

# PRECISION IN MEASUREMENT

## Ultrastabile Laser-Interferometer:

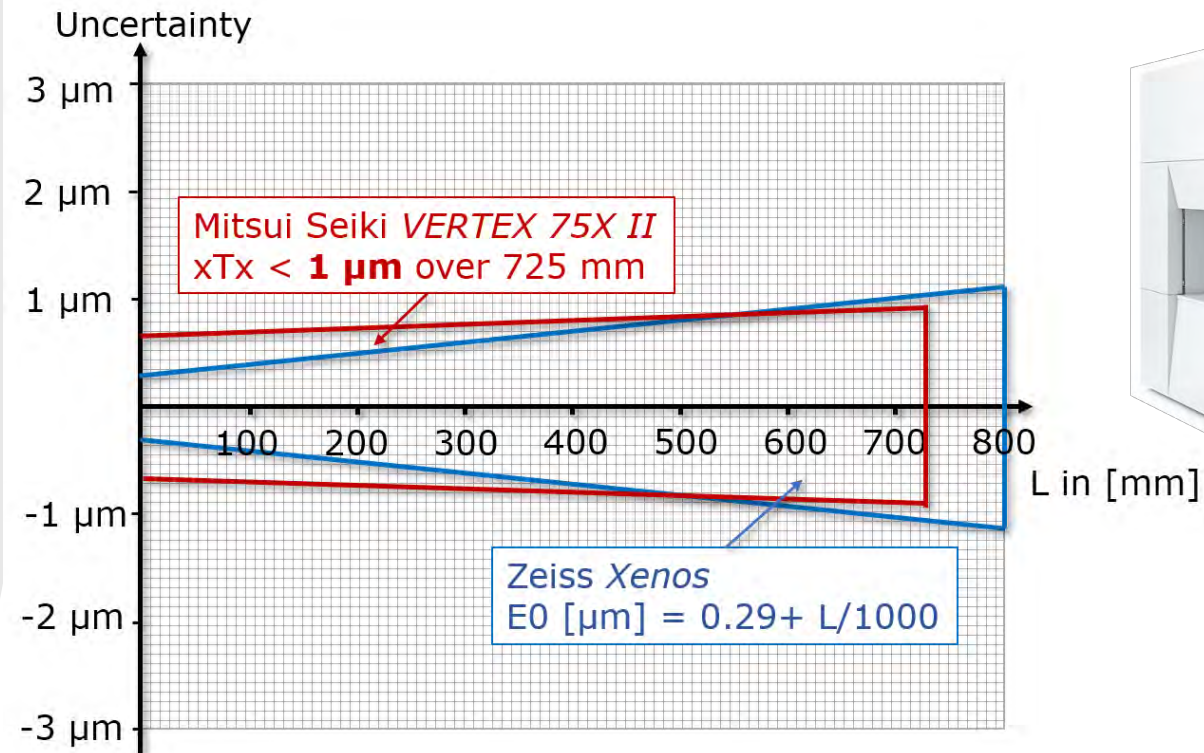
Eine Brücke zwischen  
Temperaturmesstechnik  
und laserinterferometrischer  
Präzisionsmesstechnik

Dr. Ralf Schüler  
Leiter Entwicklung



# Motivation

## Challenges of high precision manufacturing

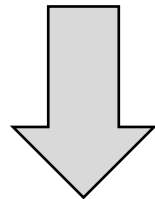


Source user: [www.mitsuiiseiki.com/products/vx750-5x.asp](http://www.mitsuiiseiki.com/products/vx750-5x.asp)  
[www.zeiss.de/messtechnik/produkte/systeme/koordinatenmessgeraete/portalmessgeraete/xenos.html](http://www.zeiss.de/messtechnik/produkte/systeme/koordinatenmessgeraete/portalmessgeraete/xenos.html)

# Motivation

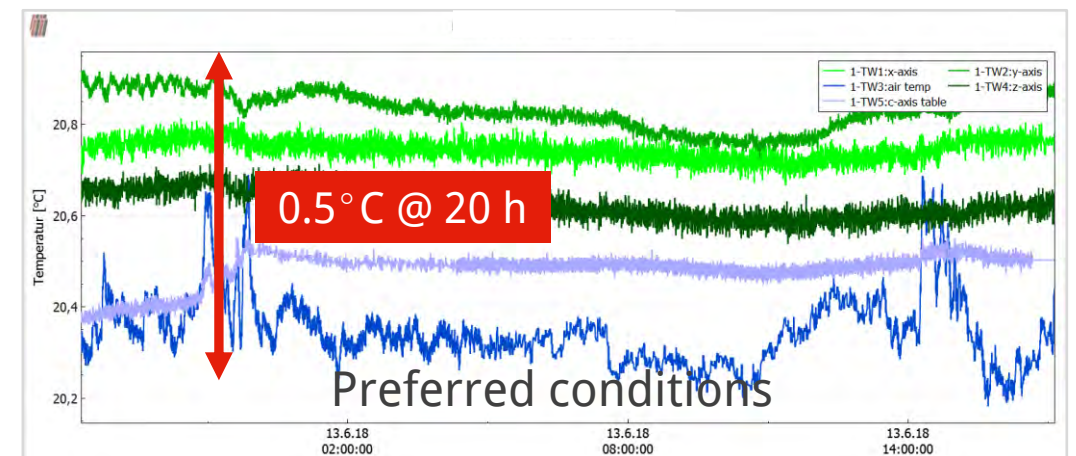
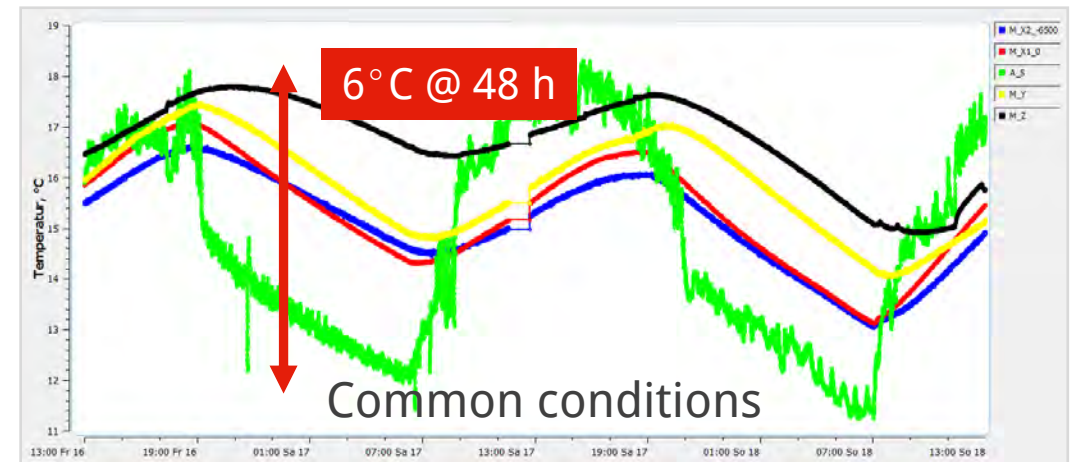
## Challenges of high precision manufacturing

- leak of temperature control for machine tool and for workpiece
- different conditions for calibration and machining
- long calibration time of the machine tool



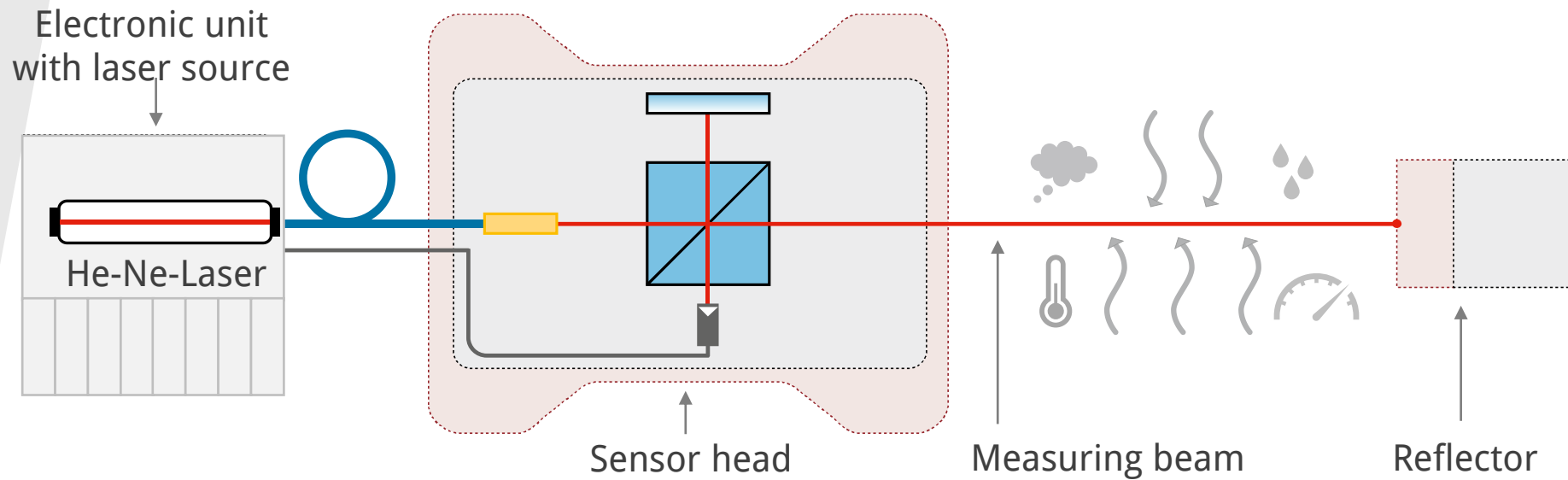
- measurement of parts directly on the machine tool (see ISO/TC 39/SC 2 proposal)
- partial calibration of the volume or parameters needed for further process

Temperature distribution



# Uncertainty of Laser Interferometers

## Laser wavelength as a scale of measurements



The quality of the measurements by laser interferometer in air depends on the accuracy of the definition of air refractive index along the measuring beam.

# Uncertainty of Laser Interferometers

## Laser wavelength in air

### Laser wavelength as length measurement standard

Laser wavelength in air  $\rightarrow$   $\lambda_{air} = \frac{\lambda_0}{n_{air}}$

$\lambda_0$  ← Laser wavelength in vacuum  
 $n_{air}$  ← Refractive index in air

### Edlen Formula for determination of the refractive index in air

$$(n - 1)_{p,t,p_w,c} = 2.8793 \cdot 10^{-9} \frac{p}{1 + 0.003671 \cdot t} \cdot (1 + 5.33 \cdot (c - 400) \cdot 10^{-7}) - 3.7 \cdot 10^{-10} \cdot p_w$$

↓ Air pressure

Humidity ↓

↑ Temperature

# Uncertainty of Laser Interferometers

## Laser wavelength in air

$$\Delta n/n = -0.929 \cdot 10^{-6} K^{-1} \cdot \Delta t$$

$\Delta t$  - change of air temperature



If we measure at **21 °C** instead of **20 °C**, we have error of **-0.93 μm** at 1 m.

$$\Delta n/n = +2.879 \cdot 10^{-9} Pa^{-1} \cdot \Delta p$$

$\Delta p$  - change of air pressure



If we measure an air pressure of **1014 hPa** instead of **1013 hPa**, we have error of **+0.27 μm** at 1 m.

$$\Delta n/n = -3.7 \cdot 10^{-10} Pa^{-1} \cdot \Delta p_w$$

$\Delta p_w$  - change of water vapor pressure of the air



If we measure at **60%** instead of **50%** relative humidity, we measure **-0.09 μm** wrong.

# SIOS environmental sensors and devices

Interferometers need precise environmental measurements for

- Temperature,
- Air pressure and
- Humidity

# Precision Climate Measuring Station LCS

## Basis System LCS-01 (wireless) and LCS-02 (wired)

- used in measuring and calibration laboratories for documentation and compensation during calibration procedure
- for monitoring precision measurements and test setups
- as module for integrating in OEM machines



