An upgraded 50 m 1D facility with refractive index monitoring

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EMRP Project IND53 'LUMINAR‘ End of Project Workshop

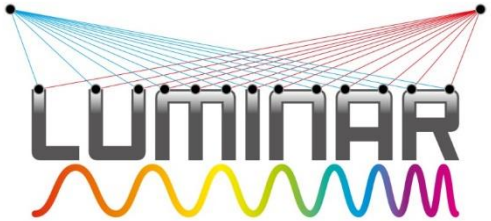
Central Office of Measures (GUM)

www.gum.gov.pl
Elektoralna 2, 00-135 Warsaw, Poland

Central Office of Measures (GUM)

- part of government administration.
- performs tasks in the scope of scientific, industrial and legal metrology.
- In 20 laboratories of GUM, the research is performed that is necessary to establish and modernise measurement standards and to develop certified reference materials.
- 15 national measurement standards (for length, plane angle, temperature, mass, resistance, capacitance, density, pH, refractive index, optical rotation, luminous flux, luminous intensity, time and frequency, inductance, DC voltage);

Length and Angle Department
Length Laboratory



EMRP IND 53 LUMINAR
Large Volume Metrology in Industry

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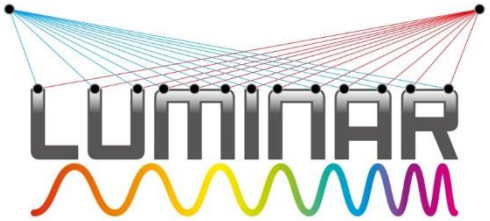
EMRP IND 53 LUMINAR – WP5



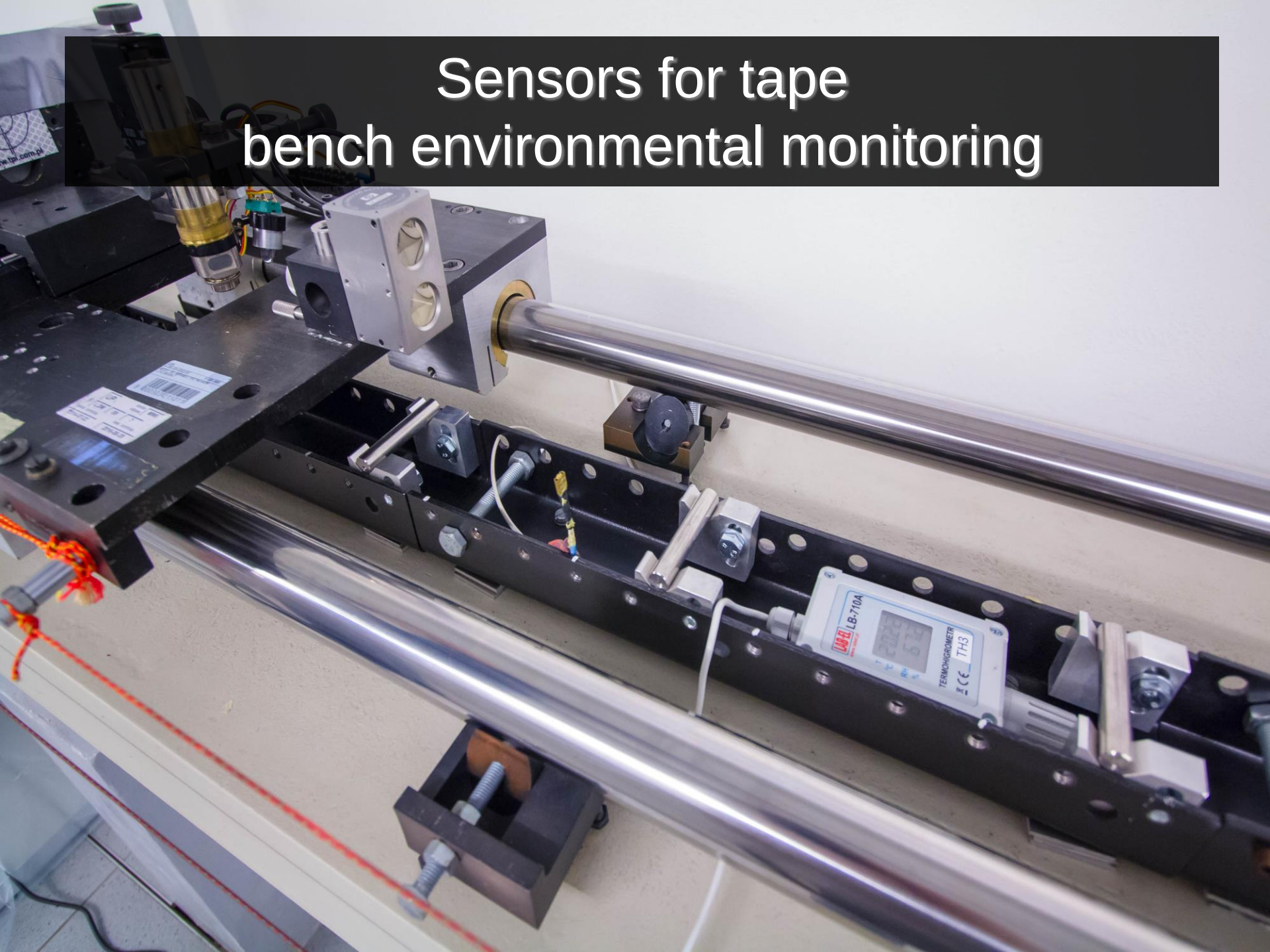
- Verification and demonstration of the capabilities of the developed new technologies, instruments and approaches – mixing measurements at JRP-Partners, with those in real-world industrial environments, and demonstration of how traceable large volume metrology in industrial environments can be achieved practically.

Task 5.1: Preparation of the GUM tape bench environment

Task 5.1: Preparation of the GUM tape bench environment

- The MG tape bench is 50 m long, offer not only a controlled standard environment at 20 °C, but also to simulate industrial environments.
- The method of measurements of the refractive index of air was based on the precise measurements of the environmental conditions (air temperature, relative humidity and atmospheric pressure) using accurate, calibrated, traceable devices. Additional sensors were applied and software for the real time data recording and analysis were developed.

