September 2009

COST Action 299 "FIDES"
Optical Fibres for New Challenges Facing the Information Society
Chair: Prof. Dr. Luc Thévenaz

Guideline
for Use of Fibre Optic Sensors

Created in the WG 4: "New Challenges in Fibre Optic Sensors"
Study Group: Applications and Standardization of Fibre Sensors
(Chairman: Dr. Wolfgang R. Habel, BAM Berlin)

Introduction

Development of standards and guidelines for performance specifications and testing for fibre optic sensors has been discussed since the mid-nineties of the last century in the scientific community as well as in the industry. Very global standards for the use of fibre optic components in data communication and telecommunication have been available for more than 20 years. Guidelines or substantial standards for fibre optic *sensors* are rather an exception. The first standard draft on generic specification of fibre optic sensors has been published in 1995 (IEC 61757-1:1995); the first draft for a specific type of fibre sensor - the fibre optic gyroscope - was published in 1996 (IEEE Standard Specification Format Guide and Test Procedures for Single-Axis Interferometric Fiber Optic Gyros; Working Draft P952/D24). Some terms used in fibre optic communication are quite close to the terminology typically used in fibre optic sensor technology. However, there are a huge number of specific issues associated with specifically fibre optic sensing systems. These items are not considered in existing guidelines or standards. For instance, standards for fibre optic sensors have to cover characteristic details related to the respective physical sensor mechanism, to the sensor response for different measurands, to the application, and finally to specific environmental conditions.

Naturally, it is not possible to cover either all different aspects of fibre optic sensors in one standard or a set of harmonized standards. This very complex matter requires specific guidelines for specific sensor types (*e.g.* distributed sensors, point sensors such as fibre Bragg grating (FBG) sensors, sensors for mechanical measurands such as strain, deformation, biological and chemical sensors or sensors for physical quantities such as pressure, humidity, and ionizing radiation).

In order to define clear guidelines and/or regulations for appropriate characterization of performance specifications and better understanding of frequently used fibre optic sensors, particular activity has been established within the European COST Action 299 "FIDES" (Optical Fibres for New Challenges Facing the Information Society) in the framework of its Working Group 4: "New Challenges in Fibre Optic Sensors".

The guideline has been developed by an international brains trust:

Prof. Dr. Berghmans (Vrije Universiteit Brussels /Belgium)
Dr. Borzycki (National Institute of Telecommun. /Poland)
Dr. Habel (BAM Federal Institute for Materials Research and Testing/Germany); Coordinator
Dr. Haase (HBM GmbH/ Germany)
Prof. Dr. Jaroszewicz (Military University of Technology /Poland)
Dr. Niklès (Omnisens SA/Switzerland)
Prof. Dr. Thévenaz (Ecole Polytechnique Fédérale de Lausanne /Switzerland)
Prof. Dr. Tur (Tel-Aviv University /Israel)
Prof. Dr. Wuilpart (Faculté Polytechnique de Mons /Belgium)

The guideline contains the following sub items:

- General terms
- Functionality
- Response characteristics
- Quantities of random nature
- Optical safety related quantities
- Closing remarks, references.

Definitions are given; if necessary, additional remarks are included.

General terms

This category describes terms affecting all or most fibre optic sensors.

Type of used fibre

Definition: It must be specified according to a known category of fibre and this category must apply for all listed performances. If performance is affected using a specific type of fibre, this must be indicated.

Type of sensor

Definition: The fibre-optic sensor type considered can be a distributed sensor that is sensitive over the whole fibre length, or the sensor is represented by a discrete (single) sensitive element or a chain/number of sensitive elements.

Distance range

Definition: It is the fibre length over which the measurement can be performed within the stated uncertainty and spatial resolution.

Note: For attenuation-limited systems it can be calculated as follows:
Distance range [km] = (Optical budget [dB] - connection loss [dB])/Linear attenuation of fibre [dB/km].

Measurement range

Definition: It is a set of values of measurands for which the error of a measuring instrument is intended to lie within specified limits (acc. to VIM 93 5.4). It is defined by the minimum and maximum allowable values of the measurand.