TT-01 with  
air temperature sensor



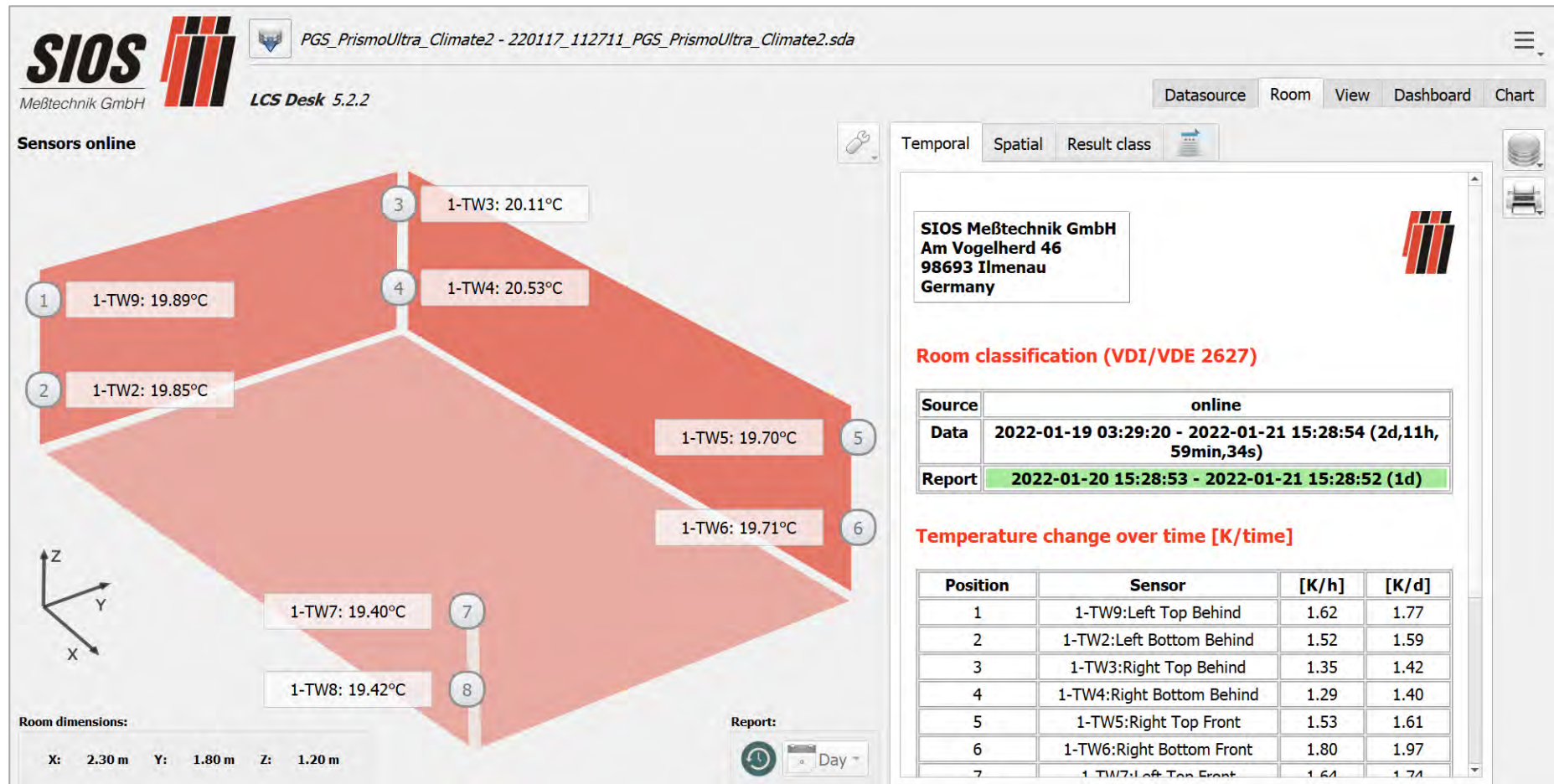
WT-01 with  
material temperature sensor

- 5 wired temperature sensor
- up to 15 wired Sensors with extension LCS-03
- 15 wireless temperature sensors
- 2 air pressure sensors
- 2 air humidity sensors



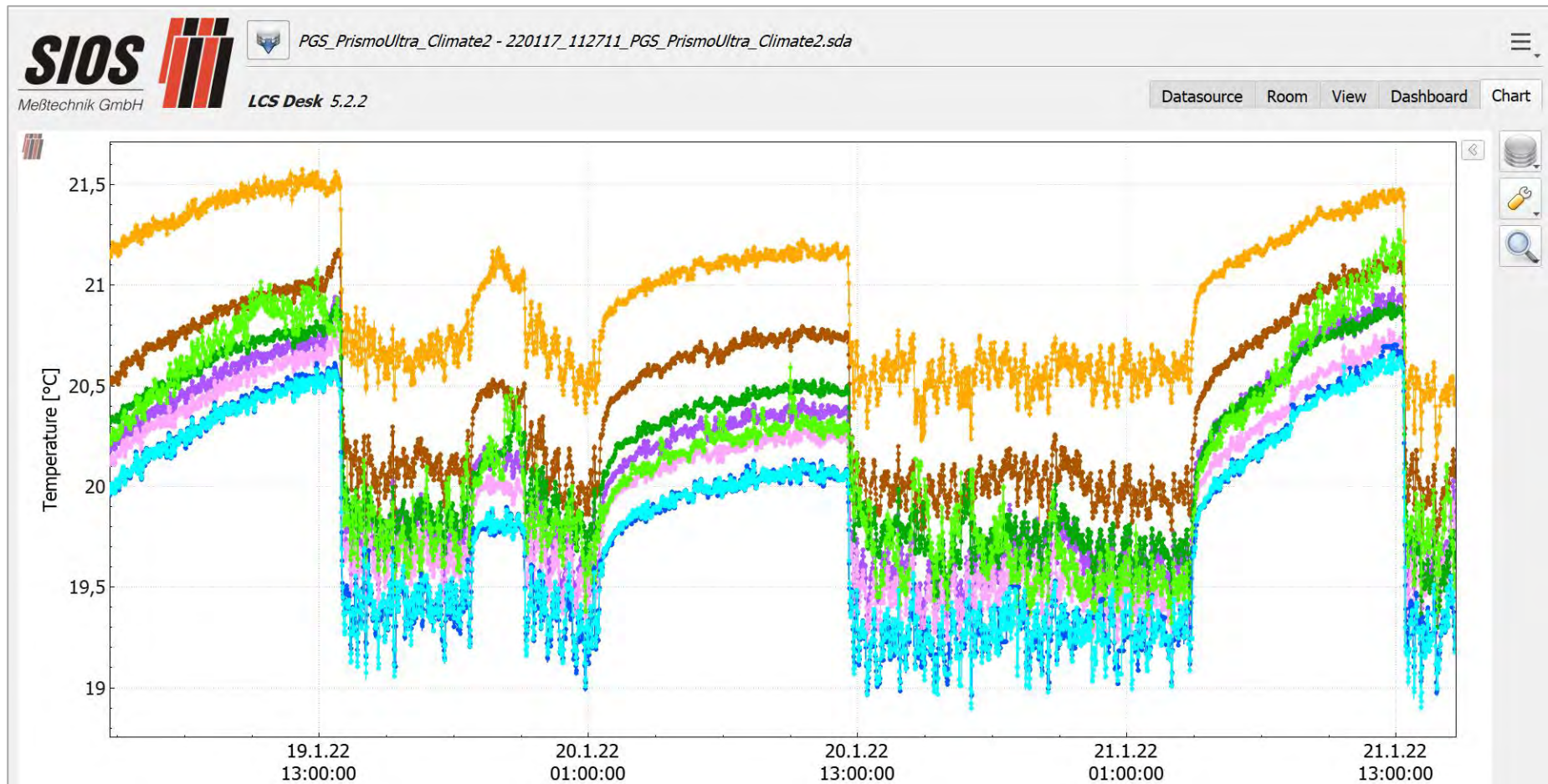
# Precision Climate Measuring Station LCS

LCS Desk recording and evaluation software – live screen sensor values



# Precision Climate Measuring Station LCS

LCS Desk recording and evaluation software – time-based chart screen



# Precision Climate Measuring Station LCS

## Application LCS Temp - evaluation system according VDI/VDE 2627

- LCS Temp is a combination of LCS-01, TT-01 or WT-01, tripods for spatial setup of sensors and software
- the measurement room classification based on VDI/VDE 2627 standard
- LCS Temp is available as wired and wireless system
- stationary and mobile version available



# Precision Climate Measuring Station LCS

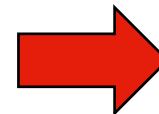
## Sensor calibration – sample DAkkS certificate

### Messergebnisse Measuring results

Temperatur Normal Temperature Standard thermometer in °C	Anzeige Prüfling Indication calibration object in °C	Anzeige- Korrektion Indication correction in K	Messunsicherheit Measuring uncertainty in mK
20,003	20,0032	0,000	37
18,995	18,9954	0,000	37
22,026	22,0264	0,000	37
25,027	25,0275	0,001	37
20,004	20,0040	0,000	37

Factory calibration certificate

DAkkS calibration certificate



System calibration by NMI

# Precision Climate Measuring Station LCS

## Sensor calibration

**SIOS Meßtechnik GmbH**  
 SIOS Meßtechnik GmbH | Tel: +49 3677 6447-0  
 Am Vogelhard 46 | Fax: +49 3677 6447-8  
 D-99663 Irenau | Mail: order@sios.de

**SIOS**  
 Meßtechnik GmbH

**SIOS Factory Test Certificate**  
 according to DIN 50 049 - 2.3 (EN 10 204)

WKS-1249  
2021-10

Objekt: Temperature transducer  
 Type: TT-01  
 Manufacturer: SIOS Meßtechnik GmbH  
 Labelling: Adhesive label No. 1504124-01  
 TT-01 Serial-No.: 16040101 TT-01  
 Client: SIOS Meßtechnik GmbH  
 Am Vogelhard 46  
 D-99663 Irenau  
 Germany  
 No. of pages: 2  
 Date of calibration: 16/09/2021  
 (mm/dd/yyyy)

**Calibration item:**  
 Temperature: Temperature transducer module TT-01 equipped with an RTD sensor for air temperature in a slotted cap. The RTD sensor is specified according to DIN EN 60751 - 13 DIN B  
 Measurement range: 0 ... +50°C  
 Accuracy: ± 0,1 K  
 Measuring element: Pt100  
 Cable length and type: 5,5 m, shielded

**Reference standard:**  
 Temperature: Reference standard: Pt precision resistance thermometer (TT-22 + s) class P100M) 4845C-6-1524-01-00200-01  
 Calibration certificate:  
 Ambient air temperature: Reference standard: 1603 636 - Thermo hygrometer  
 Calibration certificate: F59500 CA-15070-01-01-2020-09

**Calibration procedure:**  
 Calibration method: Calibration by comparing with a Pt100-precision RTD probe

1 / 2

Factory calibration certificate

**Zentrum für Messen und Kalibrieren & ANALYTIK GmbH**

**Kalibrierschein / Calibration Certificate**  
 erstellt durch das Kalibrierlaboratorium  
 issued by the calibration laboratory

**ZMK & ANALYTIK GmbH**  
 akkreditiert nach DIN EN ISO/IEC 17025:2018  
 German translation of ISO/IEC 17025:2017

Mitglied im / Member of **DAKKS**  
 Deutschen Kalibrierdienst

DAKKS  
 Deutsche  
 Akkreditierung  
 EN ISO/IEC 17025

08.17.10  
 D-K  
 13186 01-00  
 2021-12

**Objekt / Object:** Widerstandsthermometer mit Umschalt- und Datensoftware  
**Hersteller / Manufacturer:** SIOS Meßtechnik GmbH  
**Typ / Type:** P1 160  
**Serial / Prüfzettel-Nr. / Serial number:** D00974TT-01  
**Kunden / Eigentümersdaten / Customer:** SIOS Meßtechnik GmbH  
 Am Vogelhard 46  
 99663 Irenau  
**Auftragsnummer / Order No.:** BE-21-01127  
**Anzahl der Seiten des Kalibrierscheines / Number of pages of the certificate:** 4  
**Datum der Kalibrierung / Date of calibration:** 02.12.2021

Dieser Kalibrierschein dokumentiert die metrologische Rückführung auf nationale Normale zur Darstellung der Einheiten in Einklangsetzung mit dem internationalen Einheitsystem (SI).  
 Die DAKKS ist Internationaler Akkreditations-Übereinstimmender der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Kalibrierdienste. Für die Einhaltung dieser Bestimmungen sind die Wiederholung der Kalibrierung in der Benutzerverantwortung.  
 This calibration certificate documents the metrological traceability to national standards, which realize the units of measurement according to the International System of Units (SI).  
 The DAKKS is signatory to the multilateral agreements of the European co-operation for Accreditation (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates. The user is obliged to have the object recalibrated at appropriate intervals.

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 This calibration certificate may not be reproduced other than in full extent with the permission of the issuing laboratory. Calibration certificates with the full name of the approved responsible person are valid without signature.

Datum der Ausstellung / Date of issue: 03.12.2021  
 Freigegeben durch / Approved by: Dr. Dörja Jahnert  
 Dieser Kalibrierschein wurde erstellt durch / This calibration certificate was prepared by: Svenja Bork

**Kalibrierlaboratorium für mechanische, dimensionale, elektrische, thermodynamische und analytische Messgrößen**  
 Calibration laboratory for mechanical, dimensional, electrical, thermodynamical and analytical measuring quantities  
 Ostweg Witten, P.O. Chemiefabrik/Bismarck-Straße, Area A, Postfach No. 7, 03076 Bismarck-Witten  
 Tel.: +49 3494 / 69752 / E-Mail: info@zmk-witten.de / Homepage: www.zmk-witten.de