Sensors for tape bench environmental monitoring



Temperature sensors for tape bench environmental monitoring

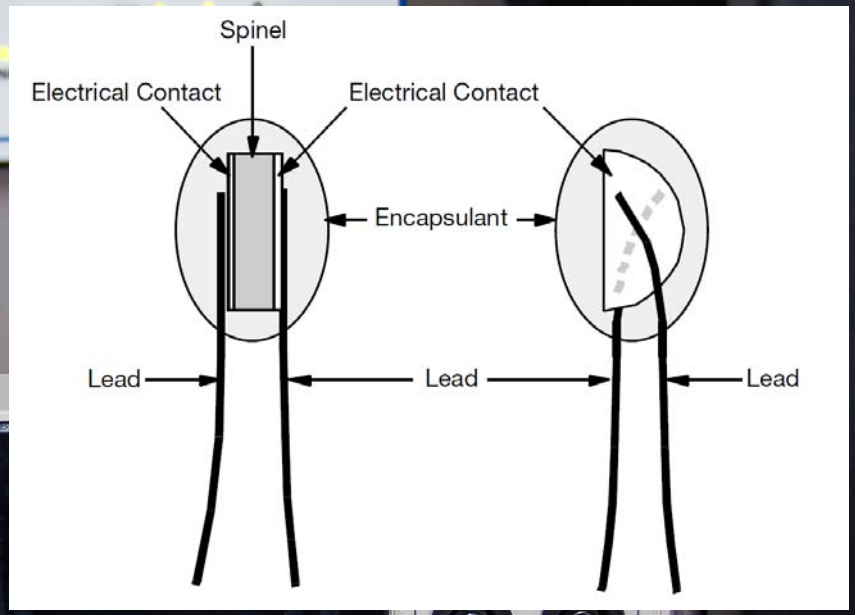
40 thermistors YSI 44031

Temperature: +/- 0,05°C

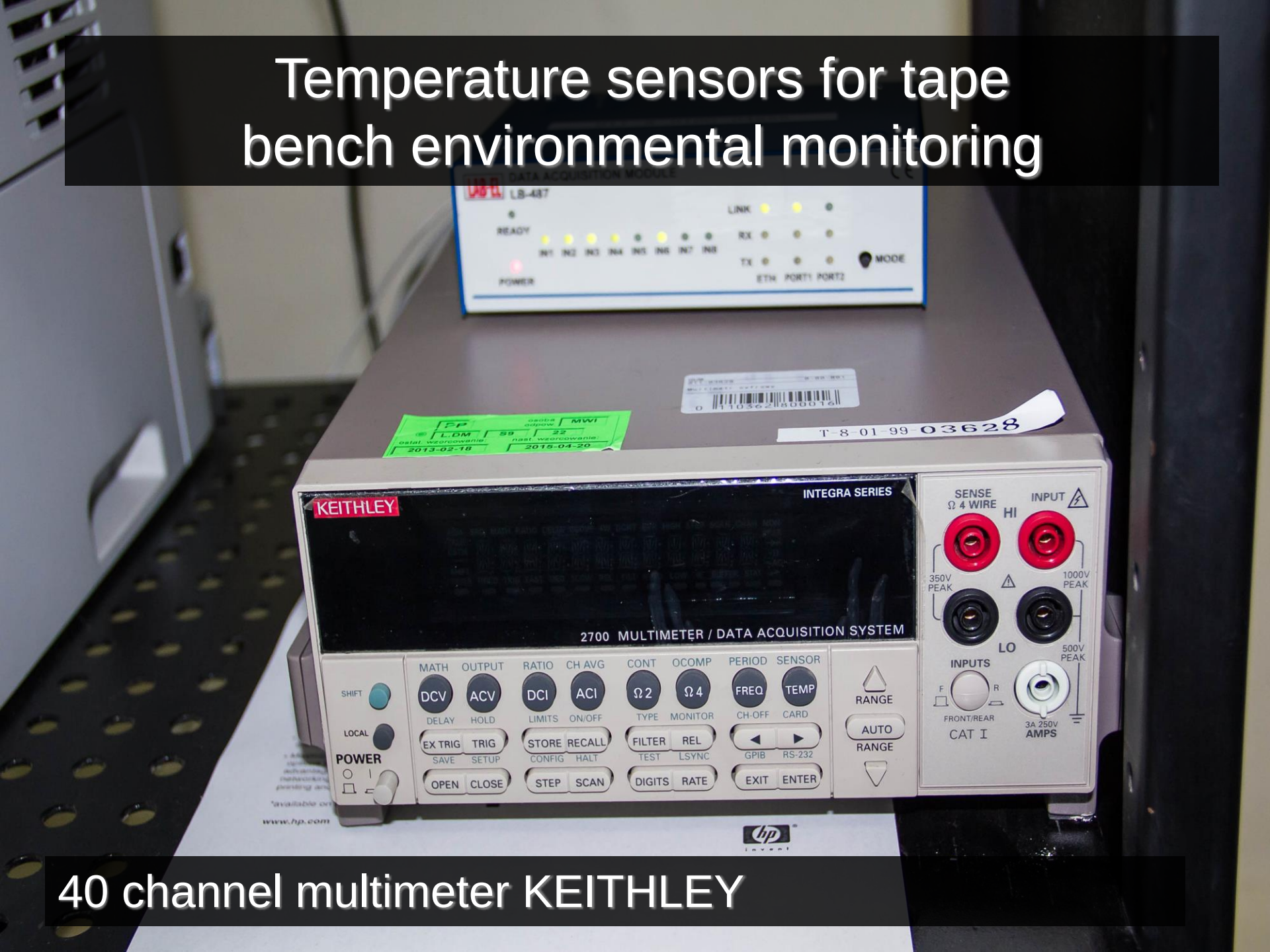
Resistance: 10K Ohm

Range: -0 ÷ 75 °C

Thermal time constant: 1 s



Temperature sensors for tape bench environmental monitoring

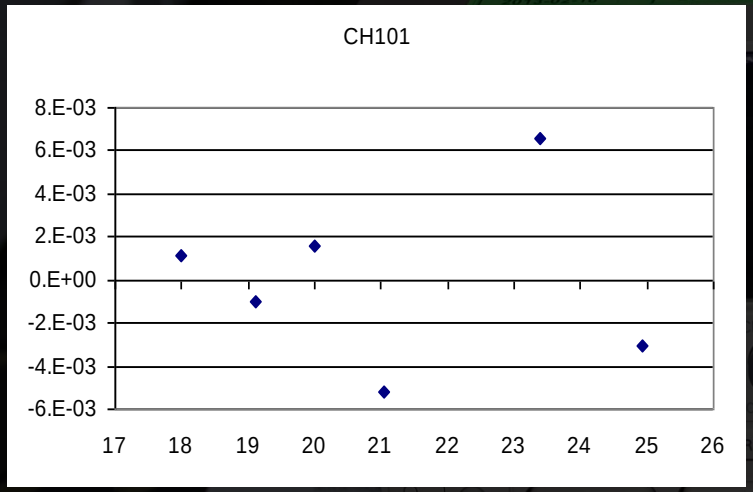


40 channel multimeter KEITHLEY

Temperature sensors for tape bench environmental monitoring

Termistors calibration

$$T = e^{a+b*R}+c$$



wide range of temerature

	a	b	c
CH101	4.206031929	-0.098672494	0.017771382
CH102	4.194857961	-0.099692019	0.515047984
CH103	4.205767398	-0.098163242	-0.070272494
CH104	4.206443882	-0.099337300	0.159070763
CH105	4.210974208	-0.100323040	0.361110074
CH106	4.208100262	-0.099593213	0.212326426
CH107	4.193217233	-0.100618374	0.745973394
CH108	4.199373170	-0.099242341	0.283308290
CH109	4.201097102	-0.098816906	0.164270602
CH110	4.191745773	-0.099582187	0.558452706
CH111	4.209253922	-0.098826072	0.040213851
CH112	4.198108996	-0.100624975	0.620169677
CH113	4.197569320	-0.101219905	0.837823148
CH114	4.200007469	-0.099409685	0.313593872
CH115	4.201497391	-0.099064231	0.265704275
CH116	4.197542021	-0.099360239	0.372576205
CH117	4.201792014	-0.099007625	0.225982958
CH118	4.207395468	-0.098695529	0.009555664
CH119	6.434561601	-0.398262086	15.486405010
CH120	4.189241830	-0.095641315	-0.370385645

