

ET VIBRATION ISOLATION AND MORE

VSL's Picodrift interferometer enables ultra-precise measurements of 1D (sub) nanometer displacements, providing traceable calibration of deviations in sensors and standards. This article presents new challenging applications using this set-up presented related to ongoing research projects on Einstein Telescope vibration isolation, microslip in clamped interfaces, and virtual standards for dimensional nanometrology. A recent optomechanical analysis of the set-up on intrinsic drift has confirmed that mechanical optical mounts are very stable for measuring long-term drift. Virtual standards consisting of highly linear piezo stacks that are calibrated by the Picodrift interferometer will be applied to various optical displacement sensors to study the periodic nonlinearities of laser interferometers.

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Introduction to Picodrift

Current advances in high-end manufacturing equipment result in the realisation of (sub)nanometer precision for production tools in, for example, the semiconductor industry. This is enabled by control systems using displacement sensors and actuators to achieve precise motion with extremely high positioning accuracy at the nanometer level.

Understanding and taking into account small systematic deviations and nonlinear errors of the sensors and actuators is essential for improving the performance of the systems. Additionally, irreversible (sub)nanometer drift phenomena in the construction and mounting of displacement sensors and actuators, such as creep, aging of bonding and glued connections, and microslip in bolted joints, influence the accuracy and repeatability.

To study these effects and to calibrate those sensors and actuators, instruments are needed with measurement uncertainties in the lower subnanometer range. In a review of calibration methods for small-range displacement sensors

[1], it was shown that interferometric methods are available down to the subnanometer measurement uncertainty level.

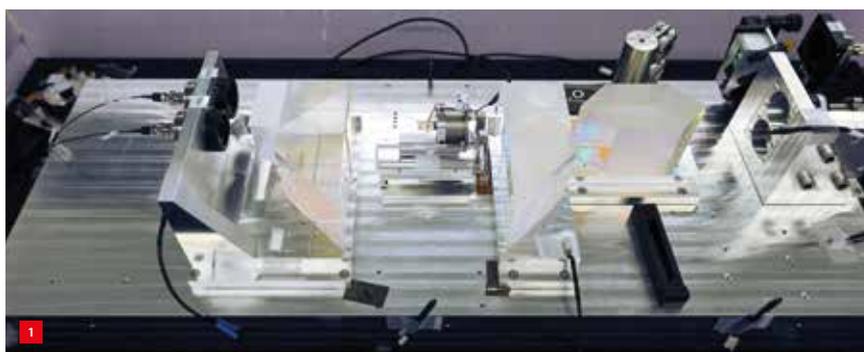
At VSL, a special balanced twin heterodyne interferometer, denoted the 'Picodrift instrument' (see Figure 1), is in operation achieving measurement uncertainties of 10 pm in the short term (seconds to minutes) and 100 pm in the medium term (hours). The design and realisation of the instrument resulted from a research collaboration between VSL, TU Delft and TNO; after being moved to VSL, it was further developed in metrology research projects to the current state. It is a versatile instrument that can be used for many different applications giving traceable calibrations for one-dimensional displacement in the (sub)nanometer domain.

This article presents the operational principle to discuss the special features of the Picodrift instrument as well as some limiting factors, followed by an analysis of the optomechanical stability of the set-up to study the intrinsic drift and ways to eliminate this drift further. Next, the current applications in research projects, such as for the Einstein Telescope, will be presented.

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The optical set-up of VSL's Picodrift instrument.

Operational principle

In short, the Picodrft instrument [2][3][4][5] consists of balanced double heterodyne interferometer arms with equal optical path length so that common perturbations such as thermal expansion in the interferometer bench are cancelled. In a heterodyne interferometer, the two arms are modulated at different frequencies (f_1 and f_2), typically in the MHz range, allowing phase detection using electronic demodulation, which is more precise and less sensitive to low-frequency noise.

