of the centre of the oscillation of the tip apex relative to the surface plane of the sample during the scan

[SOURCE: ISO 18115-2:2013, 5.34, modified – "over the surface" is replaced with "of the centre of the oscillation of the tip apex relative to the surface plane of the sample".]

3.3.6

measurement height

value of the constant height of the centre of the oscillation of the tip apex relative to the surface plane of the sample during a measurement in *constant height mode* (3.3.5)

3.3.7

measurement plane

plane at constant height above the surface where the raw data distribution is measured in *constant height mode* (3.3.5)

3.3.8

cantilever oscillation

sinusoidal z-displacement of the cantilever and thus the tip in *dynamic mode scanning force microscopy* (3.2.3)

Note 1 to entry: The z-displacement is typically induced by the oscillation of the cantilever by means of an excitation piezo, the driven frequency is close to the cantilever resonance frequency.

3.3.9

cantilever

thin force-sensing support for a *magnetically coated probe tip* (3.3.4) joined to the *cantilever chip* (3.3.10) at the end furthest from the probe tip

[SOURCE: ISO 18115-2:2013, 5.18, modified – The phrase "a magnetically coated probe tip" is used instead of "a probe tip".]

3.3.10

cantilever chip

small piece, usually of silicon, on which the *cantilever* (3.3.9) with the *magnetically coated probe tip* (3.3.4) has been fabricated and to which it is still attached as a convenient supporting structure in the probe assembly (3.3.12)

[SOURCE: ISO 18115-2, 5.26, modified – The phrase "with the magnetically coated probe tip" is added.]

3.3.11

chip holder

structure on which the *cantilever chip* (3.3.10) with the *cantilever* (3.3.9) and the *magnetically coated probe tip* (3.3.4) are mounted

Note 1 to entry: The chip holder, chip, cantilever, and probe comprise the *probe assembly* (3.3.12).

[SOURCE: ISO 18115-2:2013, 5.27, modified – The phrase "the magnetically coated" is added.]

3.3.12

probe assembly

structure comprising the *chip holder* (3.3.11), *cantilever chip* (3.3.10), *cantilever* (3.3.9) and *magnetically coated probe tip* (3.3.4) including a provision to drive a sinusoidal oscillation of the cantilever in the form of a vibration in the z-direction

Note 1 to entry: This provision typically is an excitation piezo, see ISO 18115-2.

[SOURCE: ISO 18115-2:2013, 5.20, modified– The phrase "magnetically coated probe tip" is used instead of "probe" and the phrase "including a provision to drive a sinusoidal oscillation of the cantilever in the form of a vibration in the z-direction" is added.]

**3.3.13
excitation piezo**

provision to drive a sinusoidal oscillation of the *cantilever* (3.3.9) in the form of a vibration in the z-direction exploiting the variation of a piezo active material induced by a sinusoidal electric drive signal

Note 1 to entry: See ISO 18115-2.

**3.3.14
MFM observation variable**

phase shift between sinusoidal cantilever drive signal and cantilever oscillation at fixed excitation frequency and excitation amplitude

Note 1 to entry: In principle, other measurands can also be exploited to detect the interaction between magnetic tip and sample stray field, e.g. the frequency shift of the resonance frequency of the oscillating cantilever.

**3.3.15
phase shift signal**

$\Delta\varphi$

MFM observation variable (3.3.14) defined as the phase shift between sinusoidal cantilever drive signal and cantilever oscillation at fixed excitation frequency and excitation amplitude

Note 1 to entry: The signal may be corrected by a constant offset.

**3.3.16
signal detector**

detector that transforms the amplitude and temporal course of the cantilever oscillation into an electrical signal

Note 1 to entry: In this case a light pointer combined with a sensitive photo detector (PSD).

**3.3.17
signal analysis system**

system to extract and record the *MFM observation variable* (3.3.14) as a function of the lateral displacement of the tip

Note 1 to entry: In this case a system to extract the phase shift between the cantilever driving sinusoidal oscillation and the signal detected by the signal detector. The phase shift may be offset corrected.

**3.3.18
z-scanner**

element for the realization of the vertical displacement of the specimen/probe distance during x-y-scanning

Note 1 to entry: See ISO 18115-2:2013, 5.136.

**3.3.19
x-y-scanner**

element for realization of the lateral displacement of the probe or of the specimen in the x-y-plane

**3.3.20
data pre-processing**

raw data treatment to remove known artefacts of the measurement process

**3.3.21
data levelling**

form of *data pre-processing* (3.3.20) to eliminate unwanted features from scan lines, such as drift and offsets

3.3.22**magnetic field reference sample**

magnetic sample whose *magnetic field distribution* (3.3.1) above the sample surface is well-known or can be calculated

3.3.23**cantilever resonance quality factor**
 Q

energy stored in a cantilever for a particular resonance peak divided by the average energy lost per radian of oscillation, this average being over one cycle

Note 1 to entry: A practical method of measuring the cantilever resonance quality factor is to record a resonance curve as a function of frequency. Q is approximately equal to the resonance frequency divided by the bandwidth of the resonance, and this approximation is excellent for quality factors above about 4.

