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1 Executive Summary

Introduction

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.

The Problem

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.

The Solution

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.

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 means 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.

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.

2 Project context, rationale and objectives

One of the cornerstones of trade and industry is reliable metrology. Throughout the world NMIs ensure that amounts of goods are quantified correctly, standards are established and dimensions are measured as identically as possible in across countries. However, NMIs can only achieve this if they stay at the front of what is technically possible and actively advance the state of the art of measurement.

The purpose of this project was to enable traceable length measurements by optical interferometers in the sub-nm range as well as improved capacitive displacement sensing systems and the calibration thereof. Traceability of sub-nm length measurements requires consistent modelling of the measurement system as well as cross validation between different measurement principles. To address these challenges measurements were to be improved regarding uncertainty, resolution and dynamic range of displacement.

Prior to the start of the SIB08 subnano project, the highest accuracy measurements of displacement or length were predominantly made with non-contact optical interferometers that measure in terms of the wavelength of light. The wavelength λ of an electromagnetic plane wave, (i.e. an infinitely extended wave with plane parallel wavefronts), is related to its frequency f via the speed of light c by $\lambda = c / f$. Therefore, by knowing the exact frequency of a laser and the speed of light a wavelength can be calculated. However, this wavelength is only an approximation to the *real* wavelength, as the wavefronts in real interferometers are curved and never infinitely extend. Therefore, although the approximation can be quite good in some cases, real wavelengths typically differ by parts per billion up to parts per thousand depending on the wavefront curvature and position in relation to the light source. This means, that for a wavelength in the visible light region (between 380 nm and 780 nm), the real wavelength differences can reach picometre level.

Therefore, in order to measure displacement or length, (using non-contact optical interferometers), with sub-nm accuracy, theoretical models that consider the real shape of the wavefront must be used to calculate a correction for a measured value. However, prior to start of this project, such correction models as well as a traceable calibrated wavefront sensor to actually measure the real shape of a wavefront were not readily available.

Another class of device widely used to measure displacement are capacitive sensors. This measurement principle is based on the capacitance of a plate capacitor (i.e. two electrode plates separated by a dielectric medium). By knowing the area of the electrodes, the permittivity of the medium between the electrodes, and by measuring the capacitance, the distance between the electrodes can be calculated. However, the precision of such a measurement (the number of digits resolved) can be much better than the accuracy of the quantities needed for the calculation. Therefore, although the precision can be very high, accurate measurements may drift over time and change with environmental conditions such as air pressure, humidity and temperature.

The SIB08 subnano project had two outputs; it improved length metrology and therefore directly enhanced calibration accuracy for industry and it supported NMI capability for realising other SI base units such as the kilogram. In 2011 the 24th General Conference on Weights and Measurements (CGPM) suggested the kilogram, as for the other base units, should be realised by a fundamental constant.

The scientific and technical objectives of the project 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(pm)-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. Cross 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 [10 pm (1 nanometre (nm)) for a displacement stroke of 1 µm (100 µm)].

3 Research results

3.1 Modelling

Introduction

This part of the project addressed the need for a theoretical framework for the modelling of optical interferometry and capacitive sensor operation. It addressed two specific objectives:

- 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.

3.1.1 Simulation of aberrated wavefront propagation in optical interferometers

Prior to the SIB08 subnano project, the common method for the calculation of diffraction corrections in laser interferometers was to characterise the laser beam incident on the first beam splitter in terms of Gaussian beam parameters or, (a more advanced method), in terms of intensity moments. The required information was usually gathered by scanning a matrix detector, e.g. a charge-coupled device (CCD) or a complementary metal-oxide semiconductor (CMOS) detector, through the Rayleigh range of the beam or of the beam transformed by a well characterised lens. For a stigmatic or simple astigmatic beam the second order central moments were input to an analytical formula which equated to the relative length error $\Delta z/z$ by assuming that the full power of the interfering output beams is measured by an integrating detector. The required quantities were then obtained by a fit to the scanned measurement data. However, this common method and its theoretical framework are based on the scalar paraxial approximation and it was not entirely clear whether the calculation of diffraction corrections in the order of parts per billion was inside the valid range. Therefore, a new and more rigorous framework/method was needed.

The new framework/method produced by the SIB08 project was based on vectorial diffraction theory. The vectorial ray-based diffraction integral (VRBDI), was used as the new method as it is a practical method for light propagation in optical systems and provided unprecedented accuracy. A traceable calibrated Shack-Hartmann sensor (SHS) measured the wavefront and irradiance of the input beam at a single position and from the measurements a complex amplitude was calculated. This complex amplitude was sufficient to describe the beam in space and by using Fourier optics propagation, $\Delta z/z$ could be obtained. The validity of the new method was tested by comparison with rigorous simulations of the VRBDI and no significant differences were found. The new (numeric) method was also in very good agreement with the common (analytical) method [3] which was tested by comparison using simple Gaussian beams.

As the new method showed very good agreement with the common method (i.e. the method that needed replacing), the project asked why?

The comparison between the two methods, using Gaussian beams was purely theoretical, as real laser beams are not perfect Gaussian beams. For example in the combined optical and X-ray interferometers (COXI) setup a beam emanates from a single mode fibre and is subsequently collimated and the fibre mode field is clearly not Gaussian. The exact solution for step index mode profiles comprises a zero-order Bessel function of the first kind in the fibre core and a zero-order modified Bessel function of the second kind in the cladding. Therefore, by knowing the fibres numerical aperture *NA* and the cut-off wavelength λ_c the exact mode profile can be calculated. However, often the mode-field diameter (*MFD)* is used to define a Gaussian beam by assuming $w_0 = MFD/2$. All these quantities, namely *NA,* λ_c and *MFD*, can usually be obtained from manufacturer specifications, and together with the known optical design for the collimators used in the COXI setup allow simulations of the output beam profile behind the collimator by using the VRBDI. The confident lens system design of the collimators was made available to PTB by the manufacturer Halle, Berlin.