One interferometer is dedicated to compensating for the refractive index changes in air (see Figure 2) and the other is dedicated to measuring the sample-length change. Additionally, each heterodyne interferometer consists of spatially separated beams for removing periodic nonlinearity that is normally attributed to frequency mixing due to non-perfect polarisation of optical components. The resulting length change Δx is determined directly from the measured phase difference between the two interferometers:

$$\Delta x = \frac{\lambda}{2\pi N} (\phi_s - \phi_r)$$

Here, N is the interferometer constant (2 for the Picodrft because the optical path length increase is twice the length change of the sample).

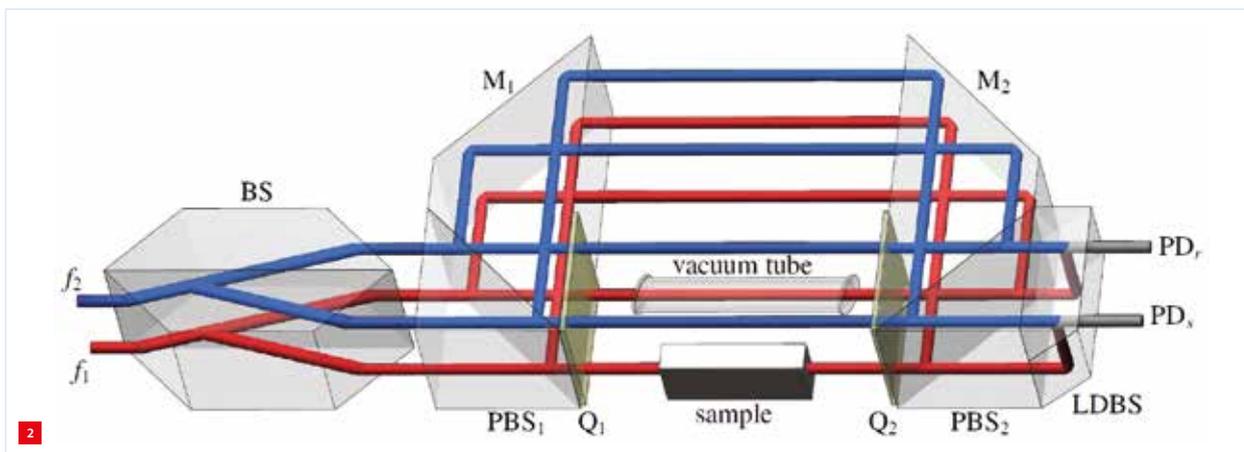
The beam separation of the upper and lower path (f_1 and f_2) and between the sample (s) and refractometer (r) is 30 mm.

The space in between the beamsplitters (PBS1 and PBS2) can be changed from 100 mm up to 200 mm in steps of 50 mm. Any sample or sensor device can be inserted at the sample position as long as the other beams are not partially obstructed. The clear diameter of the beams in the interferometer is about 2.5 mm.

The laser driving this interferometer is a tuneable external cavity laser diode that is stabilised using an in-vacuum optical cavity and the Pound-Drever-Hall technique [6]. This eliminates the laser wavelength noise for the short term. For the long-term wavelength stability and for traceability to the SI-meter [7], the laser frequency is continuously monitored by beat-note measurements with a stabilised HeNe-laser.

High temperature stability and low gradients within the system are crucial for achieving very low long-term drift. Therefore, the aluminium base plate with the optical components is placed inside a thermally isolated enclosure consisting of two layers of polystyrene around a thin sheet metal cover with aluminium foil on the outside. After acclimatisation, a temperature stability of 1 mK/h is achieved. Additional sensors for air pressure and relative humidity are also in place for refractive-index compensation when the path lengths are not fully balanced.

