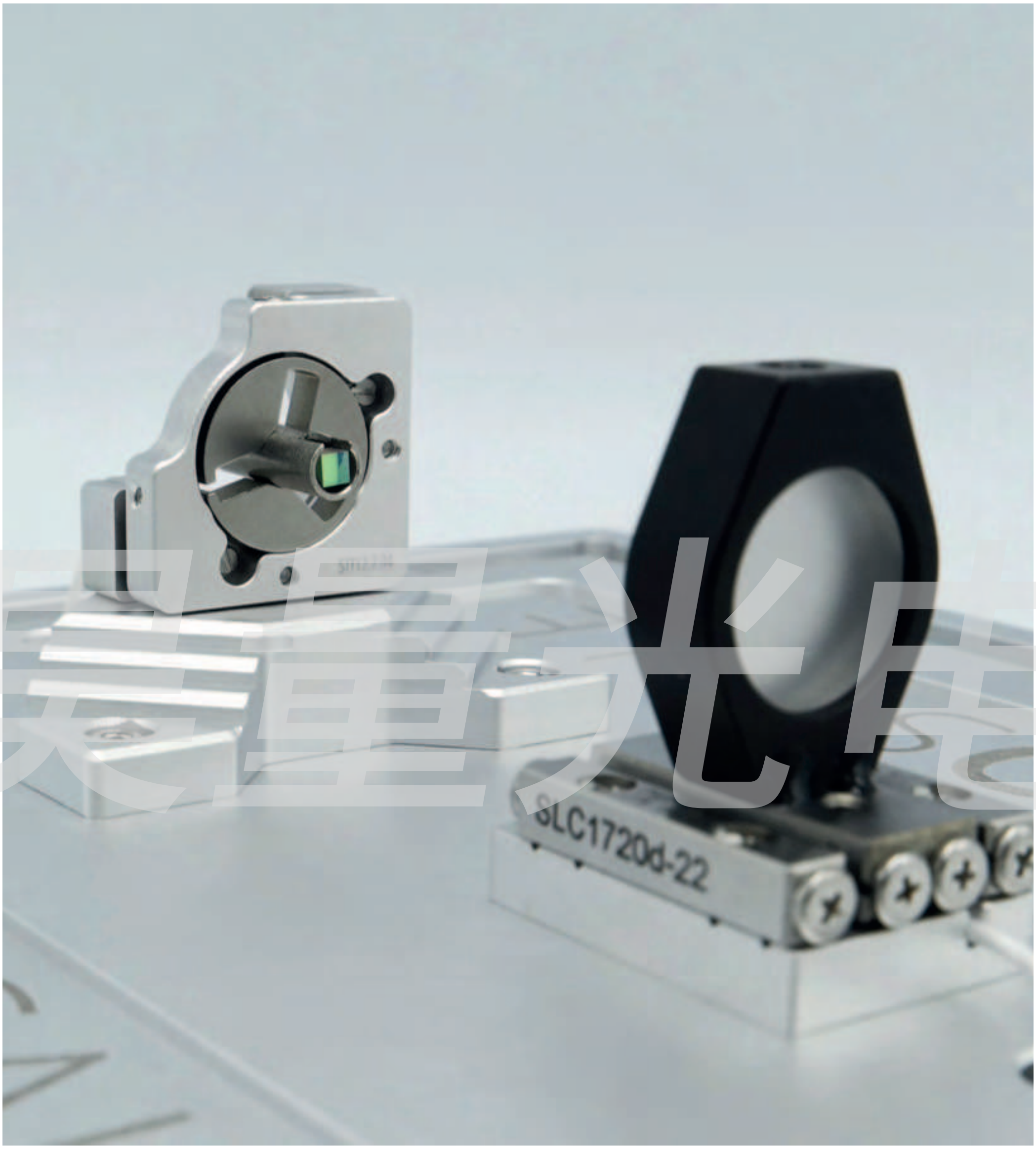
Metrology

SmarAct



SmarAct's Interferometric Solutions for Metrology

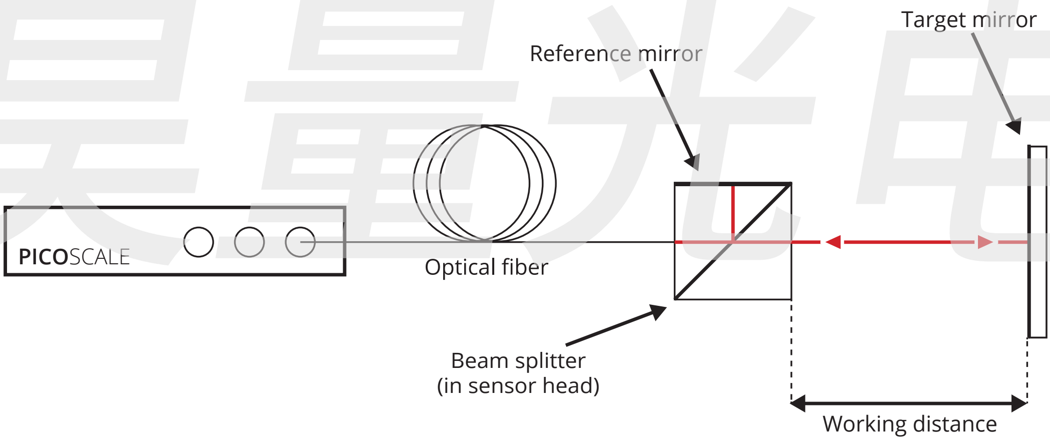
Today's standards in manufacturing, quality control and research require methods to measure distances and displacements at the highest possible accuracy. SmarAct offers a range of metrology solutions to help you characterizing and improving your processes.

SmarAct's **PICO**SCALE products are based on optical methods for the contactless measurement of displacements and vibrations. Because no physical contact is required, the objects will not be affected by the measurement. This is especially relevant for smaller objects, whose dynamics are easily influenced by the attachment of conventional measurement probes.