Termohigrometers sensors for tape bench environmental monitoring

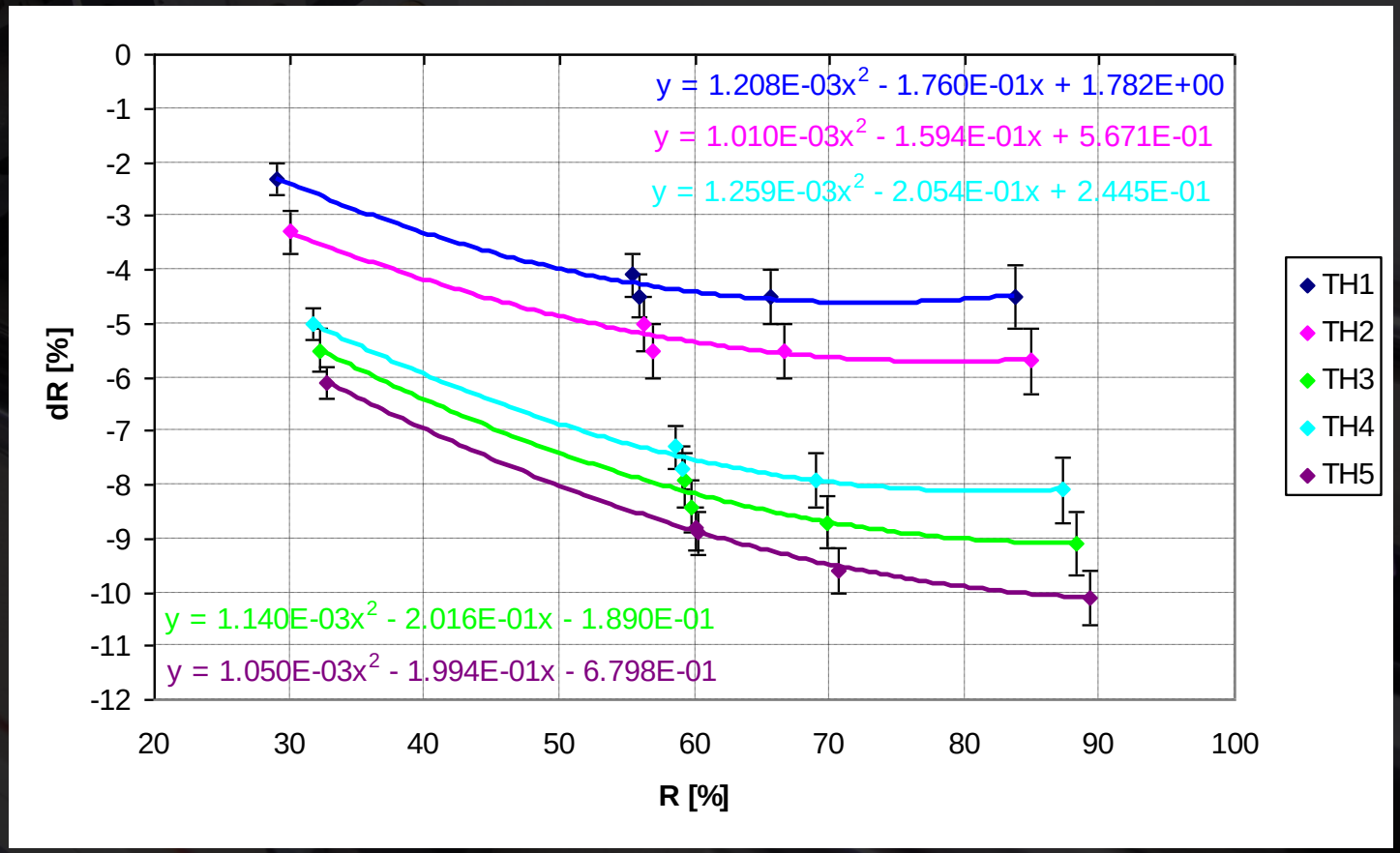
5 Termohigrometers

LAB-EL LB-710A

- Temperature (Pt-1000) +/- 0,1°C
- Humidity +/- 0,2 %

Termohigrometers sensors for tape bench environmental monitoring

Termohigrometers calibration



Air pressure sensor for tape bench environmental monitoring

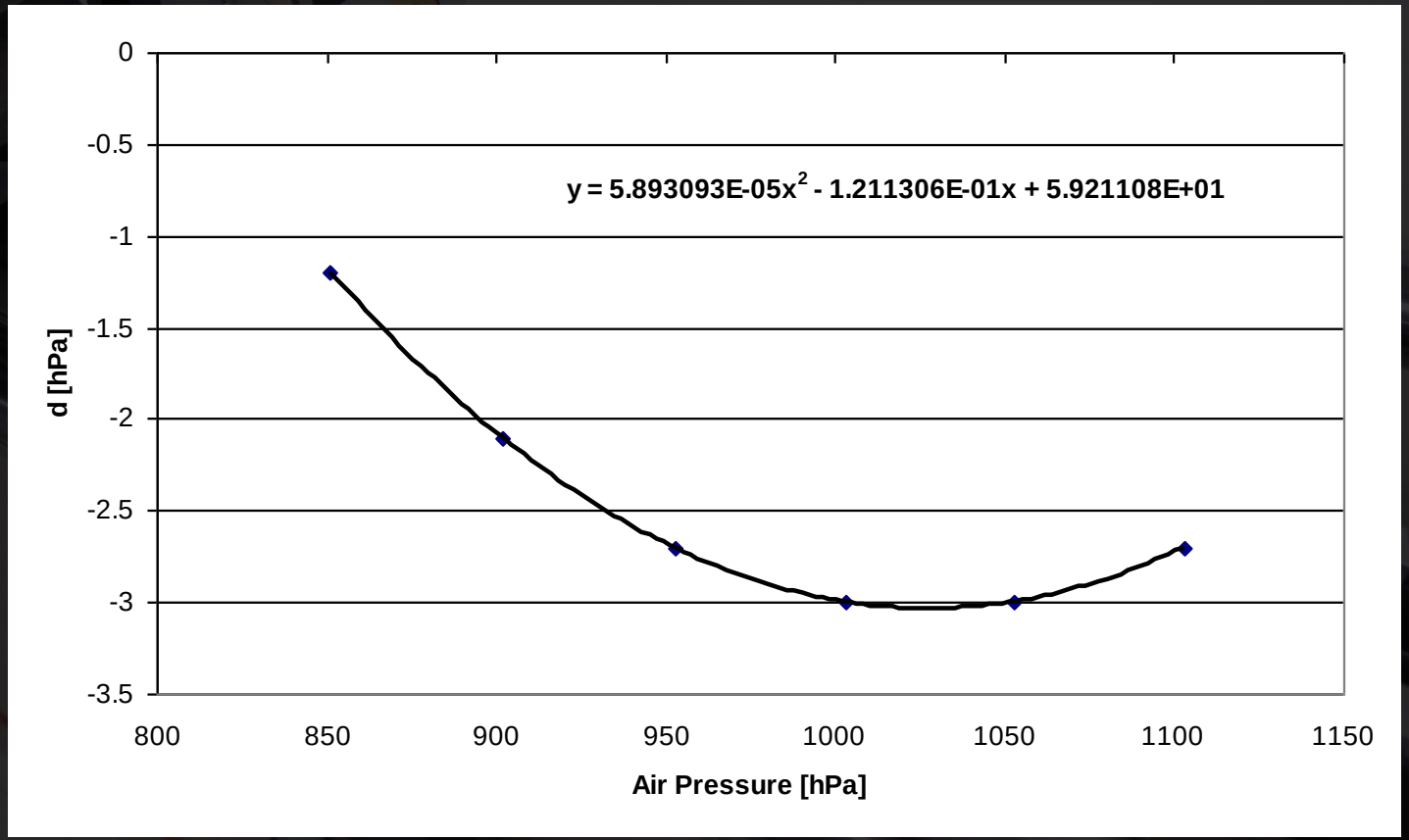
1 Barometer

LAB-EL LB-716

- air pressure +/- 1,0 hPa

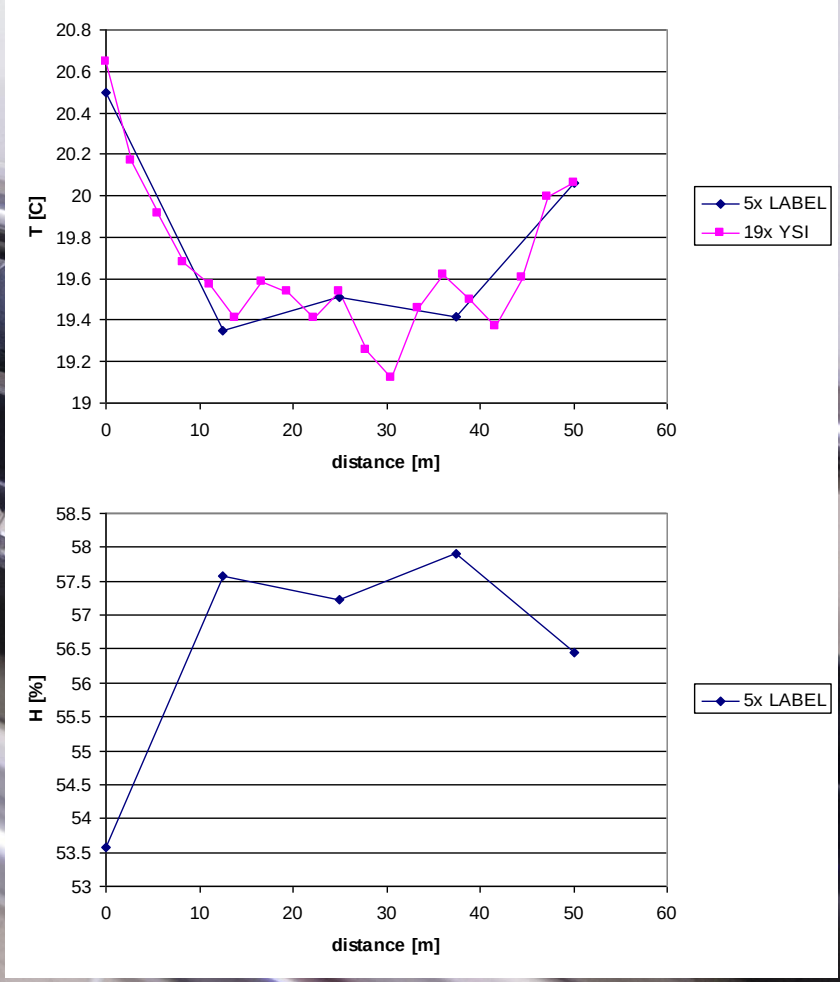
Air pressure sensor for tape bench environmental monitoring

Barometer calibration



Air pressure sensor for tape bench environmental monitoring

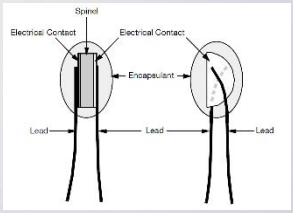
- Estimation of *u*(n) for 50 m tape bench
  - *u*(T) = 0.05 °C
  - *u*(H) = 0.6 %
  - *u*(P) = 1.0 hPa
  - *u*(CO_2) = 45 ppm
  - **$u(n) = 4.2\ 10^{-7}$**



All sensors for tape bench environmental monitoring

40 thermistors YSI 44031

- Temperature: +/- 0.05°C



5 Termohigrometers LAB-EL LB-710A

- Humidity +/- 0.2 %
- Temperature (Pt-1000) +/- 0.1°C

1 Barometer LAB-EL LB-716

- air pressure +/- 1.0 hPa

Estimation: $u(n) = 4.2\ 10^{-7}$ for 50 m tape bench

Temperature conditions in industry

- Typical location in industry
  - gradient 3.5 - 6.2 °K
- Industrial areospace assembly site
  - gradient 1-3 °K
- Industry production hall
  - gradient 1.5 °K
- PTB’s reference wall
  - gradient 0.1 °K/m

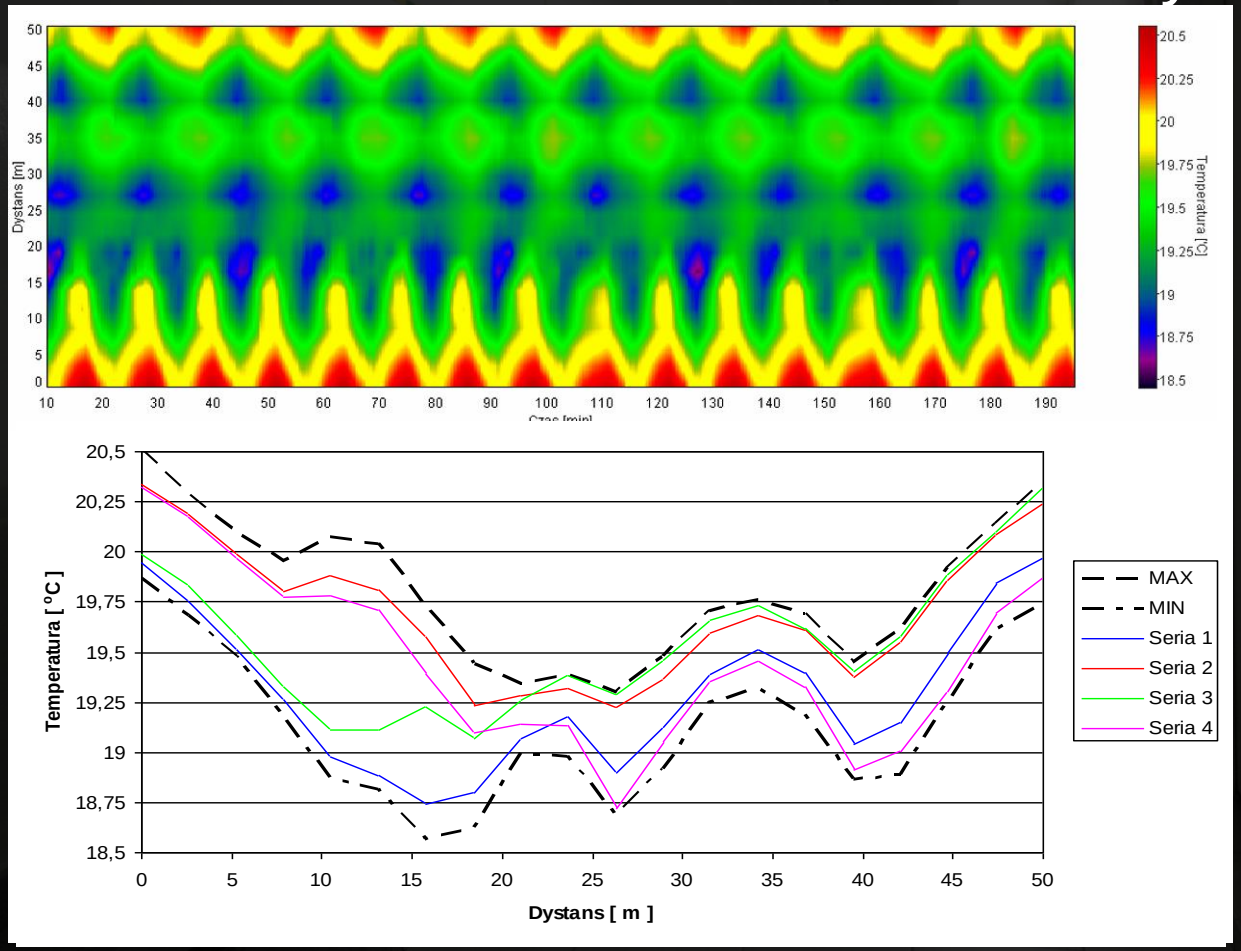
Simulation of industrial environment

GUM prepared the laboratory room for the experiments with industrial environmental conditions:

- fast and large amplitude temperature changes,
- large temperature gradient,
- air turbulences.