Over the years, the set-up has been maintained and used for tests and for calibrations, for example, of a virtual height



Schematic representation of the balanced double-sided heterodyne interferometer [2], with upper and lower beam at two different modulation frequencies, f_1 and f_2 . The beamsplitter BS provides two beams, one into the sample (s) and one into the refractometer (r) interferometer. The polarising beamsplitters (PBS₁ and PBS₂), quarter-waveplates (Q₁ and Q₂) and mirrors (M₁ and M₂) make sure the interferometer beam goes around and touches the sample at both reflective ends. In the refractometer, the interferometer beam passes through the vacuum tube to balance the optical path length. The lower and upper interferometer arms are combined in the final beamsplitter optics (LDBS) and the interference signal is detected by photodiodes (PDs and PDr). The system is fibre-coupled for receiving incoming laser beams and outcoupling to the photodiodes.

standard and a lateral standard for AFM calibration [8][9]. The virtual standards consist of precisely controlled and calibrated actuators instead of fixed structures in physical standards. Other tests have shown that the intrinsic stability of the set-up has reached as low as 0.5 nm over 19 hours [4]; however, this intrinsic stability changes over time and after maintenance of the system. Overall, the short-term stability of about 10 pm in tens of seconds is quite good, but intrinsic drift is still too high at the time scale of tens of hours, which limits the sensitivity and application of drift measurements.

Optomechanical analysis of intrinsic drift

The long-term stability of the set-up had to be improved, and this became the focus of a master's internship project [10]. The goal was to find the root cause and obtain a deeper understanding of the intrinsic instabilities, so that this knowledge can be used to improve the long-term stability.

The intrinsic drift is observed in a double dead-path difference measurement without any object in the sample interferometer. Ideally, the two interferometers should cancel out, resulting in a null differential signal unless there is a path length imbalance (x_{im}). The resulting drift (Δx_{im}) shows cross-correlation with the environmental conditions, of which air pressure has the largest cross-correlation with this imbalance:

$$\Delta x_{im} = \frac{c(\phi_s - \phi_r)}{2\pi N \eta f} - x_{im} \left(\frac{\Delta f}{f} - \frac{\Delta \eta(p, T)}{\eta} \right)$$

Here, f is laser frequency, η refractive index, p air pressure and T air temperature. The complicating issue is that these cross-correlation factors are not constant but vary slowly in time.

In the sensitivity analysis of the optomechanical stability, the motion of the optical elements (displacement and rotation) is studied assuming that this is induced by environmental changes such as thermal gradients that subsequently change the imbalance and result in measured drift. To calculate the sensitivity of the optical components, a geometrical ray-trace model of the Picodrift interferometer combined with Monte-Carlo simulations is used. The model includes wedges on optical components due to manufacturing errors (± 1 mrad), alignment errors (± 0.1 mrad), position errors (± 0.1 mm) and wedges on the reflecting faces of the sample (± 0.05 mrad). Table 1 shows the obtained values for the linearised component sensitivity to the drift in six degrees of freedom (X , Y , Z , R_x , R_y and R_z), determined by model simulations that were repeated with varying input errors.

Table 1.

Sensitivity analysis of the optomechanical stability.

Left: Linearised sensitivity to the drift in six degrees of freedom for five optical components of the Picodrift interferometer with wedges on the sample and optical components:

FC1: fibre coupler 1; FC2: fibre coupler 2; BS: beamsplitter, PBS1: polarising beamsplitter 1, PBS2: polarising beamsplitter 2, VAC: vacuum tube; see layout in Figure 2.

Right: Alignment requirements for the optical components fulfilling the maximum long-term drift specification.

