PICOSCALE Interferometer Noise and Resolution

Abstract
The **PICO**SCALE is a measurement device based on a Michelson interferometer. The signal noise of an interferometer is an important performance benchmark. This document demonstrates that the **PICO**SCALE interferometer achieves a noise level in the sub-picometer region.

1. SETUP

In order to determine the noise floor of the **PICO**SCALE, a sensor head is adjusted to a plane target mirror at 20 mm distance. The setup is mounted inside an enclosure in order to suppress perturbations by thermal expansion and air fluctuations. The data shown in section 2 is obtained with the **PICO**SCALE GUI. Except shifting each data set by its mean value, no further post processing was done.

2. RESULTS AND DISCUSSION

The **PICO**SCALE provides a range of filter streaming rates. These parameters have are crucial with respect to the noise floor of the measurement and the signal-to-noise ratio.

2.1 Time domain measurements

A displacement measurement was performed with three different frame and corresponding filter rates (1.22 kHz, 39.06 kHz and 10 MHz). The time traces for sample frequencies of 1.22 kHz and 10 MHz are shown in Figure 1. If the filter rate is high, a higher spectral range is sampled and the data is accumulated to a more noisy trace. Figure 2 shows the distribution of 10000 data points of the position of the target for three different frame and filter rates.
It can be seen that the signal becomes less noisy with decreasing filter rate. This results from the decreasing cut-off frequency for lower filter rates so that a smaller spectral range is sampled. The standard deviations for the distributions from Figure 2 are shown in Table 1.

Filter rate	Standard deviation
1.22 kHz	70 pm
39.06 kHz	86 pm
10 MHz	399 pm

Table 1. Standard deviations of the distributions of Figure 2.

2.2 Frequency domain measurements

The amplitude spectral density of the position signal is shown in Figure 3. It consists of three individual spectra:

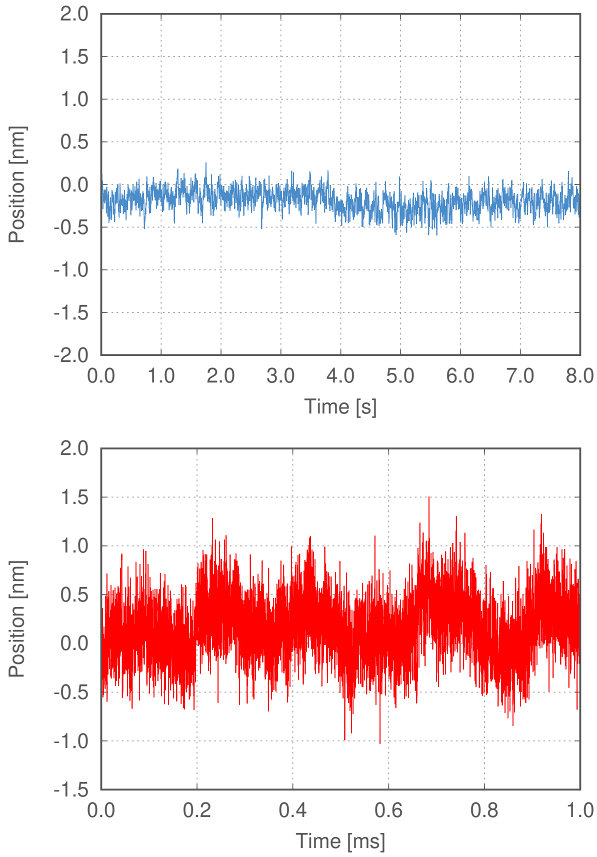

***Figure 1. Position** data for different filter rates measured at a working distance of 20 mm. **Top**: **1.22 kHz**. **Bottom**: **10 MHz**.*

- The blue curve was recorded with a sample rate of 1 Hz. Additionally, due to the very long measurement time required for this plot, the influence of fluctuations in the refractive index of air as well as thermal drift of the setup were compensated. These data were calculated using the corrected data set of Application Note 37 [**?**]. Please note, that this compensation is a valid procedure in order to infer the measurement device's performance and would only be repeatable in vacuum and using a fictional setup without any thermal drift.