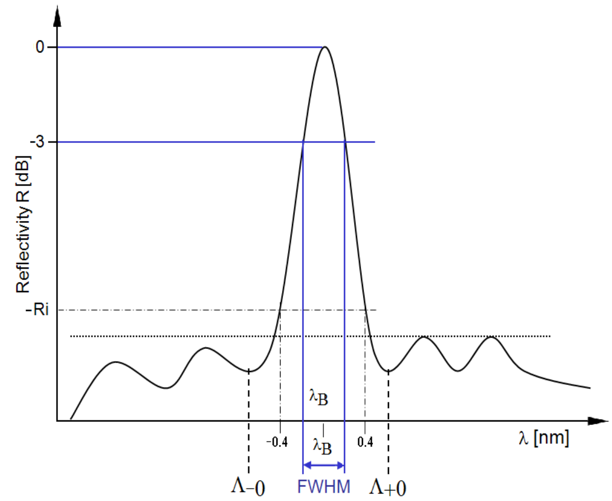
Note: It may be limited by several factors, e.g. onset of unacceptable non-linearities, mechanical issues, etc.

Wavelength of operation
Definition: It is the wavelength (range of wavelengths) of optical radiation which the sensor uses in order to provide the required information.

Subterm: Characteristic Wavelength @ reference temperature (FBG)
Definition: It is the wavelength that characterizes the sensor response at reference temperature monitored by the interrogator. It shall be given together with the experimental and numerical method used for its determination.

Note, example: The characteristic wavelength can be measured as the maximum value of the peak in reflection or as minimum value of the transmission spectra.
Important characteristics of FBG for sensors are:

- *Peak wavelength [nm]*
- *Peak wavelength deviation at room temperature [nm]*
- *Peak reflectivity [%]*
- *FWHM peak width (-3 dB bandwidth) [nm]*
- *Side lobe suppression at ± 0.4 nm [> xx dB]*
- Λ_{+0}, Λ_{-0} *(first poles (minima) of the Bragg grating reflection peak)*
- *Pulse stability (side lobe suppression)*
- *Reflectivity above the amount* R_i *with a typical spectral width of more than +/- 0.4 nm around the Bragg wavelength. For this width no additional peaks (side lobes) are expected.*



Gauge factor / scale factor @ reference conditions
Definition: It is specification how the input quantity of a measurement device is changed into the output quantity.

Note: Sometimes the term strain factor or K factor is used when a linear characteristic is assumed. The gauge factor can separately be defined for the components of a measurement system. It is only valid for defined conditions. In case of non-linear characteristic, the gauge factor can be linearized within defined amount of permissible error. Reference condition includes values and ranges for the influence quantities affecting the measurement system.

True value
Definition: It is the result of a measurement that would be obtained by a perfect measurement.

Note: Because true values are by nature indeterminate, there may be many values consistent with the definition of a given particular quantity. A number of results of measurements enable to establish best estimate for the true value with the minimum uncertainty. This estimate is called conventional true value, assigned value, sometimes reference value. The conventional true value can have an uncertainty appropriate for a given purpose which is generally accepted by convention. The expression "reference value" in this sense should not be confused with the term reference value refered to reference conditions that are prescribed for performance tests or for intercomparison of results of measurements.

Functionality

This category describes terms useful during FOS works.

Fatigue

Definition: It is a change of the result due to accumulation of mechanical damage.

Note: It can be influenced by the method of sensor attachment to the measured object and materials used.

Life expectancy / lifetime

Definition: It is a period of time during which the measuring system or its components are operating according to all its specifications in given conditions.

Note: In this time the system will perform its internal function, satisfactorily or without failure, e.g. within specified performance limits, when used in the manner and for the purpose intended, while operating under the specified application and operation environments with their associated stress levels.

Durability

Definition: It is related to the quality of a manufactured component of a measurement system or of the whole measurement system and indicates how well it withstands a sustained period of specified operation. It comprises the degree to which the system or its components can withstand physical, chemical, or environmental factors.

Note: A durable item can be used over a definite, mostly long period without being degraded or consumed.

Failure criteria

Definition: It is the measurement uncertainty (overstress, overheating, etc.) which exceeds the specified level or no results are provided.

Note: A component is considered faulty if it no longer meets applicable mandatory requirements listed in the data sheet.

Gauge length (GL)

Definition: It is the length of the measured object over which the sensor gathers information. For example, if the sensor is only anchored at two fixed points *L* cm apart, then the GL is *L*. On the other hand, if a sensor of length *l* is continuously-fixed in or to a measured object of length *L*, then the actual GL depends on the method of attachment to the measured object and is a function of the mechanical properties of both the sensor and its surrounding; it is generally longer than *l* but shorter than *L*.

Note: If a user wants to achieve a pre-determined GL, he must be very careful in selecting the procedure by which the sensor is anchored/attached/embedded. In case of continuously-fixed sensors, the fixing length must exceed the defined GL by a few tens of fibre diameter to avoid shear-lag problems at the edges. In the specific case of fracture or cracks within the GL of the sample, the final gauge length must be calculated then from the GL at fracture by subtracting from the latter the elastic portion of the elongation.