DAKKS calibration certificate

**PTB**  
 Physikalisch-Technische Bundesanstalt  
 Nationales Metrologieinstitut

**Kalibrierschein**  
 Calibration Certificate

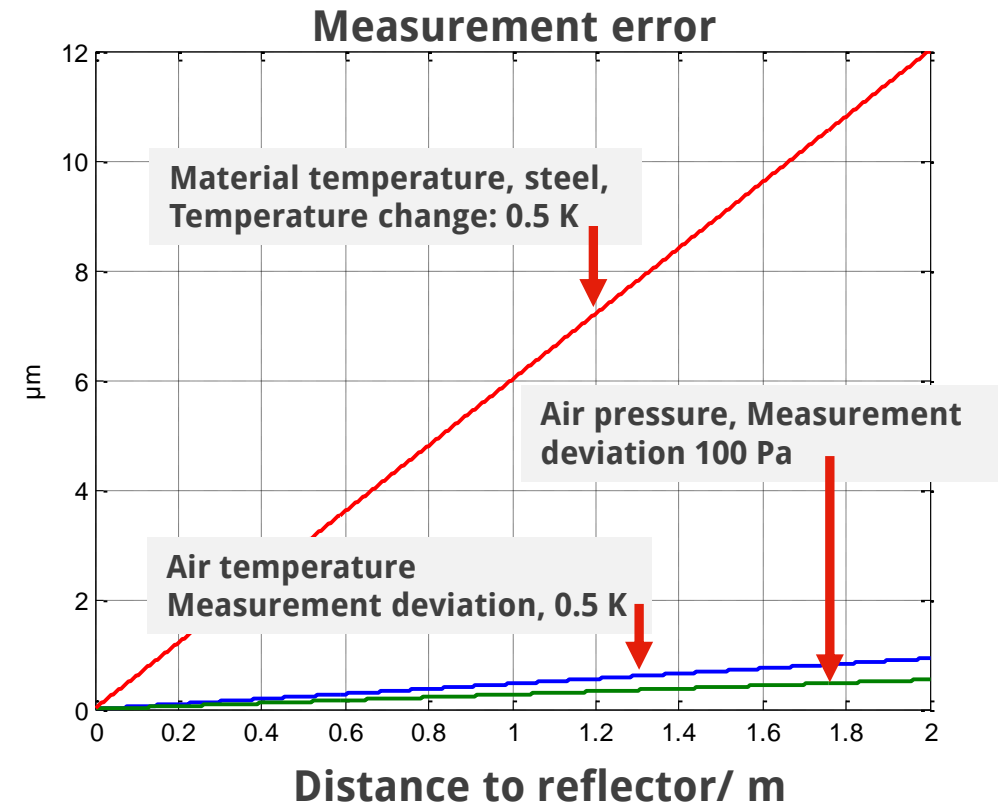
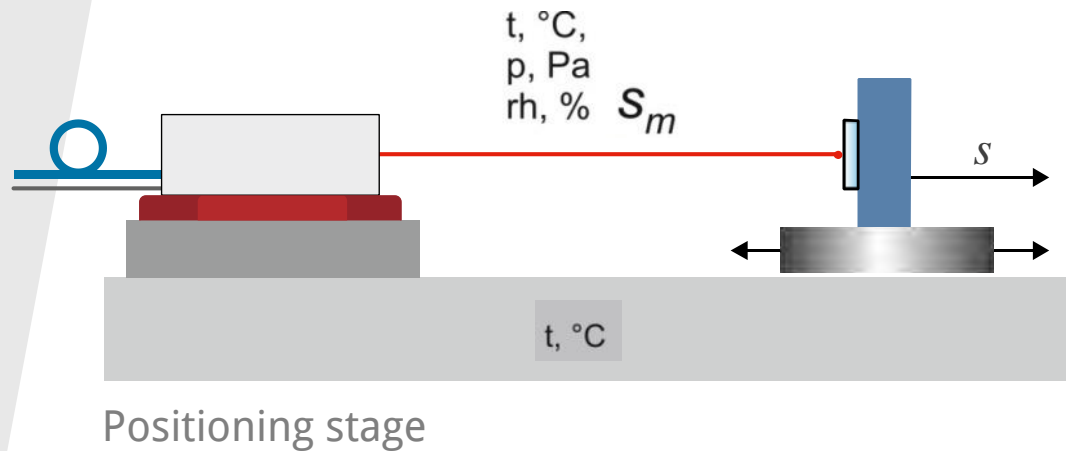
Objekt: Laserinterferometer für Längermessungen  
 Hersteller / Manufacturer: SIOS Meßtechnik GmbH  
 Typ: SP 5000 NG  
 Kennnummer / Serial No.: siehe Kalibriergegenstand  
 Auftraggeber / Customer: GTM Testing and Metrology GmbH  
 Philipp-Reis-Str. 4 - 6  
 04454 Bickenbach  
 Anzahl der Seiten / Number of pages: 6  
 Geschäftszeichen / Reference No.: PTB-5.42-4104939  
 Kalibrierzeichen / Calibration mark: 54170 PTB 21  
 Ort der Kalibrierung / Location of calibration: PTB Braunschweig  
 Datum der Kalibrierung / Date of calibration: 01.06.2021 - 16.07.2021  
 Im Auftrag / On behalf of PTB: Braunschweig, 01.07.2021  
 Dr. Florian Pollinger  
 Im Auftrag / On behalf of PTB: Tobias Meyer

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System calibration by NMI

# Environmental Impacts of Laser Interferometer

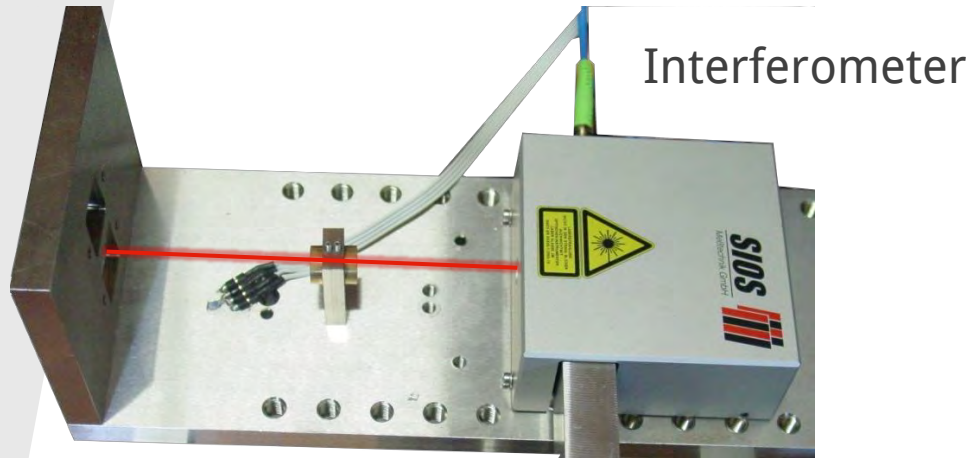
## Influences on the measurement setup



Thermal stability of the setup is important for the long time measurements.

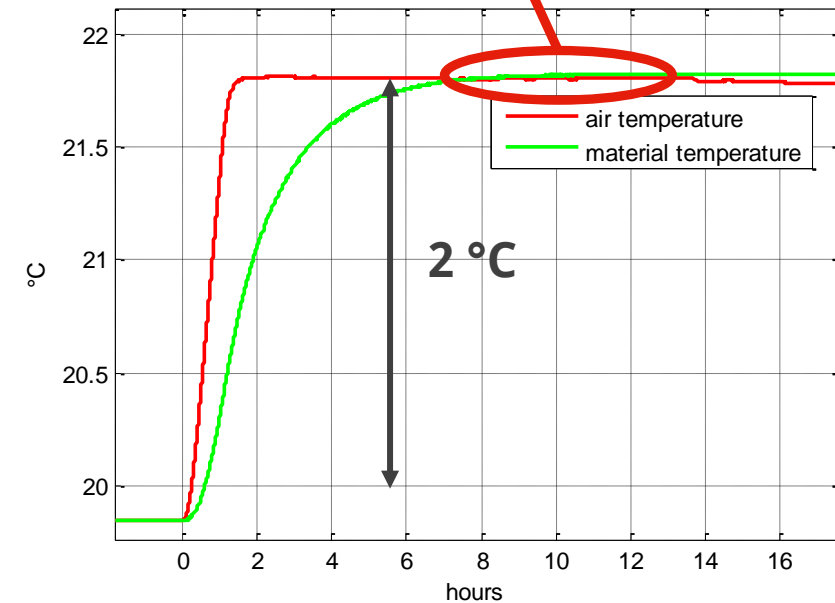
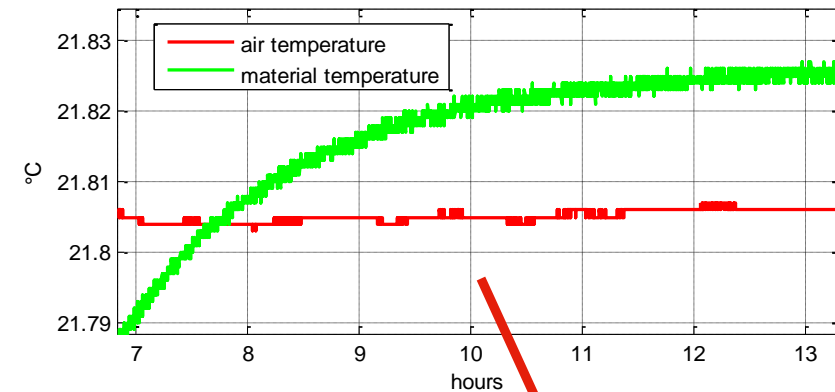
# Precision Temperature Measurements

## Measurement of Thermal Distribution in Materials



Fe65Ni35 Bracket, thickness 12 mm

After a temperature change of  $2\text{ }^{\circ}\text{C}$ ,  
the temperature in the measurement setup  
is equalized after more than **13 hours**

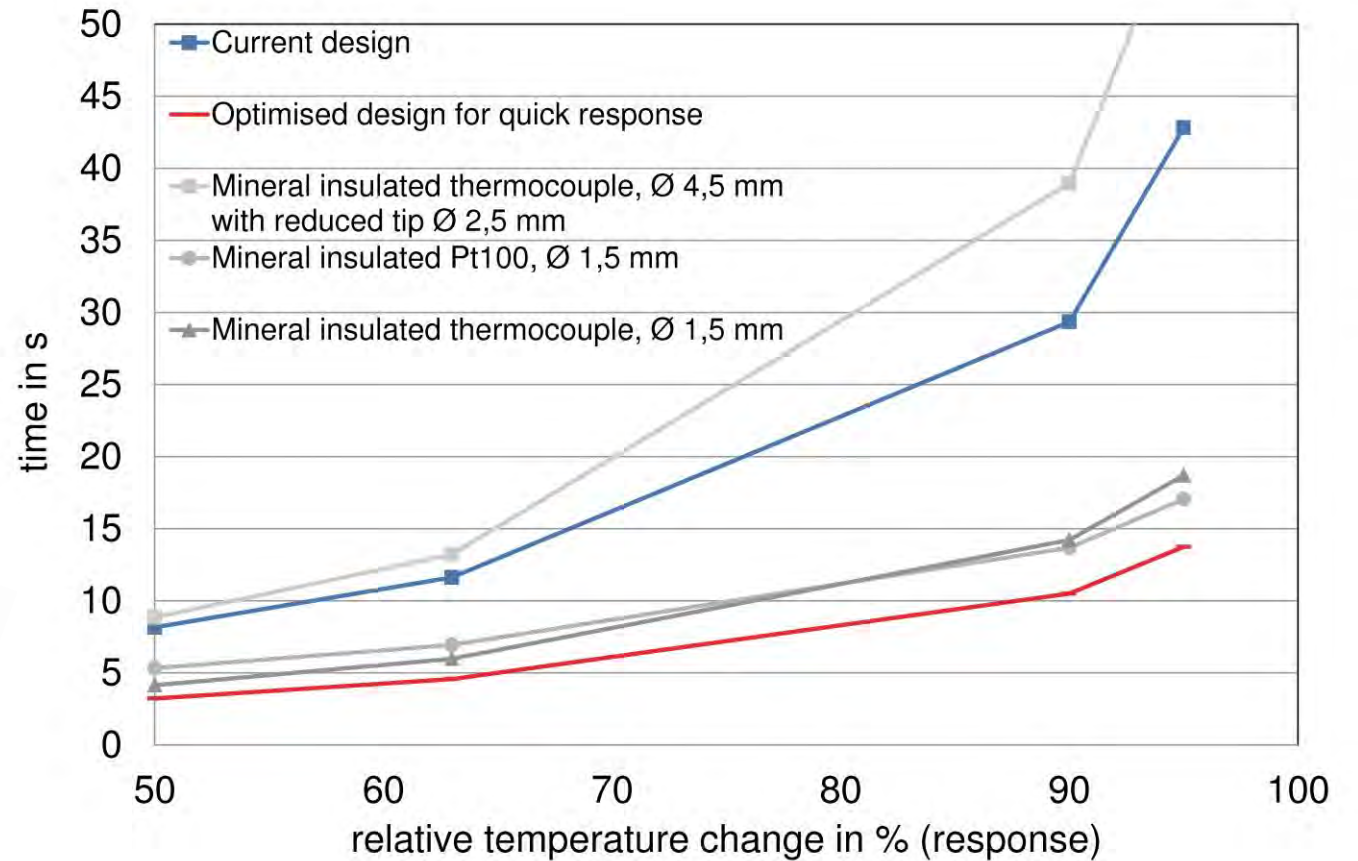


# Precision Temperature Measurements

## Fast air temperature sensor

### Objectives:

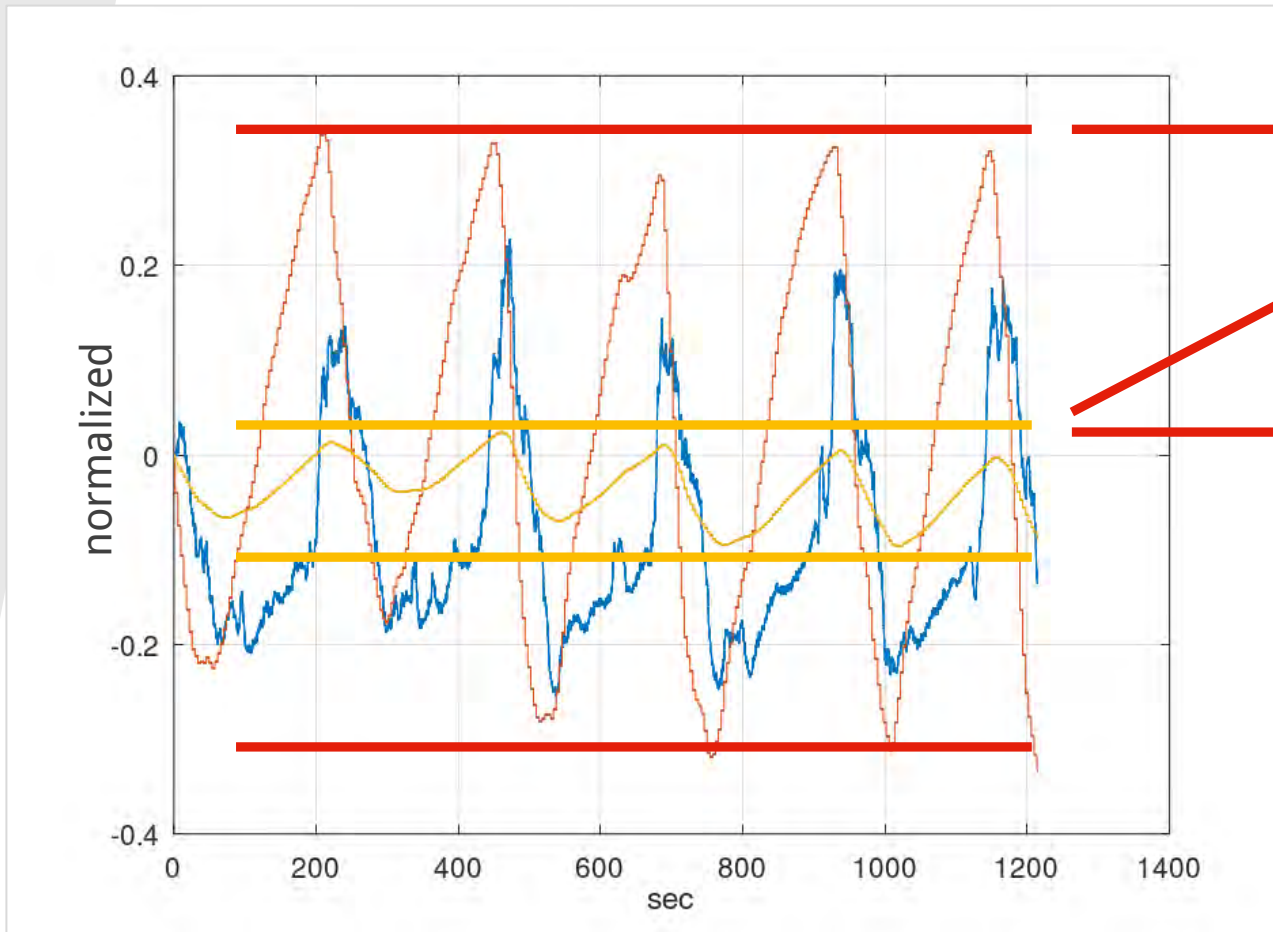
Sensor which is able to follow best air temperature changes, especially in climatized rooms