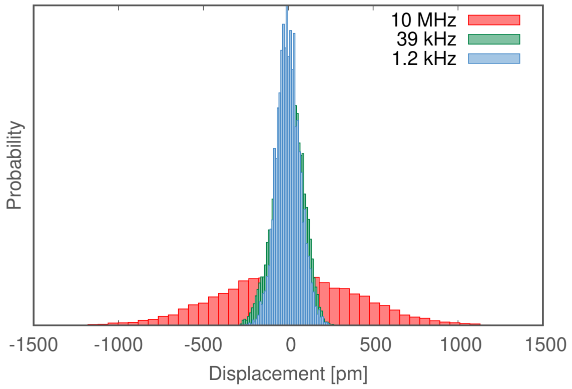

Figure 2. *Normal distributions of the position signal at different filter rates. The small deviations between the Gaussian curves and the raw data is caused by the change of target mirror position as it can be seen in Figure 1.*

- The green curve was recorded using the **PICO**SCALE graphical user interface with a frame rate of 1.2 kHz, a FFT block size of $2^{17} = 131072$, a Hanning window (no averaging).
- The red curve was recorded using the **PICO**SCALE graphical user interface with a frame rate of 10 MHz, a FFT block size of $2^{17} = 131072$, a Hanning window (10-fold averaging).

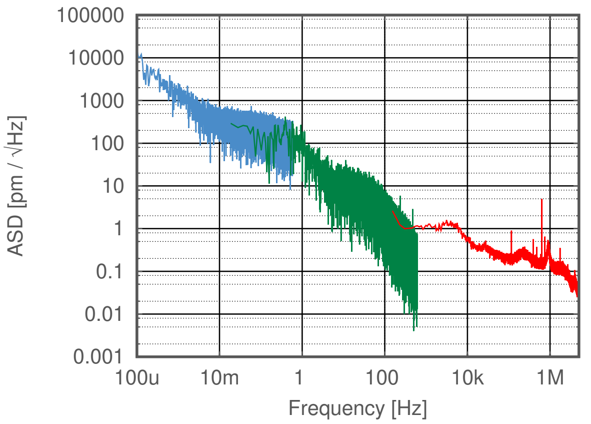

Figure 3. *Amplitude spectral density of the position signal of a mirror at 20 mm working distance. The plot consists of three spectra, recorded with sample rate of 1 Hz (blue curve), 1.2 kHz (green) and 10 MHz (red). See text for details.*

The RMS noise in individual frequency bands can be calculated as

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

where $\mathrm{ASD}(f)$ is the amplitude spectral density, and df is the effective noise bandwidth (ENBW), which depends on the sample rate, the FFT block size and the window function used. Applying this formula to the data of Figure 3 one obtains the following RMS noise levels per band:

f_{min}	f_{max}	$\delta(f_{min}, f_{max})$ **[nm]**
100 µHz	1 mHz	0.14
1 mHz	10 mHz	0.08
10 mHz	100 mHz	0.10
100 mHz	1 Hz	0.15
1 Hz	10 Hz	0.11
10 Hz	100 Hz	0.08
100 Hz	1 kHz	0.07
1 kHz	10 kHz	0.12
10 kHz	100 kHz	0.10
100 kHz	1 MHz	0.27

Table 2. *RMS values of the position noise of the* **PICO**SCALE *per frequency decade.*

2.2.1 Influence of working distance

If the working distance increases, also the noise floor increases due to laser phase noise. This effect has been measured with four different working distances from 20 mm to 1.2 m. The noise floor at different frequencies was evaluated. For example, at a frequency of 1 kHz, a linear fit reveals, that the noise floor increases with a slope of 0.058 pm mm^{-1}, cf. Figure 4.

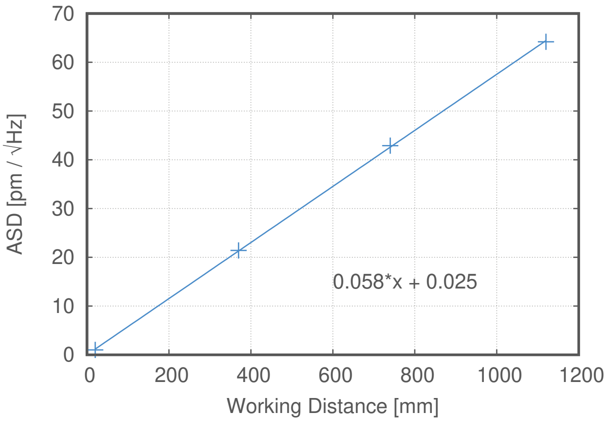

Figure 4. *Noise floor at 1 kHz measured at different working distances. Due to laser phase noise, the noise floor increases linearly.*

For different frequencies (one per decade), the slopes of the noise level can be evaluated similarly. The results are summarized in Figure 5.

3. CONCLUSION

It has been demonstrated that the **PICO**SCALE interferometer achieves a noise level in the sub-nanometer range. Regardless of the streaming frequency, the σ width of the normal distributed noise is well below 1 nm. It has also been shown, that the noise floor does never exceed 10 pm/$\sqrt{\mathrm{Hz}}$ for relevant filter rates above 100 Hz.

