PICOSCALE Interferometer V2

INTRODUCTION

Figure 1. *Photograph of the* PICOSCALE *Interferometer V2.*

The **PICO**SCALE Controller is shown in Figure 1. At the front panel, it has three connectors for sensor heads, that are mandatory equipment. In this document, the general properties of the **PICO**SCALE Interferometer are summarized. Details on the sensor heads can be found in the corresponding specification sheets.

PERFORMANCE

The key specifications of the **PICO**SCALE are summarized in Table 1 and references therein. All data are typical values and have been inferred from careful characterization measurements. They strongly depend on the setup the **PICO**SCALE is used in. Please contact SmarAct to discuss your application and possible limitations. We will be happy to assist you on your way to get the maximum out of your device and will also be able to provide detailed feasibility studies.

Resolution

The resolution of a position measurement is that position change that can be clearly identified. It depends on different influences; digital influences like the resolution of the analog-to-digital converters, but also and mainly on the performance of the analog system. There are minute fluctuations caused by noise inside the sensor signal even if the observed object is at rest. The noise can be described by spectral densities. We use in the following the so called amplitude spectral density $\mathrm{ASD}(f)$. The ASD can be converted to RMS noise values by integration over the desired frequency range:

$$\delta(f_{\min}, f_{\max}) = \sqrt{\int_{f_{\min}}^{f_{\max}} [\mathrm{ASD}(f)]^2 \, df} \tag{1}$$

Digital Resolution

In some position sensors, the digital system is the resolution limiting factor. The digital system of the **PICO**SCALE uses 16bit ADC signals. These ADC values are further processed and 48bit position values are generated. Due to internal oversampling and corresponding averaging, the digital resolution of the PicoScale is 1 pm even at 10 MHz streaming frequency and is thus not limiting.

Table 1. *Summary of key specifications (typical).*

Property	Value
Channels	3
Working distance	up to 5 m
Accuracy*	$<10^{-6}$ m/m
Periodic nonlinearities**	$<6\,\mathrm{nm}_{\mathrm{pk-pk}}$
Resolution and noise	cf. Table
Max. target velocity	$1\,\mathrm{m\,s^{-1}}$
Max. bandwidth	2.9 MHz
Max. data rate	10 MHz
Targets	mirrors, reflective surfaces, retro-reflectors
Target reflectivity	4 % – 100 %
Measurement laser	(1545 ± 15) nm laser class 1
Pilot laser	(650 ± 5) nm laser class 1
Measurement conditions***	ambient, ultra-high vacuum, cryogenic temperatures

*due to wavelength accuracy
**WD 50mm, C01 sensor head, typical working conditions
***depending on sensor head

Noise characterization - working distance

The position noise of a measurement with the **PICO**SCALE interferometer is determined by several contributions, which can partially be attributed to the **PICO**SCALE Controller and its electronics, as well as noise and/or distortions induced by the measurement setup (thermal drift, mechanical vibration, air fluctuations, etc.). In the quantification of a high resolution measurement device like the **PICO**SCALE, care must be taken to exclude the presence of the latter in order not to underestimate the capabilities of the measurement device itself.
The **PICO**SCALE contains a distributed feedback (DFB) laser which has a certain linewidth. The phase noise of the laser contributes to the position noise. The po-

sition noise increases with working distance, since the phase noise adds up for longer ranges. In Figure 2 the amplitude spectral densities of a few measurements at different working distances are shown.

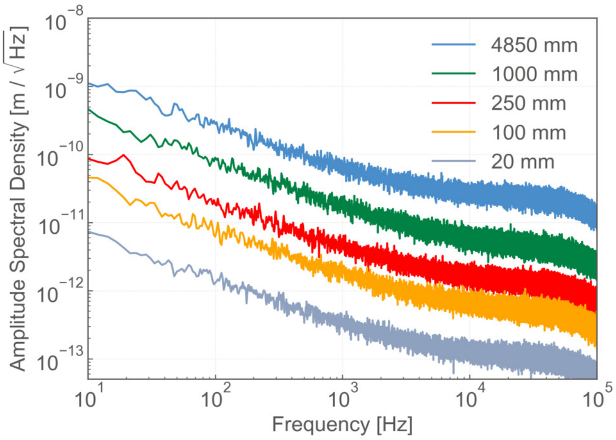

Figure 2. *Typical amplitude spectral density of a position measurement with high working distances (WD). Acoustic and mechanical noise adds to the curve at frequencies below 1 kHz and must not be attributed to the measurement device itself. (Sample frequency 312.5 kHz, FFT block size 131072, 10 averages, Hanning window.)*

