Final Publishable JRP Summary for SIB08 subnano
Traceability of sub-nm length measurements

Overview

Reliable and traceable metrology in the sub-nanometre is becoming increasingly important to industry. This project has enabled traceable length measurements by optical interferometers in the sub-nm range. It also has improved calibration methods for capacitive displacement sensing systems. Traceability of sub-nm length measurements requires consistent modelling of the measurement system, as well as cross validation between different measurement techniques. Accuracy and uncertainties of measurements have been improved which is important for the NMIs, and will feed through to instrument makers and industry.

Need for the project

Although a sub-nanometre uncertainty of a measured length or displacement appears to be rather small, and almost negligible, there are situations where it is important. Reproducibility and accuracy in this range are needed for mask positioning in multi-patterning lithography used for producing electronics for ever smaller computer-processors. Other industries with challenging requirements will also benefit, such as space instrumentation which requires a one-off calibration that must be valid for the lifetime of the instrument. The enhanced dimensional accuracy also contributes to NMI activities to realise other SI base units such as the kilogram more accurately.

The highest accuracy measurements of length or displacement are predominantly made with non-contact optical interferometers. The measurements are based on interference of monochromatic light waves whose wavelength, measured in nanometres, is very accurately known. By changing the light path of a wave and letting it interfere with another wave of identical frequency, the resulting sinusoidal signal has a period proportional to the wavelength and so provides a technique to measure length or displacement at the sub-nm level. However, real light waves, ie laser beams, are not ideal plane waves. In practice they diffract which results in progressive bending of their wavefronts, making the measurements too short. In order to measure displacements or lengths with sub-nm accuracy, theoretical models which consider the actual shape of the wavefront are used to calculate a correction to a measured value. At the start of this project, rigorous models and traceable calibrated wavefront sensors were not readily available. The project compared improved techniques based optical and x-ray interferometers, and measurements techniques between different NMIs.

In some cases it is not possible to use an interferometer, since it requires a vacuum and controlled conditions, so capacitive sensors are used instead. This is typically the case for manufacturers and researchers of nano instruments. By knowing the area of the electrodes and the permittivity of the medium between the electrodes, it is possible to calculate the distance between the electrodes precisely by measuring the capacitance. Although the precision is very high measurements may drift in time and change with environmental conditions such as air pressure, humidity and temperature, and accuracy can only be achieved by calibration traceable to national standards. The project considered how to improve the accuracy through better design, alignment and modelling. It also investigated the correlation between the different techniques, and developed transfer standards to compare them.

Report Status: PU Public

EMRP
European Metrology Research Programme
Programme of EURAMET

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Scientific and technical objectives

The purpose of this project was to enable traceable measurements and calibrations in the sub-nm range for optical interferometers, and to improve capacitive displacement sensing systems and their calibration. The different techniques were compared and the understanding of the technology was improved by modelling and validating against experimental measurements, leading to improved uncertainty, resolution and dynamic range of displacement.

The scientific and technical objectives were:

1. **Modelling**
    - Development and validation of models for the propagation of aberrated wavefronts of optical interferometers with accuracies in the sub-nanometre region.
    - Enabling model based correction in the sub-nm region of alignment errors and environment effects (temperature and humidity) of capacitive sensors.
2. **Measurement devices technology**
    - Development of a traceable wavefront sensor with an uncertainty better than $\lambda/30$.
    - Enabling the traceable calibration of wavefront sensors with an uncertainty limited only by the repeatability of the wavefront sensor.
    - Improvement of optical interferometers regarding effects caused by roughness and drift.
    - Improved Fabry-Perot Interferometer (FPI) displacement measurement and related sensor calibration to sub-nanometre uncertainty by means of a detailed uncertainty budget, with particular attention to environmental effects (temperature, humidity), sensor referencing, alignment, noise and drift of the FPI set-up. The target uncertainty for an existing metrological FPI is sub-nanometre for a displacement stroke of 1 µm and 10 nm for a stroke of 100 µm.
    - Sensor calibration methodology using FPI and supporting sub-nm uncertainty, specifically investigated for selected capacitive sensors.
    - Step-change improvement of the FPI to picometre-range uncertainty by means of improved ambient stability, referencing compatibility and optical frequency comb traceability to the time standard. The target uncertainty is 10 pm for a displacement stroke of 1 µm.
    - Enabling quantised positioning of x-ray interferometer measurements with a resolution of 24 pm (improvement by a factor of 8), quadrature counting of x-ray fringes and scanning ranges up to 10 mm.
    - Development of an improved sensor design for capacitive sensors with lower sensitivity to alignment and environmental effects.
3. **Validation**
    - Analysis of alignment errors in the arcmin region and environmental effects on capacitive sensors by referencing to optical and x-ray interferometers.
    - Specified requirements and reviewed technology available for displacement transfer standards.
    - Characterised prototype displacement transfer standard facilitating cross-validation of at least 2 different types of interferometers with a sub-nanometre uncertainty [10pm (1nm) for a displacement stroke of 1µm (100µm)].