In Figure 1 a comparison between simulated and measured irradiance profiles is shown. Before the measurement, the collimation was optimised by the positioning of the fibre end in relation to the collimator whilst minimising the Zernike defocus terms delivered by the SHS. For the exact fibre mode profile the *NA* was fitted inside its uncertainty of ±10%. Even by exhausting the full uncertainty range of the manufacturers *MFD* specification it was not possible to fit the simulation of the Gaussian mode-field to the measured data, as can be seen in Figure 1.

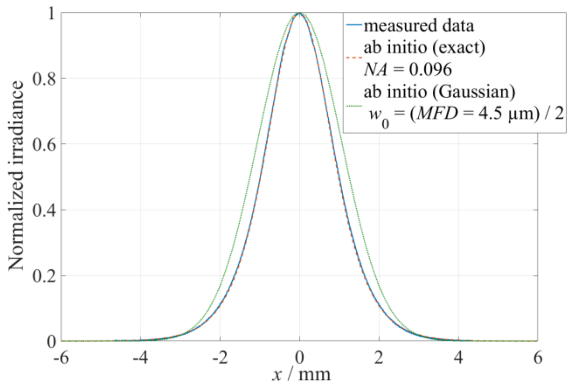

Figure 1. *Comparison of ab initio simulated irradiance of collimated output beam in COXI setup against measured data. The exact mode profile for step-index fibres can be fitted inside the manufacturer specification to the measured data, but this is not possible for the Gaussian profile.*

The relative length error for the two simulated beam types, determined by the Fourier optics propagation technique, was shown to be different:

- $\Delta z/z_{\mathrm{Gaussian}} = -1.7\times10^{-9}$
- $\Delta z/z_{\mathrm{exact}} = -1.8\times10^{-9}$

Therefore, it can be concluded that simply using Gaussian beams for the calculation of the diffraction correction is not advisable.

The above experiment was performed in air. However, the COXI experiment was designed to run in vacuum conditions to avoid any negative effects from the refractive index on the measured lengths. Therefore, a collimator adjusted in air may not be quite so well collimated in a vacuum. A measurement of the wavefront in vacuum was not possible with the project’s SHS. The only exception is the use of a glass vacuum window which may influence the beam. However this impact is not expected to be significant, as it is not currently possible to adjust the collimator when inside the vacuum (i.e. evacuated) vessel; although it would be desirable to pre-adjust the two COXI collimators in air such that they become well-adjusted in a vacuum.

In order to calculate the impact of evacuation (i.e. vacuum conditions) on a collimator which has been well-adjusted in air and to determine whether pre-adjustment can yield optimal collimation in a vacuum, the project performed simulation of the collimator design using the VRBDI. In Fig. 2 the resulting wavefront profiles can be seen. The effect is quite remarkable, and the impact on the relative length error is significant. The flat wavefront yields $\Delta z/z_{\mathrm{flat}} = -1.8\times10^{-9}$ while the curved wavefront causes $\Delta z/z_{\mathrm{curved}} = -2.7\times10^{-9}$. Comparing this to the combined uncertainty of 3×10^{-9} for the determination of the Si-28 lattice parameter shows that the effect is significant. However, it should be possible to pre-adjust the collimators in air and check the evacuation (vacuum) impact on the actual wavefronts behind the vacuum window, and by roughly knowing the amplitude of this effect the iterative procedure should become much less tedious.

A more detailed and rigorous study on the new measurement procedure using the traceable calibrated SHS and estimation of its uncertainty by use of the VRBDI was started after the end of the project. At the time of the writing of this report the respective paper has still been in preparation.

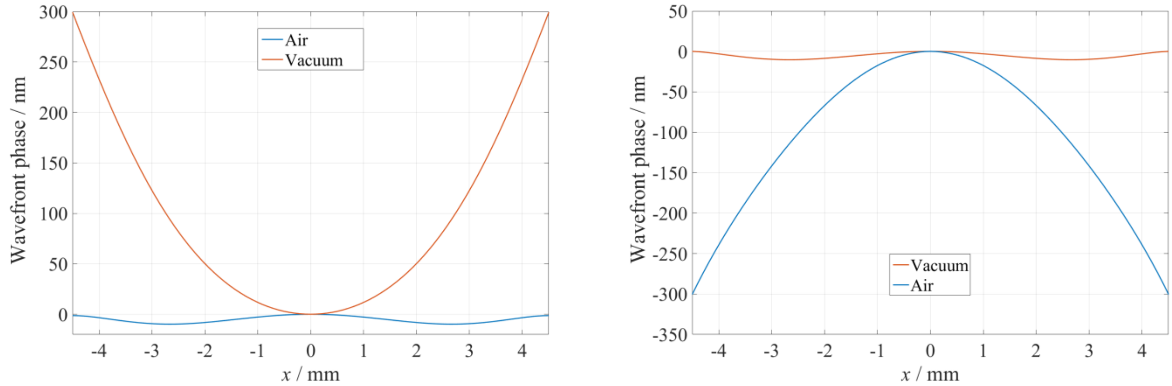

Figure 2. Simulated wavefront profiles of a lens system collimator before and after evacuation (under vacuum conditions). Left: the collimator has been optimised for operation in air. Right: the wavefront was “pre-curved” to become optimal after evacuation (under vacuum conditions).

The phase retrieval in homodyne interferometers was an additional investigation of the project, and project partner CMI developed simulation software for the Monte Carlo modelling of errors in homodyne interferometer fringe interpolation. The software developed by CMI allowed the calculation of errors and their statistical distributions with respect to the input parameters and distributions. The empirical formula for error calculations under common conditions was derived from the Monte Carlo models and was presented by the project at the MacroScale 2014 conference and is available on-line. The results containing empirical sensitivity coefficients for error contributions will support the use of homodyne interferometry by end-users [13].