The **PICO**SCALE *Interferometers* are widely used in positioning technology and allow tracking of displacements at pm resolution. A variety of sensor heads have been developed to adapt the measurement to your exact requirements. This includes the operation at different distances, on different samples but also the measurement of angles. Special sensor heads are available for extreme conditions such as cryogenics, high radiation and vacuum.

Beyond measuring displacements, **PICO**SCALE *Interferometers* are used for the characterization of the dynamic performance during motion. Because the positional data is measured at a very high bandwidth, vibrations can be accurately identified in real time. For detailed modal analyses, SmarAct offers the **PICO**SCALE Vibrometer. Here, the interferometer probe beam is raster-scanned over the sample and the frequency response is accurately determined at up to 1 million measurement positions.

The **PICO**SCALE *Vibrometer* is a turnkey solution to measure vibrations of micromechanical structures with sizes that range from just a few µm up to several cm. Applications include the testing of MEMS, miniature loudspeakers and microphones but also actuators and transducers. Because the instrument is equipped with an integrated megapixel microscope, it is excellently suited to visualize vibrational modes at high spatial and temporal resolution.

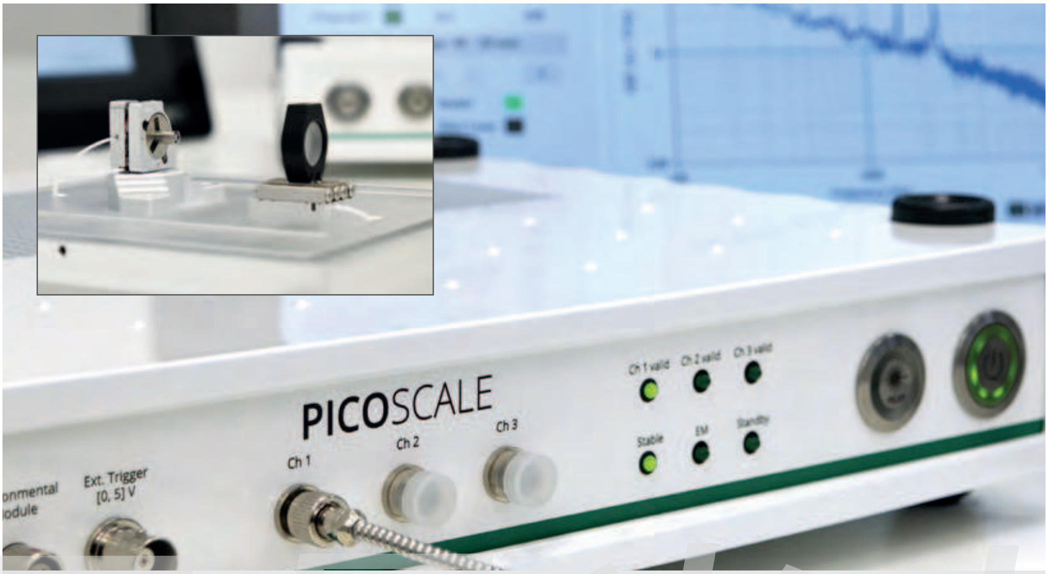


The Core Technology: Interferometry

All **PICO**SCALE products are based on a Michelson interferometer, a precise method to measure displacements and vibrations. The Michelson interferometer consists of a wavelength-stabilized laser, a beam splitter, a target and a reference mirror.
At the beam splitter, the light from the laser is divided into two arms. One arm is directed to the target surface while the other is directed to the reference mirror. After the light of both arms is reflected by the target surface and reference mirror, respectively, it travels back to the beam splitter. Here, both arms recombine and interference takes place.
The interference signal contains information on the displacement of the target surface with respect to the reference mirror.

Metrology

Measuring Displacements - PICOSCALE *Interferometer*



PICOSCALE *Interferometer Inset: Sensor measuring the displacement of a target mirror.*

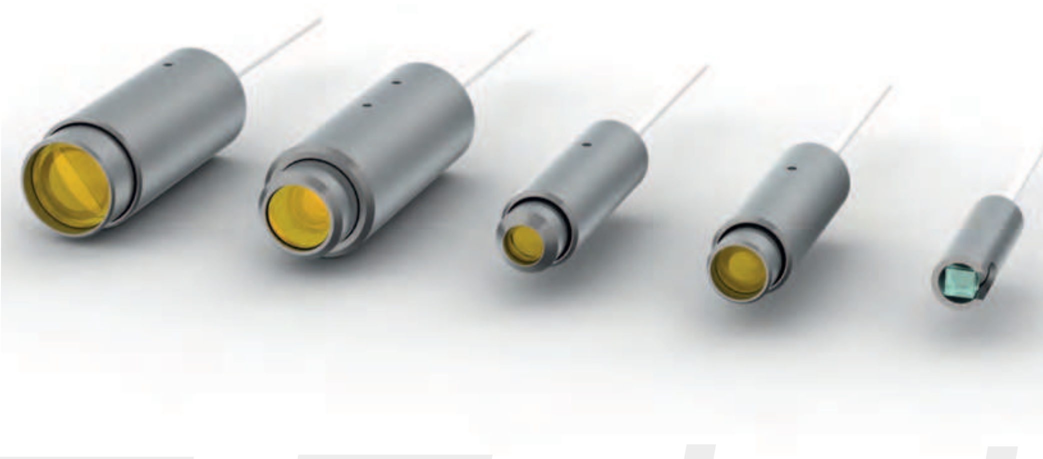
PICOSCALE *Interferometer*

For high precision displacement measurements, SmarAct offers the **PICO**SCALE *Interferometer*, a powerful sensor with picometer resolution. Based on an extremely compact Michelson interferometer, non-invasive measurement with low restrictions on the target reflectivity can be realized very efficiently.