Simulation of industrial environment

Two air conditioners at both ends of laboratory

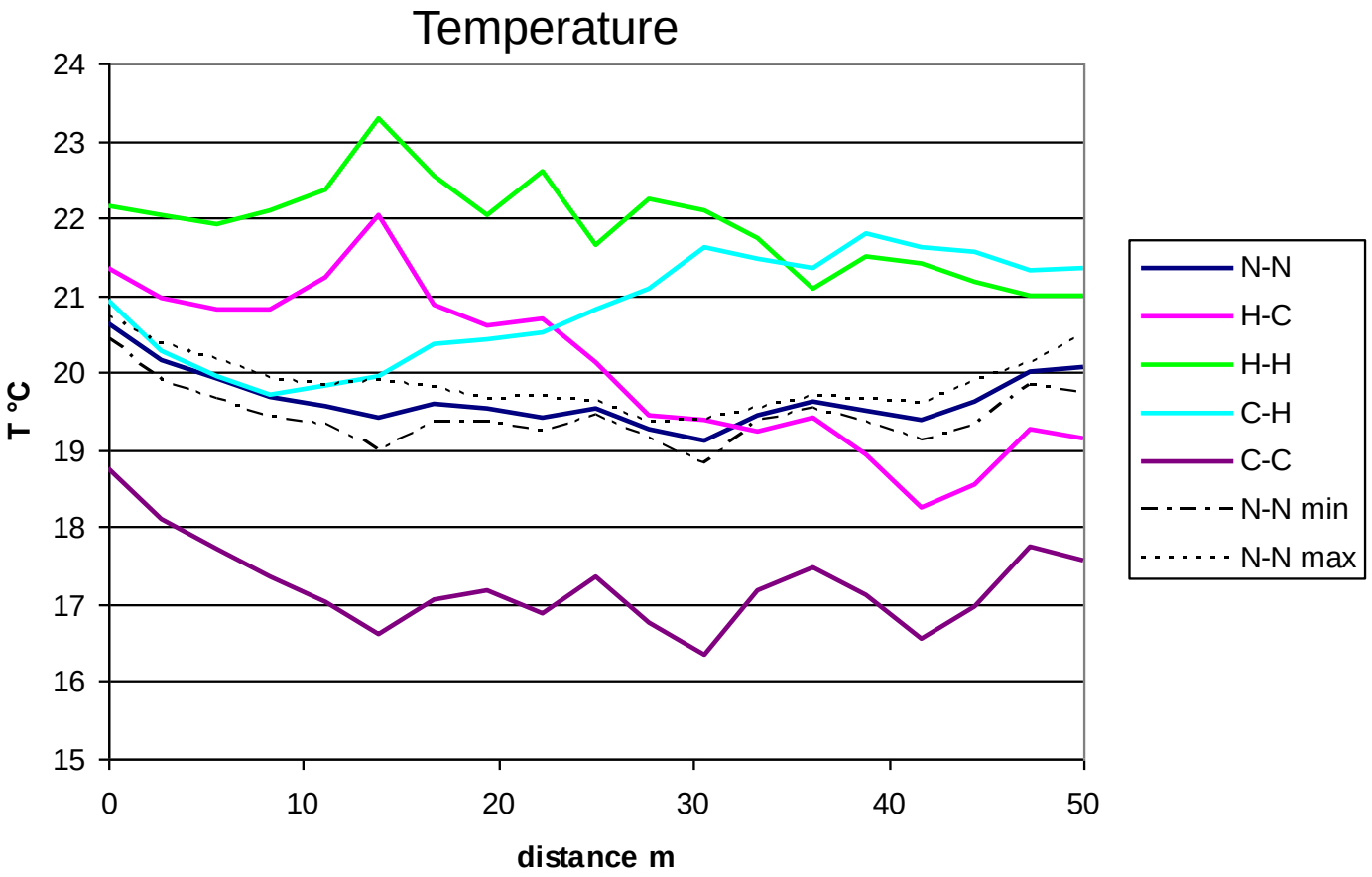


Simulation of industrial environment

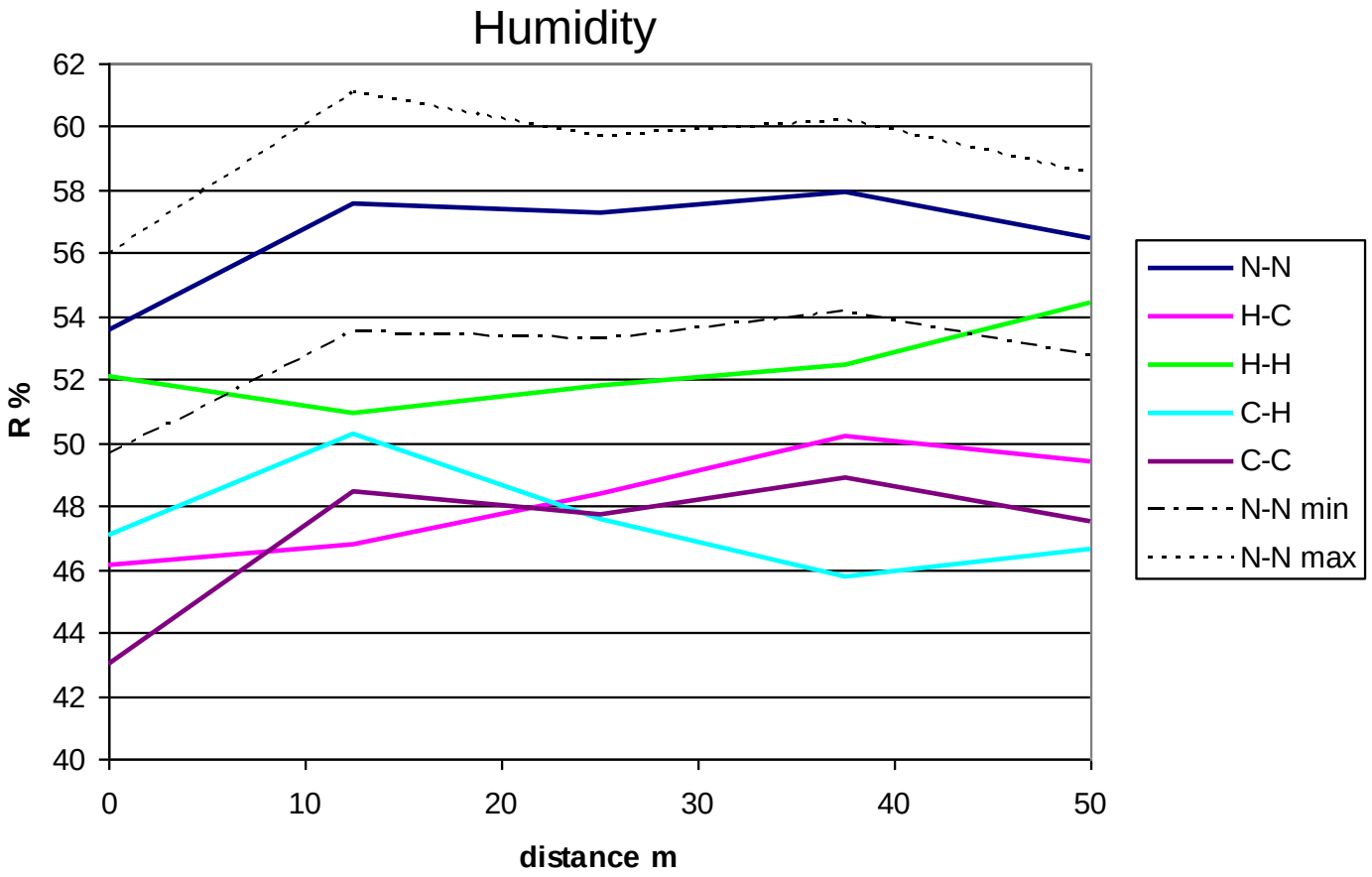
Air conditioners settings:

- Flat (stable) 20-20 °K
- Gradient 25-15 °K
- Flat (hot) 25-25 °K
- Gradient 15-25 °K
- Flat (cold) 15-15 °K

Simulation of industrial environment



Simulation of industrial environment



Simulation of industrial environment

Air conditioners settings vs results after 2 hours:

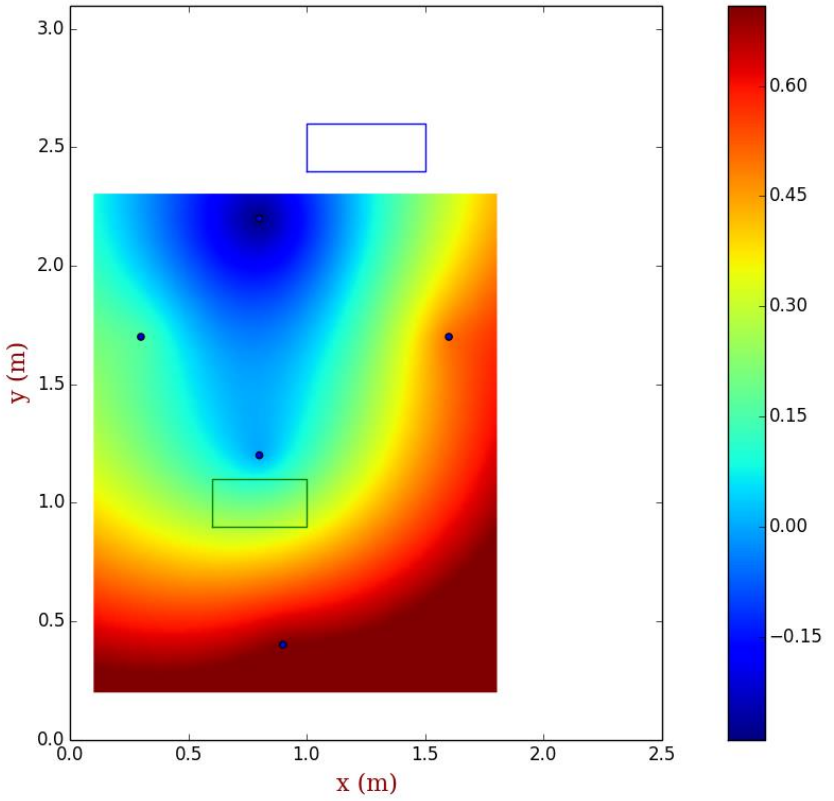
- Flat (stable) 20-20 °K - 20.4-19.5 °K
- Gradient 25-15 °K - 22.1-18.2 °K
- Flat (hot) 25-25 °K - 23.5-21.0 °K
- Gradient 15-25 °K - 19.7-21.7 °K
- Flat (cold) 15-15 °K - 18.7-16.3 °K