3.1.2 Model-based correction of capacitive sensor alignment errors

Another class of device for length metrology are capacitive sensors. They are used in many areas of nanotechnology that require nano-positioning with sensors that are integrated into nano-positioning stages e.g. in the semiconductor industry. The benefits of capacitive sensors include their simplicity, robustness, high precision and low power dissipation. However, when using them to measure dimension/length with sub-nanometre accuracy proper alignment between the target and the sensing electrode is crucial.

In response to this issue, the project’s Researcher Grant at TU Delft (REG(TU Delft)), developed a built-in capacitive sensor head self-alignment function based on a thermal motor with alignment down to 1 μm and tolerances of less than 100 nm. The highlight of the self-alignment mechanism is that it does not deteriorate the mechanical stability of the sensor after alignment. Building on this work REG(TU Delft) also established a multi-segment probe system (see section 3.2.5) and a transfer standard based on the concept has also been proposed (see section 3.3.3) [2, 11, 12].

During the project, the partners, NPL, VSL and TUBITAK enhanced and adapted their interferometer setups according to capacitive sensor calibration needs. This resulted in the NPL XRI developing sub fringe positioning capability by half, (96 pm) and quarter x-ray fringe (48 pm), steps. The VSL FPI facility was also made available for commercial test and calibration services for displacement sensors and TUBITAK’s enhanced Differential Fabry-Perot Interferometer (DFPI) was adapted for the detection of very small angles as part of EMRP project SIB58 Angles (see section 3.2).

Further to this, various sources of errors in capacitive sensors were investigated by the project, such as alignment (tilt), edge effects, mechanical instability, surface roughness, air permittivity dependence on environment conditions (temperature, pressure and humidity). Each of these error sources was modelled and described quantitatively. The capacitive sensor model was verified with experimental results from capacitive sensor tests using the Fabry-Perot Interferometer (FPI) facility at VSL (see section 3.3.1). Based on the results, a sensor calibration procedure was proposed and the capacitive sensor model and results were presented at the 9th Int. Conf. on Sensing Technology (ICST) 2015, Auckland.

<u>**Conclusions**</u>

The project addressed the objective to develop and validate models for the propagation of aberrated wavefronts of optical interferometers with accuracies in the sub-nanometre region and produced a new theoretical/modelling framework and beam characterisation methodology. Additionally, the VRBDI developed by the project is a versatile simulation tool which can be used to solve difficult propagation problems and has been published in the Journal of the Optical Society of America A (the source code is also publically available) [4].

The self-consistency of the project's new method of beam characterisation and determination of relative length error can be tested (in the future) when the X-ray interferometer (XRI) in the COXI set-up is operational. At this point, a dedicated de-adjustment of the collimator can be used to check the invariance of the measured and corrected lattice parameter. In addition, in the near future the project's COXI set-up may be used to deliver (the long-awaited) independent value for the lattice parameter of Silicon (Si ^{28}) needed to support the Crystal Density Method (CDM) method for the redefinition of the SI unit the kilogram. Indeed, the methods developed in this project, i.e. the modelling framework, the calibrated SHS and the calibration setup, are already an essential part of the CDM method. The development of the calibrated SHS and calibration setup are described in sections 3.2.1 and 3.2.2, respectively.

The project also addressed the objective to enable model based correction in the sub-nm region of alignment errors and environment effects (temperature and humidity) of capacitive sensors. It did so by developing a validated capacitive sensor model for error sources such as alignment (tilt), edge effects, mechanical instability, surface roughness, air permittivity dependence on environment conditions (temperature, pressure and humidity). Further to this (REG(TU Delft)), developed a built-in capacitive sensor head self-alignment function based on a thermal motor with alignment down to 1 μm and tolerances of less than 100 nm and partners.

The key research outputs were:

- The modelling of wavefront effects has been set on a sound theoretical basis.
- A new method of traceable beam characterisation has been established which is accounts for the actual shape and asymmetry of the wavefront.
- An empirical formula for error of homodyne interferometer fringe interpolation has been found.
- A model for the main error sources in the capacitive sensors was developed.

3.2 Measurement devices technology

<u>**Introduction**</u>

This part of the project addressed the need for improved measurement devices and technology and involved joint working between project partners NPL, and VSL and REG(TU Delft), which was important for identifying critical issues and expert knowledge for the development of the capacitive sensor calibration instrumentation and methodologies. Similarly relevant for the investigations was the availability of the capacitive probe systems from the project's collaborators and REG(TU Delft).

The work addressed the following eight specific objectives:

- o 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.

3.2.1 Development of a traceable wavefront sensor

The procedure described in subsection 3.2.2 was applied for the absolute calibration of two types of wave front sensors which were significantly different regarding lateral resolution, sensor size, and acquisition and evaluation time. One wave front sensor was a lateral shear interferometer (SI), developed by REG(BIAS). The key elements in this SI wave front sensor were two wedge prisms that formed an air wedge and allowed adjustment of both, the magnitude and the orientation of the shear. The second wave front sensor was a temperature stabilised Shack-Hartmann sensor (SHS) calibrated and operating at a temperature of 0° C. The key element of the SHS sensor was a microlens array, each lens with a size of $(0.256\ \mu m)^2$ and a focal length of 17.7 mm. The project showed that both wave front sensors (i.e. the SI and SHS) could satisfy the requirements regarding the uncertainty of better than $\lambda/30$ for the systematic sensor error. The calibration procedure for both the Si and SHS wave front sensors was repeated over a four month time period, and the systematic sensor errors that were determined deviate by no more than 7.2 nm (peak-to-valley (PV)) from the mean sensor error, corresponding to $\lambda/70$ at a wavelength of 532 nm. In addition, the reconstructed shapes of the wave front, determined from calibrations using either the SI or the SHS wave front sensor, differed by no more than ± 15 nm (PV), therefore confirming the validity of the calibration procedure, too.