Sensor heads are available for general purpose or optimized for specific tasks like angular or differential measurements. Furthermore, we provide sensor heads for use in vacuum, cryogenic or other harsh environments. Due to their compactness, they fit into almost every setup.

Powerful firmware modules and versatile accessories complement the **PICO**SCALE portfolio to emphasize its use as a laboratory device for synchronization with other devices, signal generation, real-time calculation and many more applications.

Key Features	
Resolution [pm]	1
Number of Channels	3
Working Distance [mm]	0 ... 1000
Maximum Target Velocity [m/s]	2
Data Rate [MHz]	Up to 10
Measurement Laser Wavelength [nm]	1550, laser class 1
Pilot Laser Wavelength [nm]	650, laser class 1
Measurement Conditions	Ambient, high vacuum, ultra-high vacuum, cryogenics, hard radiation
GPIO Interface	3 x ADC, 5 x DAC, Serial data, AquadB
Controller Chassis	33 x 27 x 7.2 cm, weight 3.5 kg (tabletop) 48.2 x 31 x 4.5 cm, weight 3.8 kg (19” rack)



Selection of sensor heads

About PICOSCALE Sensor Heads

The PICOSCALE sensor heads are mandatory equipment to perform high resolution displacement measurements. Within the heads, the probe and the reference beam interfere, and the interference pattern contains the information on the target mirror's position. Currently, SmarAct offers three classes of sensor heads with different beam geometries that were designed for a great variety of applications.

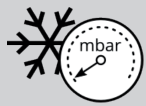
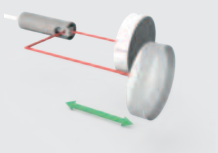
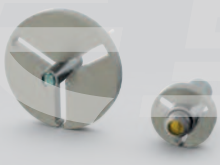
Customization

Since SmarAct designs and manufactures all pro-ducts in-house, we can efficiently design and produce customized sensor heads. This includes integration of PICOSCALE sensor heads into SmarAct's motion systems and customized solutions with specific properties according to your needs. Please contact SmarAct's direct and flexible customer support.

	C01	C02	C03	F01	L01
Beam Geometry	Collimated			Focused	Line Focused
Focal Distance [mm]	-			10*	30 or 50
Beam Waist Diameter [µm]	400	1520	1590	28*	50 x 1590
Working Distance [mm]	13 ... 650	0 ... 1000	0 ... 500	10 ± 0.5*	30 ± 10
Angular Working Range [°]	± 0.05	± 0.013	± 0.013	± 2*	± 1.3 (focused axis) ± 0.05 (collimated axis)
Dimensions [mm]	4 x 13	9 x 23	6 x 21	6 x 21	9 x 26
Conditions	Air, HV, UHV, CRYO	Air, HV, UHV			
Typical Targets	Mirror	Mirror/Retro-Reflector		Small samples	Cylindrical samples

** for a sensor head with 10 mm focal distance. Focal distance can be selected between 8 and 30 mm.*

Metrology
Measuring Displacements - Sensor Head Options and Accessories

Sensor Head Options	
	Several sensor heads are available for different environments such as ambient air, ultra-high vacuum, cryogenic or hard radiation.
	For C01 sensor heads different beam splitter cubes are available: • Standard: The reference mirror is directly coated to the side surface. • Front reference: The reference mirror is coated to the front surface so that the measurement beam exits perpendicularly. • External reference: Without coating, differential displacement measurements become possible (see picture).
	The sensor heads are connected to the controller by optical glass fibers. In addition to our standard polyamide fibers we offer a robust metal shielding (see picture), PTFE for UHV and radiation resistant PEEK tubing.
Mounting Accessories	
	We offer adapter plates for all sensor heads to fix them in conventional ½″ or 1″ mounts. The sensor head is automatically secured in the adapter when it is fastened in a mount.
	Remote alignment of sensor heads with SmarAct's STT mirror mount. A small aluminum spacer with 1/2″ diameter can be attached for easy assembly in setups with strict space constraints.
	Manual alignment mount by using flexures and fine adjustment screws.
	Angular measurement assembly with three C01 sensor heads in a L-shaped configuration. Furthermore, a variant for C03 heads is available, which can be used together with a corresponding retro-reflector target assembly.

Software and Graphical User Interface

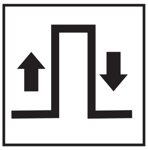
Included with every **PICO**SCALE is an extensive software bundle with drivers, libraries, LabVIEW® VI's as well as a variety of supplementary documents. All functions of the device are explained in the **PICO**SCALE User Manual and the most common applications are explained in short User Guides. If you still need support, please do not hesitate to contact our well-trained technical sales team.

Every **PICO**SCALE is delivered with a graphical user interface to configure the device. All firmware modules can conveniently be addressed with a few clicks.
Furthermore, all data sources can be monitored in customizable panels. The data can be directly displayed in a time series or pre-processed to show spectra or spectral densities, for example.

Metrology
Measuring Displacements - Firmware Modules

Firmware Modules

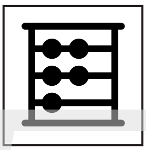
The **PICO**SCALE provides a number of unique firmware modules that can be linked almost arbitrarily. Ultra-fast response times are realized as all modules directly run on the controller itself to easily set up complex experiments without programming software code.