# Precision Temperature Measurements

## Measurement of Air Temperature by Different Sensors



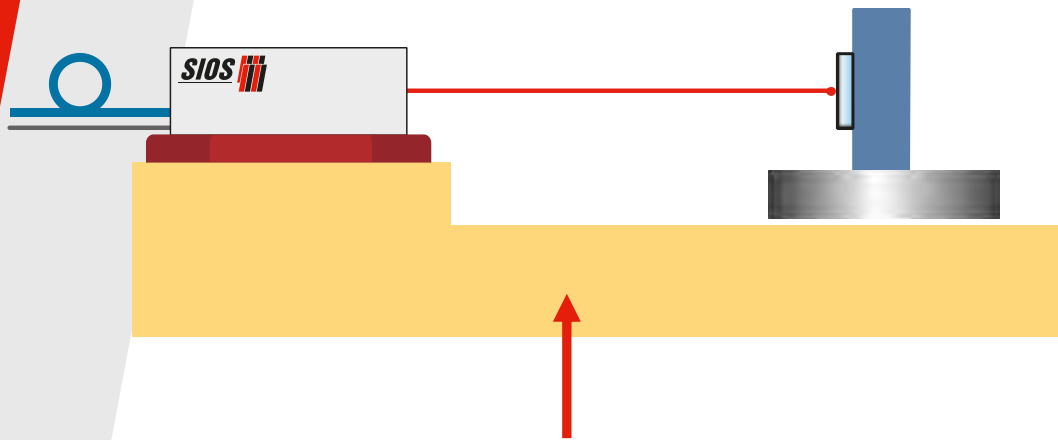
Simultaneous measurements that differ in **phase** and **amplitude**

# Long Term Stability Concept

## Concept comparison

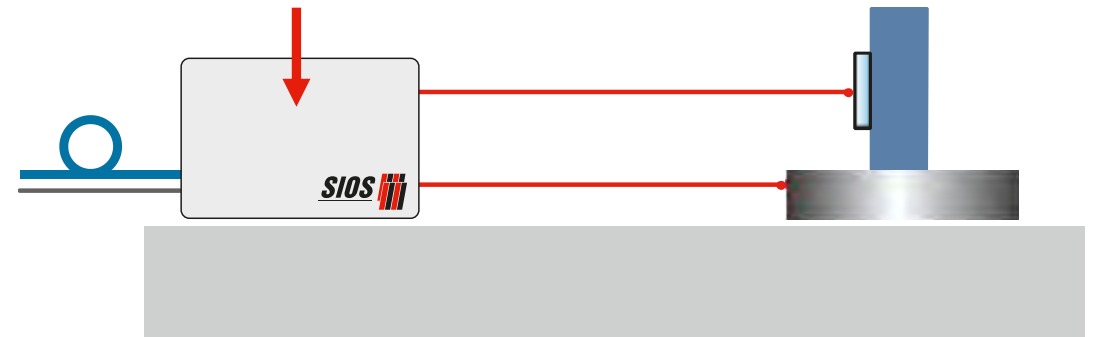
Thermal compensation by metrology frame

Thermal compensation by interferometer principle



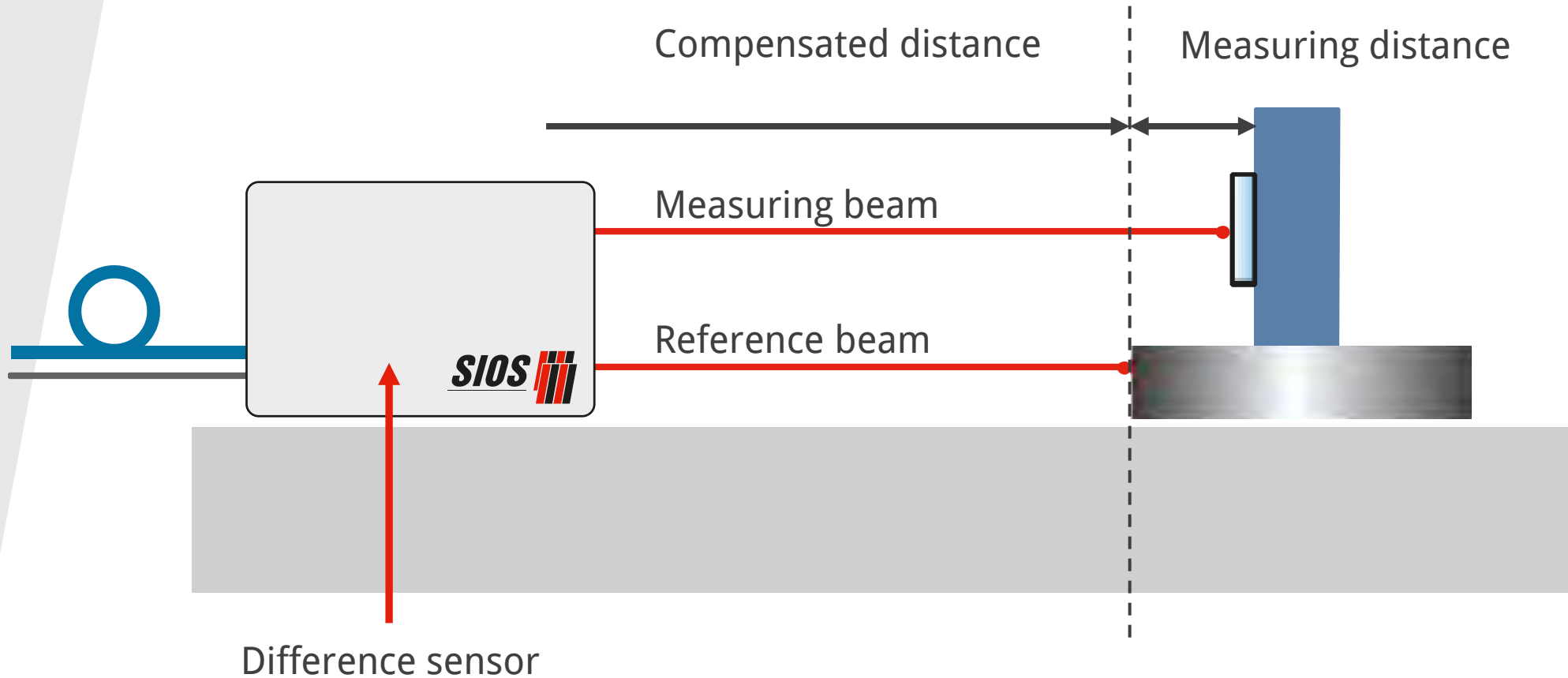
Ultra stable frame  
metrology frame: Zerodur, Invar

Differential interferometers



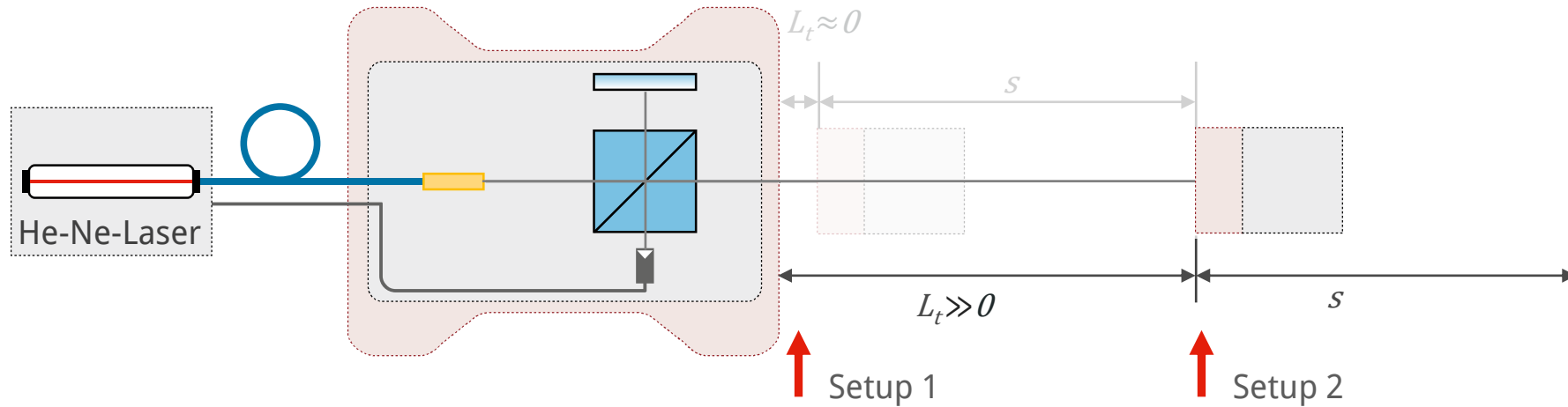
# Long Term Stability Concepts

## Differential Interferometer Concept



# Dead Path of Laser Interferometer Setup

## Dead Path Definition and Correction



Dead path of laser interferometer is a difference of lengths of measuring and reference beams in air at the **moment of setting** the interferometer value to **zero**

Dead path  $L_t \approx \mathbf{zero}$ , if the interferometer is set to zero at Setup 1

Dead path  $L_t \gg 0$ , if the interferometer is set to zero at Setup 2

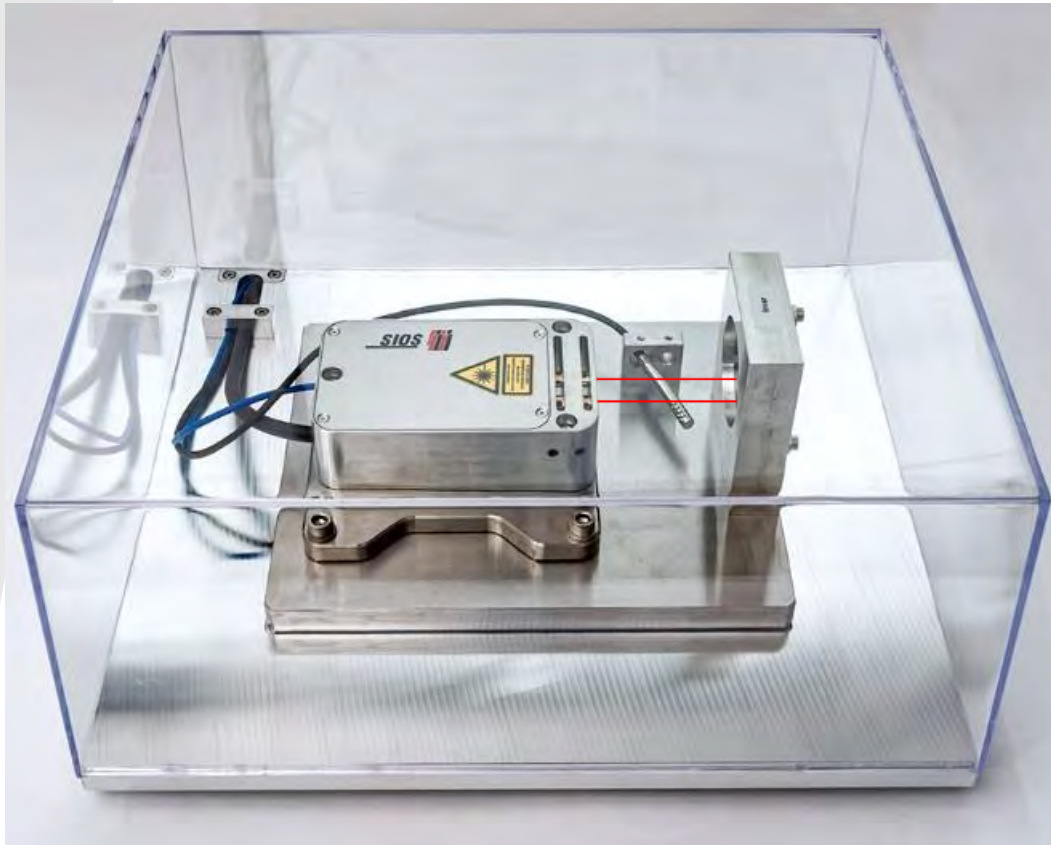
**Dead path correction**  $L_{corr} = -L_t \cdot \left(1 - \frac{n_0}{n}\right)$