Simulation of industrial environment

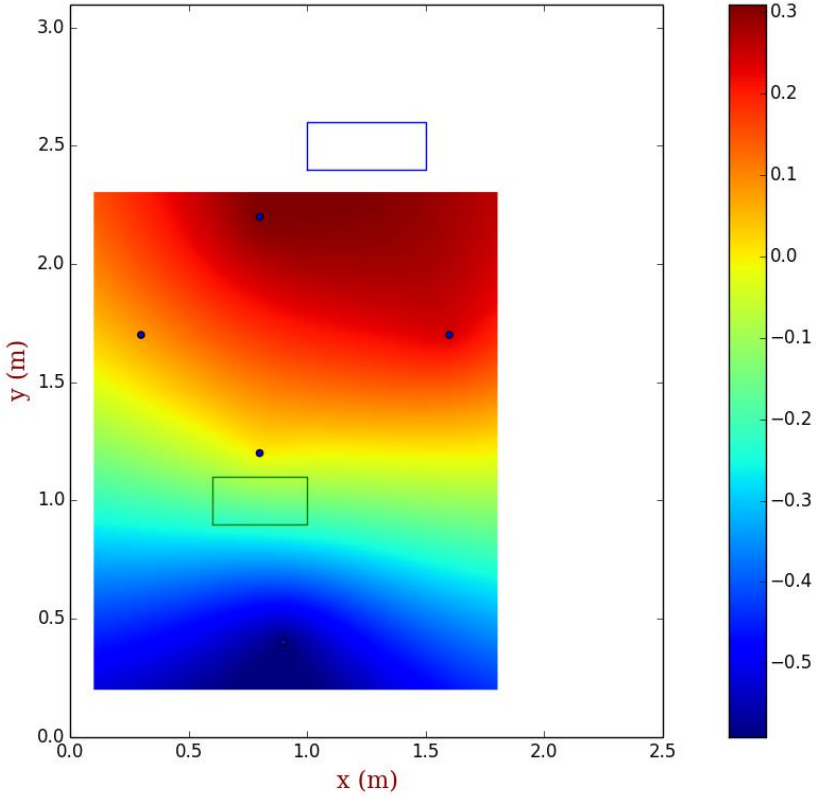
- Stable
  - Difference 50m - 1 °K, 7.8 %
  - Difference 10m - 1 °K, 7.8 %
  - Gradient - 0.1 °K/m, 0.16 %/m
- Max
  - Difference 50m - 3.9 °K, 6.7 %
  - Difference 10m - 2.3 °K, 5.9 %
  - Gradient - 0.4 °K/m, 0.23 %/m

