Metrology aspects of the IDS3010

Standards and traceability

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Introduction

The attocube Industrial Displacement Sensor (IDS) is an optical sensor that measures displacements of a target. Thus it has to fulfil metrological standards. The validation that the IDS' displacement measurement performs in accordance to the International Length Standard is physically rooted in its technical design and certified by National Metrology Institutes participating in the CIPM-MRA (CIPM Mutual Recognition Arrangement [1]). Furthermore, the performance is quality-checked during the production process. By this we can assure our customers that the system's specification is validated with full traceability.

This Technical Note explains the metrological aspects of the IDS that are important. In that context, we explain why it is necessary for us to at least distinguish three different concepts of quantifying a displacement measurement (in accordance to the International Vocabulary of Metrology (VIM) [2]) and how the technical design of the IDS is linked with them. We give an explanation to what extent the overall measurement accuracy of the system is certified, why its precision is dependent on the application and why resolution is merely an electronic feature.

IDS working principle

The measuring principle of the IDS is based on interferometry. To measure displacements of a target the IDS sends out a laser beam of a certain wavelength, which is additionally modulated with several MHz. The laser beam gets coupled into an optical fiber and reaches a sensor head in which the ferrule of the fiber ends. The remaining light travels to a reflective target. The light reflected from the target is coupled back into the fiber and finally interferes with the light reflected at the ferrule interface. This interference signal is detected and processed by the IDS. The laser is modulated to create a second, 90° phase-shifted, interference signal, which is used to build a Lissajous figure (see Figure 1). The target displacement Δx is measured by analyzing the phase change $\Delta\Phi$ of the Lissajous figure and is proportional to the laser wavelength λ:

$$\Delta x = \frac{\lambda}{4\pi} \cdot \Delta\Phi \quad (1)$$

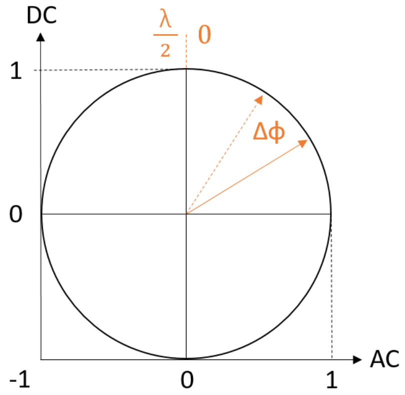

Figure 1: The normalized Lissajous figure which is based on two 90 ° phase-shifted sinusoidal interference signals (AC and DC)

IDS measurement accuracy (trueness)

Measurement accuracy – if averaged, the measurement trueness – describes the closeness of agreement of the IDS displacement measurement value compared to the true target displacement value (see Figure 2). In general, a high trueness of the measured values implies minimized systematic errors.

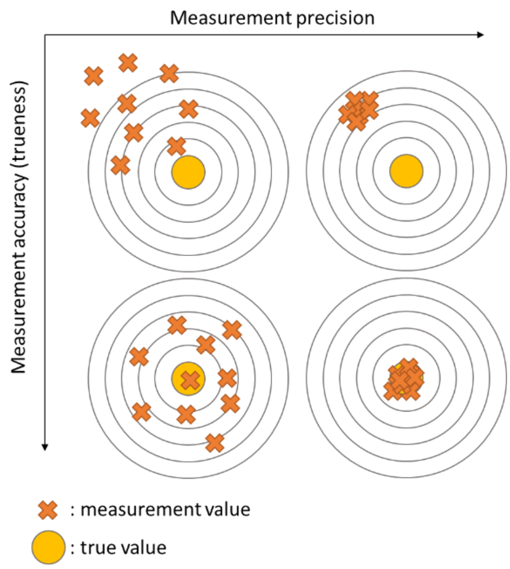

Figure 2: The difference between measurement accuracy (trueness) and measurement precision

Laser wavelength (NIST traceable): The laser wavelength is assumed to be constant and its value is internally stored in the IDS. In dependence to equation (1), it mainly defines the slope of the sensor characteristic curve for the full linear range. A deviation of the stored from the true laser wavelength value would directly result in a systematic measurement error that sums up with additional displacement. Therefore, it is crucial that the absolute laser wavelength is known and adjusted very precisely. To reference the wavelength of the laser a gas cell is integrated in the IDS. This gas cell is filled with acetylene gas featuring stable absorption peaks at certain wavelengths. A control loop is implemented to adjust the laser wavelength to an absorption peak at 1530.3711 nm. The position of the absorption peak is known with an expanded uncertainty (k=2) of ±0.3 pm. This is certified by NIST, the National Institute for Standards and Technology of the United States [3].