← Air refractive index at the moment of setting interferometer value to zero

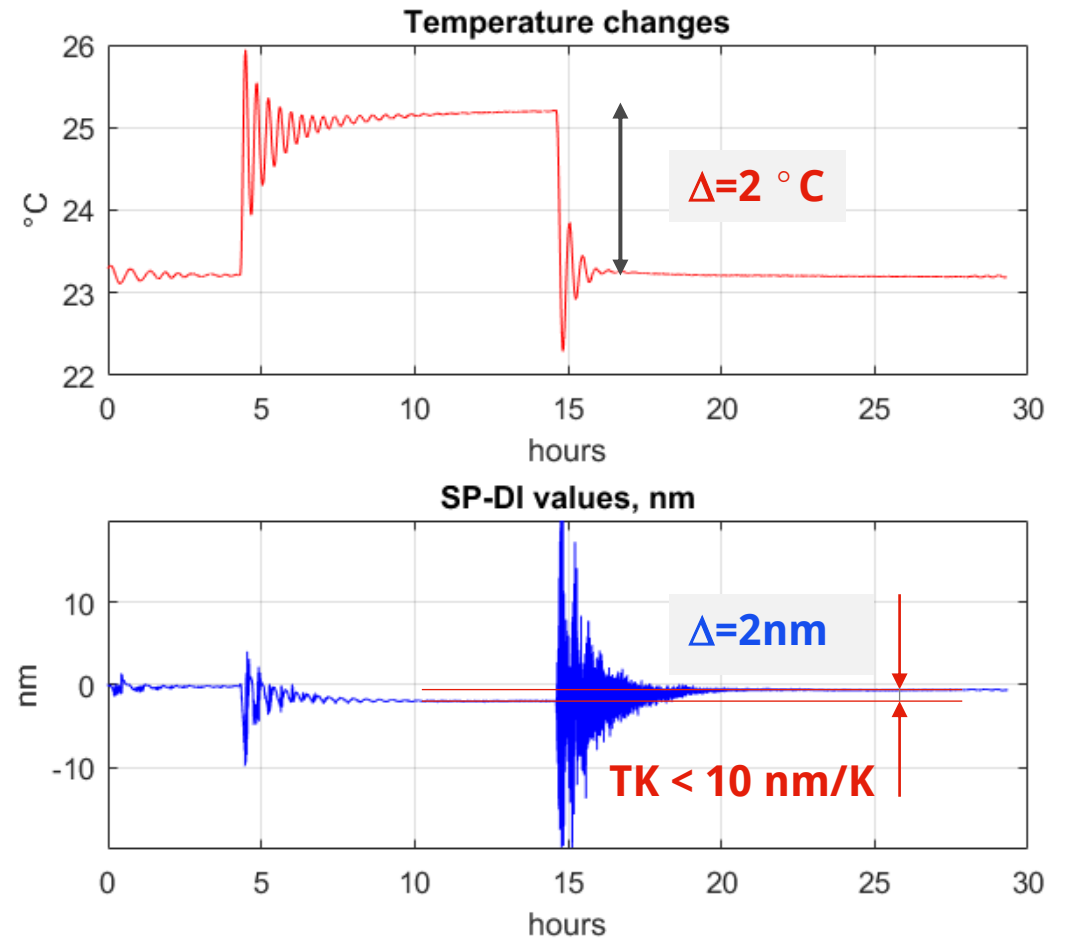
← Current air refractive index

# Differential Interferometers

Lowest sensitivity to the temperature

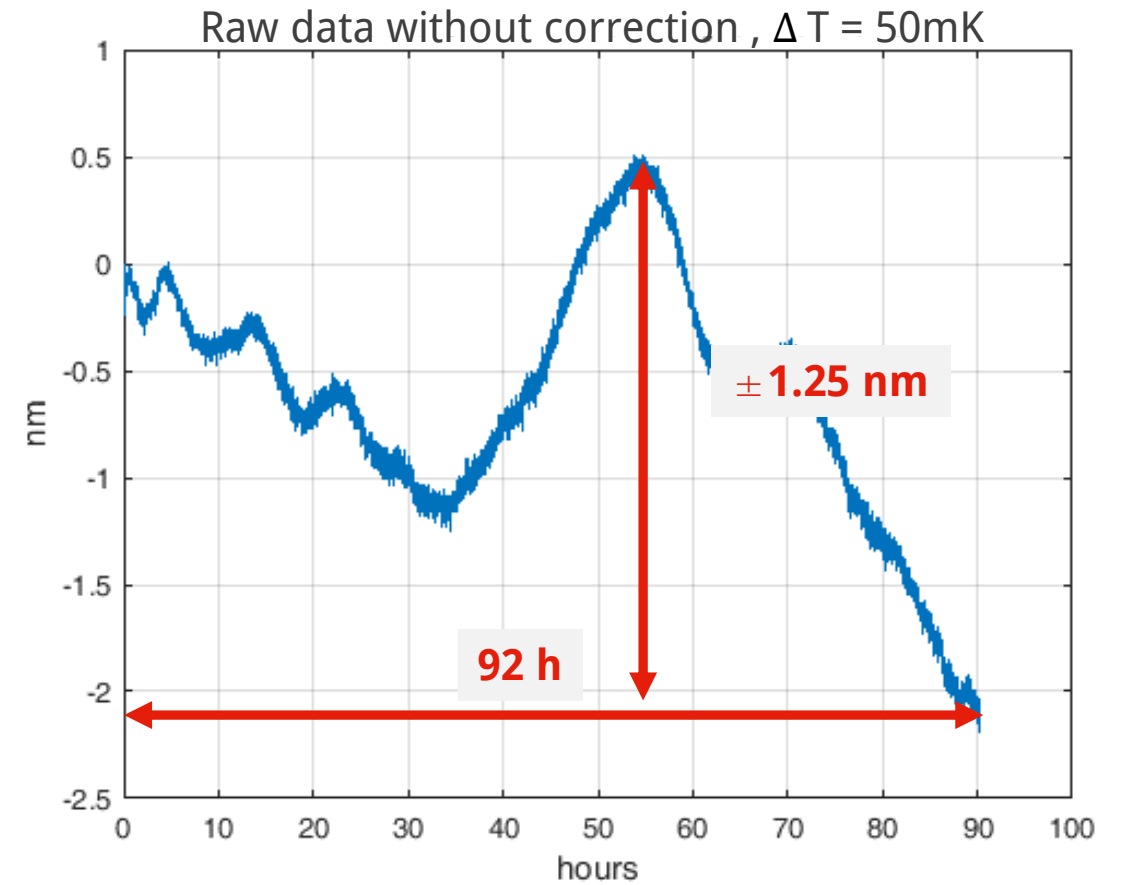
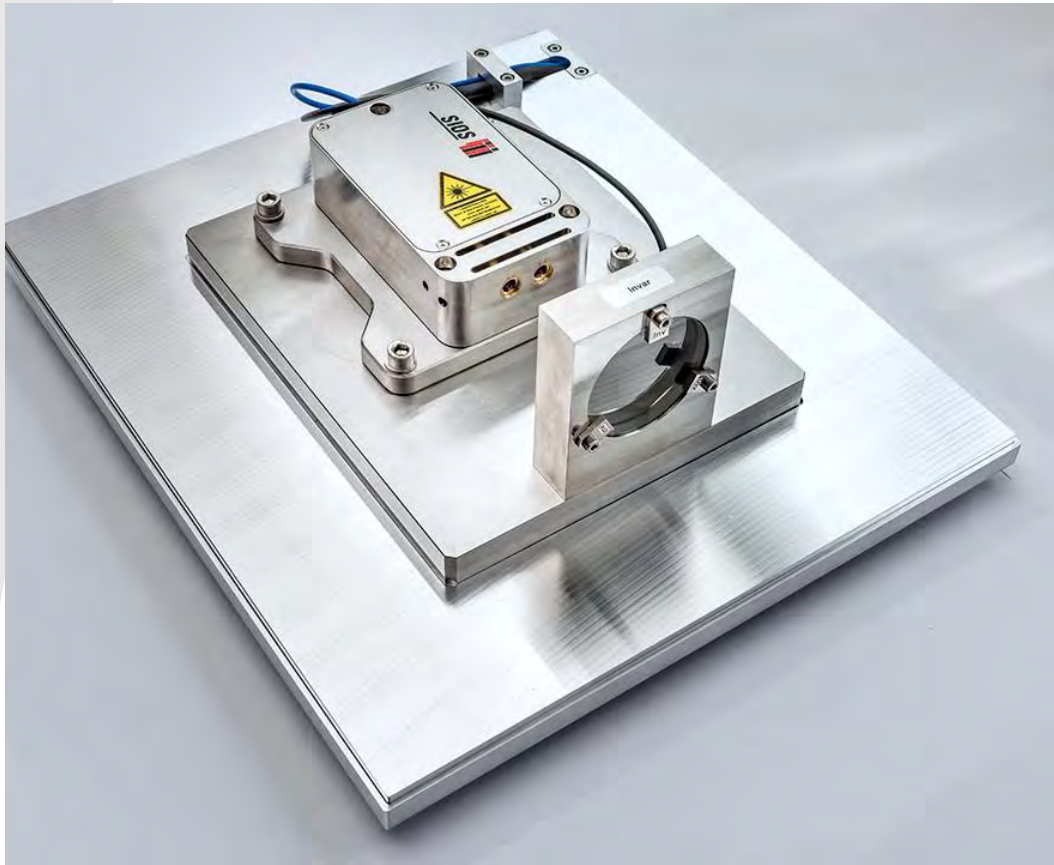