3.2.2 Enabling traceable calibration of wavefront sensors

In interferometric length measurements the shape of the laser beam is relevant if sub-nm accuracy is required, and corrections are required depending on the aberrations of the beam. To determine the absolute shape of a wave front a calibrated sensor is required, and to determine such an absolute calibration the systematic error of the sensor needs to be determined, and is typically performed by a comparative measurement to a reference wave front which is (assumed to be) known. The SIB08 project developed the first ever method for absolute calibration of wave front sensors, where knowledge of the shape of a reference wave was not required. The project's absolute calibration procedure was based on an extended stitching scheme. This is where the sensor is moved stepwise across an unknown reference wave front, and in order to determine the defocus and astigmatism the relative tilt between the sensor and wave front during the scan is simultaneously measured by an autocollimator. This new absolute calibration procedure therefore provides, traceability via a calibrated angle measurement device and a calibrated flat mirror. In addition to the systematic sensor error the shape of the reference wave is also determined by the absolute calibration procedure.

Sensor parameters affecting the measurement result also have to be determined, e.g. the effective focal distance and pixel spacing for the SHS or the lateral shear for the SI. In previous sensitivity and standstill measurements pixel noise and tilt fluctuations were obtained which allowed pixel by pixel evaluation of the associated uncertainty of the systematic sensor error. However, due to lack of comparative measurements, the project performed a validation of the calibration procedure, by inserting different transparent optical elements into the calibration set-up. The elements were implemented either fix to the wave front or fix to the sensor to modify the reference wave front respectively and the systematic sensor error determined from this. The change in optical path length, which was interferometrically verified using a Fizeau-interferometer, was deduced from the difference in measurements and the deviations were in total less than ±10 nm for the systematic sensor error, with the corresponding reference wave fronts demonstrating a difference of better than $\lambda/30$ (PV) at a wavelength of 532 nm.

3.2.3 Improvement of optical interferometers regarding effects caused by roughness and drift

In many other types of length interferometers wavefront error is among the largest of the non-length dependent error sources, e.g. double ended gauge block interferometry (DEI) which is a promising technique for transferring the metre from laser wavelength to the most widely used transfer standards of length gauge blocks. With this technique, measurement of the gauge blocks can be made without mechanical wringing which otherwise slowly degrades the surfaces of the gauge block. However, due to technical difficulties, DEI cannot currently be widely used.

Three independent methods for evaluation of the phase correction for DEI were studied by the project. The first method used an integrating sphere for the surface roughness correction and refractive index literature values for the phase change based on the complex refractive index of the material for correction. The second method evaluated the phase correction from the difference between DEI and a single ended gauge block interferometer (SEI) using results obtained with a quartz plate. The third method used the differences (from separate measurements) between results obtained with quartz or steel auxiliary platens. Only a few gauge blocks per set needed testing by the project with the 3 methods, in order to obtain the required phase correction The SEI and DEI results from the methods with different phase correction determination methods were then collated and evaluated. The results showed that the uncertainty estimate for gauge block calibration with DEI produces a similar standard uncertainty to that obtained with the best SEIs, $u=\sqrt{[(10.0\text{ nm})^2+(118\times10^{-9}\,L)^2]}$ nm. This is an excellent result and supports the use of DEI more widely by NMIs. The results have been discussed with the BIPM Consultative Committee for Length (CCL) Discussion group DG1 for gauge block metrology and were also published in Metrologia [10].

3.2.4 Improved FPI displacement measurement and related sensor calibration

Reliable operation of highly accurate displacement sensors requires traceability to primary standards. Key to this is that any calibration is an actuated displacement target to reference the displacement sensor under test with simultaneous traceable tracking of the target displacement.

FPI displacement provides high accuracy with direct traceability to optical frequency standards. In order to achieve this, one of the FPI cavity mirrors is displaced using a precision actuation gear whilst a measurement laser tracks the change of optical resonance frequency over the changing cavity length. The FPI facility (MetFPI) of project partner VSL is a versatile platform for adapting measurement targets in common displacement motion with the FPI cavity mirror. Furthermore, using a displacement sensor facing the actuated target a highly accurate calibration can be performed by the MetFPI facility. The objective for this part of the project was an improved sub-nm FPI displacement measurement and related sensor calibration uncertainty. As part of this, improvements made to the VSL MetFPI facility were made and the uncertainty budget investigated with particular attention on environmental effects, sensor referencing, alignment, noise and drift of the FPI. The results gave a sub-nm uncertainty for a displacement stroke of 1 µm and 10 nm for a stroke of 100 µm. The achieved results are linked to the calibration methodology in section 3.2.5.

Thermo-mechanical stability and alignment are crucial for reducing uncertainty from system drift and displacement scale error. As part of the improvements for the MetFPI facility, stable sensor mounting hardware with the necessary positioning alignment abilities was produced. As were, electrical isolation features enabling the necessary electrical probe potential or grounding condition for the displacement target and the capacitive sensor under test. In addition, a gold coated laser-grade mirror was used as a high quality displacement target electrode. The MetFPI facility was also improved by establishing, optical fibre coupling towards and from the FPI on a separate breadboard, in order to give improved foam-box style ambient shielding of the FPI instrument. This improvement in the shielding also provided millikelvin temperature stability over several hours, thereby supporting measurement procedures with sub-nm short-term uncertainty and a few nanometre long-term uncertainty.

The improvements for the MetFPI also included a better measurement laser frequency lock scheme together with an improved FPI cavity finesse, which produced a reduction in the noise level (resolution) of the instrument of less than 100 pm PV. Further to this, an intra-cavity glass cell, covering most of the optical path of the FPI cavity, was used in quasi-hermetically sealed atmospheric condition, in order to reduce the air pressure induced measurement excursions form the nm-scale to a few 100 pm. Piezo-geared alignment actuators allow sensitive nm-scale set-point adjustment of the mounted sensor and the FPI displacement gear. Therefore, auxiliary capacitive sensors were added to the MetFPI facility for monitoring, and, the FPI gear sensor, when calibrated on its own, gave faster processing of the displacement steps in sensor calibration.