Simulation of industrial environment

Humidity



Temperature

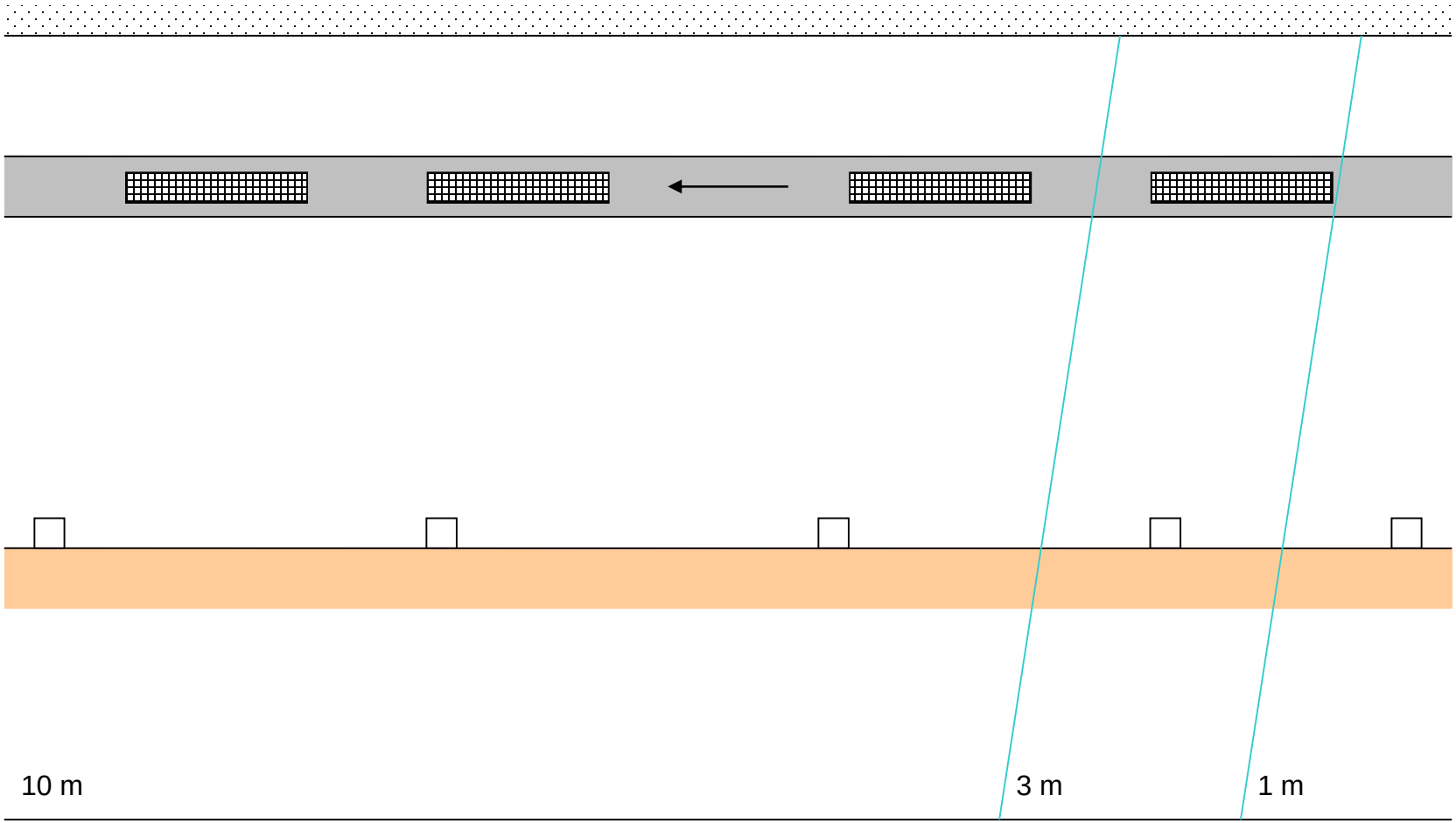


Simulation of industrial environment

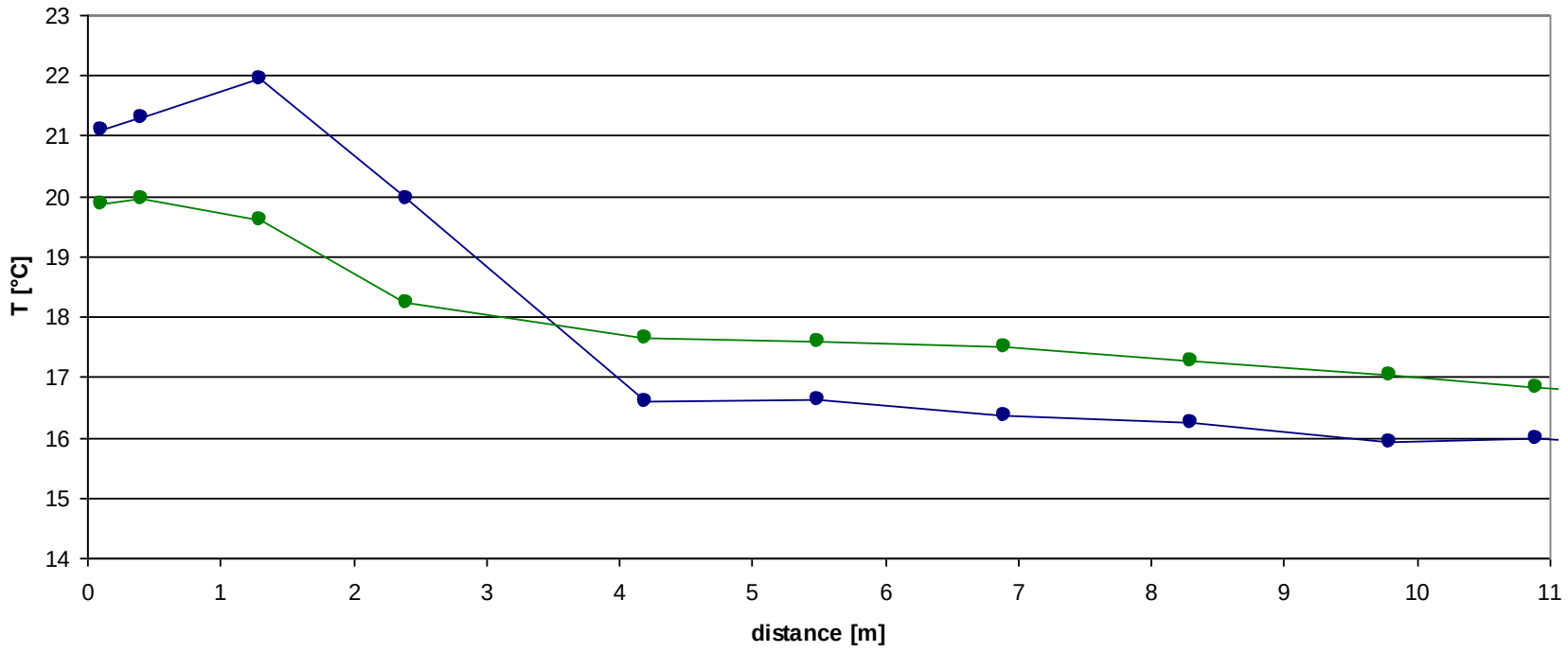
- 2x 2kW heaters HB CH-2004ST

Simulation of industrial environment

Simulation of industrial environment

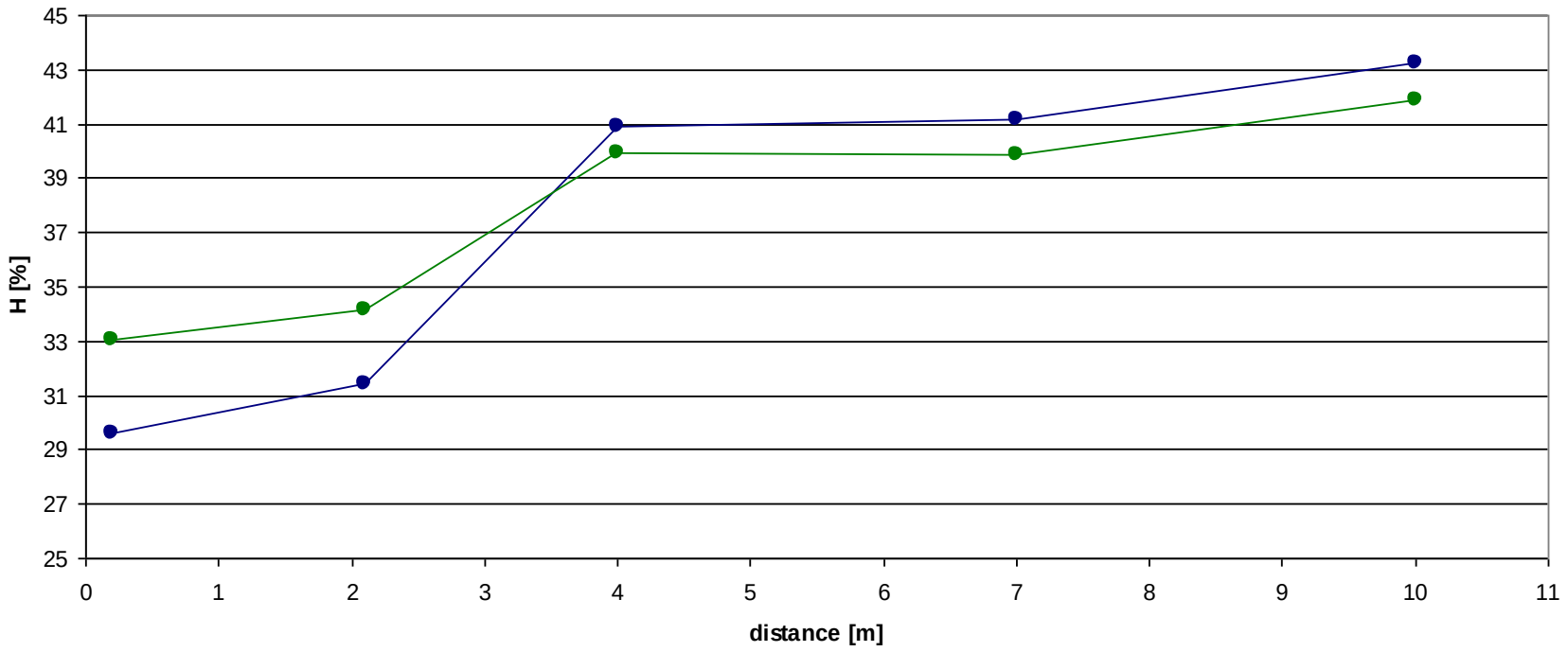


Simulation of industrial environment



10 m gradient: 3.8 °K -> 6.3 °K

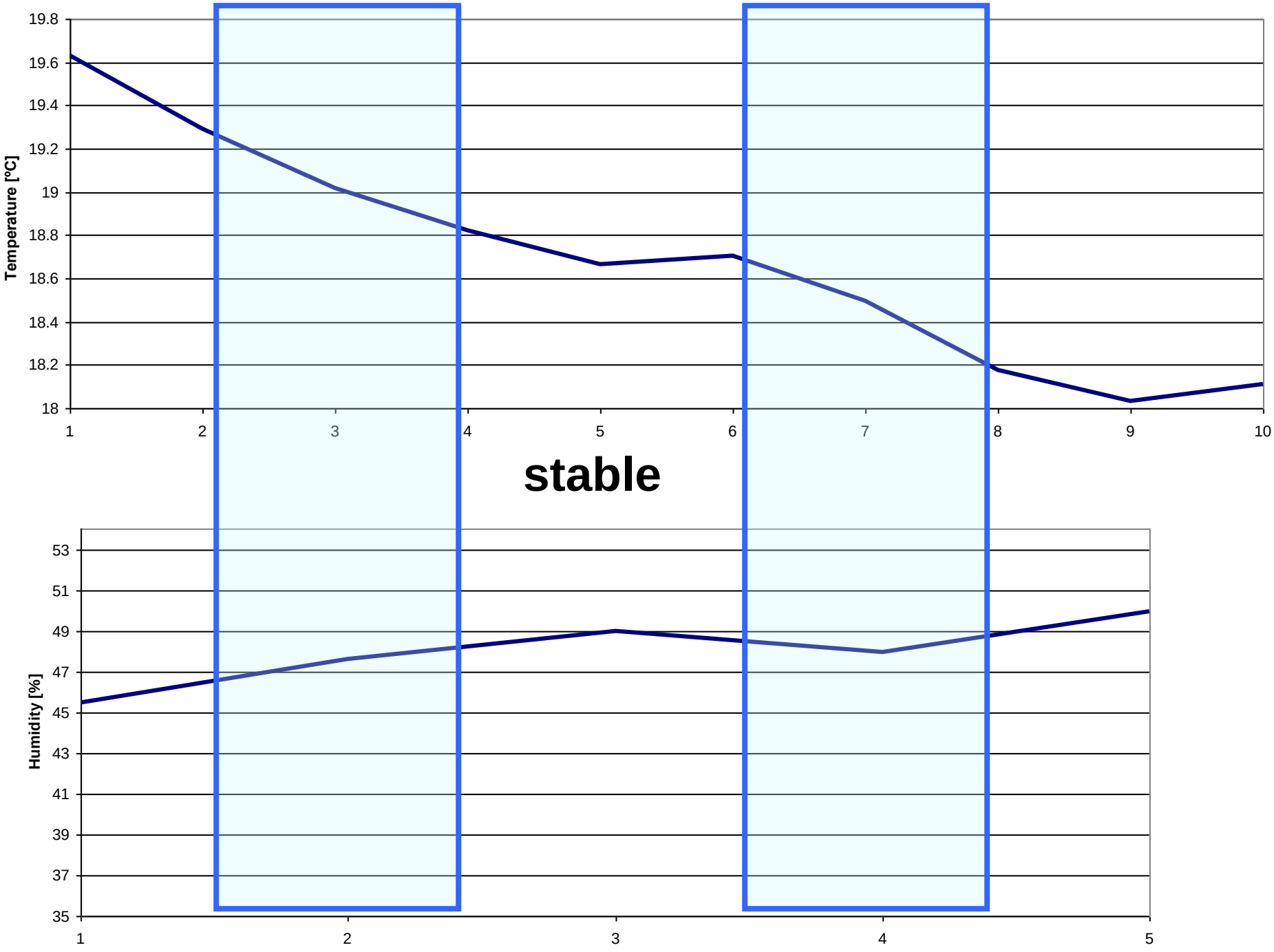
Simulation of industrial environment

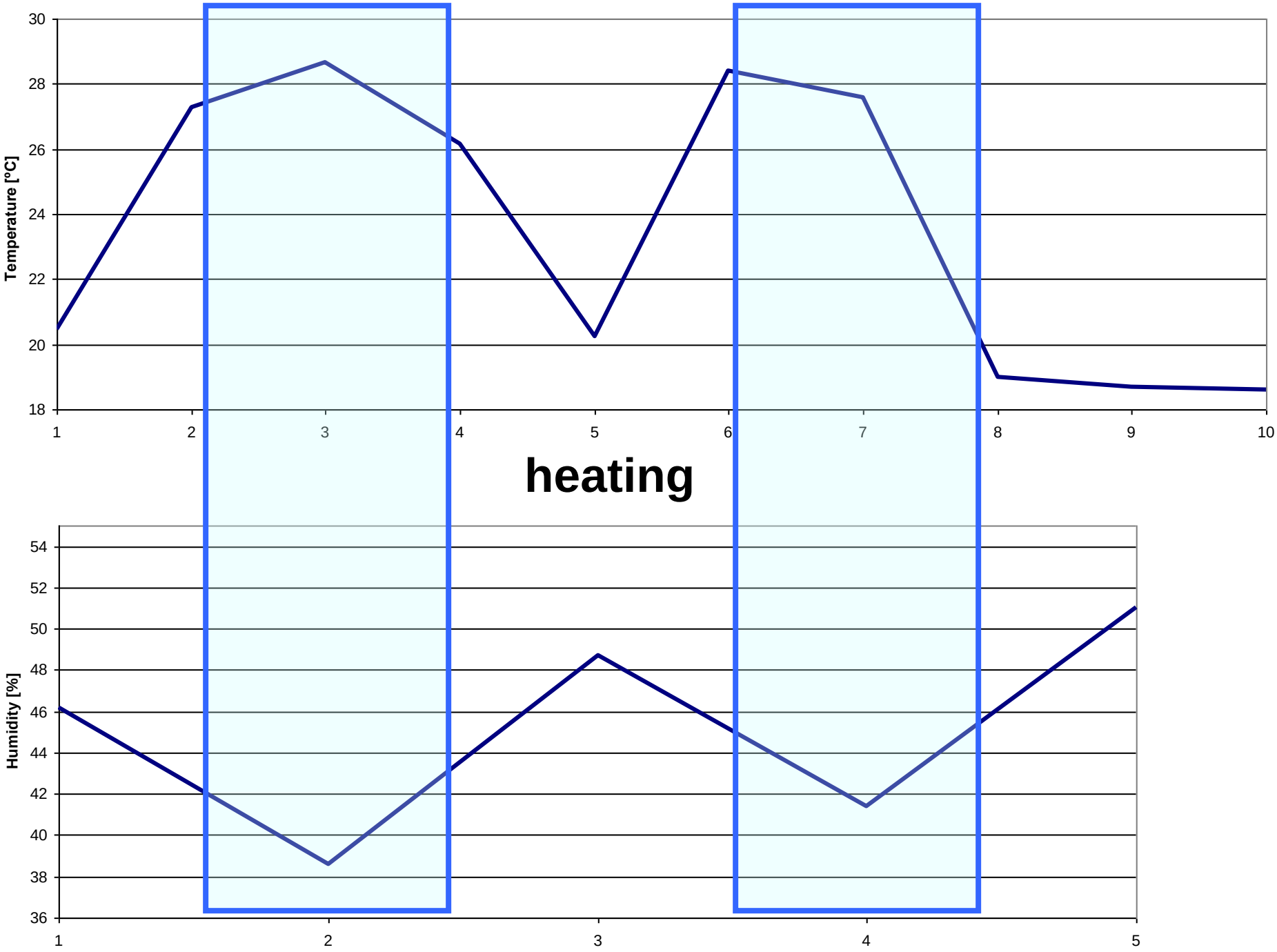


10 m gradient: 8,8 % -> 13.6 %

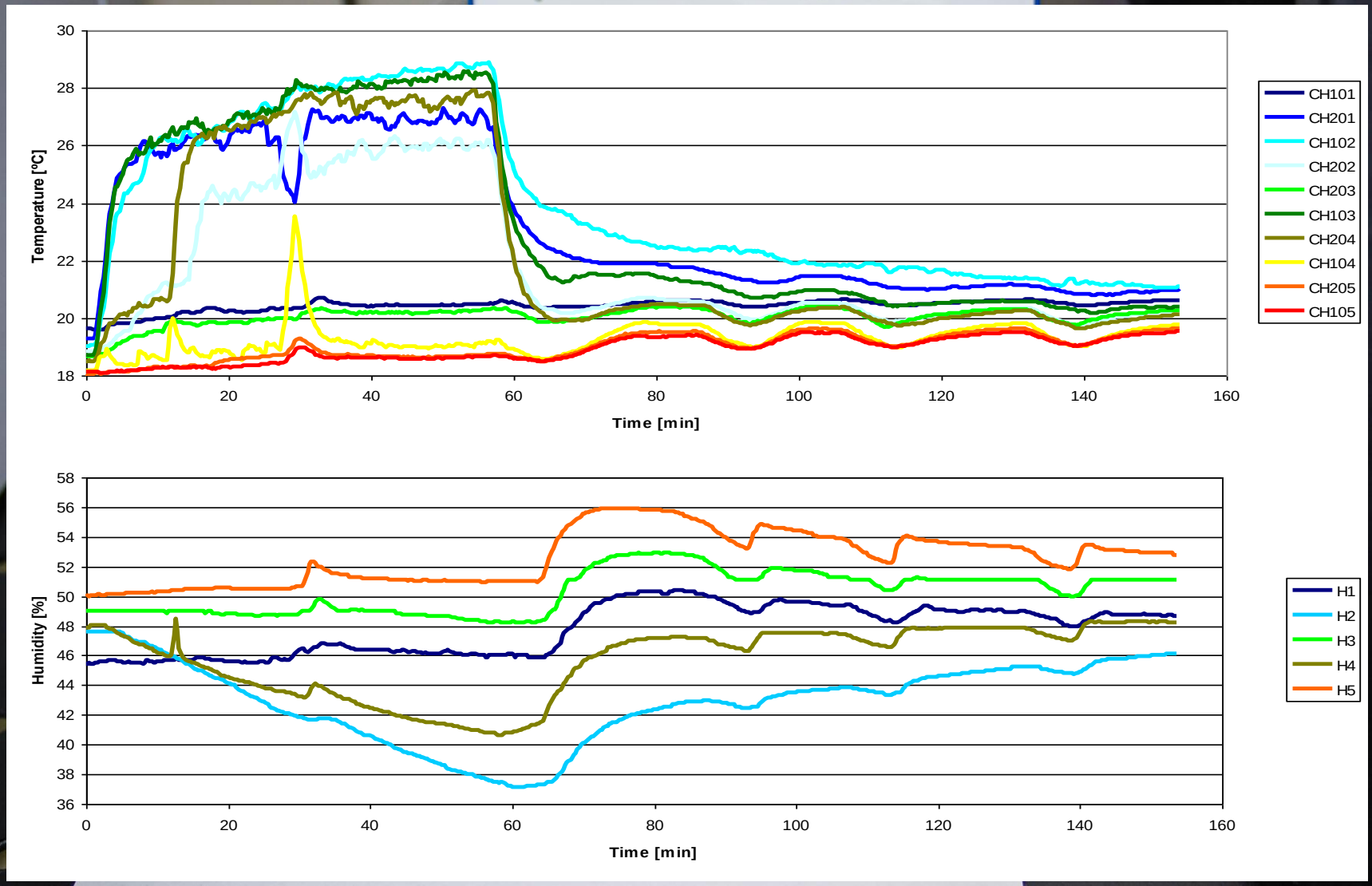
Simulation of industrial environment

Simulation of industrial environment