Results

Modelling

Systematic effects which are inherent in measurement systems can influence the measured values. Modelling these effects mean that a more accurate corrected value can be calculated and measurement predicted. Then experiments can be used to check the results and if necessary adapt or correct the model. Iterations between theory and experiment improves the results of both.

The project has established a theoretical framework, based on Maxwell's equations, to model, evaluate and correct systematic errors in interferometer setups. The vectorial ray-based diffraction integral (VRBDI) method has been developed [5] which can model beam forming optics, and achieve greater accuracy than has been possible before. Computer models and simulations were evaluated to obtain statistical statements about measurement uncertainty and empirical sensitivity coefficients. A software package has been developed and is freely available on MATLAB Central File Exchange [6] to simulate diffraction in optical systems. Comparisons of wavefront and irradiance distributions of simulated beam forming optics with respective measurements, have given confidence to the understanding of the underlying physics, correction factors and uncertainty.

For the capacitive sensors, different theoretical models were checked against each other for relevant systematic effects. Different formulas were tested against experimental data and chosen according to the agreement of the respective fit functions. Furthermore, a calibration procedure with corrections for temperature, pressure, humidity, tilt and edge effects was proposed.

Measurement devices technology

For a capacitance sensor it is important that the facing electrodes are parallel to each other. A self-actuating capacitance sensor which can optimise itself to achieve this condition has been further improved and finalised during the project by TU Delft. Furthermore, drift measurements and comparisons against the most accurate optical interferometers at VSL and NPL were performed. While the former were successful the latter were troubled by noise which could not be resolved during the project.

The following work was done to improve the measurement device technology:

- Several concepts for improved actuation of the XRI have been developed. Routines for quadrature detection of the XRI signals have been written. These allow sub fringe positioning capability of the XRI half, (96 pm) and quarter x-ray fringe (48 pm), steps. In addition, the XRI can be operated in a free running mode where one fringe is 192 pm and position data can be continually collected.
- A prototype FPI scheme (dubbed pmFPI) was conceived and experimentally investigated at VSL, aiming for picometre-level measurement uncertainty [1,2]. Electronic drive noise from the off-the-shelf piezo-geared displacement actuation stage, together with vibrational noise, limited the achieved read-out resolution to 14 pm.
- A feasibility study addressed requirements and technical issues for a practical displacement transfer standard supporting sub-nanometre calibration uncertainty. The multi-segment capacitive probe system from TU Delft and Arsen Development was experimentally investigated as a potential implementation of a travelling capacitive sensor transfer standard that offers compatibility for interfacing both the VSL Metrological FPI (MetFPI) and the NPL XRI [3].
- The MetFPI of VSL provided a versatile platform for adapting displacement targets for sensor referencing. Stable sensor mounting and alignment hardware was implemented together with improved laser frequency stabilization and ambient thermal shielding. A dedicated calibration methodology was investigated at hand of the two exemplarily chosen capacitive sensing systems.
- The TUBITAK differential Fabry-Perot interferometric (DFPI) system has been redesigned and improved for displacement measurements in the range from 10 pm to 10 µm (or more) where an uncertainty ≤ 3 nm has been achieved. A comparison was made between the XRI and the TUBITAK DFPI system: the XRI was operated in the quadrature mode of operation with both sub fringe positioning and free running modes of operation.

For an absolute wavefront measurement the systematic sensor error of the measurement device has to be known. While the calibration of a wavefront sensor is typically performed by using a reference wavefront which an assumed wavelength, a calibration scheme was developed where no knowledge about the shape of the reference wave is required. A temperature stabilised Shack Hartmann wavefront sensor was calibrated with an uncertainty smaller than 7 nm.

A procedure for evaluating the wave front correction for different parts of the interferogram of Double Ended gauge block interferometer (DEI) is explained and modified. Excellent results are obtained with this new method and double ended GB interferometers are likely to be more widely used by NMIs.

To conclude, this objective improved the capabilities of the NMI to measure lengths or displacements with significantly smaller uncertainty and enabled more accurate comparisons of the respective setups between NMIs.

Validation

Validation relies on adequate testing to check theory against experiment results. The validation of capacitors was successfully completed, but the assembly of the XRI setup at PTB is still ongoing. Therefore the envisaged methodology to validate the optical simulation software will use the future measurement of the Si-28 lattice constant: varying the wavefront of the interferometer beams and applying the corresponding correction to the measured values for the lattice parameter should yield agreement within the estimated uncertainty interval. The modelling tools developed by the project will help future research into measurement techniques.