In addition to the work done on the VSL FPI successful measurements were performed at project partner NPL for quadrature and sub-quadrature XRI displacements for a stroke up to 1 μm. The measurement results from NPL's improved XRI showed that the differential configuration (dual channel configuration) reduced the temperature drifts and influence of environmental effects by around two orders of magnitude.

Another set of measurements were performed for angle measurements (angular displacements) using the DFPI of project partner TUBITAK using a High Precision Small Angle Generator (HPSAG). The opto-mechanical system for angle measurements included 2 concave mirrors and the HPSAG was mounted on an Aluminium (Al) breadboard with a 2 cm thickness. This Al breadboard was isolated from the optical table with foam and in order to reduce the influence of environmental effects the whole measurement system was covered by 2 foam boxes. The temperature fluctuation inside the foam boxes was less than a few mK for measurement times of a few minutes. Not all mechanical parts of the angle measurement system including DFPI and HPSAG were developed from invar (i.e. a nickel–iron alloy notable for its uniquely low coefficient of thermal expansion), however the drift of the system for a measurement time of more than 500 s was < 3 nrad and the peak-peak fluctuation for a 1 s averaging time was sub-nanoradian.

3.2.5 Sensor calibration methodology using FPI

A calibration methodology for the specific case of capacitive sensors was investigated by the project using the VSL MetFPI facility with the improvements described in section 3.2.4. To extend the improvements to the FPI, two capacitive sensing systems where investigated, 1) a commercial off-the-shelf system with a pencil-shaped probe, provided by project collaborator IBS Precision Engineering, and 2) the multi-segment probe system of REG(TU Delft) and Arsen Development Ltd.

The project took detailed measurements on the noise and drift stability of the MetFPI facility with the two different capacitive sensing systems [6, 14]. The results showed that the measurement uncertainty depends on the detailed sensor application requirements. For example, a fast procedure with a few calibration points on a relatively coarse sampling grid led to a smaller uncertainty compared to the slower fine sampling that is typically needed for sensor linearity validation. The FPI measurement uncertainty for the relatively quick processing of short displacement strokes up to 1 μm was smaller than 500 pm (k=2). However, thermo-mechanical drift and scale errors, e.g. from angular sensor alignment, lead to 1 nm uncertainty for 10 μm stroke and to 10 nm uncertainty for explored displacement stroke larger than 100 μm.

Further investigations with the VSL MetFPI facility and with the NPL XRI were also performed to address the performance of the self-aligning capacitance sensor system of REG(TU Delft) (see section 3.1.2).

TUBITAK developed an experimental set-up for extended range measurements, based on the combination of resonance counting and beat frequency measurements. TUBITAK's combined method used resonance counting for the integer termed displacements whereas the fractional part of the displacements were obtained through the beat frequency measurements. The fractional part of the displacement was obtained by tuning the laser frequency on top of the resonance. The beat frequency difference obtained prior and after the displacement was then used for the measurement of the displacement considering the Free Spectral Range (FSR) of TUBITAK's Differential Fabry-Perot Interferometer (DFPI). TUBITAK's combined method for extended range measurements was actuated for a stroke of up to 100 μm in a closed-loop configuration and the interferometer together with the developed software was used to simulate capacitive sensor mounting and characterisation on the TUBITAK DFPI. Preliminary results for an extended range up to 80 μm (with the possibility of going up to 100 μm in the future) were obtained by TUBITAK with an uncertainty of about 10 nm.

3.2.6 Step-change improvement of the FPI to picometre-range uncertainty

At VSL, picometre-range uncertainty for FPI was aimed for in an experimental study using a modified and compact FPI set-up with improved ambient stability, sensor referencing versatility and practical traceability to a robust optical wavelength meter bench. The target uncertainty was 10 pm for a displacement stroke of 1 µm. The modified FPI set-up was dubbed pmFPI.

A short (< 0.5 mm) high-finesse optical cavity was chosen for the pmFPI, in order to limit the prohibitive air refractive index fluctuations in ambient measurement conditions. The compact, small-sized optical pmFPI bench also facilitated thermo-mechanical stability and shielding. Traceability for the pmFPI was established using a portable wavelength meter rather than by using the more fragile and costly iodine stabilised standard laser used with the longer cavity of VSL's MetFPI facility.

Scaling of the air refractive index fluctuations down to 10 pm equivalent relative displacement were observed with the pmFPI test bench and the selected components in the pmFPI produced their expected performance, e.g. a high cavity Finesse with 13 MHz FWHM resonance line width. This gave a laser frequency referencing resolution equivalent of 5 pm (SDEV) displacement [5]. However, electronic drive noise from the off-the-shelf piezo-geared displacement actuation stage in the pmFPI, together with vibrational noise, limited the achieved read-out resolution to 14 pm. Displacement steps of 50 pm were observed with the pmFPI, but this was limited by the drive resolution of the stage.

At TUBITAK, a picometre-range uncertainty was also aimed, using their DFPI with improved ambient stability, sensor referencing versatility and traceability to the Rb atomic transitions. The target uncertainty was again 10 pm for a displacement stroke of 1 µm.

The versatility of TUBITAK's DFPI was increased by using its differential configuration. This was done, such that environmental effects could be reduced by one or more orders of magnitude depending on the opto-mechanical loop of the measurement systems. The uncertainty budget for TUBITAK's modified DFPI was investigated, with particular attention on the improved environmental effects (temperature, humidity) and alignment etc. From the results, TUBITAK found that the uncertainty was predominantly due to the measured frequency difference from the displacement stroke and FSR measurements. Other error contributing factors were either too small (such that they were negligible) or were suppressed by use of the DFPI (dual) configuration. The expanded uncertainty value of the TUBITAK DFPI for a displacement stroke of 1 µm was calculated to be 6.2 pm.