Temperature [ºC]
19.8
19.6
19.4
19.2
19
18.8
18.6
18.4
18.2
18
1
2
3
4
5
6
7
8
9
10
stable
Humidity [%]
53
51
49
47
45
43
41
39
37
35
1
2
3
4
5


Temperature [°C]
30
28
26
24
22
20
18
1
2
3
4
5
6
7
8
9
10
heating
Humidity [%]
54
52
50
48
46
44
42
40
38
36
1
2
3
4
5

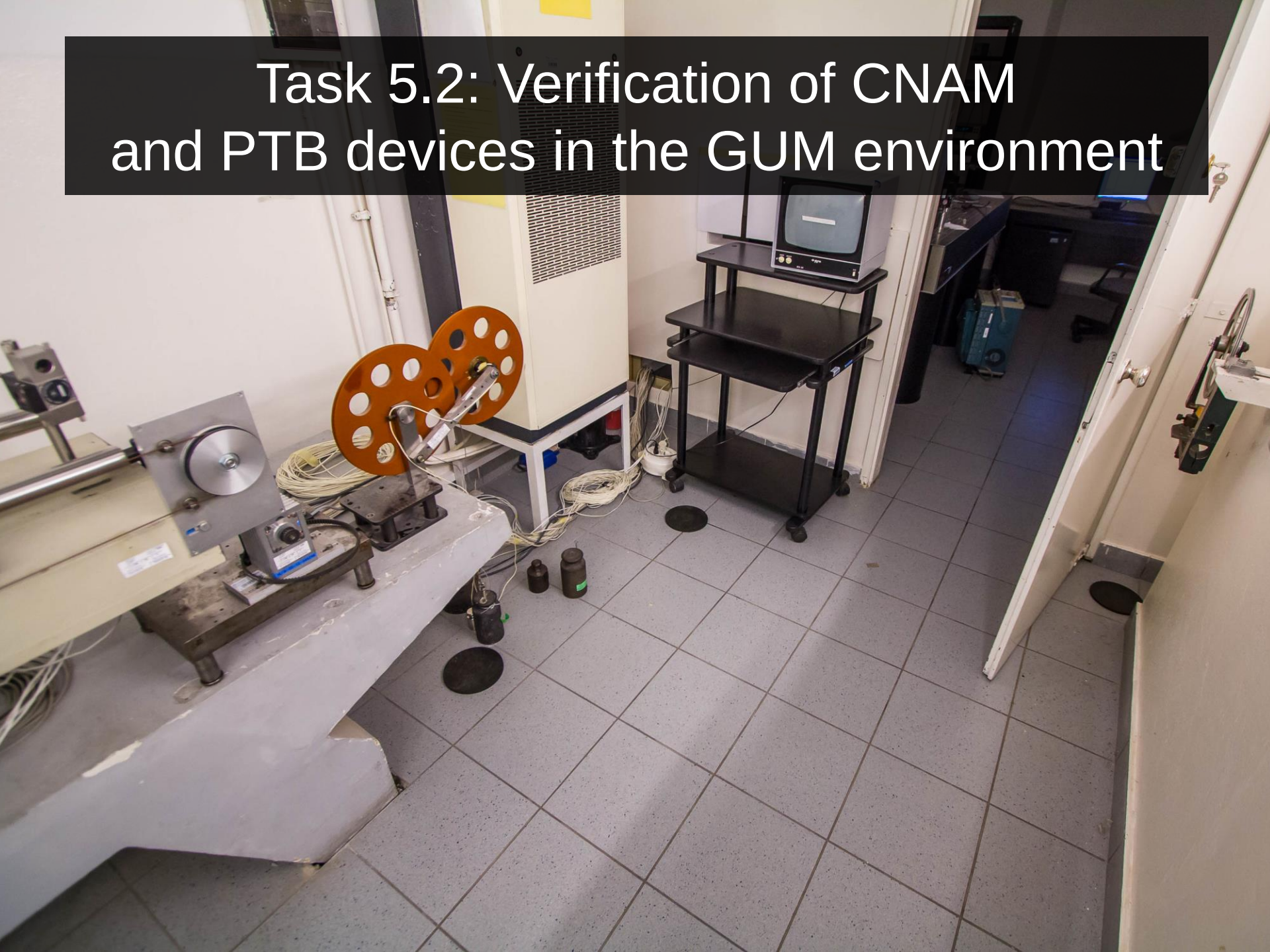
Simulation of industrial environment



Simulation of industrial environment

- Stable
  - Difference 50m - 1 °K, 7.8 %
  - Difference 10m - 1 °K, 7.8 %
  - Gradient - 0.1 °K/m, 0.16 %/m
- Max
  - Difference 50m - 3.9 °K, 6.7 %
  - Difference 10m - 2.3 °K, 5.9 %
  - Gradient - 0.4 °K/m, 0.23 %/m
- Heaters
  - Difference 10m - ~8 °K, ~10 % (not stable)