Sampling interval

Definition: It is time interval between two consecutive data points digitized by the sensing device, normally converted to distance given in metres, using user-defined parameters such as refractive index.

Note: It may depend on the distance range and other sensing device settings. The sampling interval is consequently a non-physical parameter and does not contain any information about the spatial resolution of the measurement system itself. It however contributes to the distance and location uncertainties.

Optical power dynamic range

Definition: It corresponds to the maximum cumulated one-way or two-way loss (it must be indicated) in the optical link between the interrogator and the measurement point that makes possible a measurement with a specified performance.

Note: The measurement uncertainty, resolution and interrogator settings (pulse width, averaging time etc.) are interdependent and cannot be specified independently. In particular, loss budget can be improved at the expense of increased averaging time and/or uncertaintanty of measurement.

Warm-up time

Definition: It is the duration from power-on until the system performs in accordance with all specifications.

Measuring time

Definition: It is the required duration to obtain the result of a measurement (IOS VIM93 3.1) within specified uncertainty, spatial resolution and distance range.

Updating time

Definition: It is the duration between two subsequent results produced by the measuring system.

Limiting conditions

Definition: They are extreme conditions that a measuring instrument is required to withstand without damage or without degradation of specified metrological characteristics when it is subsequently operated under its rated operating conditions (acc. to VIM 93 5.6)

Response characteristics

This category gives correlation between output quantities of a measurement system and corresponding quantitative characteristics of the measurand

Resolution

Definition: It represents the smallest change in the measurand, meaningfully detectable by the measurement system. The resolution is limited by either the instrument readout or precision, whichever is bigger.

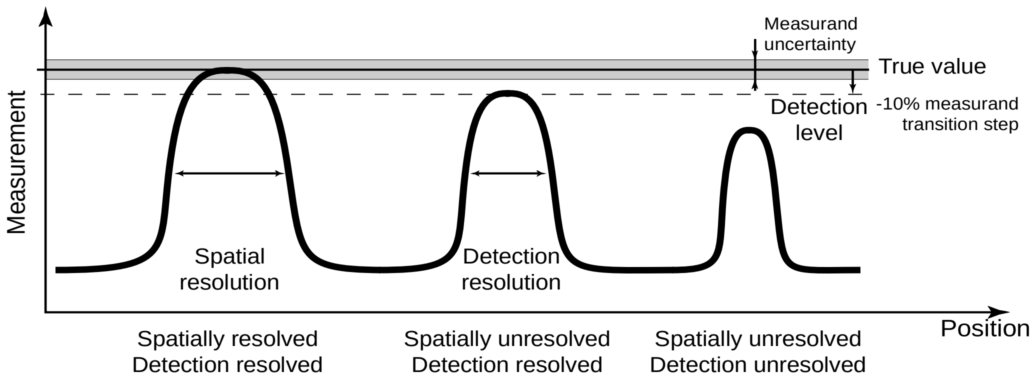
Spatial resolution

Definition: It is specified for a fibre by the minimum distance between two step transitions of the measurand of at least 20 times of its resolution.

Subterm:
Measuring spatial resolution
Definition: It is the minimum distance over which the system is able to indicate the value of the measurand within the specified uncertainty.

Subterm:
Detection spatial resolution
Definition: It is the minimum distance that generates results that are within 10% of the measurand transition amplitude.

Example:

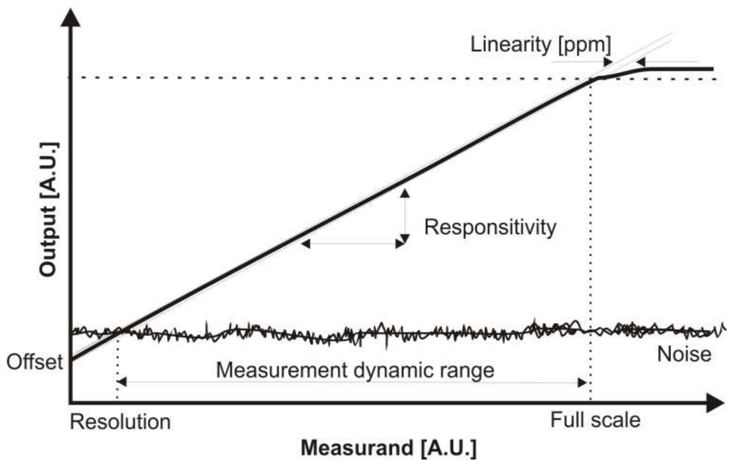


Measurement dynamic range

Definition: It is the ratio of the difference between the extremes of the measurement range (measurement span) to the resolution (the smallest detectable change), often expressed in dB.