Advanced Trigger

Fast Trigger Pulse Processing for:

- Synchronization with master clock of external devices
- Triggered data acquisition
- Alert system in case of unforeseen events, e.g. loss of optical signal, to be used as an emergency stop of external motion systems



Calculation System

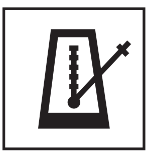
Real-time Data Processing for:

- Calculation of angles
- Scaling of results
- Output of position data via the GPIO interface within control loops
- Output of functions based on user defined look-up tables

Signal Generator

Arbitrary Function Generator for:

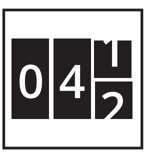
- Basic signal generator functionality (sine, square, sawtooth, custom)
- Excitation of targets and analysis of their frequency response with 1 mHz to 2.5 MHz



Clock Generator

Generate your Own System Clock for:

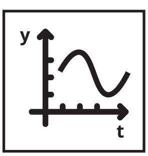
- Timing of internal or external processes
- Generation of periodic trigger events with 1 mHz to 10 MHz



Counter

Counter Module Used for:

- Counting of user defined trigger events
- Counting the clock pulses between trigger events
- Counting of system clock pulses for absolute timing of data



Stream Generator

Configuration of Data Stream to User PC:

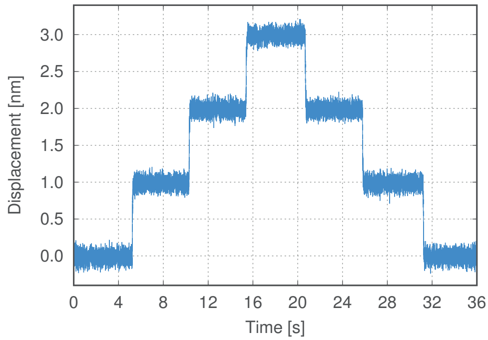
- Up to 10 MHz data rate
- Many options to filter data
- Connected to trigger module for synchronized data acquisition

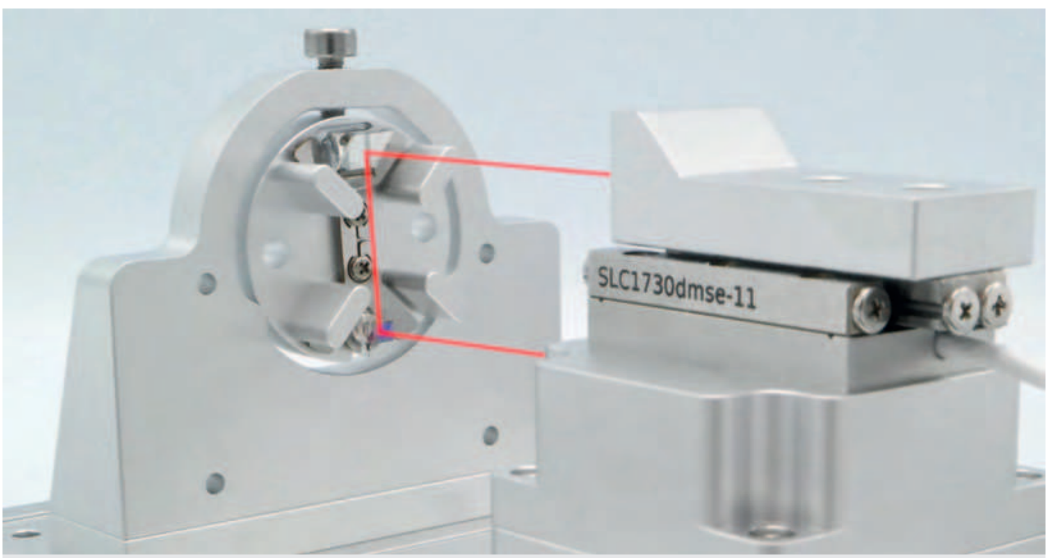
Application Examples

PICOSCALE as Closed-loop Sensor

The **MCS**2 is SmarAct's most powerful modular control system. The **PICO**SCALE can be easily linked to the **MCS**2 as a displacement sensor. By using the interferometer's position data, the performance of closed-loop positioning can significantly be improved compared to standard sensor types. Furthermore, the results of the **PICO**SCALE *Calculation System* are available as data sources allowing for angular control, for example.

A **PICO**SCALE differential sensor head is used to track the position of a target mirror mounted on a SmarAct SLC1730 stage relative to another mirror mounted on the base. Due to the differential measurement, air fluctuations are intrinsically reduced. Using the **PICO**SCALE in combination with the **MCS**2 consequently allows for sub-nanometer closed-loop movements.





Setup for differential displacement measurement. The lower beam is aligned to the rigid base while the upper beam is reflected off a mirror attached to a moving slide.

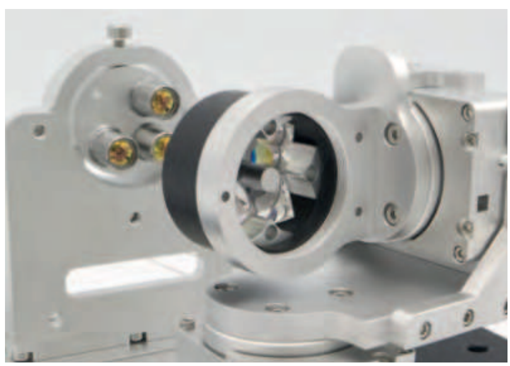
Metrology
Measuring Displacements - Application Examples

Device Synchronization

Using the **PICO**SCALE advanced trigger module, internal and external events can be used to synchronize processes.
Accurate timing of the Interferometer's data with a master clock is obtained with a few clicks.
For example, we showed that the average output power of the interferomter can be reduced by two orders of magnitude for use in cryogenic applications. By using a fast optical switch with very small duty cycle, the interferometer position calculation was only active when the switch transmitted power to the setup. This flexibility cannot be found in any other system on the market.