If the working distance increases, also the noise floor increases due to laser phase noise. This effect has been measured with different working distances from 15 mm to 5 m. The results are summarized in Table 2 and Figure 3. As expected, the noise increases linearly with the distance.

Table 2. *Selection of RMS values of the position noise of the* **PICO**SCALE *in the frequency decade (1 kHz,10 kHz) for different working distances (WD), inferred from the amplitude spectral densities of Figure 2.*

WD [mm]	RMS noise [nm] [1 kHz - 10 kHz]
20	0.02
100	0.11
250	0.27
1000	1.03
4850	4.21

Noise characterization - frequency dependency

In Figure 4, the amplitude spectral density of a position measurement with stable measurement setup is shown. The measurement was performed in air, but care was taken, that no mechanical vibrations were coupled to the setup. The graph shows three spectra, recorded with sample rates of 1.2 kHz, 312.5 kHz and 10 MHz. The orange line represents an empirical model that can be used to estimate the noise for

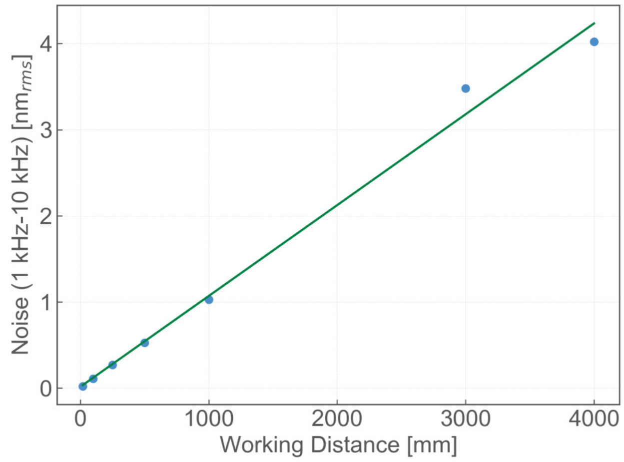

Figure 3. *Root-mean-square (rms) noise in the frequency band (1 kHz, 10 kHz) for different working distances. The noise increases linearly with working distance due to laser phase noise.*

frequencies >1 Hz. It is given by the formula

$$\mathrm{ASD_m}(f, WD_R)\left[\frac{\mathrm{pm}}{\sqrt{\mathrm{Hz}}}\right] = WD_R\left(0.2 + \sqrt{\frac{375^2}{15^2 + f^2}}\right) \tag{2}$$

where f is the sideband frequency and $WD_R = \frac{X}{20\,\mathrm{mm}}$ with X is actual the working distance.
The data of Figure 4 can be used to estimate the RMS noise in different frequency bands. The total noise over all bands is given by[1]

$$\Delta = \sqrt{\sum_{f_{min}, f_{max}} \delta(f_{min}, f_{max})^2}\,. \tag{3}$$

[1] The noise contributions in each band are uncorrelated so that "the variance of the sum is the sum of variances".

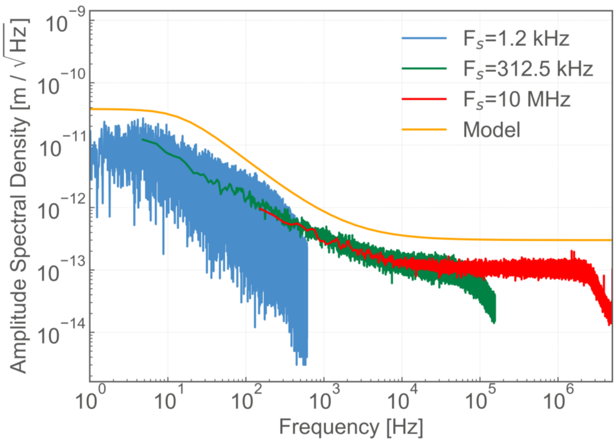

Figure 4. *Amplitude spectral density of a position measurement with a quasi-monolithic setup at a working distance of 20 mm. (Sample frequency 1.2 kHz, 312.5 kHz and 10 MHz, FFT block size 131072, 10 averages, Hanning window.)*

