PICOSCALE Interferometer: Thermal expansion coefficient of Invar and long-term stability

1. INTRODUCTION

The **PICO**SCALE *Interferometer* is a displacement sensor device based on a compact Michelson interferometer. Here, we demonstrate the measurement of the thermal drift of Invar, which is a metal alloy with extremely low thermal expansion coefficient. The experimental setup is shown in Figure 1. A PS-SH-C01-NO sensor head was mounted in an Invar block such that any thermal expansion of the optical fiber and the collimating optics have minimal influence on the position of the front surface of the beam splitter, which is the point of reference of any **PICO**SCALE displacement measurement. The target mirror, a standard glass substrate with protected silver coating, was clamped from its rear side so that its front surface was pressed to the Invar in the direction of the measurement beam and thus any thermal expansion of the glass substrate would not affect the length of the optical path. While the **PICO**SCALE controller was placed in a temperature-stable environment, the Invar block was actively temperature stabilized. Every two hours the setpoint of the temperature controller was altered by $\Delta T = 5\,\mathrm{K}$.

2. SETUP

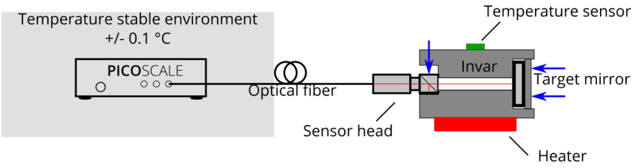

Figure 1. *Experimental setup. The sensor head as well as the target mirror were mounted in a solid block made from Invar. The sensor head's beam splitter was clamped such that its front surface, i.e. the point of reference, was not suffering thermal expansion of the preceding optics. The target mirror was also pressed against the Invar block. The setup was actively temperature controlled using a heater and temperature sensor mounted beneath and on top of the block, respectively.*

3. RESULTS

3.1 Temperature ramps

The position drift measured by the **PICO**SCALE is shown in Figure 2. Clearly, the Invar block expands for high temperatures (315 K) and for low temperatures (310 K) the objects dimensions reduce again. After each variation of the setpoint the controller overshoots.

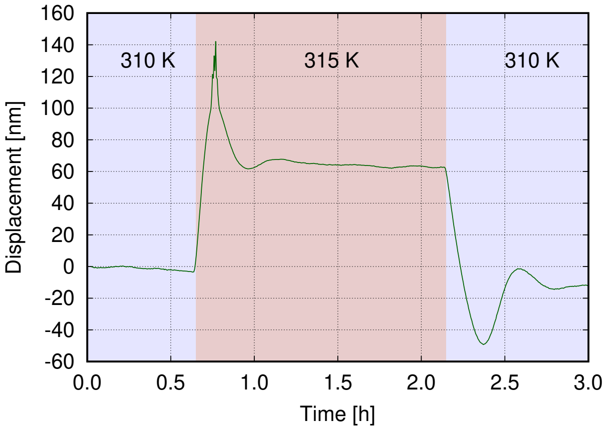

Figure 2. *Position measured by the* **PICO**SCALE *which is only corrected for influences of the optical deadpath, i.e. mainly air pressure fluctuations. In the red shaded area the Invar was heated to 315 K while in the blue area the setpoint was 310 K.*

After the system has reached a steady-state, one can infer a total expansion of the optical path of

$$\Delta x = 75\,\mathrm{nm}/\Delta T = 15\,\mathrm{nm/K} \tag{1}$$

The optical path within the block is about $x = 19.5\,\mathrm{mm}$ so that the thermal expansion coefficient can be calculated to be

$$d/dT = \frac{\Delta x}{x} = 0.77 \times 10^{-6}/\mathrm{K}\,. \tag{2}$$

3.2 Long-term stability

The long-term stability of the system has been verified subsequently. The system has been left unaffected for three days and the result is shown in Figure 3.

The red curve in the figure shows the *optical* drift measured by the **PICO**SCALE. This means that environmental fluctuations influence the refractive index of air that appears as a virtual drift of the target mirror. Air pressure fluctuations have the strongest impact on the refractive index of air. In Figure 4 the air pressure fluctuations during the time of the measurement are shown, revealing strong correlations of air pressure with the measured optical displacement.