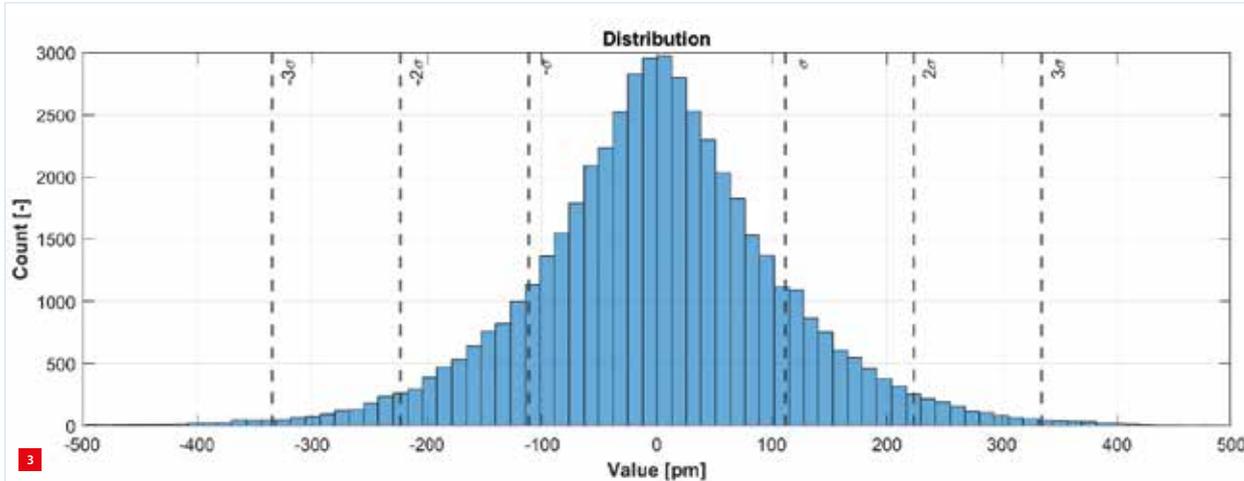
Alignment requirements						
	X [µm]	Y [µm]	Z [µm]	R _x [µrad]	R _y [µrad]	R _z [µrad]
FC1	100	100	100	100	100	500
FC2	100	100	100	100	100	500
BS	100	100	100	250	50	500
PBS1	50	100	100	50	250	500
PBS2	50	100	100	50	250	500
VAC	100	100	100	250	250	500

Alignment requirements						
	X [µm]	Y [µm]	Z [µm]	R _x [µrad]	R _y [µrad]	R _z [µrad]
FC	4,000	390	2	388	2,620	2
FC2	3,515	367	2	313	2,480	2
BS	170	0.1	0.1	2	1,500	124
PBS1	2,550	3	10	515	41	242
PBS2	3,340	3	10	780	55	245
VAC	0	0	0	4	4	0

To estimate the potential thermally induced displacement after acclimatisation, the measured worst-case maximum gradient of 2 mK has been taken into account to estimate bending of the base plate, resulting in maximum in-plane motions of 10 nm translation and 50 nrad rotation of the optical components. These estimations were taken as input into simulation to estimate the intrinsic drift, resulting in 110 pm standard uncertainty, as can be seen in Figure 3, which is smaller than the observed long-term intrinsic drift of ± 0.5 nm. Currently, it can be concluded that the optomechanical stability of the optical components is not the major limiting factor for long-term measurements, but that it can be improved.

Measurement uncertainty due to component motions (worst-case 50 nrad rotation and 10 nm translation), alignment changes and first-order manufacturing errors (wedges), as derived from Monte-Carlo simulation of the geometrical ray-trace model.

Still to be investigated are (1) air-path minimisation, which would limit the spatial refractive-index variation, and (2)



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Validation of instruments by traceable standards

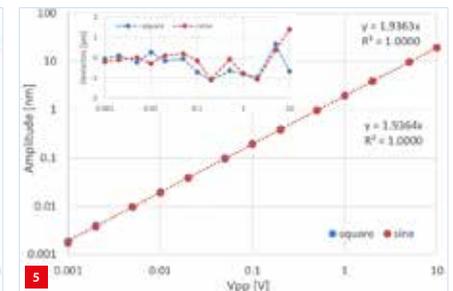
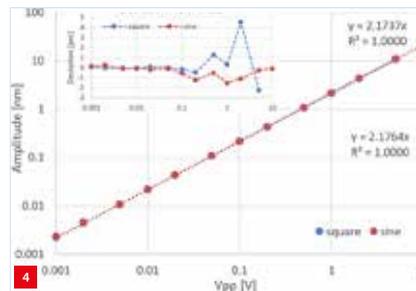
The task of VSL, as the National Metrology Institute of the Netherlands, is to provide traceability to the SI for the industry. With the Picodrifft instrument, VSL enables nanometrology down to very small displacements in the (sub)nanometer range. This is very valuable for the development and application of sensors and measuring instruments to study, for instance, the noise, nonlinearities and absolute accuracy.