Table 3. *Measured RMS values of the position noise in nm of the* **PICO**SCALE *per frequency decade and for different working distances (WD) (black). The values in orange are calculated using Equation 2, and represent an* ***upper bound****. Please note that the model is only validated for frequencies above 1 Hz.*

Frequency Band [Hz]	RMS noise [nm] WD=20 mm *Measured*	RMS noise [nm] WD=20 mm *Upper Bound*	RMS noise [nm] WD=1 m *Upper Bound*
0.01 – 0.1	0.05	-	-
0.1 – 1	0.03	-	-
1 – 10	0.04	0.11	5.3
10 – 100	0.03	0.12	6.8
100 – 1k	0.02	0.06	3.0
1k – 10k	0.02	0.05	2.1
10k – 100k	0.04	0.09	4.8
100k – 1M	0.13	0.29	14.3
1M – 5M	0.18	0.60	30.0
Total Δ	0.24	0.70	34.9

In Table 3 the RMS noise for a compact 20 mm long setup is summarized. For larger working distances, the RMS noise is extrapolated, knowing that the noise increases linearly with working distance.

Low pass filters

The **PICO**SCALE features low pass filters that limit the bandwidth and sufficiently reduce the noise in the system. The system filters can be set in 23 steps according to

$$f_{LP} \approx 2.3\,\text{MHz}/2^n \quad , n \in [1, 23] \qquad (4)$$

(If no filter is set, n=0, the bandwidth is limited by a $f_{LP} = 2.9$ MHz analog low-pass filters.) For example, if one is able to limit the bandwidth to 10 kHz (n=8, $f_{LP} \approx$ 9 kHz), and the lowest frequency of interest is 1 Hz, one only need to add (acc. to Equation 3) the noise contributions of the four frequency bands (1 Hz, 10 Hz), (10 Hz, 100 Hz), (100 Hz, 1 kHz) and (1 kHz, 10 kHz). For a working distance of 0.1 m this gives a RMS noise of $\Delta = 0.30\,\text{nm}_{\text{rms}}$, compared to $\Delta = 1.17\,\text{nm}_{\text{rms}}$ in the full band (0.01 Hz, 5 MHz).

Thermal stability

Within the **PICO**SCALE controller there are electronic components, which are generally sensitive to thermal stress, which may affect the laser wavelength stabilization and thus the accuracy. In order to quantify the effect of thermal stress on the actual position reading, the controller was placed in a climate chamber, and the temperature was cycled between 20 °C and 25 °C, (cf. Figure 5). The sensor head and target were not in the chamber and did not experience the thermal stress. Consequently, all observed drift that correlates with the chamber temperature can be attributed to the controller[2]. We find, that the observed drift was below ± 1 nm. The temperature dependence of the position reading is thus

$$\frac{\mathrm{d}x}{\mathrm{d}T} = \frac{2\,\mathrm{nm}}{5\,°\mathrm{C}} = 0.4\,\mathrm{nm}\,°\mathrm{C}^{-1}\,. \tag{5}$$

Assuming that the temperature solely affects the laser wavelength[3], one can calculate the relative error by using the working distance of the setup (20 mm) as

$$\frac{\mathrm{d}}{\mathrm{d}T} = \frac{2\,\mathrm{nm}}{20\,\mathrm{mm}\cdot 5\,°\mathrm{C}} = 0.02\,\mathrm{ppm}\,°\mathrm{C}^{-1}\,, \tag{6}$$

which is, for example, well below the thermal expansion coefficient of common materials in a setup (aluminum: 23 ppm/°C, iron: 12 ppm/°C, glass: 10 ppm/°C). Furthermore, the time constant of the effect is very long and other noise sources are typically orders of magnitudes stronger than the thermal effect on the controller electronics.