3.2.7 Enabling quantised positioning of XRI measurements and quadrature counting

Routines were written for quadrature fringe counting using NPL's XRI and a new detection system was installed using split channel scintillation counters. This enabled quantised positioning in steps of 50 pm (0.25 of a lattice spacing) and continual bi-directional measurement of the position of the moving component of the XRI based on the quadrature X-ray signal. A successful comparison was performed between NPL's XRI and TUBITAK's DFPI, however a scanning range of 10 mm was not achievable with NPL's XRI.

3.2.8 Development of an improved capacitive sensor design

For the development of an improved sensor design for capacitive sensors with lower sensitivity to alignment and environmental effects; a prototype was developed based on REG(TU Delft)'s capacitive sensor with self-alignment (see section 3.1.2), together with a modified sensor plate. This approach was chosen because of its ability to provide feedback about the alignment (tilt) with respect to the target and because of the absence of power dissipation in the sensing area after the alignment procedure is complete. A new sensor interface was also developed (based on previous designs by REG(TU Delft) and Arsen Development Ltd) and using a charge balancing method for capacitance measurement because due to its very good temperature stability and long term stability. Known issues such as relatively poor differential linearity were also addressed and improved with the new sensor interface. The key parameters of the new sensor interface were: 6 channels; 9, 18 or 36 pF measurement range; 17-bit resolution for 2 ms conversion time. During qualification testing of the new sensor interface, it demonstrated temperature stability better than 2 ppm/K and very low offset capacitance. The results from the qualification tests were presented at the 20th IMEKO TC4 Int. Symposium and 18th Int. Workshop on ADC Modeling and Testing.

Conclusions

A traceable wavefront sensor has been developed which offers wavefront measurements with an uncertainty smaller than $\lambda/30$. It has been calibrated by a procedure which does not need knowledge about the reference wavefront which is also an output of this procedure.

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 it open possibilities for using Double ended GB interferometers more widely by NMIs.

The Metrological Fabry-Pérot Interferometer (MetFPI) of VSL provides 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. Detailed insights were gathered on noise and drift stability of the MetFPI sensor calibration facility. The achieved measurement uncertainty depends on the more detailed sensor application requirements. A fast procedure with few calibration points on a relatively coarse sampling grid leads to smaller uncertainty as compared with a slower fine sampling as is typically needed for sensor linearity validation. The MetFPI measurement uncertainty for relatively quick processing of short displacement strokes up to 1 μm is smaller than 500 pm. Drift and scale errors contribute, however, to several nanometre uncertainty for strokes larger than 100 μm. The MetFPI resolution is usually better than 100 pm.

A dedicated calibration methodology was investigated at hand of the two exemplarily chosen capacitive sensing systems, namely a commercial off-the-shelf system provided in collaboration by IBS Precision Engineering and the multi-segment probe system TU Delft and Arsen Development. Detailed insights were gathered on noise and drift stability of the MetFPI sensor calibration facility.

A prototype FPI scheme (dubbed pmFPI) was conceived and experimentally investigated at VSL, aiming for picometre-level measurement uncertainty. Electronic drive noise from the off-the-shelf piezo-geared displacement actuation stage, together with vibrational noise, currently limits the achieved read-out resolution to 14 pm.

Several concepts for improved actuation of the x-ray interferometer have been developed. These include a dual actuator with capacitance sensors which did not perform satisfactorily due to excessive noise and drift in the commercial sensor electronics. A new single point actuator has been developed and a first version of a low noise power supply for the PZT has been tested.

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.

Known conversion principles for capacitance measurement were studied. The charge balancing method was considered as most suitable for the particular application. Its advantages and drawbacks were analysed and presented on ISMTII 2013 conference. A paper “Highly-stable Electronic Sensor Interface for Capacitive Position Measurement” was published in KEM (Key Engineering Materials) journal. Based on this analysis, the electronics for the capacitive sensor interface was developed. The solution was presented on I2MTC 2014 conference.

The key research outputs were:

- Calibration of two different types of wave front sensors and evaluation of the uncertainty budget; both sensors satisfy the requirements regarding the uncertainty for the systematic sensor error of being less than $\lambda/30$.
- Development and validation of a set-up for absolute calibration of wave front sensors;
- A new method for high accuracy determination of phase correction in double ended gauge block interferometry has been developed.
- A metrological Fabry-Pérot interferometer was instrumentally improved for sub-nm displacement measurement uncertainty.
- A differential Fabry-Pérot interferometer (DFPI) was improved for sub-nm displacement measurement uncertainty.

- Uncertainty budget for the differential Fabry-Pérot interferometer has been established.
- Application of differential Fabry-Pérot interferometer for sub-nanoradian angle measurements has been introduced.
- An experimental set-up for an extended range measurement (100 μm) has been developed. This combined method makes use of both the resonance counting and beat frequency measurements for integer and fractional parts of the displacement strokes respectively.
- A calibration methodology for capacitive displacement sensors using the Metrological FPI was developed.
- An experimental test bench with a short cavity FPI showed down-scaling of ambient atmospheric perturbation to 10 pm displacement measurement equivalent.
- Investigation of the multi-segment capacitive sensing system referenced to a FPI showed pm-level resolution and nm-level long-term drift stability.
- The performance of this capacitive system together with the referencing to FPI and XRI is a promising basis for further investigation toward sub-nm displacement standard instrumentation and methodology.
- With the improved Metrological FPI instrumentation, and the explored capacitive sensor measurement procedures, VSL has gained more versatility to address displacement sensor validation, linearisation and calibration with more detailed customisation of the uncertainty budgeting to the actually investigated systems.
- A new multi-channel capacitive sensor interface with 17-bit resolution for 2 ms conversion time and very good temperature- and long term stability was developed.
-

3.3 Cross validation

Introduction

This part of the project addressed the need for cross validation of results by the project partners. The work addressed the following three specific objectives:

- o Analysis of alignment errors in the arcmin region and environmental effects on capacitive sensors by referencing to optical and x-ray interferometers.
- o Specified requirements and reviewed technology available for displacement transfer standards.
- o Characterised prototype displacement transfer standard facilitating cross-validation of at least 2 different types of interferometers with a sub-nanometre uncertainty [10 pm (1 nm) for a displacement stroke of 1 μm (100 μm)].