Additionally, VSL has development methods based on virtual standards consisting of highly linear piezos that are calibrated by the Picodrifft instrument and can be used to calibrate instruments such as atomic force microscopes (AFMs) in (sub)nanometer ranges where physical standards lack or are less useful [9]. Below, currently running research projects are presented showing challenging applications of the Picodrifft instrument.

Calibration of piezo stacks (virtual height standard)

Over the years, recalibration of the piezo stacks (virtual standards) for AFM calibration [8] has been used as a benchmark for the performance of the Picodrifft instrument; see Figure 4. A recent recalibration is compared to past calibrations; see Table 2. A minor decay in sensitivity is observed, which can be attributed to aging of the piezo stack. These piezo stacks are powerful standards for calibrating nanometrology instruments, such as AFMs or

white-light interferometers (WLIs), in the subnanometer scanning range where physical standards have limitations.



Piezo calibration, with insert showing the nonlinearity.

(a) Step height.

(b) Shear.

Table 2.

Piezo-stack (virtual height standard) sensitivity in pm/V for the actuation range from 1 mV to 10 V amplitude for sinusoidal and square wave operation with 10 Hz frequency, as measured in the past years (see Figure 9 in [8]).

Sensitivity [pm/V]	2016	2019	2024
Sinusoidal wave	1,967	1,942	1,935
Square wave	1,967	1,931	1,938

SENVIDET

In a cooperative research project called SENVIDET (Sensor Engineering for Noise and Vibration Isolation and Damping in Einstein Telescope), fibre-based optical sensors and interferometers will be improved to get the performance at the level that is needed for a gravitational-wave detector.

The research is aimed at reducing the noise levels at low frequencies; see also the SENVIDET article on page XX ff.

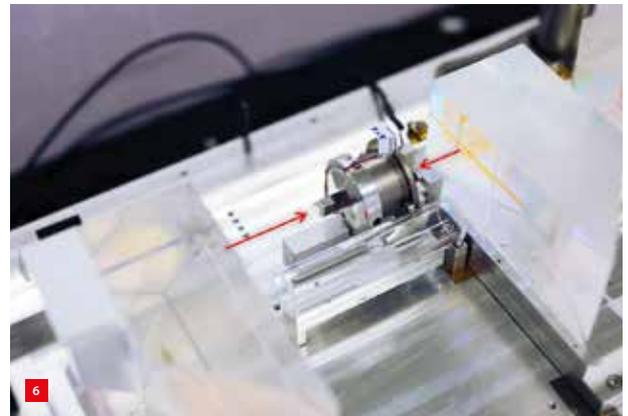
The role of VSL in this project is to provide validation methods for the displacement sensors by using metrology solutions based on the Picodrifting instrument. Validation could be done directly by comparing, or indirectly by using the virtual standards and will result in novel calibration methods for displacement sensors at ultralow frequencies.

DINAMO

A European metrology research project called DINAMO (Digitalization route for dimensional nanometrology) aims to establish a digitalisation route for dimensional nanometrology, focusing mainly on the measurement of dimensions, position, form and roughness at the microscale to nanoscale level. VSL contributes to the development of programmable virtual height and lateral standards (see Figures 5 and 6) for use in the automated processing of measurement data for calibrating scanning probe microscopes and potentially other instruments, such as WLIs.

Within this project, a novel dynamic application of the virtual standards will be explored from quasi-static to drive frequencies ranging from tens to several hundreds of kHz. Additionally, the height standards can be programmed to any arbitrary function for simulating different step heights of surface profiles in order to test the response of the instrument. This requires investigation of the calibration methods and uncertainty estimations for the calibration with the Picodrifting instrument.

This requires an upgrade of the signal processing and validation of the measured displacements at high frequencies up to 2 MHz.