Environmental Compensation Unit (DAkkS traceable): Any interferometric device that is operated in environmental conditions is biased by a systematic error due to fluctuations of the refractive index caused by air temperature, pressure and humidity. To compensate that systematic error, the IDS has to be operated together with the Environmental Compensation Unit (ECU). Every ECU is calibrated against a reference which was calibrated by a DAkkS (the national accreditation body for the Federal Republic of Germany) certified laboratory.

IDS displacement measurement (PTB traceable): The validity of the laser wavelength and the index compensation by the ECU are the main systematic errors within the displacement measurement that can sum up. To assure the accuracy of the system's displacement measurement, attocube did verify the IDS sensor characteristic curve by calibrating a standard IDS system including the ECU at the PTB, the National Metrology Institute of Germany. The accuracy of the IDS system's displacement measurement was calibrated over a working distance of 10 meters (see Figure 3). The resulting systematic error of the IDS displacement measurement was quantified to be lower than 0.0 ± 0.4 ppm (k=2) within a working distance of 0 to 10 m [4]. Thus even the PTB reference-interferometer was not able to perform a significantly more accurate displacement measurement. Based on this result, attocube is able to guarantee that IDS measurements including ECU compensation of larger displacements are more accurate than 1 ppm, and anticipated to be even close to 0 ppm up to 3 m.

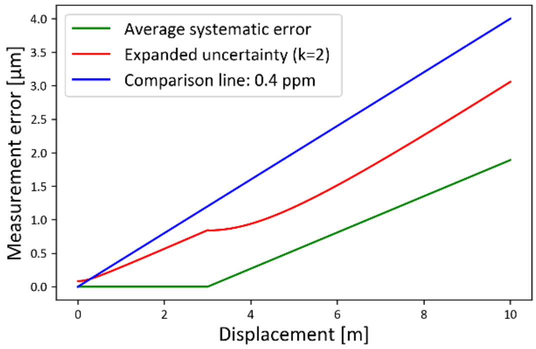

Figure 3: *Systematic measurement error of the IDS certified by the PTB [4]*

Quality control: Performing an experimental verification for the high measurement accuracy of the IDS during the production process would require too high demands. But for every IDS that is produced, it is experimentally checked that the laser wavelength is set to the correct gas cell absorption peak. During another test a target is moved over a distance of 500 mm. The measured displacement values are not allowed to vary from the values, measured by a reference IDS, by more than ± 1 µm, corresponding to ± 2 ppm. This test shows, that the laser wavelength is in fact locked on the correct absorption peak. This assures that the systematic error of the individual IDS stays in accordance with the PTB certificate.

IDS measurement precision (stability and noise)

The measurement precision (see Figure 2) is usually quantified by the standard deviation σ of a measurement. Its value is strongly related to the system's noise level, its repeatability and – over duration – its stability. An exemplary measurement in the attocube catalog shows a measurement on a target located at an absolute distance of around 77 mm. The experiment took place under vacuum condition over 20 hours at a signal bandwidth of 100 Hz [5]. The result shows an outstanding signal stability (no significant drift over 20 hours). In that sense the stability test's result concludes a measurement precision σ of only 55 pm. But the sensor's noise behavior and such the measurement precision is dependent on different parameters, such as the chosen sample rate, applied filtering or the absolute target distance. To get more insight into the spectral distribution, Power Spectral Density (PSD) plots of the IDS noise measured under different conditions are available on request.