3.3.1 Analysis of alignment errors and environmental effects on capacitive sensors

As mentioned in Section 3.1.2, a model for the correction of capacitive sensor alignment errors in the arcmin region was proposed by REG(TU Delft). The capacitive sensor model of partner REG(TU Delft) was then verified (i.e. cross validated) with experimental data from tests of capacitive sensors against the MetFPI facility at VSL. Using the capacitive sensor model and the calibration procedure developed in section 3.1.2, an accuracy of better than 2 nm was obtained for a displacement range of 5 to 20 μm with only 2 calibration points. The cross validation as well as the investigation of environmental effects, i.e. humidity and pressure, with the XRI of partner NPL could not be completed during the project's lifetime due to problems with electronic noise (see 3.3.3).

3.3.2 Requirements and review of available technology for displacement transfer standard

Cross-validation of primary measurement facilities at the NMI level and calibration of displacement sensing instrumentation on site in industrial or other metrology facilities requires a transfer standard that is not only accurate to the sub-nanometre level but also economical in terms of use. The project performed a feasibility study to examine the requirements for and the technical issues associated with the production of such a transfer standard (thereby supporting sub-nanometre calibration uncertainty). In the first stage of the study, the requirements and the currently available technology were identified. In the second stage of the study, an experimental investigation explored capacitive displacement sensing as a candidate for the implementation of the transfer standard. In this second stage of the study, two conceptually different interferometers, namely the VSL MetFPI and the NPL XRI were used and data from them was used for cross-validation purposes. The target uncertainty for the transfer standard was 10 pm (1 nm) for a stroke of 1 µm (100 µm), see section 3.3.3.

A transfer standard is constituted from several key elements such as displacement sensors, target interfaces, displacement actuation and traceability to primary standards. Therefore, important decisions included whether the *travelling* element of the transfer standard/method is an active sensor or a passive scale artefact, and whether it carries traceability on its own (e.g. a crystal lattice constant) or requires calibration.

Noise level (resolution) and drift stability (precision and accuracy) are also vital not only for modular constituents (of a transfer standard) but also for the overall set-up of a calibration instrument. VSL's MetFPI and NPL's XRI offered good performance when located at their respective NMIs, however emphasis was needed for achieving similar performance levels for a travelling system (i.e. transfer standard) and for the hardware mounting for the transfer standard in terms of relevant sensitive alignment degrees of freedom. Similarly important were the transfer standard's measurement procedures and handling methodology, cost effectiveness, complexity, compatibility and time-efficiency of operation.

From the results of the study a variety of instruments were found to meet the requirements for a transfer standard, but all require further development and validation. Such instruments include:

- Compact differential optical displacement interferometers as active sensing standards;
- Resonant FPI as active sensing standards;
- XRI for traceability of silicon mono-crystal passive transfer artefacts;
- Capacitive active displacement probe systems;
- Hybrids of the above mentioned, complementing range and referencing needs;
- Dynamic active displacement standards, e.g. virtual step-height calibration standards.

3.3.3 Characterisation of prototype displacement transfer standard and cross-validation

The capacitive sensor with self-alignment system of REG(TU Delft) from section 3.1.2 was experimentally investigated as a potential (travelling) transfer standard that could be compatible with both the VSL MetFPI facility and the NPL XRI. The compatibility of the capacitive sensor system was due to the system's multi-segment probe configuration and self-alignment functionality. However, in order to specifically match the capabilities of NPL's XRI a differentially measuring dual sensor version of the REG(TU Delft) capactive sensor system was manufactured. This differentially measuring dual sensor version of the system also had the benefit of being able to compensate for ambient air dielectric constant variability in the capacitance measurement.

Mounting, alignment, referencing, measurement procedures and performance of the capacitive sensor with self-alignment system were experimentally investigated and cross validated with both VSL's MetFPI and NPL's XRI. The results showed that the electrical (isolation and shielding) state of the measurement set-up was critical in terms of achieving pm-level noise performance. At the NPL XRI the problems with electrical (isolation and shielding) were only identified towards the end of the project and therefore it was not possible to make further measurements with the capacitive sensor self-alignment system using the XRI in order.

At VSL's MetFPI facility a capacitive sensing resolution of a few picometres was observed with the capacitive sensor system under high sensitivity conditions i.e. with the shortest probe-target working distances smaller than 5 µm. Picometre-level resolution was also observed with large probe-target working distances, i.e. displacement beyond 100 µm. Drift stability, i.e. reproducibility, was at the nm-level for the capacitive sensor system corresponding to the established performance of VSL's MetFPI. In addition to this, it is worth noting that the multi-segment probe electrode signals allowed extremely precise angular alignment of the probe electrode disk with respect to the displacement target electrodes (the internal alignment errors from the FPI itself then dominating). The only negative effect on the capacitive sensor system was climate dependence of the air dielectric constant from pressure and humidity, which were observed as signal excursions during sudden weather events. Therefore, separate investigations with a climate chamber test rig will be necessary to complete the validation of the capacitive sensor system as a transfer standard. However, based on these results, REG(TU Delft) improved the model-based sensor linearization methodology of the capacitive sensor system.

Conclusions

Based on cross-validation experiments of the sensor against the interferometer, a model for the capacitive sensor was chosen and a calibration procedure with corrections for temperature, pressure, humidity, tilt and edge effects was proposed. A paper about this work is prepared and accepted for ICST 2015 conference.