Note 2 to entry: The bandwidth of the resonance can be measured from a plot of the square of the amplitude against frequency. The bandwidth is the frequency interval between the two points 3 dB below the peak maximum on either side of the peak. This is, to an error of less than 0,25 %, the full width at half maximum height (FWHM) of this curve, so the FWHM can be judged a more convenient and sufficiently accurate measure of bandwidth for many practical purposes.

[SOURCE: ISO 18115-2:2013, 5.127, modified – The term is "cantilever resonance quality factor" instead of merely "quality factor" and, accordingly, the more general phrase "a given resonator" is replaced with "a cantilever". The original Note 1 is omitted.]

3.3.24**oscillation amplitude**
 A_{osc}

tip oscillation amplitude caused by the *cantilever oscillation* (3.3.8) in *dynamic mode scanning force microscopy* (3.2.3)

Note 1 to entry: The oscillation amplitude for an approached intermittent contact mode measurement and for a constant height measurement may be different.

3.3.25**lift height**
 z_{lh}

vertical distance by which the distance of the oscillation centre of the probe's tip apex to the sample surface is increased in between intermittent contact mode and constant height measurements

3.3.26**measurement height**
 z

distance of the oscillation centre of the probe's tip apex to the sample surface in a dynamic mode MFM

Note 1 to entry: Instruments typically give a *lift height* (3.3.25) value for the MFM measurement in a dynamic mode. The tip-sample distance is the sum of the lift height and the *oscillation amplitude* (3.3.24) as measured when the probe is approached to the sample surface.

3.3.27**scan size**
 S_x, S_y

length and width of the scanned area in the scan plane

3.3.28**pixel size**
 $\Delta x, \Delta y$

length and width of the area represented by each measured point in a 2D raster image

3.3.29**cantilever canting angles** θ, φ

azimuthal and polar angles describing the tilt of the cantilever with respect to the MFM measurement plane in polar coordinates

Note 1 to entry: See ISO 18115-2:2013, 5.92 Note 2 to entry and 5.119.

3.3.30**tip magnetization orientation** M_{tip}

sign of the net effective magnetic charge distribution of the magnetic tip, described as "up" or "down" or as "+" or "-"

Note 1 to entry: The underlying tip magnetization distribution depends on the structure of the probe tip and the coating method of the magnetic thin layer.

Note 2 to entry: The tip can be magnetized in a magnetic field higher than the tip coercive field normal to the cantilever.

3.3.31**effective magnetic charge distribution** σ_{eff}

hypothetical 2D magnetic monopole distribution that results in the same magnetic field above a sample or below a magnetically coated tip as the underlying 3D magnetic volume material

3.3.32**sample under test****SUT**

material whose magnetic field distribution is to be measured

3.3.33**spring constant****force constant** C

quotient of the applied normal force at the probe tip by the deflection of the cantilever in that direction at the probe tip position

[SOURCE: ISO 18115-2:2013, 5.92]

3.3.34**pseudo-Wiener deconvolution**

deconvolution applying a pseudo-Wiener-filter for noise suppression in a deconvolution in Fourier space with regularization parameter α

Note 1 to entry: The formula that applies is as follows, where the asterisk marks the complex conjugate:

$$A(k, z) = \frac{B(k, z)}{C(k, z)} \rightarrow A(k, z) = B(k, z) \frac{C^*(k, z)}{|C(k, z)|^2 + \alpha}$$

3.3.35**regularization parameter** α

constant in the *pseudo-Wiener deconvolution* (3.3.34) that approximates the noise characteristics of the image

3.3.36**tip transfer function****TTF** F^{TTF}

distribution of the stray field gradient generated by the magnetically coated tip in the measurement plane

3.3.37**discrimination**

data treatment process where the data entries in a data distribution are dichotomized resulting in a binary data set with entries +1 or -1

Note 1 to entry: The dichotomization is effected on the basis of a threshold value ι as discrimination criterion. Data entries less than ι are assigned the value -1, data entries greater than or equal to ι are assigned the value +1.

3.4 Key control characteristics measured according to this document**3.4.1****magnetic field distribution of the reference sample** H_z^{ref}

magnetic field distribution (3.3.1) of the perpendicular magnetic field component of the reference sample in the *measurement plane* (3.3.7)

3.4.2**measured phase shift distribution of the reference sample** $\Delta\varphi^{\text{ref}}$

raw data distribution (3.3.2) being the *phase shift signal* (3.3.15) distribution in *dynamic mode scanning force microscopy* (3.2.3) of the reference sample measured in the *measurement plane* (3.3.7) in *constant height mode* (3.3.5)

3.4.3**instrument calibration function****ICF**

scanning magnetic field microscopy (3.2.6) system response function in real or partial Fourier space that relates the measured signal to the magnetic field distribution

Note 1 to entry: In this case, it relates the *measured phase shift distribution of the sample under test* (3.4.4) to the underlying *magnetic field distribution of the sample under test* (3.4.5). For magnetic force microscopy, the ICF is a linear function of the frequency spectrum of the measured signal. The ICF is calibrated using a reference sample.