Air temperature and the relative humidity have also been recorded, but they do have minor influence on the refractive index of air. However, if air pressure,

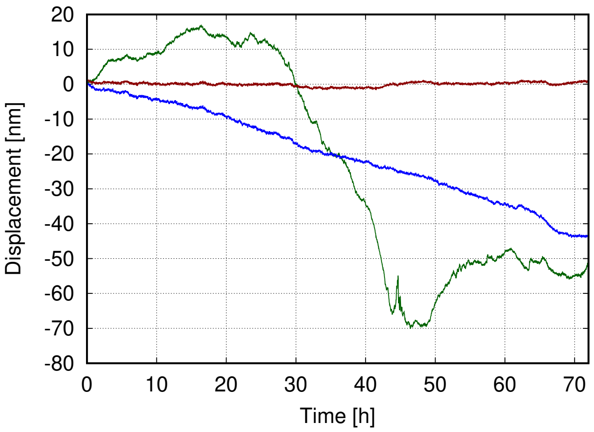

Figure 3. *(red) Position measured by the* **PICO**SCALE*, i.e. optical drift. (blue) Position with deadpath correction, i.e. geometrical drift. (green) Position with thermal correction. See text for details.*

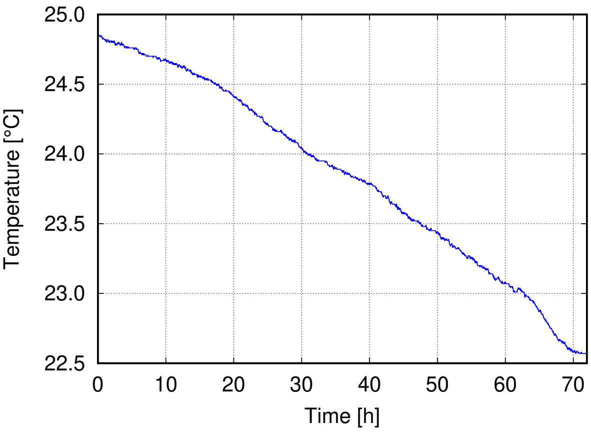

Figure 5. *Temperature of the laboratory. During the measurement time of three days the temperature in the laboratory decreased by about 2 °C. This directly correlates with the blue curve in Figure 5.*

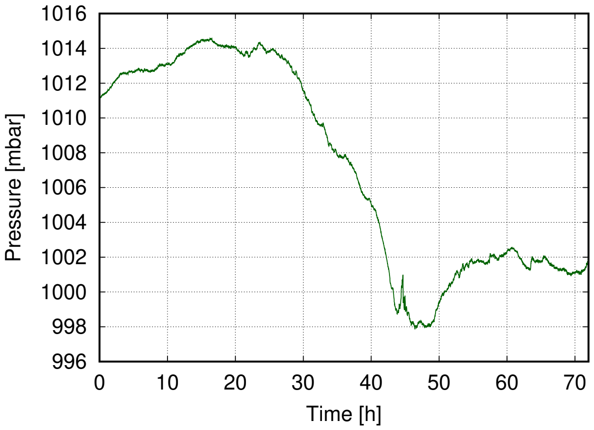

Figure 4. *Air pressure in the vicinity of the experimental setup. A strong correlation of the air pressure with the measured optical displacement is apparent (red curve in Figure 3).*

air temperature and relative humidity are used to calculate the refractive index of air and subsequently to correct the optical displacement, the geometrical displacement can be inferred (blue curve in Figure 3). What is left is the thermal expansion of the setup: In a final step, the recorded temperature (cf. Figure 5) can be used to correct the data for thermal expansion of the setup. The green curve in figure 3 is obtained if the recorded temperature variations and a thermal expansion coefficient of 1×10^{-6} 1/K is assumed.

3.3 Discussion

The experiments shown here present the possibilities to track thermal expansions of experimental setups with the **PICO**SCALE on a proof-of-principle basis. In a first step, the setup was heated to two different temperature setpoints. The thermal expansion can be inferred. In a second scenario, the setup was kept in thermal equilibrium with the laboratory. As the temperature in the laboratory was reduced by about 2 K, also here a thermal expansion can be observed, but on a much longer timescale.
Both measurements show that a thermal expansion coefficient can be inferred. However, the values differ slightly and the reasons for this might be that in both scenarios the environmental parameters are used to calculate the refractive index of air and subsequently to correct fluctuations that appear as a virtual drift of the target mirror. Only after these corrections, the thermal expansion of the setup is revealed appropriately as air pressure has a strong influence on the optical path of the laser beam. However, due to the compactness of the setup, the environmental parameters inside the Invar could not be measured, so that the environmental compensation accuracy is limited. The air inside the housing is expected to be a few degrees warmer than in the environment, but only the ambient air is used for compensation. Warmer air typically has a lower refractive index so that the optical path decreases for increasing temperature and thus the thermal expansion coefficient is underestimated with the method presented here. The thermal expansion coefficient estimated in the long-term measurement is expected to be more accurate as both, environmental sensor and experimental setup, are in environmental equilibrium and experience the same fluctuations. Ideally, one should perform the experiment in vacuum to fully exclude the influence of the ambient air.

4. SUMMARY

The measurements described in this application note demonstrate that the **PICO**SCALE can be used as a high precision sensor to determine thermal expansion coefficient even of intrinsically extremely stable setups. Typically, these drifts occur on relatively long timescales so that high long-term stability of the measurement device is required.

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