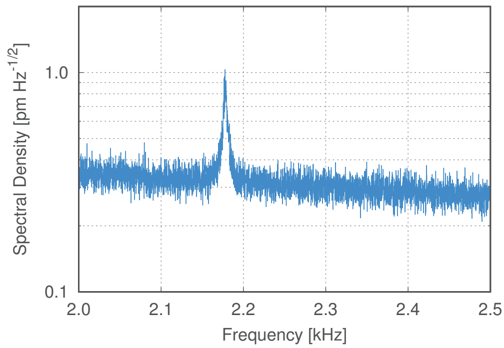
Closed-Loop Angle Control

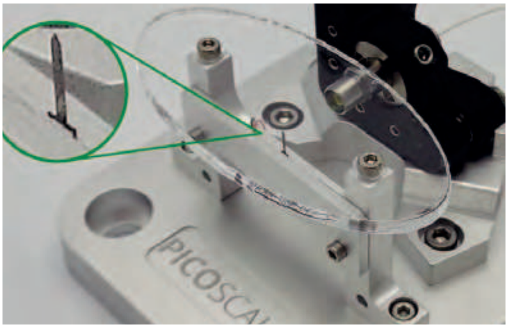
Three position channels are used in the **PICO**SCALE *Calculation System* to infer angular motions of a target. The output can be directly used as sensor data in a **MCS**2 *Controller* so that closed-loop angular positioning is possible without the need of a permanent user PC interface.
You achieve alignment and stabilization of components such as Laue lenses with interferometric accuracy.



Vibration Measurement

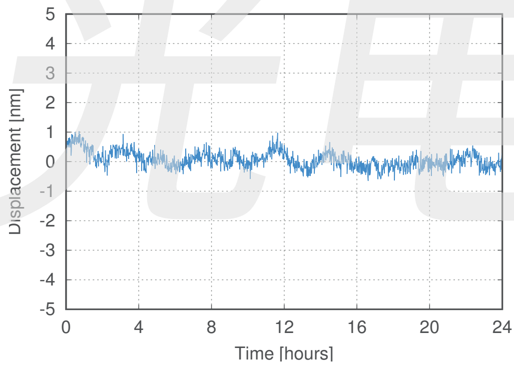
A **PICO**SCALE sensor head is used to measure the thermally exited motion of a small cantilever. The spectral analysis of the displacement data reveal a single picometer oscillation amplitudes on a 300 fm / √Hz noise floor.





Stability Measurement in Ambient Air

A sensor head and a target mirror are mounted on a metal block with a working distance of 20 mm. The displacement of the target mirror as well as the environmental parameters are recorded for a full day. After real-time correction for changes of the refractive index of air using the **PICO**SCALE *Environmental Module* and compensation for thermal drifts, the stability of the system is within 1 nm (2σ = 563 pm) in ambient air for this specific setup.



A **PICO**SCALE *Sensor Head is aligned to a mirror. Both components are mounted on a rigid base plate.*

Data and Signal Interfaces

The **PICO**SCALE *Interferometer* offers various methods to extract data. Connections to a user PC can be established via USB and/or Ethernet (multi-user ready).

Key Features	
USB and Ethernet	Data transfer to a user PC with up to 10 MHz data rate of all available data sources. Up to two connections at the same time.
Serial Data	Serial data transmission of displacement or *Calculation System* data.
AQuadB	Incremental transmission of displacement or *Calculation System* data.
Analog Inputs	3 analog-to-digital converters with up to 16 bit resolution accessible via the **PICO**SCALE *Breakout Box.*
Analog Output	5 digital-to-analog converters with up to 16 bit resolution accessible via the **PICO**SCALE *Breakout Box.*
Trigger Inputs/ Outputs	1 input at the controller front plate, 9 inputs/outputs accessible via the **PICO**SCALE *Breakout Box.*

PICOSCALE *Breakout Box.*

PICOSCALE *Breakout Box*

The optional **PICO**SCALE *Breakout Box* provides a simple and convenient access to the many different interfaces of the **PICO**SCALE controller. Analog and digital GPIOs can be accessed via BNC connectors while the DDI (AquadB or Serial Data) signals are mapped to D-Sub 15 connectors.

Key Features	
Digital 1-4	0 ... 5 V, rising/falling edge time < 50 ns
Digital 5-9	0 ... 3.3 V, rising/falling edge time < 50 ns
ADC 1	16 bit resolution, 10 MSa/s, bandwidth 2 MHz, ± 10 V input voltage
ADC 2, ADC 3	16 bit resolution, 100 kSa/s, bandwidth 40 kHz, ± 10 V input voltage
DAC 1	12 bit resolution, 10 MSa/s, bandwidth 2 MHz, ± 10 V output voltage
DAC 2-5	16 bit resolution, 200 kSa/s, bandwidth 150 kHz, ± 10 V output voltage
DDI Ch 1 - Ch 3	0 ... 5 V differential output
Power	12 V/250 mA source to supply external circuitry

	Accuracy	Resolution
Temperature [°C]	0.5	0.01
Pressure [mbar]	1.5	0.02
Humidity [% RH]	1.8	0.04

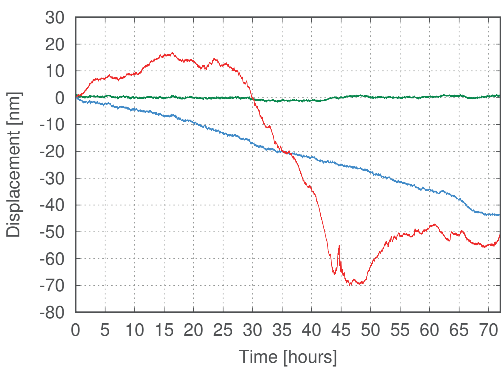
PICOSCALE *Environmental Module*

The *Environmental Module* is an accessory product for the **PICO**SCALE. It monitors the environmental parameters such as temperature, relative humidity, and air pressure. With these data the **PICO**SCALE controller is able to correct the recorded displacement data online for changes in the refractive index of air and thus virtual drifts of the target mirror.