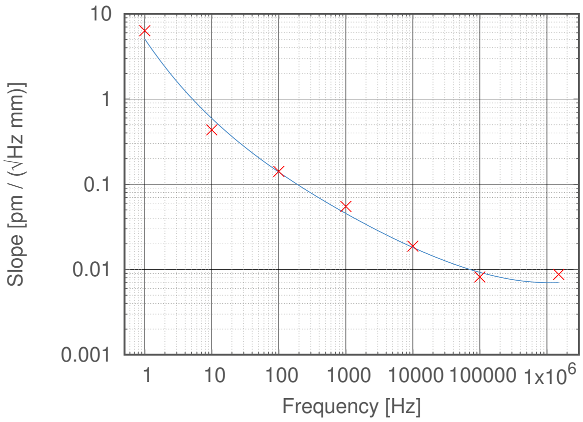

Figure 5. *Graph of the slopes of the noise floor, evaluated as exemplarily shown in Figure 4. (The blue curve is not based on a specific physical model, but a Bézier curve roughly matching the data points.)*

A. DIFFERENTIAL MEASUREMENTS

If the **PICO**SCALE shall be operated at larger working distances and the increasing noise floor is problematic, SmarAct recommends to use differential sensor heads. Due to the Michelson principle, it is possible to also guide the reference beam of the interferometer externally so that the effective working distance can be kept very short. This will reduce the noise floor significantly, as shown in Figure 6. For details and discussion of the applicability of this technique please contact SmarAct.

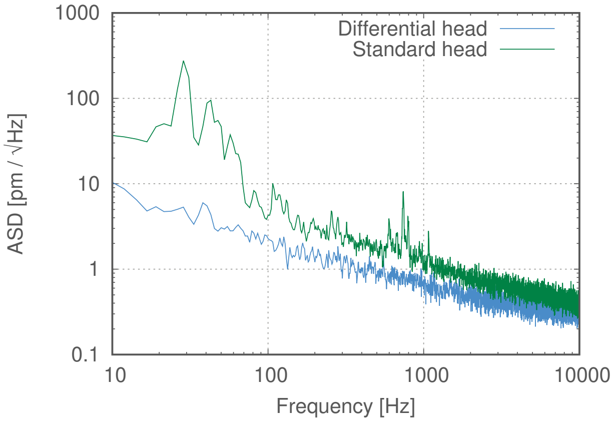

Figure 6. *Comparison of the differential assembly with a standard sensor head at the same working distance of 40 mm. The differential assembly shows lower noise, especially at low frequencies, as the effective working distance is smaller and fluctuation in the ambient conditions are efficiently cancelled out.*

Alternatively, to ease alignment, two sensor heads can be used: The position signal of the individual sensors can be subtracted in the **PICO**SCALE *Calculation System* in realtime and common-mode noise (such as laser phase noise) is subtracted.

Sales partner / Contacts

Germany

SmarAct GmbH
Schuette-Lanz-Strasse 9
26135 Oldenburg
Germany

T: +49 441 - 800 879 0
Email: info-de@smaract.com
www.smaract.com

France

SmarAct GmbH
Schuette-Lanz-Strasse 9
26135 Oldenburg
Germany

T: +49 441 - 800 879 956
Email: info-fr@smaract.com
www.smaract.com

USA

SmarAct Inc.
2140 Shattuck Ave. Suite 302
Berkeley, CA 94704
United States of America

T: +1 415 - 766 9006
Email: info-us@smaract.com
www.smaract.com

China

Dynasense Photonics
6 Taiping Street
Xi Cheng District,
Beijing, China

T: +86 10 - 835 038 53
Email: info@dyna-sense.com
www.dyna-sense.com

Natsu Precision Tech
Room 515, Floor 5, Building 7,
No.18 East Qinghe Anning
Zhuang Road,
Haidian District
Beijing, China

T: +86 18 - 616 715 058
Email: chenye@nano-stage.com
www.nano-stage.com

Shanghai Kingway Optech Co.Ltd
Room 1212, T1 Building
Zhonggeng Global Creative Center
Lane 166, Yuhong Road
Minhang District
Shanghai, China

Tel: +86 21 - 548 469 66
Email: sales@kingway-optech.com
www.kingway-optech.com

Japan

Physix Technology Inc.
Ichikawa-Business-Plaza
4-2-5 Minami-yawata,
Ichikawa-shi
272-0023 Chiba
Japan

T/F: +81 47 - 370 86 00
Email: info-jp@smaract.com
www.physix-tech.com

South Korea

SEUM Tronics
1109, 1, Gasan digital 1-ro
Geumcheon-gu
Seoul, 08594,
Korea

T: +82 2 - 868 10 02
Email: info-kr@smaract.com
www.seumtronics.com

Israel

Trico Israel Ltd.
P.O.Box 6172
46150 Herzeliya
Israel

T: +972 9 - 950 60 74
Email: info-il@smaract.com
www.trico.co.il