Scale factor
Definition: It is the inverse of the ratio of a change in the stimulus to corresponding measured change. It may depend on the value of the stimulus.

Example:



Responsivity
Definition: It expresses the change in the response (output signal) of a complete measurement system to the corresponding change in the stimulus (input signal).

Note: It may depend on the value of the stimulus, and then the responsivity must be specified separately for each value. Normally, it is not dimensionless and cannot be expressed in Percent.

Linearity
Definition: It is the tolerance to which a response characteristics of a measurement system approximates a straight line in the measurement dynamic range.

Note: Practically, deviation from linearity is usually expressed in ppm.

Drift
Definition: It is a slow change of the metrological characteristics of the measurement system.

Note: It indicates a lack of stability due to environmental and operational affects, material effects (e. g. creep of adhesive) or storage conditions. Drift effect in a running measurement system causes a change of the output signal without variation of the input signal. Drift must be evaluated and indicates how often a measurement system needs recalibration. It must be distinguished between recalibration of devices and applied sensors (which is usually complicated or impossible). Concerning the scale factor, it can suffer from drift from zero or offset drift, or from a drift from the slope, or combinations of both. The estimated amount of the drift has to be expressed as an error estimate in the measurement result.

Cross-sensitivity
Definition: It is unwanted change of measurement result due to influence of physical factors other than the measurand.

Note: Typically, this is influence of temperature on mechanical sensors.

Full Scale
Definition: It is the largest allowable value of the measurand.

Note: It may be limited by several factors, e.g. onset of unacceptable non-linearities, mechanical issues, etc

Quantities of random nature

These quantities describe unpredictable variations in measurement results affecting system reliability

Accuracy

Definition: It qualitatively expresses the closeness of the measured value to the true or ideal ('master') value of the measurand. Accuracy represents the difference between the measured result and the true value and is affected by both bias and precision.

> *Note: Accuracy should not be confused with the term precision.*
> *Achieving high accuracy requires careful control of all factors influencing operation of measuring system, e. g. temperature, barometric pressure, etc.*

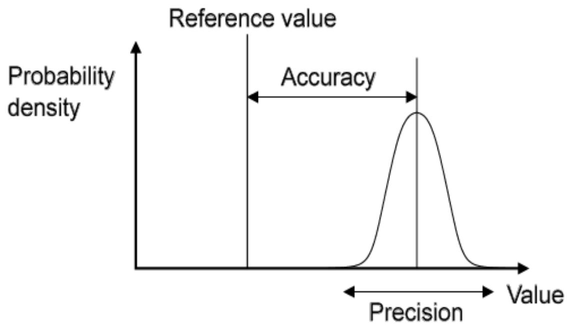
> **Subterm:**
> **Location accuracy**
> Definition: The displayed location minus the true location.
> Note: This error is a function of the location.

> **Subterm:**
> **Distance accuracy**
> Definition: The distance between two events provided by the measurement device minus the true distance.

Precision

Definition: It describes how repeatable a measurement result is. Precision is expressed by the estimated standard deviation of a specified series of measurements. (Sometimes precision is expressed as a multiple of the estimated standard deviation, e. g. 2σ). The smaller the dispersion of the measured values, the better the precision; precise measurement results need not to be necessarily accurate (e.g. due to bias). Therefore a result of a single measurement should be interpreted as drawn from an ensemble with the measured standard deviation.

Example:



Repeatability

Definition: It is closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement (acc. to VIM 94, 3.6).

Reproducibility

Definition: It is closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement (acc. to VIM 94, 3.7).

Uncertainty of measurement

Definition: It means doubt about the validity of the estimate *y* for the measurand *Y* and reflects the lack of knowledge of the exact value *Y*. Uncertainty is expressed by a parameter $u_c(y)$, associated with the result of measurement *y* that characterizes the dispersion of the values that can reasonably be attributed to the measurand. The parameter can be an estimated standard deviation (or a given multiple of it), or the half-width of an interval having a stated level of confidence.

> *Note: The evaluated dispersion $u_c(y)$ must be additionally reported to the estimate y of the measurand Y; it should preferably be stated in the ways proposed in the 'Guide to the Expression of Uncertainty in Measurement' (GUM), ISO 1995, chapter 7. The dispersion comprises uncertainties evaluated from the statistical distribution of the results of series of measurements, and also unknowable quantities due to possible errors.*
>
> *Uncertainty of relative measurements is usually significantly lower than the uncertainty defined above and rather depends on precision and drift.*

Bias

Definition: It is the difference between the measured result after averaging and the 'true' value. The true value can be obtained either by measuring a reference standard maintained by the national standard organisations or by using a traceable measuring instrument.