Key Features	
Number of Channels	10
Sensor Connection	M8 connectors
Measurement Mode	4-wire
Sensor Type	PT1000, Class A
Sensor Tolerance [°C]	0.15

PICOSCALE *Temperature Box*

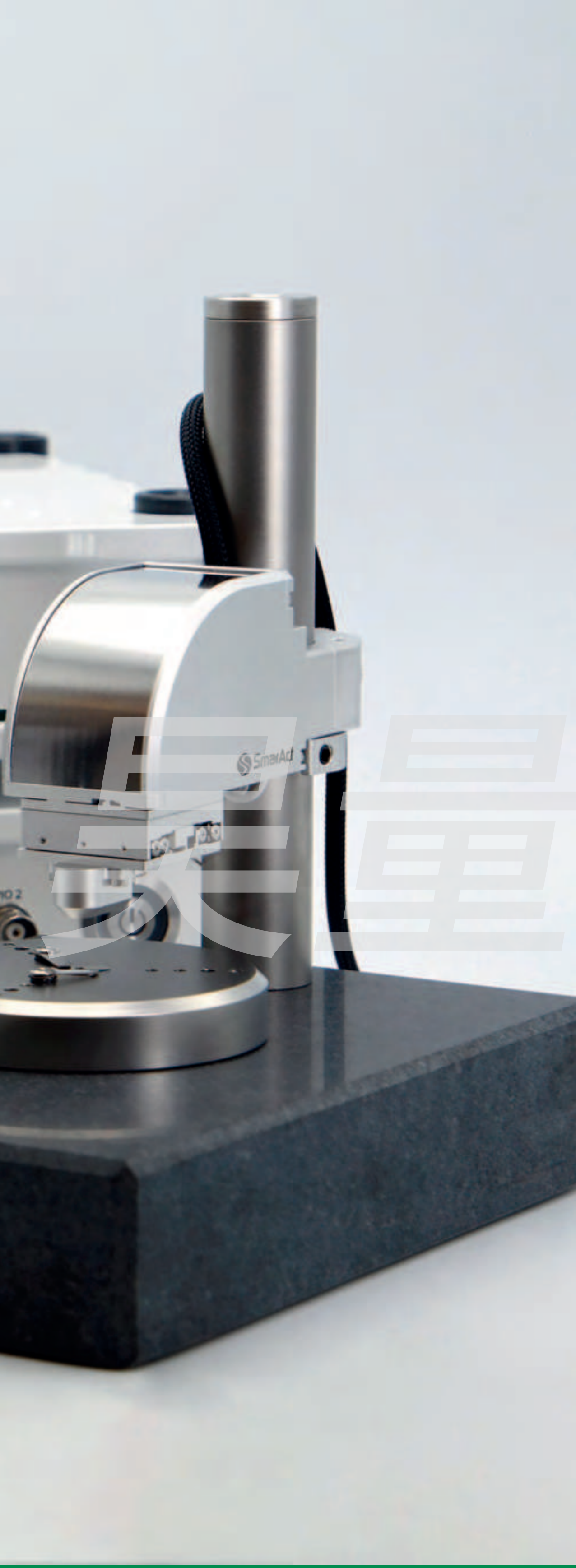
The **PICO**SCALE *Temperature Box* is a powerful accessory for the **PICO**SCALE *Interferometer*. The *Temperature Box* provides ten channels to connect platinum temperature sensors, which can be very compact. The sensors can be mounted to very confined setups to perform local temperature measurements. Furthermore, the sensors can be directly used to measure the temperature of a material. Compensation for thermal expansion becomes more accurate because the data can be directly processed in the **PICO**SCALE *Calculation System*.



Closed-Loop Position Correction

The **PICO**SCALE *Environmental Module* is used to record pressure, relative humidity and temperature of the ambient air of a setup, and consequently changes in the air's refractive index are corrected. The compact sensors of the **PICO**SCALE *Temperature Box* were attached to the experimental setup so that the thermal expansion coefficient was inferred. As the sensor data is available in the **PICO**SCALE *Calculation System*, the thermal expansion can also be subtracted immediately. The graph on the left shows the uncorrected position measured by the **PICO**SCALE *Interferometer* (red), the displacement with activated deadpath correction (blue), and the position corrected for thermal drift (green).

The **PICO**SCALE *Vibrometer* combines pm resolution interferometry with a 3D positioning system to provide a complete modal analysis of complex micromechanical devices.

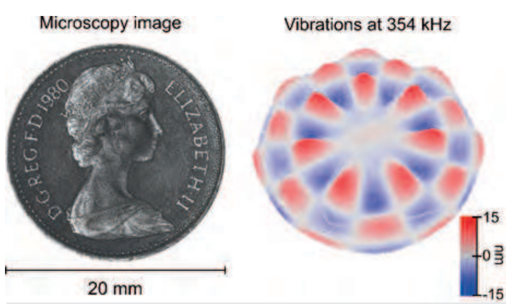


Imaging Vibrations

The **PICO**SCALE *Vibrometer* is designed for mega-pixel imaging of vibrational modes of structures like actuators, sensors and MEMS. This is achieved by raster-scanning a tightly focused laser beam of a Michelson interferometer over the sample to measure the vibrations for each pixel of the microscopic image. Vibrations in the sample can be induced by the advanced piezo-based shaker stage but also directly with an electrical signal that is generated by the **PICO**SCALE *Vibrometer*.

The use of SmarAct's closed-loop piezo positioners makes it possible to analyze structures with sizes from just a few µm up to 20 mm. A unique feature of the **PICO**SCALE *Vibrometer* is that the interferometer laser beam is used simultaneously to record a microscopy image of the sample. This microscopy image is thus intrinsically aligned with the vibration measurements and a separate microscope imaging system is not required.

The **PICO**SCALE *Vibrometer* is delivered as a turnkey system and includes an extensive software package for data acquisition and analysis.



Megapixel microscopy image of a coin (left image). The coin was excited with the shaker stage at 354 kHz and the resulting vibrations were recorded simultaneously at each pixel of the image, from which a vibration image can be reconstructed (right image).