Measurement setup on Invar frame



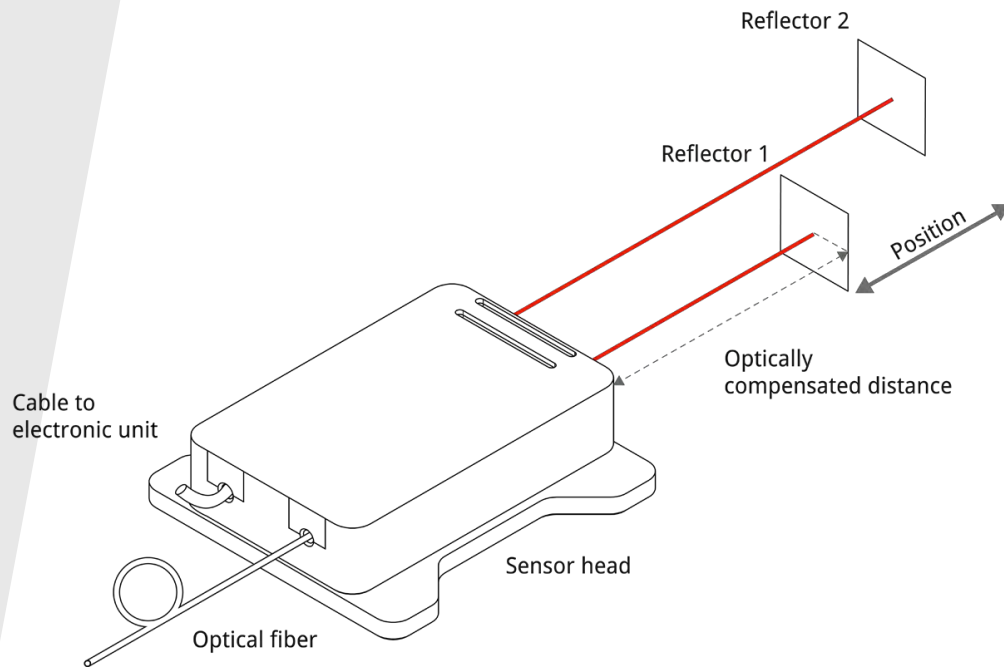
# Differential Interferometers

## Long term stability of differential laser interferometer

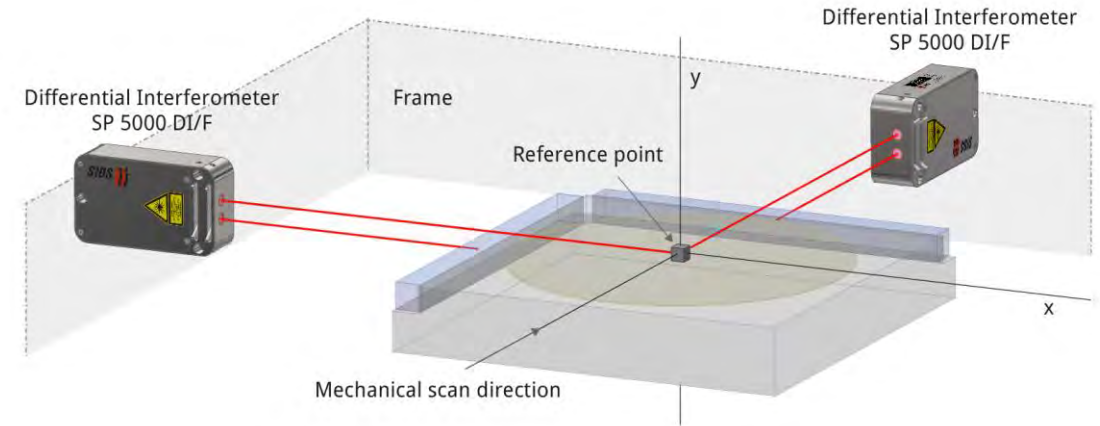


# Differential Interferometers

## Usage for high precision feedback control



SP 5000 DI/F



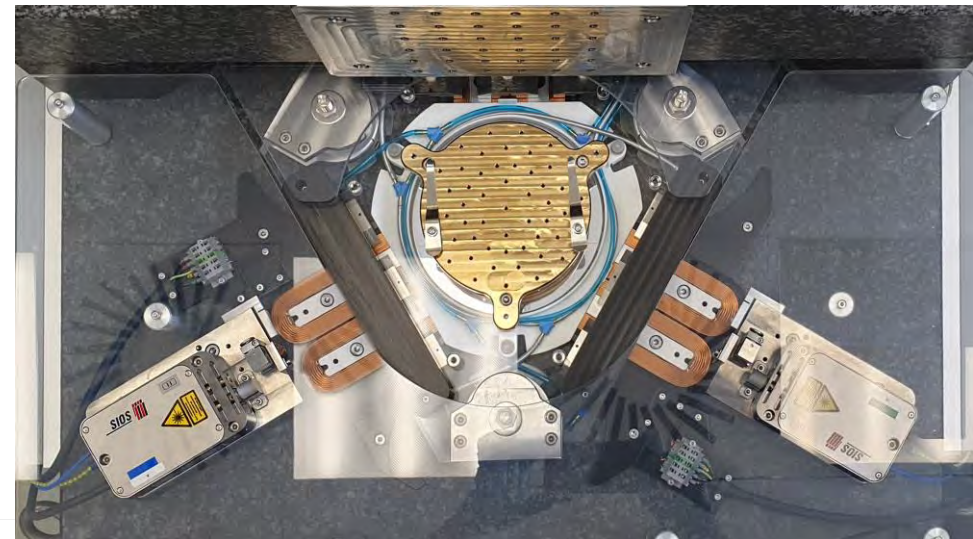
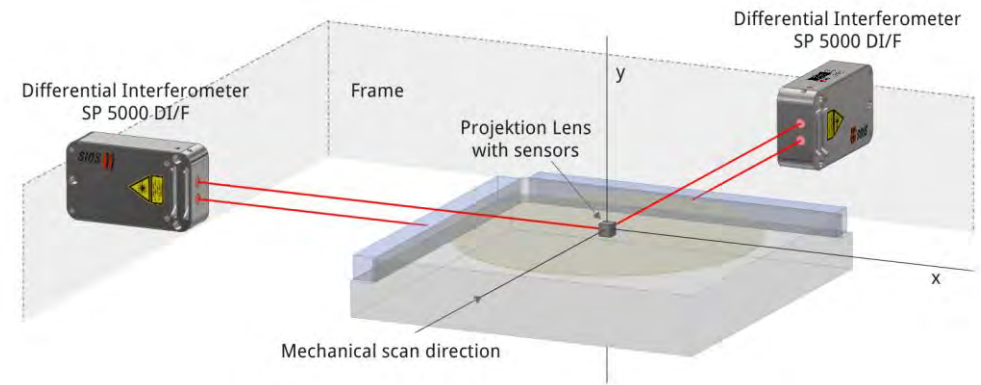
Application example

# Differential Interferometers

## Differential displacement measurements



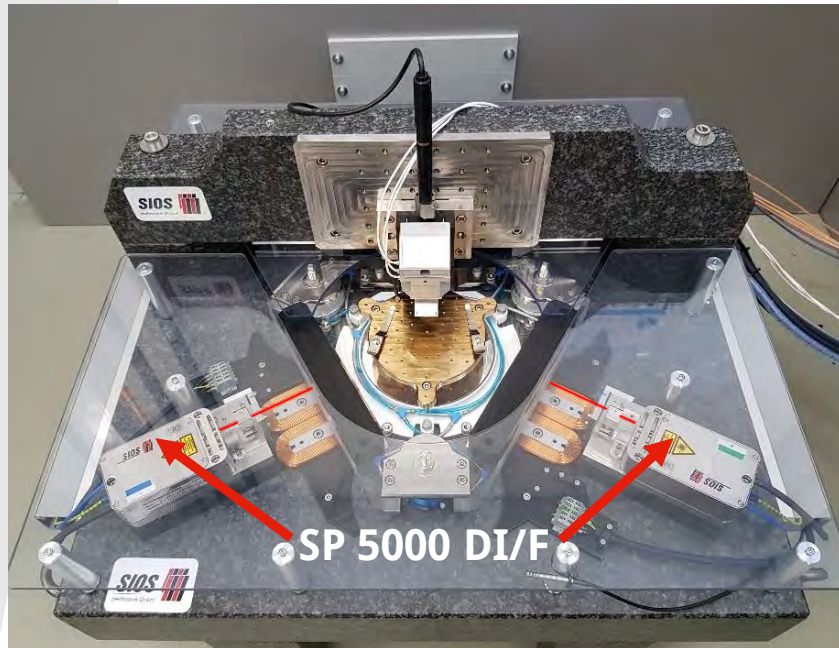
SP 5000 DI/F





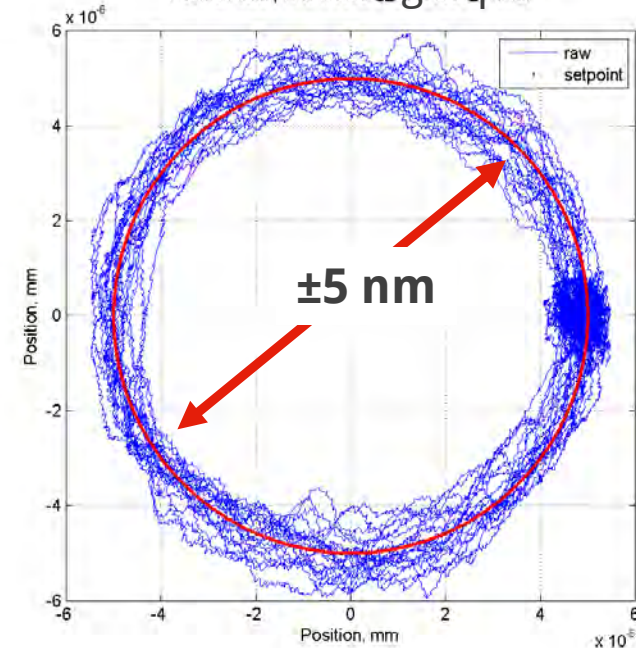
# $\mu$ Positioning Platform

## Positioning capabilities



Travel range  $\varnothing$  100 mm  
Measuring resolution 0.02 nm

### Control and moving capabilities



$E_{y\_rms} = 0.41$  nm  
 $E_{x\_rms} = 0.29$  nm

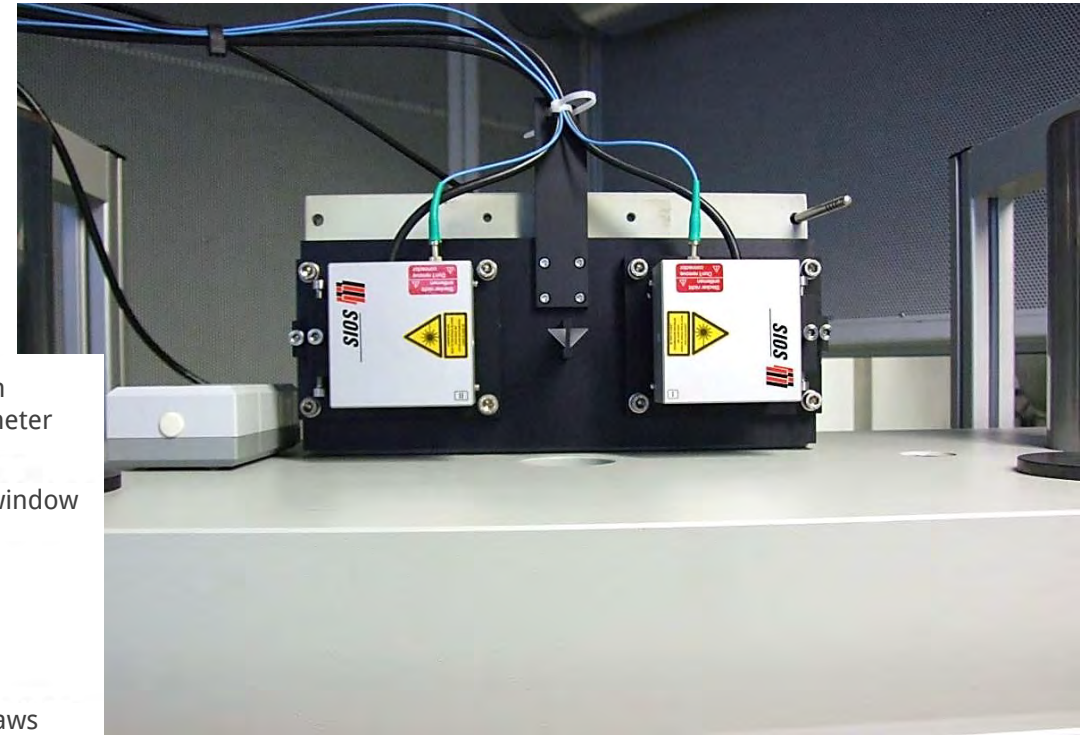
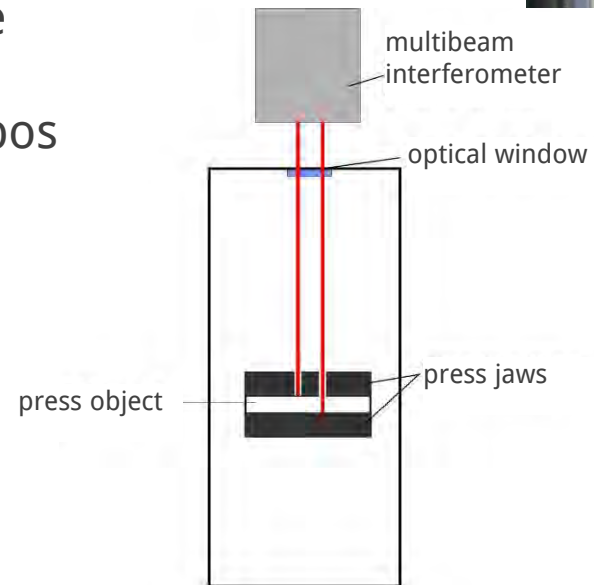
Best positioning performance for entire range

# Customer Application

## Differential measurement in a material testing stand

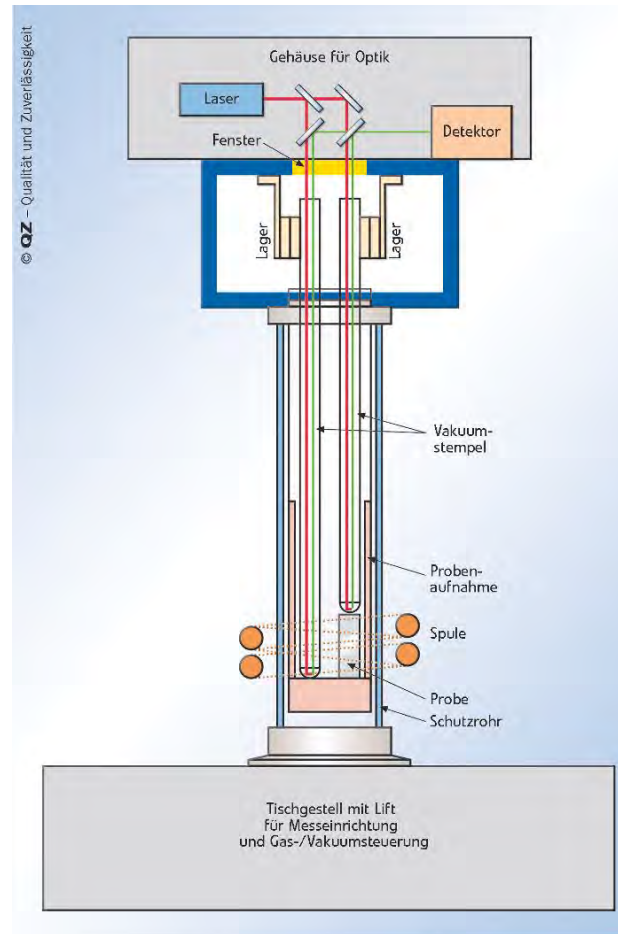
### Solution

- independent adjustment of laser beams by use of two single beam sensors
- beam separation variable
- focusing of laser beams pos