Noise

Definition: It is a random variation in the measurement result unrelated to the measurand. It primarily affects the precision of measurement.

Stability

Definition:

It is the ability of a measurement system to maintain its metrological characteristics and meet other specifications over the intended service time.

Optical safety quantities

The cited guidelines refer to safe use of fibre optic sensors with laser-based interrogators.

Optical safety procedures and requirements for optical transport systems:	ITU-T G.664, 2006-03 (International Telecommunication Union/ITU - Telecommunication Sector)
Safety of laser products:	IEC 60825-1 CORR 1: 2008-08, Part 1: Equipment classification and requirements IEC 60825-2 INT 1: 2008-04, Part 2: Safety of optical fibre communication systems
European norm for laser safety eyewear: Personal eye-protection. Filters and eye-protectors against laser radiation (laser eye-protectors)	EN 207 (issued 1998, amended 2002)

Note: The European norm is stricter than the American norm (ANSI Z 136) that only regulates the required optical density. More precisely, the safety glasses should be able to withstand a continuous wave laser for 10 seconds, or 100 pulses for a pulsed laser.

U.S. standard for eyewear protection & safe laser use:	ANSI Z136 series, e. g. ANSI Z136.1 - Safe Use of Lasers ANSI Z136.2 - Safe Use of Lasers in Optical Fiber Communication Systems Utilizing Laser Diodes and LED Sources

See also: FIBRESYSTEMS EUROPE. Laser safety: standards guarantee best practice. 2002, Oct 29, 2 pages.

Closing remarks, references

This guideline is the collective work of the members of the COST 299 Study Group WG 4/ SG 3: 'Applications and Standardization of Fibre Sensors'. The COST 299 members are interested in dissemination of this guideline; and therefore it is wanted and recommended to refer to this guideline. The intellectual property rights have to be respected by citation of this COST 299 Guideline.

Papers /books	Habel, W.R.: Reliable Use of Fibre Optic Sensors. In: Encyclopedia of Structural Health Monitoring. (Eds: Boller, C. et al.). John Wiley & Sons. 1. Edition January 2009. Chapter 155. 13 pages ISBN-10: 0-470-05822-6, ISBN-13: 978-0-470-05822-0
	Tennyson R (Ed.). Installation, use and repair of fibre optic sensors. Design Manual ISIS-M02-00, Canada, Spring 2001 and Civionics Specification. Design Manual No. 6, October 2004 (Chapter 2: Specifications for fibre optic sensors (FOS). ISIS Canada Research Network.
	Dyer S.D. Key metrology considerations for fiber Bragg grating sensors. Proc. of SPIE, vol. 5384 (2004) 181-189.
	Fernandez A.F, Gusarov A, Berghmans F, Kalli K, Polo V, Limberger H, Beukema M Nellen P. Round-robin for fiber Bragg grating metrology during COST270 action. Proc. of SPIE, vol. 5465 (2004)210-216.
Web-Information	RILEM Technical Committee "Optical Fibre Sensors" http://www.rilem.net/tcDetails.php?tc=OFS
	The Association of German Engineers (VDI), Society of Experimental Stress Analysis (GESA). http://www.vdi.de/strukturmonitoring
Standards/Guidelines	IEC Final Draft 61757-1:1998: Fibre optic sensors – Part 1: Generic specification (Original language: German); SN EN 61757-1:1999-01 (Swiss Standard)
	VDI/VDE Guideline 2660, 2009-05: Optical Strain Sensors based on Fibre Bragg Grating. The Association of German Engineers (VDI), Society of Experimental Stress Analysis (GESA). http://www.beuth.de ICS: 17.180.99 ,33.180.10
	ISO/IEC Guide 98-3:2008: Uncertainty of measurement - Part 3: Guide to the expression of uncertainty in measurement. ISO, Geneva 2008, ISBN 92-67-10188-9.
	International Vocabulary of Basic and General Terms in Metrology (VIM). Beuth Verlag GmbH Berlin/Wien/Zurich, 2nd Ed. 1994, ISO/IEC Guide 99:2007-12 (English/French), http://www.beuth.de
	ITU-T G.664, 2006-03: Optical safety procedures and requirements for optical transport systems

This Guideline document has been confirmed at the COST 299 Management Committee meeting in Wroclaw/Poland, September 9, 2009.