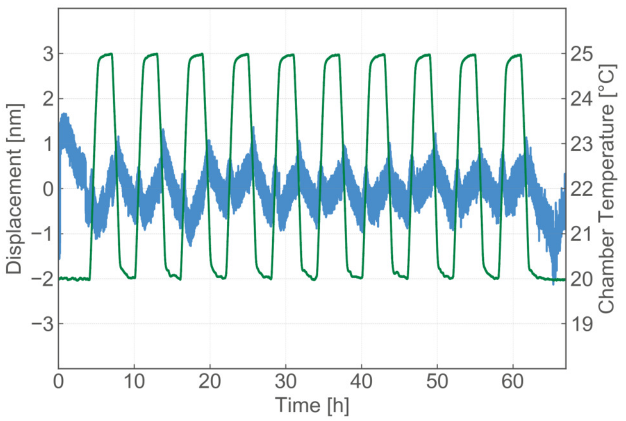

Figure 5. *Displacement data (blue) of a static setup when the* **PICO**SCALE *Controller is in a climate chamber, which is cycled ten times from 20 °C to 25 °C (green).*

INTERFACES

DC power supply connector

The **PICO**SCALE Controller is powered with a 12 V the provided original AC/DC power supply. System ground is connected to protective earth (PE) inside the external AC/DC power supply. The power consumption is below 30 W.

Breakout Box Interface

The **PICO**SCALE Controller has a mini ribbon 50 connector which provides several interfaces including analog and digital GPIOs as well as Digital Differential Interfaces (DDI) for all three channels to be accessible via the Breakout Box.

[2] For details on this measurement please contact SmarAct.

[3] The impact on the laser wavelength is considered the worst case scenario, as other effects will not scale linearly with working distance.

External trigger input

The SMA connector can be used to input a digital signal in order to trigger internal processes.

SmarAct Sensor Interface (SI)

The SmarAct SI interfaces the **PICO**SCALE Controller with other SmarAct products, e.g. the Modular Control System 2 (**MCS**2). In this configuration the **PICO**SCALE Controller can act as sensor module for the motion system.

USB 2.0 device interface

To configure the **PICO**SCALE Controller the system has to be connected to a PC. Therefore, a USB 2.0 cable can be connected here and the connection can be established with the graphical user interface, for example. The USB interface is one of the main bidirectional communication interfaces of the **PICO**SCALE Controller. It provides a USB 2.0 high speed connection with data rates of up to 480 Mbits/s.

Ethernet

The Ethernet interface is the second main bidirectional communication interface of the **PICO**SCALE Controller. The interface is configured via the embedded PC and is able to provide Gigabit Ethernet.

USB 2.0 host interface

The USB host interface is used for software updates and diagnostic snapshots via an USB stick.

System ground

A 4 mm banana socket can be connected to system ground and to bring several devices to the same electrical potential.

Breakout Box

Figure 6. *Photograph of the* **PICO**SCALE *Interferometer V2 with Breakout Box V2.*

The **PICO**SCALE Breakout Box (BOB) provides simple and convenient access to the variety of signals at the mini D ribbon 50 connector. The connectors of the Breakout Box are placed in three groups. Analog and digital GPIOs can be connected via BNC connectors while the Digital Differential Interfaces (DDI) are mapped to DSub 15 connectors.

Differential Digital Interface (DDI)
The Differential Digital Interface (DDI) provides differential digital signals, which can be used for different digital protocols, e.g. AquadB and Serial Data. The output levels of the specific DDI signals are fully compliant with TIA/EIA RS-485.

Digital GPIOs
The Breakout Box features 6 digital I/Os. The digital I/O voltage level can be configured as 3.3 V or 5.0 V. All digital GPIOs are optimized for a 50 Ω system impedance to ensure best signal integrity. The direction and the voltage level of the digital I/Os can be configured within the **PICO**SCALE graphical user interface.
The digital I/Os support a maximum frequency of 10 MHz, however it is recommended to use the digital GPIOs with a maximum frequency of 1 MHz. Using higher frequencies may cause asymmetries in the duty cycle of the signal. The best signal form can be achieved in a 50 Ω environment. A appropriate coaxial cable with short connections should be used.