# Customer Application: Dilatometer

Dilatometer for measuring of the thermal expansion coefficient

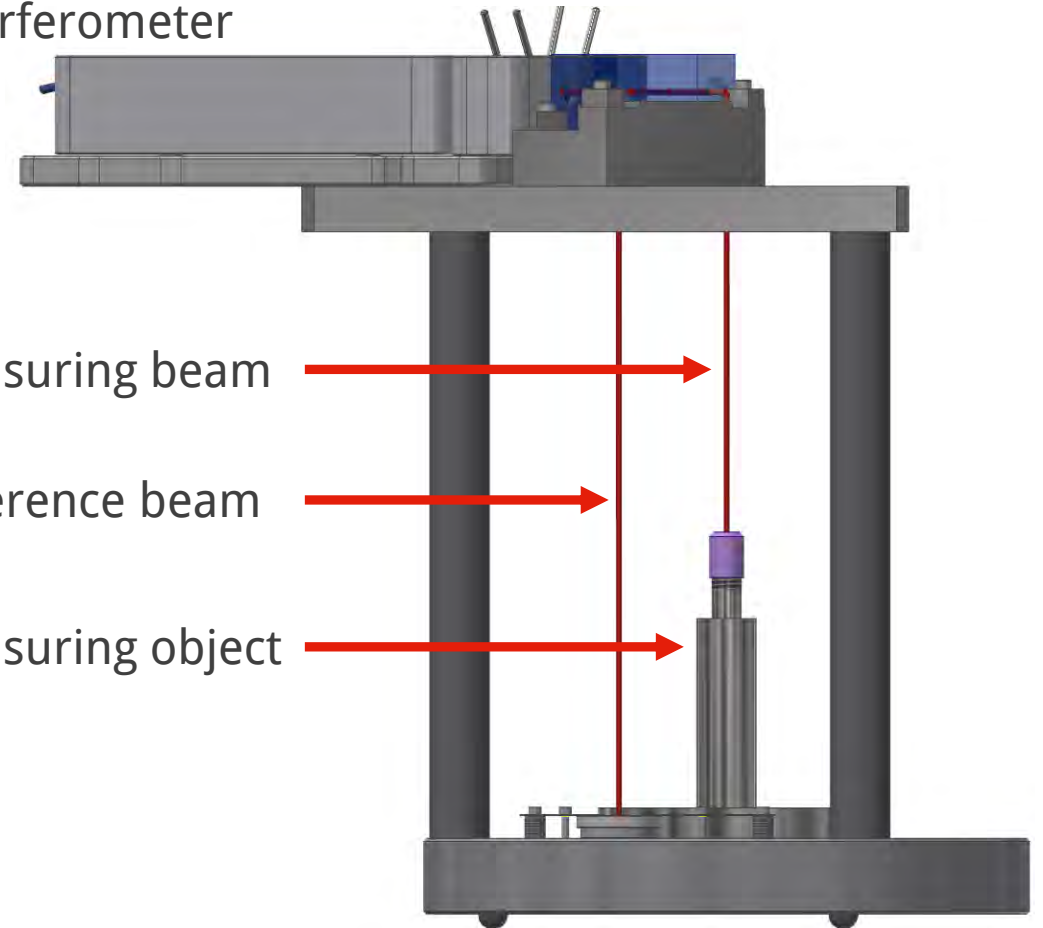


# Determination of Thermal Behavior of Objects

Based on Differential Interferometer



Interferometer



Measuring beam

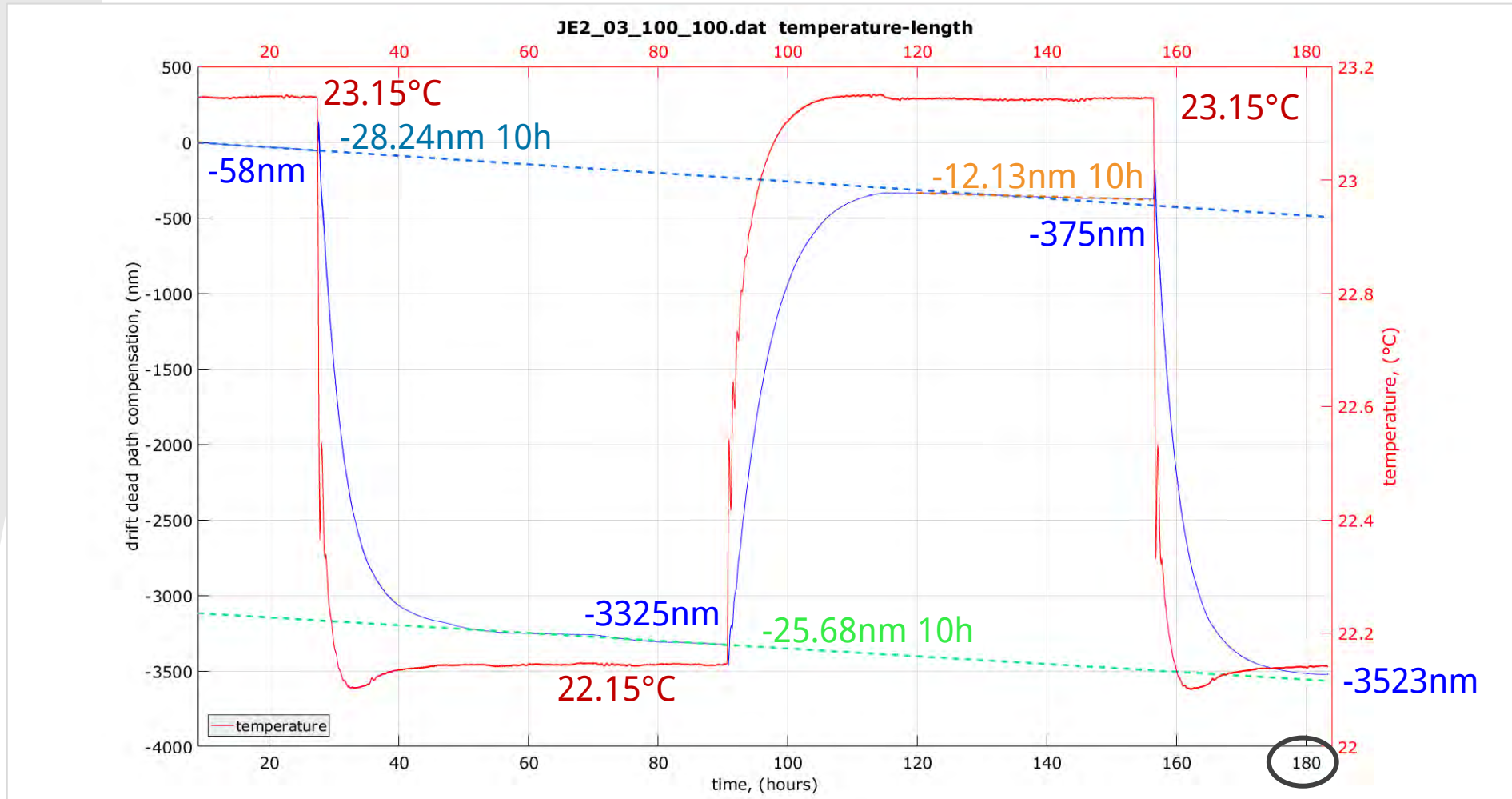
Reference beam

Measuring object

Customer sample

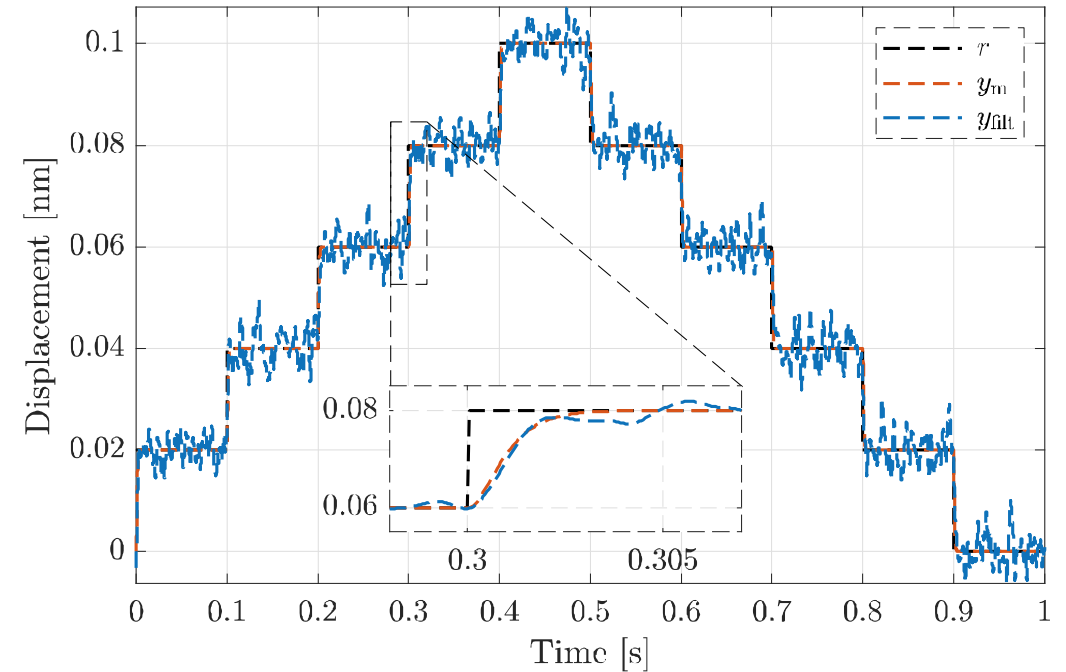
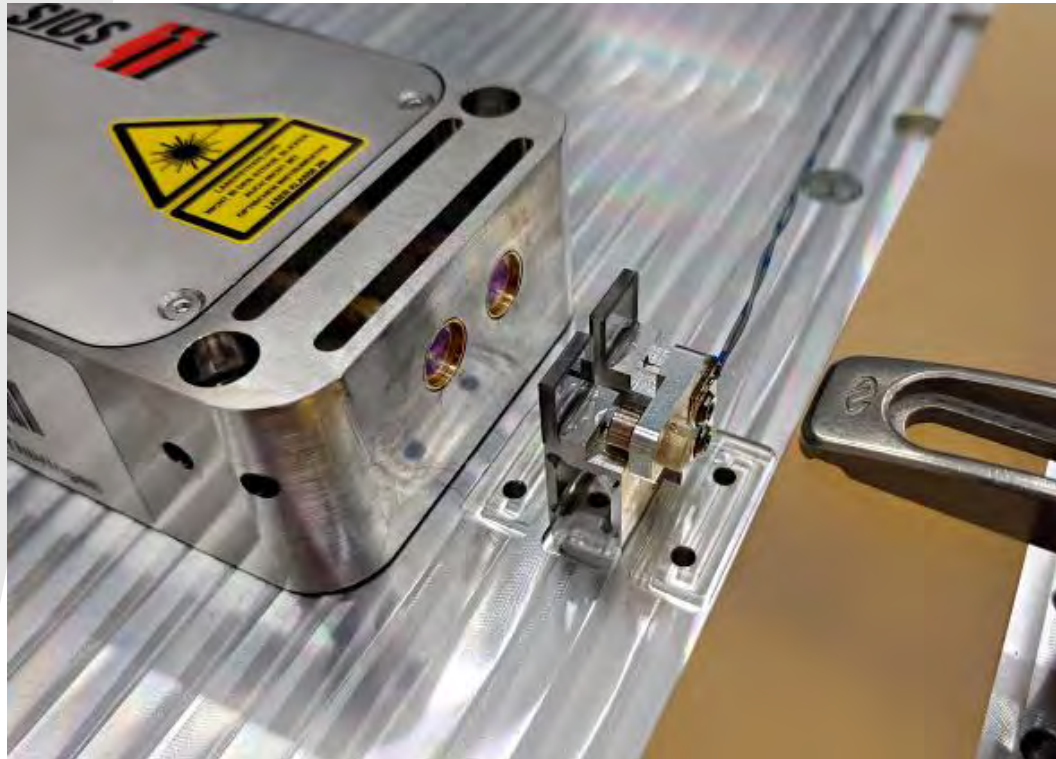
# Determination of Thermal Behavior of Objects

Based on Differential Interferometer



# Picometer-Scale Positioning

of a linear drive system via feedforward-feedback control



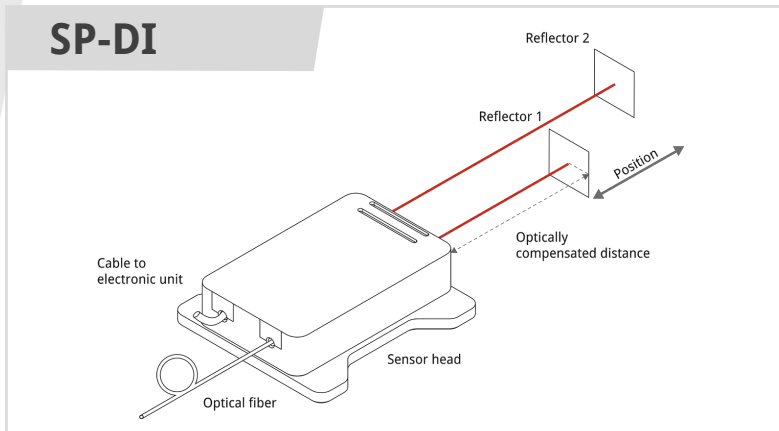
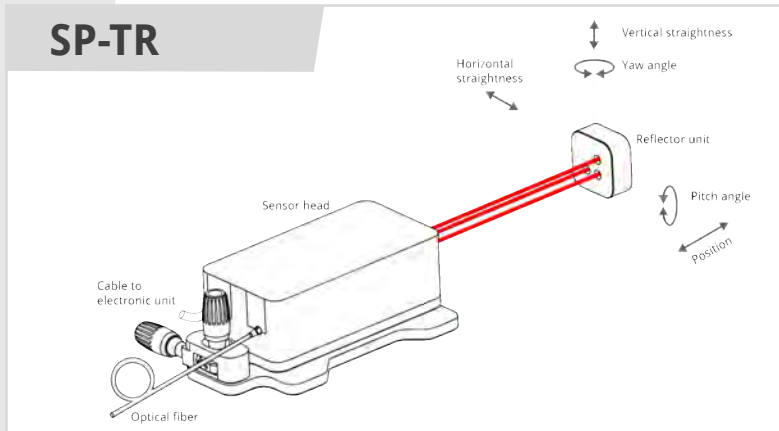
Source: Picometer-Scale Positioning of a Linear Drive System via Feedforward-Feedback Control

Alex S. Huaman, Michael Katzschmann, Steffen Hesse, Christoph Schaffel, Christoph Weise, Denis Dontsov, Eberhard Manske and Johann Reger

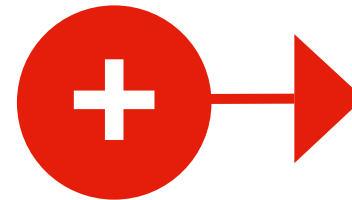
ICM 2021 International Conference of Mechatronics, Japan