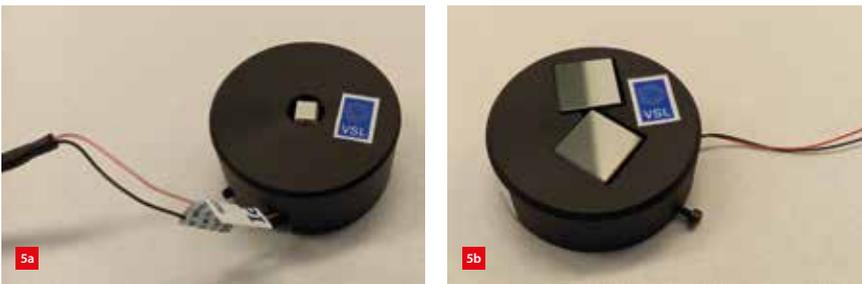


Virtual height standard inserted in the Picodrifting instrument for calibrating the sensitivity (pm/V).

CTE calibrations of gauge blocks

Gauge blocks are the most accurate physical realisations of length standards and gauge-block interferometers are the instruments for length calibration with the lowest measurement uncertainty. The coefficient of thermal expansion (CTE) of a gauge block needs to be known with a low measurement uncertainty for achieving the best calibration result for the length of a gauge block.

Static CTE calibrations can be quite elaborate in time because the full instrument has to be stabilised to several temperature points for estimating the CTE value. The Picodrifting instrument, which has a very high sensitivity to length changes and is equipped with high-accuracy temperature sensors, could be used to dynamically measure the CTE of gauge blocks. Either a cooled or heated gauge block is inserted (see Figure 7) into the sample path of the interferometer and has its temperature relaxed to the ambient temperature while measuring the change in length and simultaneously recording the material temperature.



The virtual standards.
(a) Height.
(b) Lateral.

CHAOS

In a research project called CHAOS (Characterisation of High-Speed Acoustic Optical Sensors), VSL will develop a calibration method based on the Picodrifting instrument for characterising fibre-optic sensors at high frequencies for ultrasonic applications. For this, the bandwidth of the Picodrifting instrument will be increased to enable measurement of displacements at those high frequencies.



Steel gauge block of 40 mm inserted into Picodrifting for measuring length change related to material temperature to calibrate the CTE.

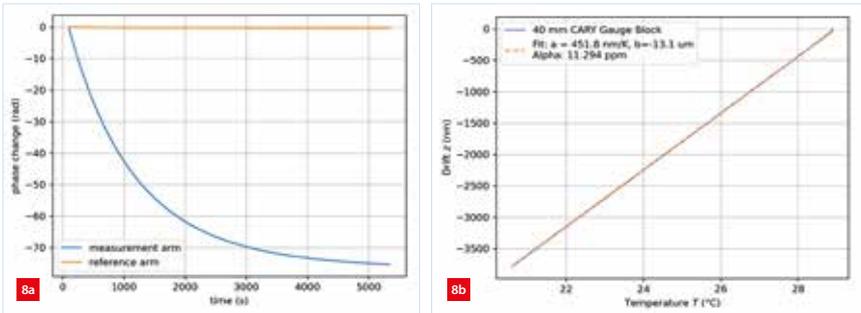
Figure 8 shows a measurement result for a 40-mm gauge block cooling down from 29 °C to room temperature.

Typically, such a measurement lasts between one and two hours. This measurement method is currently being tested, and the calibration method will soon be validated including the measurement uncertainty value.

drift) or between interfaces (i.e., adhesive connection and clamping). In a recent bachelor project by a student from TU Eindhoven [11], an insert tool for the Picodrifting instrument has been designed for measuring and studying the pre-sliding motion of clamped surfaces, also known as microslip. This test bench functions as a force frame and guide for accurately applying a load and isolating the pre-sliding effect, while the Picodrifting instrument measures the displacement in the only permitted direction.

Currently, in a follow-up project, an improved microslip set-up is being developed; it will be integrated in the Picodrifting instrument for characterising the pre-sliding behaviour of various samples, materials and geometries using the extreme sensitivity of the interferometer. The set-up comprises various modules to align the sample to the interferometer, in order to accurately apply clamping forces up to 2,000 N, and to precisely control a varying tangential force in the plane of contact that represents accelerations of future motion stages.