BOB analog IO
The Breakout Box provides three analog input (ADC) and three analog output (DAC) single ended signals with a nominal voltage range of ±10 V and 16 bit resolution. ADC1 is working with the maximum signal bandwidth of 2.5 MHz, ADC2 and ADC3 have a limited bandwidth of 100 kHz.
DAC1 is working with the maximum position signal bandwidth of 2.5 MHz, DAC2 and DAC3 have a limited bandwidth of 100 kHz. The maximum output current is 100 mA.

DIMENSIONS AND CONDITIONS

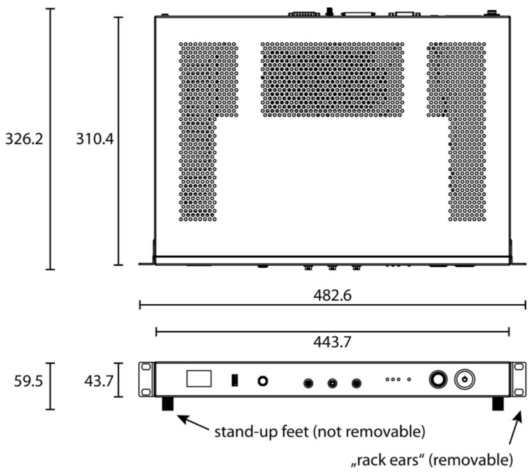

Figure 7. *Controller Dimensions. Weight 3.7 kg.*

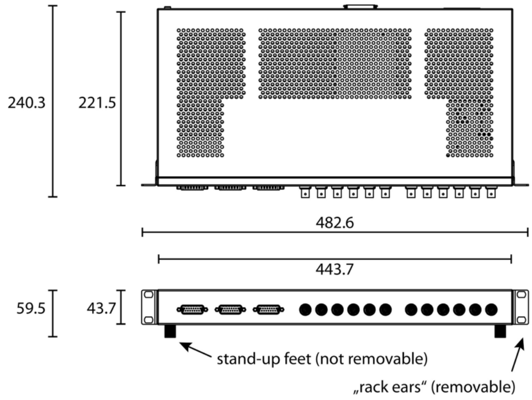

Figure 8. *Breakout Box Dimensions.*

Table 4. *Operation conditions for* **PICO**SCALE *Controller.*

Property	Parameter
Degree of Pollution (acc. to EN 60664-1:2007)	2
Power supply	12 V DC ±5 %
Input current	3.0 A
Operation temperature	15 °C - 30 °C ±2.5 °C dynamic*
Relative humidity	20% to 80% RH non-condensing
Storage temperature	0 °C - 50 °C
Transport temperature	0 °C - 50 °C
Altitude	up to 2000 m

*Maximum temperature fluctuations during measurement that guarantee performance.

LASER SAFETY

The **PICO**SCALE is a Class 1 laser product. Because of its special properties, laser light poses safety hazards not associated with light from conventional sources. Even though the **PICO**SCALE is inherently eye-safe, it is good practice to avoid direct exposure to human eye and skin, and ensure the optical path is well controlled. Furthermore, optical ports shall always be covered with the protective caps, when unused. (This also protects them from contamination and permanent damage.) The safe use of the laser depends upon the user being familiar with the instrument and the properties of laser radiation.

Figure 9. *Laser safety label on the front panel of the Controller.*

Output parameters
The **PICO**SCALE Controller contains an infrared diode laser (1530–1560nm). Furthermore, most models feature an additional pilot laser (640–660nm).
The laser output powers are given in Table 5.

Table 5. **PICO**SCALE *Laser output powers per channel (maximum) for the two wavelengths.*

Wavelength	Max. Power (standard)	Max. Power (-HP option)
640–660nm	350 µW	-
1530–1560nm	400 µW	700 µW

Completeness of contents
The hazards and warnings listed in this section are incomplete. Before operation, the user has to read the user manual, which contains more safety information.

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