Initial measurements of the dual self aligning sensor against the XRI were made and found to have a high level of noise. Work was directed to reducing the noise to an acceptable level but this took until the end of the project. Work will continue to assess the sensor after the end of the project.

A feasibility study addressed requirements and technical issues for a practical displacement transfer standard supporting sub-nanometre calibration uncertainty. Diverse sensor system specifications require compatibility in displacement range and interface. A transfer standard methodology is constituted from several key elements such as displacement sensors, target interfaces, displacement actuation and traceability to primary standards. Important choices are whether the travelling element of the transfer method is an active sensor or a passive scale artefact, and whether it carries traceability on its own (e.g. a crystal lattice constant) or requires a calibration. The multi-segment capacitive probe system from REG(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 MetFPI and the NPL XRI.

The key research outputs were:

- Successful cross-validation of self aligning capacitive sensor with model comprising corrections for temperature, pressure, humidity, tilt and edge effects against MetFPI;
- Feasibility study for a practical displacement transfer standard supporting sub-nanometre calibration uncertainty;
- Proposal of multi-segment capacitive probe system from REG(TU Delft) and Arsen Development as potential implementation of a transfer standard offering compatibility for interfacing both the VSL MetFPI and the NPL XRI;

4 Actual and potential impact

The project aims were to develop improved traceability of dimensional nanometrology in high end instrumentation used at NMIs and in high tech industries. The main subjects of research have been X-ray and optical interferometry as well as capacitive sensors, interfacing and calibration methodology.

From now on, traceable laser beam characterisation for the calculation of diffraction corrections in optical interferometers can provide actual shape and asymmetry of the beam wavefront which could not be taken into account properly using traditional methods. A Fourier optics propagation technique based on the 2D wavefront data accounts for any arbitrary wavefront shape. The details are not yet published but will be in the near future.

The developments which made the above achievement possible, a traceable calibration setup for wavefront sensors, a calibrated Shack-Hartmann sensor and a rigorous simulation tool for the propagation of coherent light in optical systems, the vectorial ray-based diffraction integral (VRBDI), have already generated impact in the measurement setup at PTB for the lattice parameter of Si-28 which is part of the endeavour to redefine the kilogram by the Crystal Density Method (CDM). Beyond that, these methods can be adopted by other NMI or high-tech companies to improve the traceability of their laser interferometers. The VRBDI can be used in propagation problems which were hard to tackle before. The source code has been made available and the main article introducing the method is already cited. Therefore, it is likely that it will generate further impact in other fields like optical design, optical interferometry, wavefront sensing, beam characterisation and academia.

TUBITAK's Differential Fabry-Pérot Interferometer (DFPI) has been applied to detection of very small angles in the scope of another EMRP project (SIB58 Angles – Angle Metrology). During application, down to 1 nanoradian (nrad) angular steps within the range up to 0.5 arcsec (2500 nrad) were generated using TUBITAK's High Precision Angle Generator (HPSAG) and these steps were detected using the TUBITAK DFPI and frequency stabilised lasers as an alternative and outperforming method to conventional angle interferometers. It is expected that the knowledge produced will be of benefit to the synchrotrons & XFEL community, gamma ray spectroscopy applications, fundamental physics, and scientific space missions as well as NMIs and angle measurement device manufacturers.

The VSL Metrological FPI facility, as a result of this project, now is available for commercial test and calibration services for displacement sensors. Beyond this project's focus on studying high-end capacitive probe systems, the configuration of the FPI with referencing targets and measurement procedures is equally useful for calibration and linearization of other types of displacement sensors, e.g. non-contact optical interferometers. At VSL the FPI complements the dimensional stability measurement abilities of the VSL Picodrift Interferometer, that was further developed in the course of the previously completed EMRP project IND10 "Thermal design and dimensional drift".

TU Delft and Arsen Development established a multi-segment probe system and tested it by executing calibration procedures with FPI and XRI. A concept for a traceable transfer standard based on the multi-segment probe system has been proposed. This implies that it will be possible to compare bulky immobile length comparators of different NMI between each other by exchange of a transfer standard which is based on this concept. Therefore, it will be possible to check the uncertainties of these setups against each other. In the long term this will lead to improved accuracies because systematic errors may be identified more easily.

ISO/TC213 visited MIKES on Sept 20, 2013. The Subnano project and double ended interferometry were introduced to visitors. Double ended gauge block interferometry was discussed within CCL DG1 Gauge Blocks. The excellent results for the newly developed method open possibilities for using Double ended GB interferometers more widely by NMIs.

The main stakeholders of this project are the NMIs itself where the main impact is generated. The sensibility for systematic wavefront effects has already increased at some NMIs. The prospect for a traceable transfer standard for displacement may lead to length comparator comparisons between NMIs. One cutting edge NMI metrology project, the re-definition of the kilogram, already benefits from this project. The enhanced measurement capabilities acquired during this project lead to standardised, traceable and validated measurement methods for calibrating precision instruments; enhance the quality assurance of national metrology institutes, the calibrations they perform for customers and potentially improve ultimate quality of the products manufactured in Europe, thereby enhancing the competitiveness of European industry. Some particular results are also directly important for the semiconductor fabrication, lithography, and nano-positioning industry. The simulation tools developed are freely available and may benefit the optical design community, precision optics and academia.

The project generated:

- 12 participations and/or communications to metrology committees (BIPM Working Group on Dimensional Nanometrology (WG-N), EURAMET technical committee);
- 14 publications in peer reviewed journals or conference proceedings;
- 11 conference presentations and 5 posters;
- 7 training events (workshops for internal audience);
- 24 dissemination activities (visits to stakeholders, events, press releases, newsletters and websites);
- 4 end user uptake & exploitation activities;
- 15 research / stakeholder collaborations at the European level;
- 1 patent;
- 1 exploitable foreground (general advancement of knowledge).

5 Website address and contact details

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Project website: http://www.ptb.de/emrp/subnano.html

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