# Triple-beam Differential Laser Interferometers

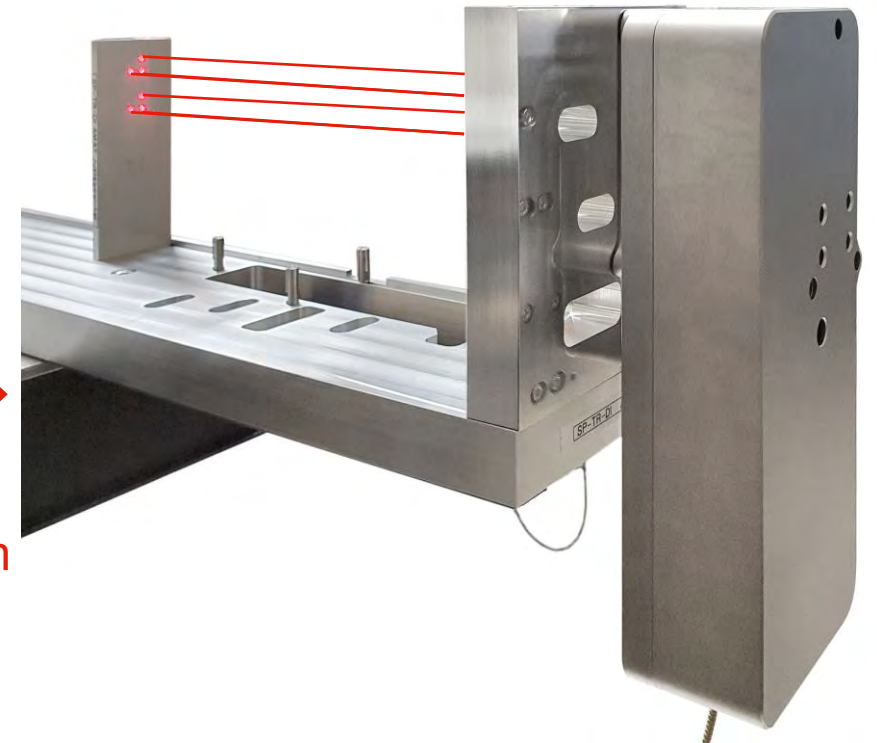
**NEW: length, pitch and yaw by differential principle**



combination of  
differential stability



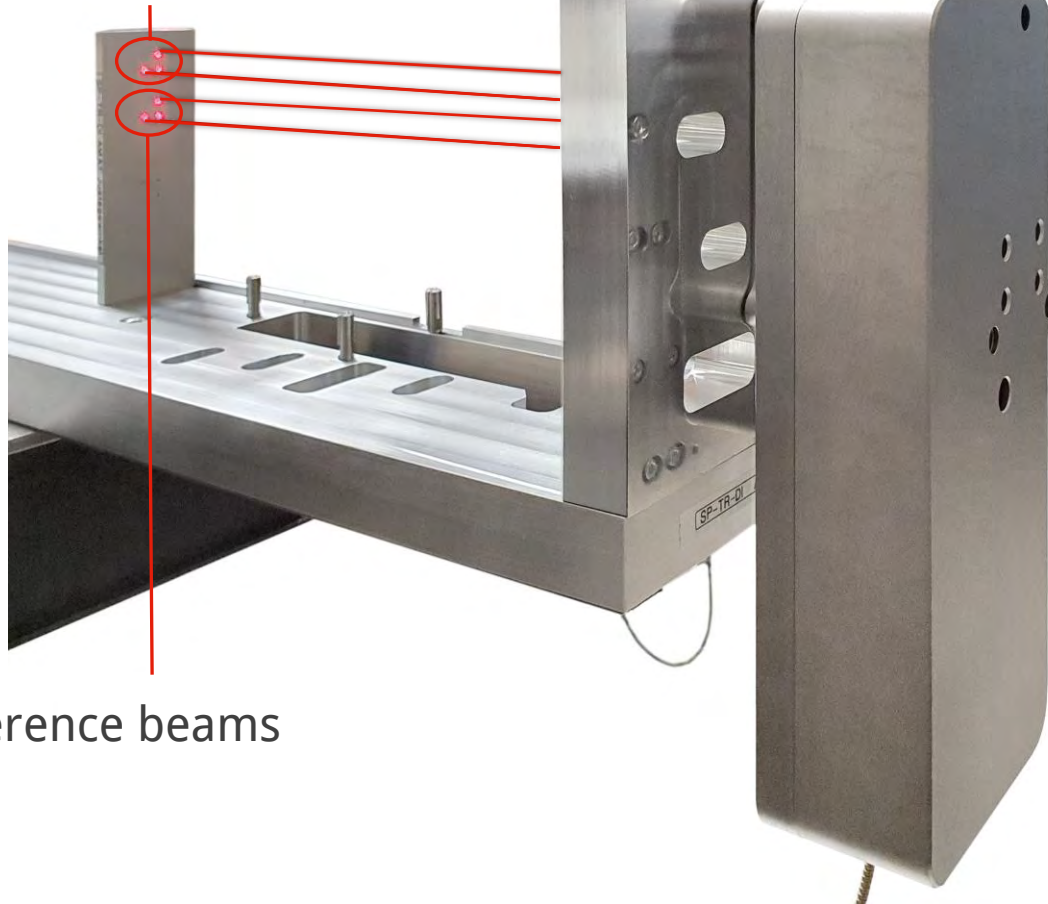
multi-degree of freedom  
measurement



# Triple-beam Differential Laser Interferometers

**NEW: length, pitch and yaw by differential principle**

3 measurement beams



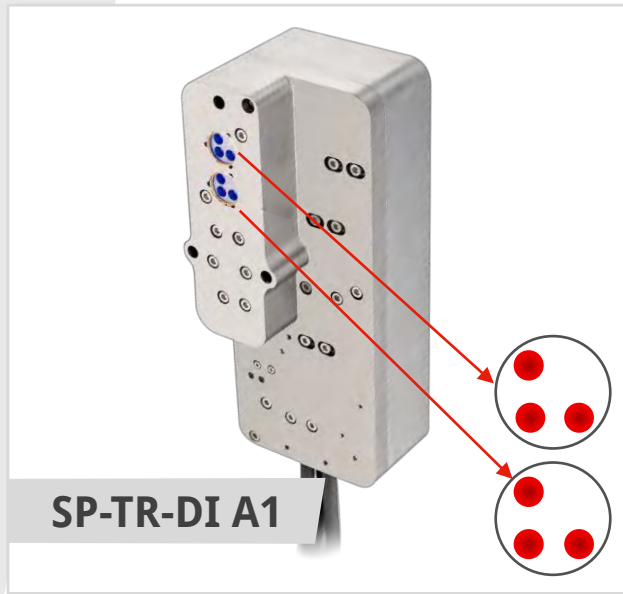
3 reference beams



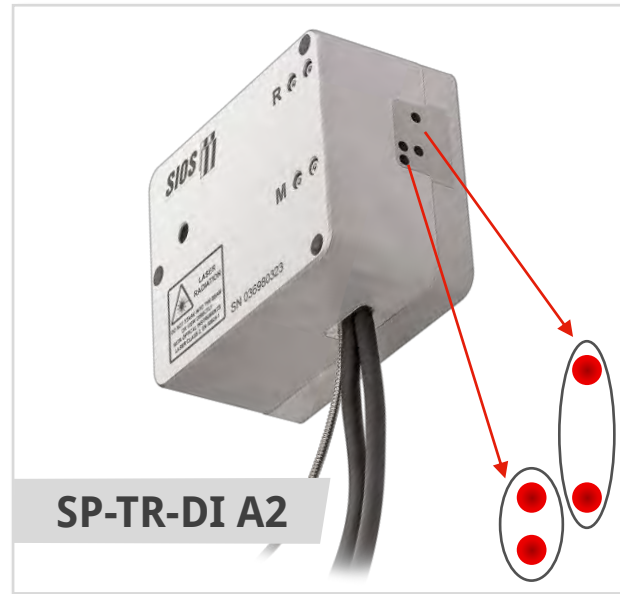


# Multi Beam Differential Interferometers

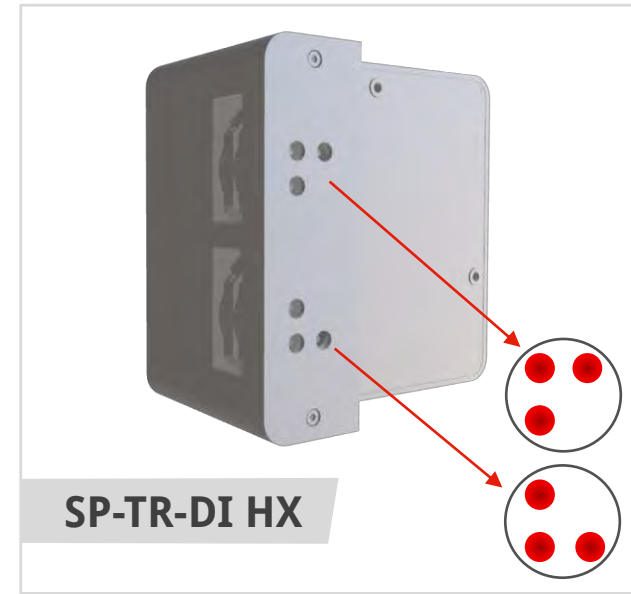
## Differential length and angular measurements



- Triple beam differential
- 6 mm beam distance
- small beam footprint
- compatible to vacuum chamber



- high stable differential length measurements
- interferometric pitch angle measurements
- perfect for x-y stages



- fully differential SP-TR system
- 12 mm beam distance
- suitable for reflector applications

# Low-Tech Hack by Zaber

Which factors influence highly accurate measurement results?

**Zaber Technologies**  
2.228 Follower:innen  
2 Monate • Bearbeitet •

Ever used a low-tech hack in a high-tech test? We have! In a recent test, our LDM linear stage demonstrated exceptional incremental movements of only 4 nanometers (a nanometer is one millionth of a millimeter). To perform measurement ... mehr anzeigen

[Übersetzung anzeigen](#)

Gaby Rösner und 44 weitere Personen  
2 Kommentare • 1 direkt geteilter Beitrag

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Zaber LinkedIn post looking for 4 nm positioning steps under standard lab conditions:

- measurement setup
- environmental conditions

# Low-Tech Hack by Zaber

## Low-tech hack for precision measurements

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Ever used a low-tech hack in a high-tech test? We have! In a recent test, our LDM linear stage demonstrated exceptional incremental movements of only 4 nanometers (a nanometer is one millionth of a millimeter). To perform measurements at such fine resolution, we needed to keep air currents to a minimum in the beam path of our [SIOS Messtechnik GmbH SP 5000 C5 laser interferometer](#). A quick hack was to use an inverted potato chip box as an air barrier.

We'd love to hear some of your "it's not pretty, but it works" hacks in the comments. No judgment!

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using an inverted chip box as an air barrier to quickly minimize airflow

# Low-Tech Hack by Zaber

How can the influencing factors be minimized?



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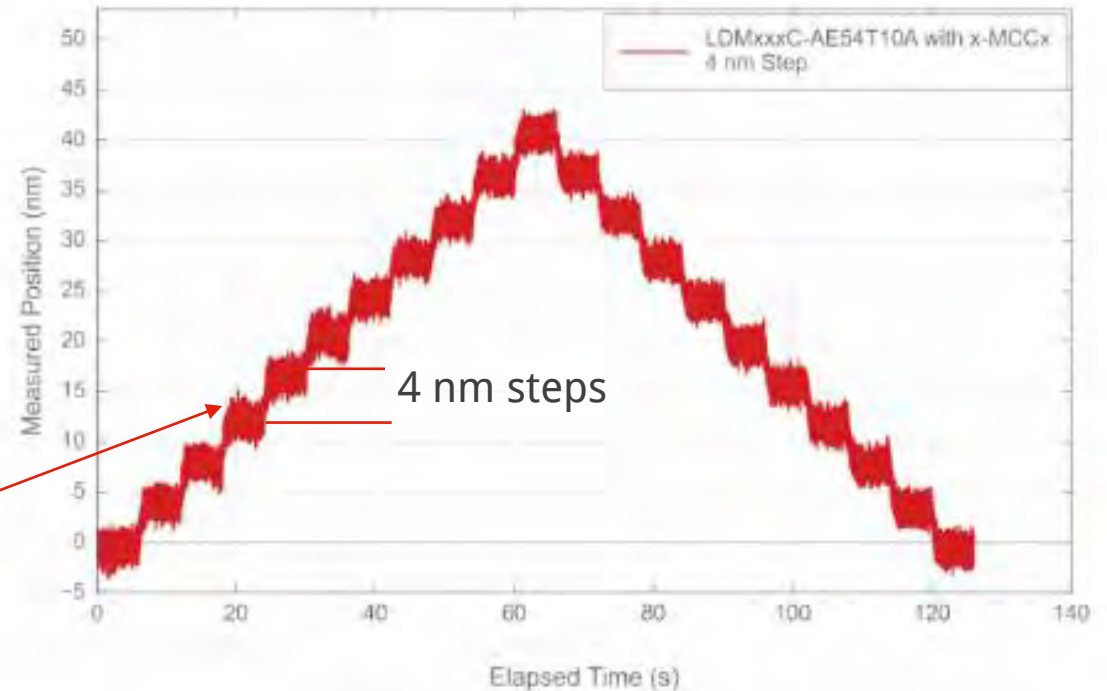
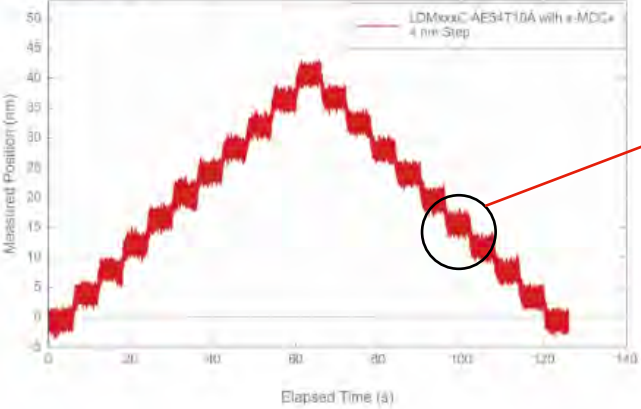


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# SIOS Meßtechnik GmbH

**THANK YOU VERY MUCH FOR YOUR ATTENTION!**

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