Some pre-testing has already been performed to validate submodules in the set-up (Figure 9). The outcomes of the microslip experiments will provide experimental insight into the microslip behaviour, which is of ever-growing importance for the stability of clamped connections on faster motion stages, enabling higher throughputs and more accurate positioning for future semicon production machines.

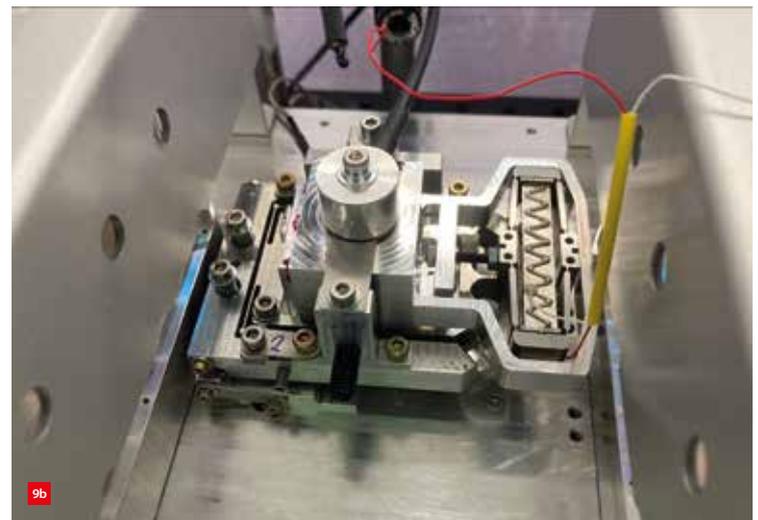
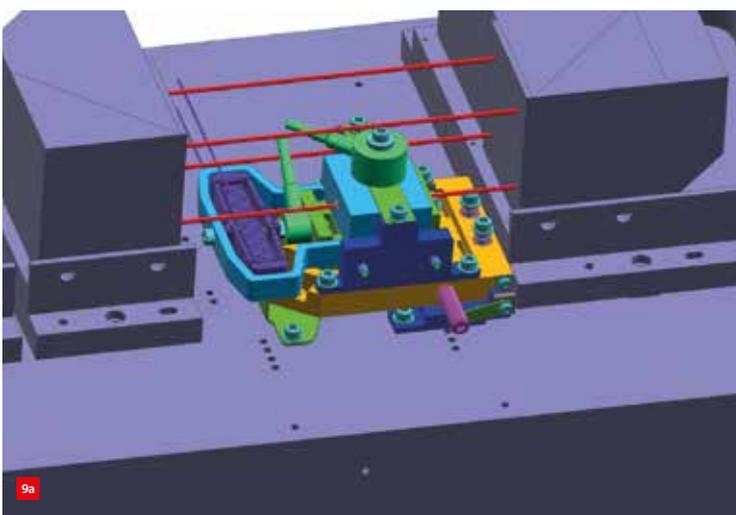


Measurement result for a 40-mm gauge block cooling down from 29 °C to room temperature.

- (a) Measured phase change in the sample interferometer with the gauge block inserted (measurement arm) and the refractometer interferometer (reference arm), showing the exponential cooling to room temperature.
- (b) Resulting contraction of the gauge block plotted versus material temperature during cooling down, showing the estimated CTE value of $11.29 \cdot 10^{-6} \text{ K}^{-1}$.

Special insert for studying microslip

The Picodrifting instrument is, due to its double-ended measuring configuration, especially suited for detecting slowly varying length changes in materials (i.e., creep and



Microslip set-up integrated in the Picodrifting instrument.
 (a) CAD model.
 (b) Realisation, as photographed in the pre-testing phase.

Outlook

This article has presented current applications of the Picodrift instrument at VSL. Recent technology research grants related to the Einstein Telescope have boosted the interest in interferometric sensors for detecting motions at low frequencies, to be applied for vibration damping in control loops. This specific application relates to similar challenges in (sub)nanometer measuring instruments and sensors for which VSL develops metrology solutions. The outcomes of the presented projects will enable novel calibration methods at either low or high frequencies where (sub)nanometer displacements are involved.

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