3.4.4**measured phase shift distribution of the sample under test** $\Delta\varphi^{\text{SUT}}$

measured *phase shift signal* (3.3.15) distribution with respect to the perpendicular magnetic field component of the sample under test in the *measurement plane* (3.3.7)

3.4.5**magnetic field distribution of the sample under test** H_z^{SUT}

magnetic field distribution (3.3.1) of the perpendicular magnetic field component of the sample under test in the *measurement plane* (3.3.7)

Note 1 to entry: The magnetic field *raw data distribution* (3.3.2) being the *phase shift signal* (3.3.15) distribution in a *dynamic mode scanning force microscopy* (3.2.3) of the sample under test measured in the *measurement plane* (3.3.7) in *constant height mode* (3.3.5).

3.5 Symbols and abbreviated terms

Abbreviation	Description
DFT	discrete Fourier transform
ICF	instrument calibration function
KCC	key control characteristic
MFM	magnetic force microscopy
MOIF	magneto-optical indicator film
MR	magneto-resistive
NC-MFM	non-contact magnetic-force microscopy
SHM	scanning Hall microscopy
SMF	scanning magnetic field
SUT	sample under test
TTF	tip transfer function

Symbol	Corresponding uncertainty (if applicable)	Description
α	$u\alpha$	regularization parameter
A_{osc}	uA_{osc}	tip oscillation amplitude
C	uC	cantilever spring constant
δ_{DW}	$u\delta_{\text{DW}}$	domain wall transition width
D		instrument sensitivity
$f(x,y)$	$uf(x,y)$	domain wall kernel
$\Delta\varphi^{\text{ref}}(x,y,z) /$ $\Delta\varphi^{\text{ref}}(\mathbf{k},z)$	$u\Delta\varphi^{\text{ref}}$	reference sample measurement raw data (phase shift data) in real / partial Fourier space
$\Delta\varphi^{\text{SUT}}(x,y,z) /$ $\Delta\varphi^{\text{SUT}}(\mathbf{k},z)$	$u\Delta\varphi^{\text{rSUT}}$	SUT measurement raw data (phase shift data) in real / partial Fourier space
$\Delta A = \Delta x \times \Delta y$	$u\Delta A, u\Delta x, u\Delta y$	pixel size in x - / y -direction
H		environmental humidity
$H_z^{\text{ref}}(x,y,z) /$ $H_z^{\text{ref}}(\mathbf{k},z)$	uH_z^{ref}	z -component of the magnetic field distribution of the reference sample in real / partial Fourier space
$H_z^{\text{SUT}}(x,y,z) /$ $H_z^{\text{SUT}}(\mathbf{k},z)$	uH_z^{SU}	z -component of the magnetic field distribution of the SUT in real / partial Fourier space
k_x, k_y		spatial wave vector components in x - / y -direction in partial Fourier space
$\mathbf{k} = (k_x, k_y)$		vector of the spatial wave vectors in x - / y -direction in partial Fourier space
$k = \sqrt{k_x^2 + k_y^2}$		modulus of the vector of the spatial wave vectors
K_u, K_d		perpendicular anisotropy constant, magneto-static energy density

Symbol	Corresponding uncertainty (if applicable)	Description
$m(x,y)$ / $m(k_x, k_y)$		normalized magnetization distribution in real / Fourier space
$M^{\text{eff}}(x,y,z)$ / $M^{\text{eff}}(\mathbf{k}, z)$		effective magnetic charge pattern in real / Fourier space
M_S	uM_S	saturation magnetization
m_S	um_S	magnetic moment per unit area
M_{tip}		tip magnetization orientation, "up" or "down"
N_x, N_y		pixel number in x - / y -direction
Q	uQ	tip quality factor
$\sigma^{\text{eff}}(x,y)$ / $\sigma^{\text{eff}}(\mathbf{k})$		effective magnetic charge distribution in real / partial Fourier space
S_x, S_y		scan size in x - / y -direction
T		environmental temperature
θ, φ	$u\theta, u\varphi$	canting angles of the cantilever in the setup in polar coordinates
W		sensor sensitivity function
x, y		in-plane scan spatial coordinates
z	uz	tip-sample distance

4 General

4.1 Measurement principle, general

Scanning magnetic field sensors measure either the total stray field amplitude or one or several components of the magnetic field vector distribution of a sample under test (SUT), such as, for example, the perpendicular field component $h_z(x,y,z)$ [5][10][11][12][13][14][15][16]. For the following, we assume that the sensor is scanned over the SUT in an x - y -plane at a constant height z . At any position of the scanning system (x,y,z) , the sensor signal is detected with a detection unit and further processed by an analysis system.