System Controller

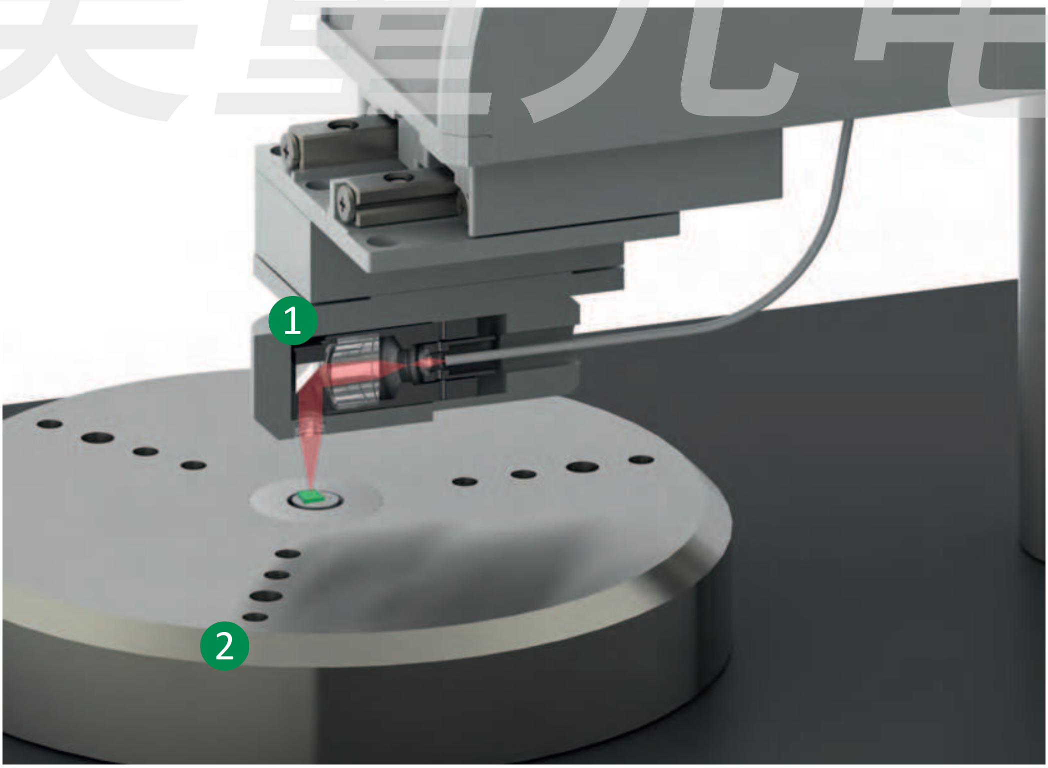
The vibrometer controller hosts all the necessary optical components and electronics to generate an infrared laser beam and to detect the interference signal that is received from the sensor head. Furthermore, it contains the circuitry to convert the measured interferometric data into a position signal in order to extract frequency, amplitude and phase of the vibrations. The stage controller contains the electronics for operating the 3D positioning stage in closed-loop and to provide access to internal system signals through the different GPIO connectors. Additionally, it includes a high-bandwidth power amplifier to drive the shaker stage to enable modal analysis.

1 3D Positioner with Sensor Head

The 3D positioner is used to scan the interferometer over the region of interest. It is built around three SmarAct closed-loop positioners enclosed in a compact protective housing. The sensor head is mounted on the lowest positioner and contains a miniature Michelson interferometer with focusing optics and is connected via a single-mode optical fiber to the vibrometer controller.
The 3D positioner with sensor head is mounted on a 25 mm diameter post so that its height is easily adjusted to accommodate samples of different dimensions. It is possible to remove the assembly from its mounting post in order to install it in a custom setup.

2 Shaker Stage

The shaker stage can be used to mechanically actuate a sample over a wide frequency range. It is based on a fast piezo based actuator mounted in a solid stainless steel housing and driven by the stage controller. To allow a reliable analysis of the dynamic characteristics of the sample, the shaker stage was optimized to deliver a smooth response by minimizing pronounced peaks in its amplitude spectrum.



Extensive Software Package

The **PICO**SCALE *Vibrometer* is delivered with two programs that can be operated in parallel:

1. The vibrometer control software is required to operate the instrument with a regular PC. An intuitive user interface allows to perform complicated measurements with a few mouse clicks.

2. The vibrometer view software is offered to analyze the recorded vibrometry data. It contains a variety of options to process the data for visualization optimization in 2D and 3D but also to export the recorded binary data file into formats that can be easily imported by third party software.

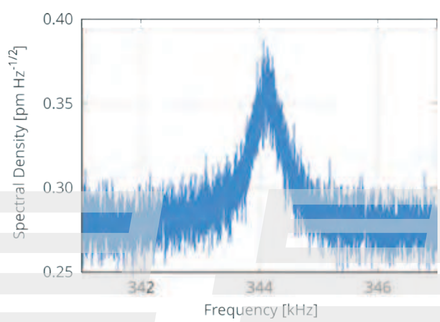
Key Features		
Vibration Measurements	Vibration Resolution in Single Point Mode [pm]	< 1
Vibration Measurements	Vibration Resolution in Imaging Mode [nm]	0.1
Vibration Measurements	Frequency Range [MHz]	Up to 2.5[1]
Optical Microscope	Optical Lateral Resolution [µm]	2 ... 7[2]
Optical Microscope	Working Distance [mm]	1.5 ... 10[2]
Optical Microscope	Maximum Image Size [mm]	20 x 20
Optical Microscope	Minimum Pixel Size [µm]	1
Optical Microscope	Maximum Number of Pixels	1000 x 1000
Dimensions	Controller	2 units of each 33 x 27 x 7.2 cm (W x L x H), combined weight 7.6 kg
Dimensions	Scanning Stage	5.5 x 11.0 x 7.5 cm (W x L x H), weight 0.25 kg
Dimensions	Scanning Mount	Granite stone 15 x 20 x 4 cm (W x L x H) with stainless Steel post 2.5 x 15 cm (Ø x H), combined weight 4.3 kg
Dimensions	Shaker Stage	Stainless Steel 8 x 1.5 cm (Ø x H), weight 0.5 kg