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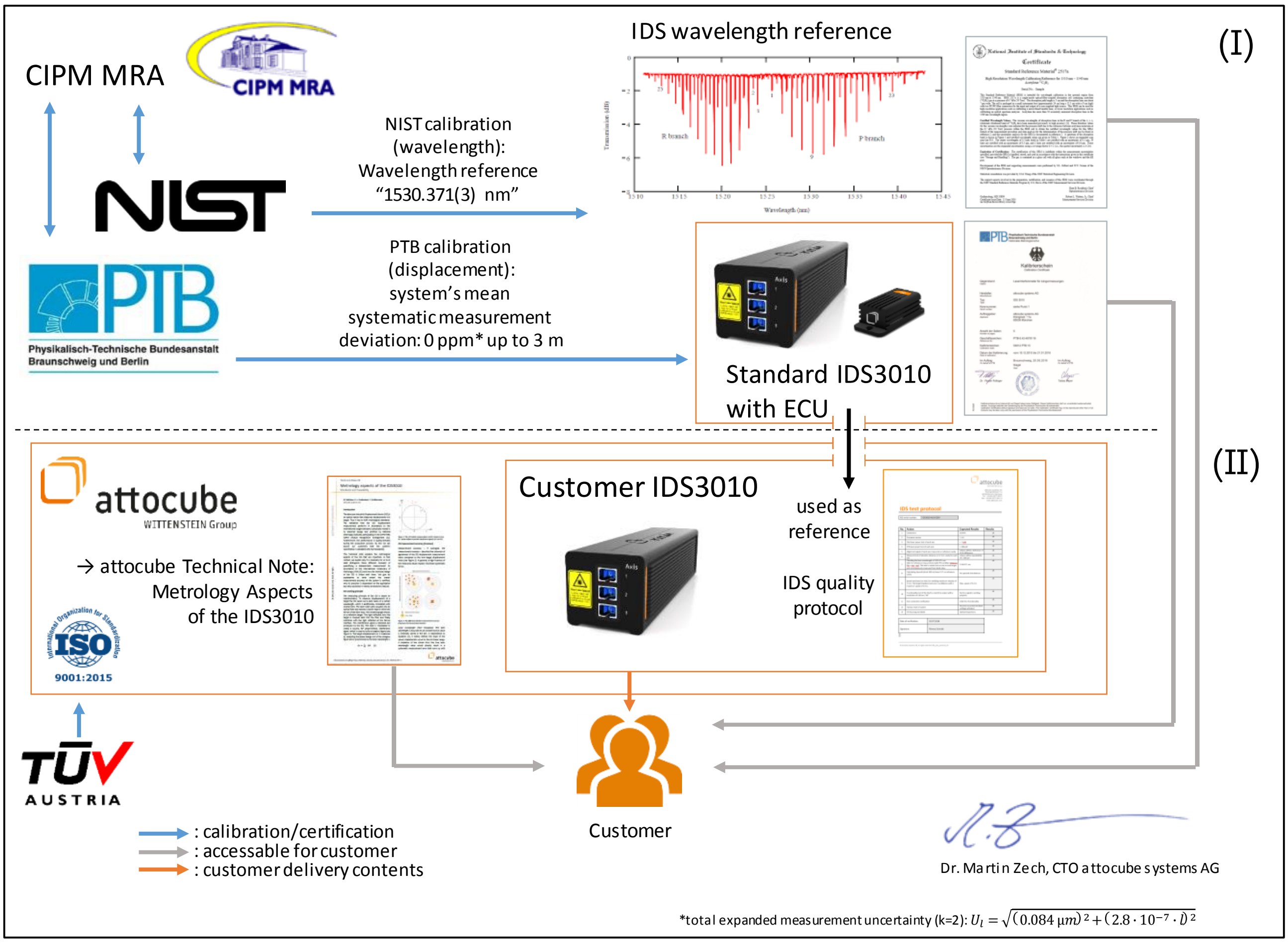

Figure 4: *IDS traceability chart – (I): National Metrology Institute Calibration Certificates that are available and (II) the attocube internal aspects that ensure highest quality of the product*

IDS measurement resolution:

The measurement resolution is the smallest increment of displacement that the sensor can read. This property is based on the resolution of the IDS internal ADC (Analog-to-Digital Converter). The IDS ADC is chosen such that the effective displacement resolution equals 1 pm. Due to the fact that the detected signals show noise levels at higher orders of magnitude, the resolution of 1 pm will be more than sufficient.

Conclusion

In this paper we clarified the different terms that attocube uses to describe the high quality of the IDS displacement measurement and how the IDS specification is certified by National Metrology Institutes and by this traceable to the International Length Standard. These dependencies including the presence of this Tech Note are summed up and illustrated in the IDS traceability chart (see Figure 4).

References

[1] CIPM, MRA. "Mutual recognition of national measurement standards and of calibration and measurement certificates issued by national metrology institutes." (1999).

[2] Joint Committee for Guides in Metrology. "International vocabulary of metrology—Basic and general concepts and associated terms (VIM)." (2008).

[3] IDS laser wavelength NIST calibration certificate: https://www-s.nist.gov/srmors/certificates/2517A.pdf

[4] IDS displacement measurement accuracy PTB calibration certificate: marketing.attocube.com/acton/attachment/4434/f-0449/0/-/-/-/-/PTB%20Zertifizierung%20IDS%20%28d%29.pdf

[5] attocube product catalog: http://publications.attocube.com/attopublications/0308916001475672499

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