Actual and potential impact

Dissemination of results

Findings from the project were presented at 19 conferences including Macroscale 2014 and Nanoscale 2016. In addition, presentations were given during 7 visits to stakeholders and companies.

Actual impact

The project has improved traceability of dimensional nanometrology in high end instrumentation used at NMIs and in high tech industries. Modelling of the measurement system, as well as cross validation between different measurement techniques meanst that accuracy and uncertainties of measurements have been improved. The results enhance the quality assurance of national metrology institutes and the calibrations they perform for customers.

TUBITAK's DFPI has been applied to the detection of very small angles down to 1 nanoradian (nrad). The results will enable standardised, traceable and validated measurement methods for calibrating precision instruments; it is expected that the knowledge will benefit the synchrotrons and XFEL community, as well as gamma ray spectroscopy applications.

A patent regarding an instrument to determine surface topographies has been issued.

The VSL MetFPI facility is available for commercial test and calibration services for displacement sensors. The configuration of the FPI with referencing targets and measurement procedures is also useful for calibration and linearisation of other types of displacement sensors.

The NMI metrology project on the re-definition of the kilogram is already benefiting from this project by using sufficiently accurate beam characterisation from the wavefront metrology methods.

Potential impact

Applications for the accurate measurement techniques include metrology for the semiconductor fabrication and lithography, and nanopositioning. Improving the quality of products manufactured in Europe will potentially enhance the competitiveness of European industry.

A new calibration service utilising DEWLI will be available at MIKES soon. This will reduce the uncertainty level of gauge block calibrations for end users e.g. in engineering industry.

The Consultative Committee for Length (CCL) DG1 will deliver the results for ISO TC213 and this might initiate change in the ISO3650 leading to new definition of the gauge block central length and improved accuracy in interferometric gauge block metrology.

List of publications

[1] D. Voigt, A.S. van de Nes and S.A. van den Berg, “Practical Fabry-Perot displacement interferometry in ambient air conditions with subnanometer accuracy”, Proc. SPIE 9203, Interferometry XVII: Techniques and Analysis, 920308 (August 18, 2014).

[2] D. Voigt and A.S. van de Nes, “Capacitive Sensor Calibration with Fabry-Perot Interferometry”, Macroscale 2014, Recent Developments in Traceable Dimensional Metrology, 28-30 October 2014, BEV – Bundesamt für Eich- und Vermessungswesen, Vienna, Austria.

[3] R. Nojdelov, S. Nihtianov, A. Yacoot and D. Voigt, “Capacitance-to-Digital Converter for Accurate Displacement Measurement in the Sub-nanometre Range”, 20th IMEKO TC4 Int. Symposium and 18th Int. Workshop on ADC Modeling and Testing, Research on Electric and Electronic Measurement for the Economic Upturn, Benevento, Italy (September 15-17, 2014).

[4] R. Nojdelov, D. Voigt, A.S. van de Nes and S. Nihtianov, “Investigation of error- and drift sources in a capacitive sensor system for sub-nanometer displacement measurement”, 9th Int. Conf. on Sensing Technology (ICST), Auckland, New Zealand (December 8-10, 2015).

[5] B. Andreas, G. Mana, and C. Palmisano, “Vectorial ray-based diffraction integral,” J. Opt. Soc. Am. A **32**(8), 1403-1424 (2015), http://dx.doi.org/10.1364/JOSAA.32.001403

[6] http://www.mathworks.com/matlabcentral/fileexchange/52210

[7] A Lassila and V Byman, “Wave front and phase correction for double-ended gauge block interferometry”, 2015 *Metrologia* **52** 708, http://dx.doi.org/10.1088/0026-1394/52/5/708

JRP start date and duration:	July 2012, 36 months
JRP-Coordinator: Birk Andreas, PTB Tel: +49 531 592-4336 E-mail: Birk.Andreas@PTB.de JRP website address: http://www.ptb.de/emrp/subnano.html	
JRP-Partners: JRP-Partner 1 PTB, Germany JRP-Partner 2 CMI, Czech Republic JRP-Partner 3 VTT, Finland JRP-Partner 4 NPL, United Kingdom	 JRP-Partner 5 TUBITAK UME, Turkey JRP-Partner 6 VSL, Netherlands JRP-Partner 7 INRIM, Italy
REG-Researcher 1: (associated Home Organisation):	Stoyan Nihtianov TU Delft, Netherlands
REG-Researcher 2: (associated Home Organisation):	Carlo Palmisano UNITO, Italy
REG-Researcher 3: (associated Home Organisation):	Claas Falldorf BIAS, Germany

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