[1] lowest frequency in imaging mode is 50 Hz
[2] depending on sensor head

Metrology
Measuring Vibrations - Application Examples

Characterizing Vibrations by FFT Analysis

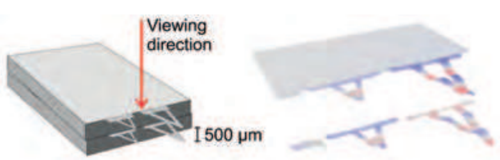
At each position of the imaged structure, the out-of-plane vibrations can be measured by interferometry. When a single or a few positions are measured on the sample, the data can be simply transformed into the frequency domain by a fast Fourier transform (FFT), which will reveal the frequency response at the measured positions. FFT plots consisting of up to 2.5 million data points can be recorded with the **PICO**SCALE *Vibrometer*, which allows a high-resolution analysis of the recorded spectra.



FFT plot showing the amplitude spectrum of a micro cantilever measured at a single position. Although the cantilever was not actively excited, the high resolution of the interferometric measurements still allows to detect the thermal fluctuations, in this case 0.36 pm at 344 kHz.

Optical Sectioning with Confocal Microscopy

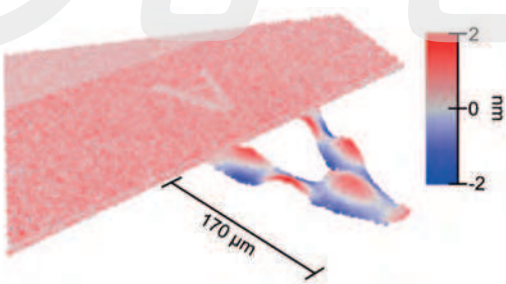
The sensor head employs a confocal measurement principle: only light reflected from the focal plane will be detected while all out-of-focus light is suppressed. This results in a higher signal-to-noise ratio of both the microscopy and vibration data. Furthermore, it becomes possible to image through semi-transparent materials and to image samples that are partly hidden by other objects, a feature that is especially useful when investigating structures that consist of multiple layers.



Measuring vibrations of multi-layered samples. Two AFM cantilever chips were positioned on top of each other such that the view on the lower cantilevers was blocked by the upper ones. By confocal imaging of each of the layers, the vibrations can still be clearly resolved.

Recording Megapixel Vibration Images with a Lock-in Amplifier

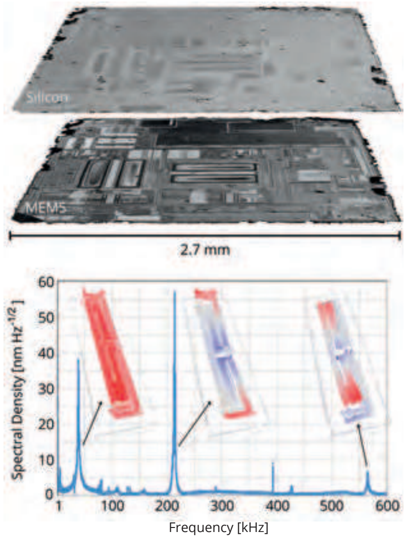
When a high number of positions on a structure need to be measured, the recording of individual FFT spectra becomes impractical due to the very high amounts of data that need to be processed. To overcome this, the **PICO**SCALE *Vibrometer* is equipped with a dual-phase lock-in amplifier.
Basically, the lock-in amplifier extracts the amplitude and phase at one specific frequency from the measured data and thereby reduces the amount of data to just two values. Finally, the use of a lock-in amplifier allows on-the-fly analysis of the vibrations. It is thus possible to record vibration images while quickly raster-scanning the measurement laser over the region of interest. This reduces the recording time of images with a high number of pixels enormously.



3D deflection plot of a micro cantilever that was excited at 2.1 MHz. The plot was reconstructed from the amplitude and phase information that was obtained by the lock-in amplifier.

Measuring MEMS through Silicon with an Infrared Measurement Laser

All **PICO**SCALE products are based on an infrared 1550 nm laser source. A unique advantage of using such wavelength is that it allows to 'look' through materials that are non-transparent for visible light such as silicon. Nevertheless, when the measurement laser is focused on a silicon

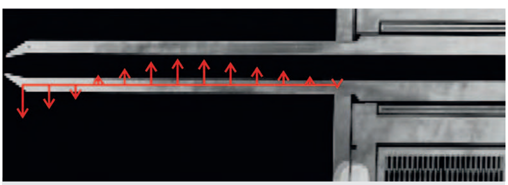


Measuring vibrations of MEMS through a packaging of silicon is made possible by confocal imaging with an IR light source. We thank InvenSense, a TDK Group Company, for their support with this application example.

structure, the reflection is still high enough to record a microscopic image and to measure the vibration of the structure.

Measuring Lateral Vibrations

With the interferometric measurement principle only out-of-plane vibrations (parallel to the optical axis) can be measured. To enable the measurement of in-plane vibrations (perpendicular to the optical axis) a module has been developed that records a sequence of microscopic images that span a single vibration cycle (conceptionally similar to stroboscopic imaging). Through optical flow algorithms, in-plane vibrations as small as 10 nm can be extracted from laterally moving parts of the sample.



Measuring lateral vibrations. With a tracking routine the in-plane motion of selected parts of the imaged microgrippers can be measured.

Integration in Custom Setups

The sensor head is combined with the 3D positioner in a compact assembly. This makes it possible to integrate the vibrometer in custom setups and even in vacuum chambers (upon request). The use of SmarAct's motor technology makes it possible to position the laser beam with very high accuracy at any part of the sample. This can be used to measure vibrations at specific points on the sample at very high resolution, for example to reveal sub-pm vibrations.