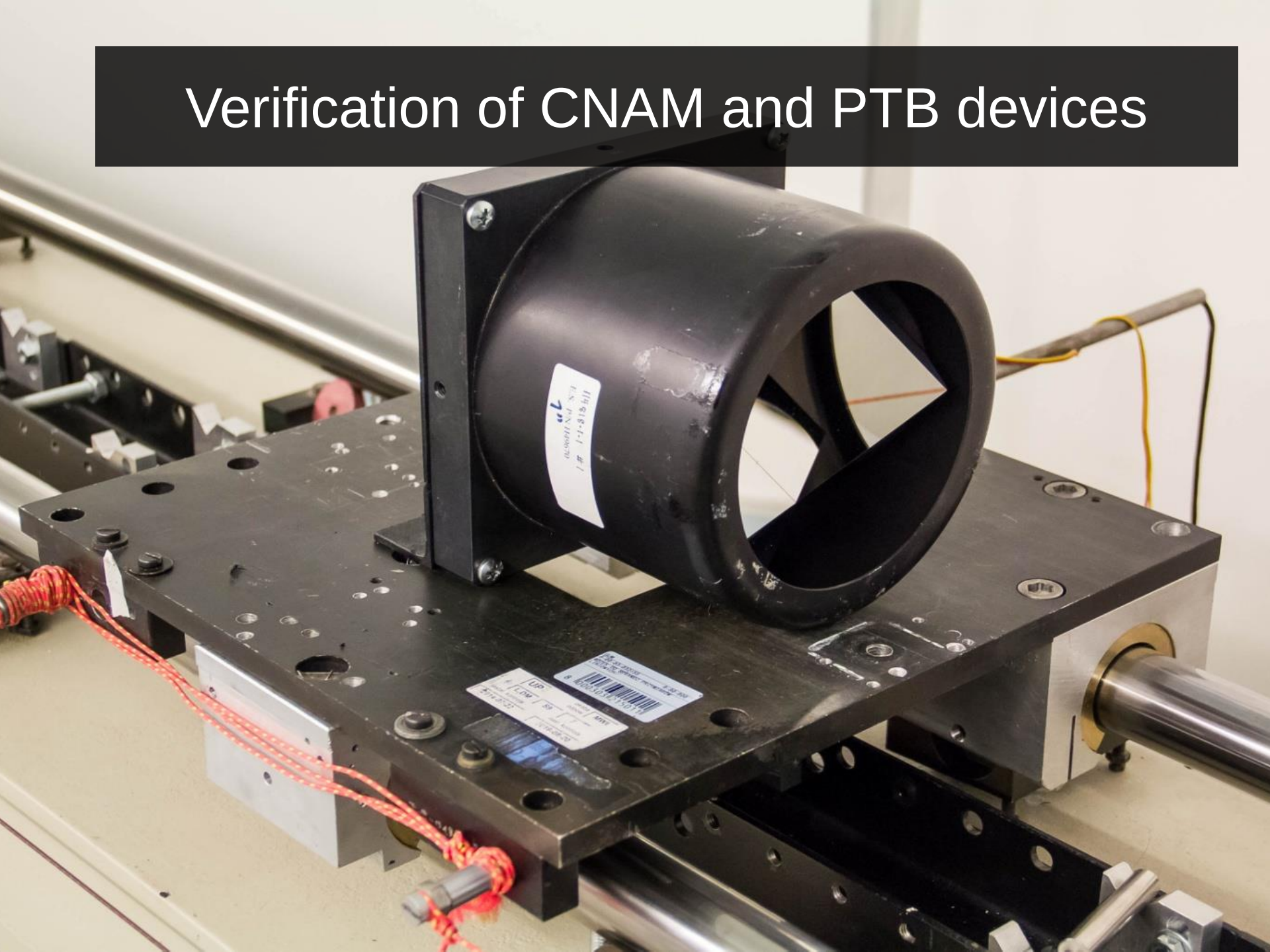
Task 5.2: Verification of CNAM and PTB devices in the GUM environment

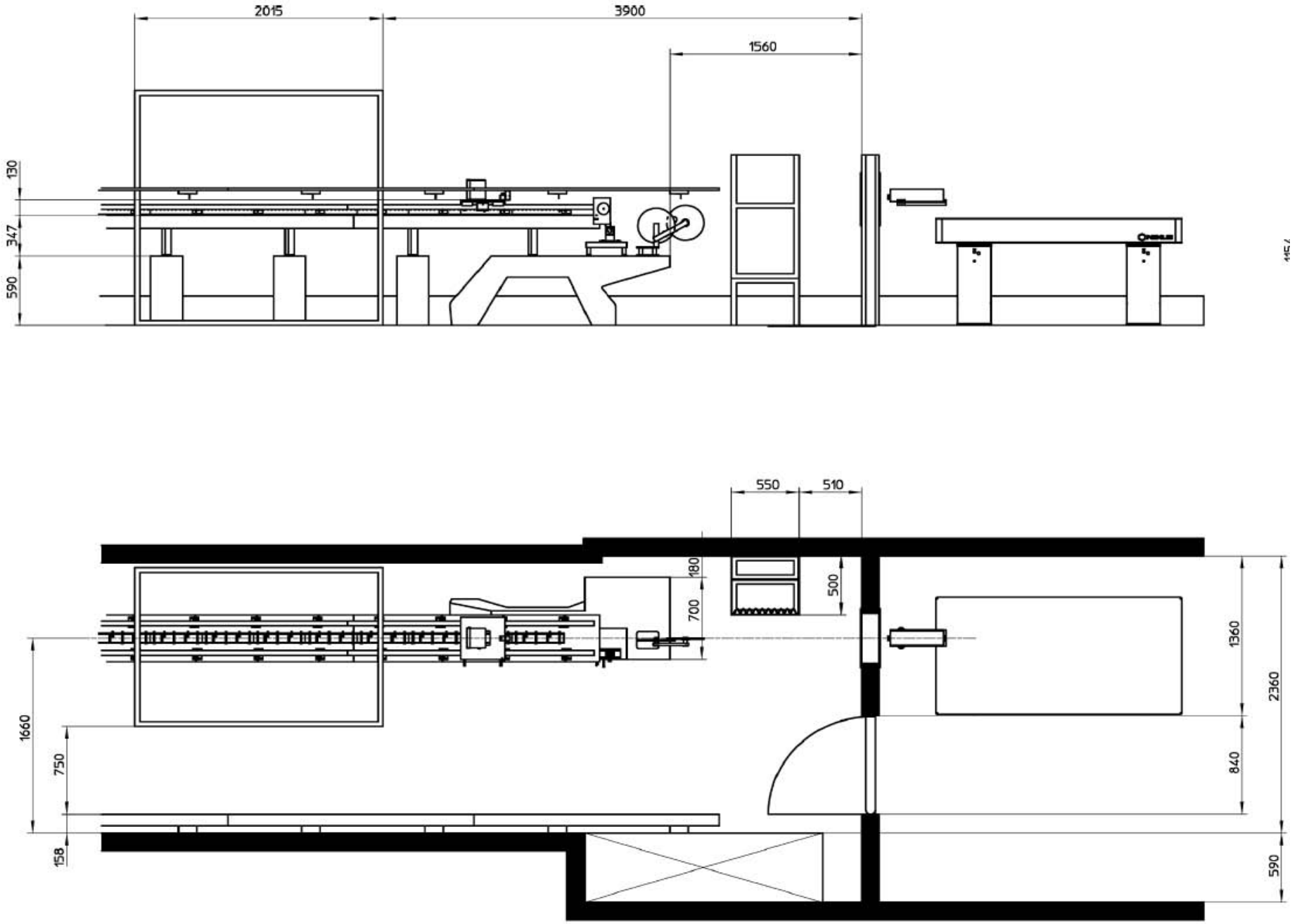


Task 5.2: Verification of CNAM and PTB devices in the GUM environment

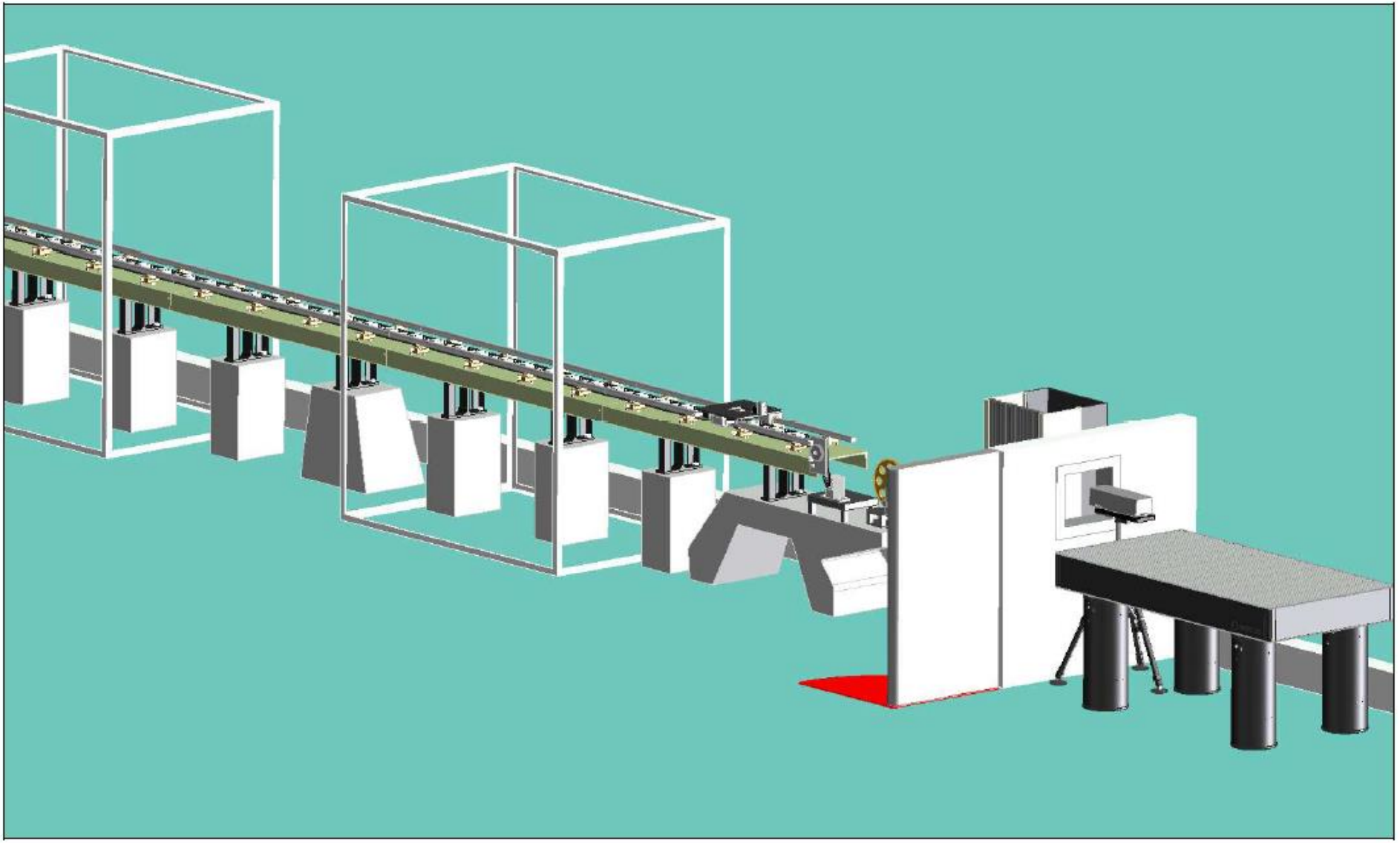
- Verification of the performance of the CNAM refractive index compensated ADM system and PTB compensated self-tracking IFM system against the GUM system in the simulated industrial environment.
- In Feb 2016 CNAM and PTB took their systems to GUM and operate it in comparison against the GUM system (operated by GUM).

Verification of CNAM and PTB devices

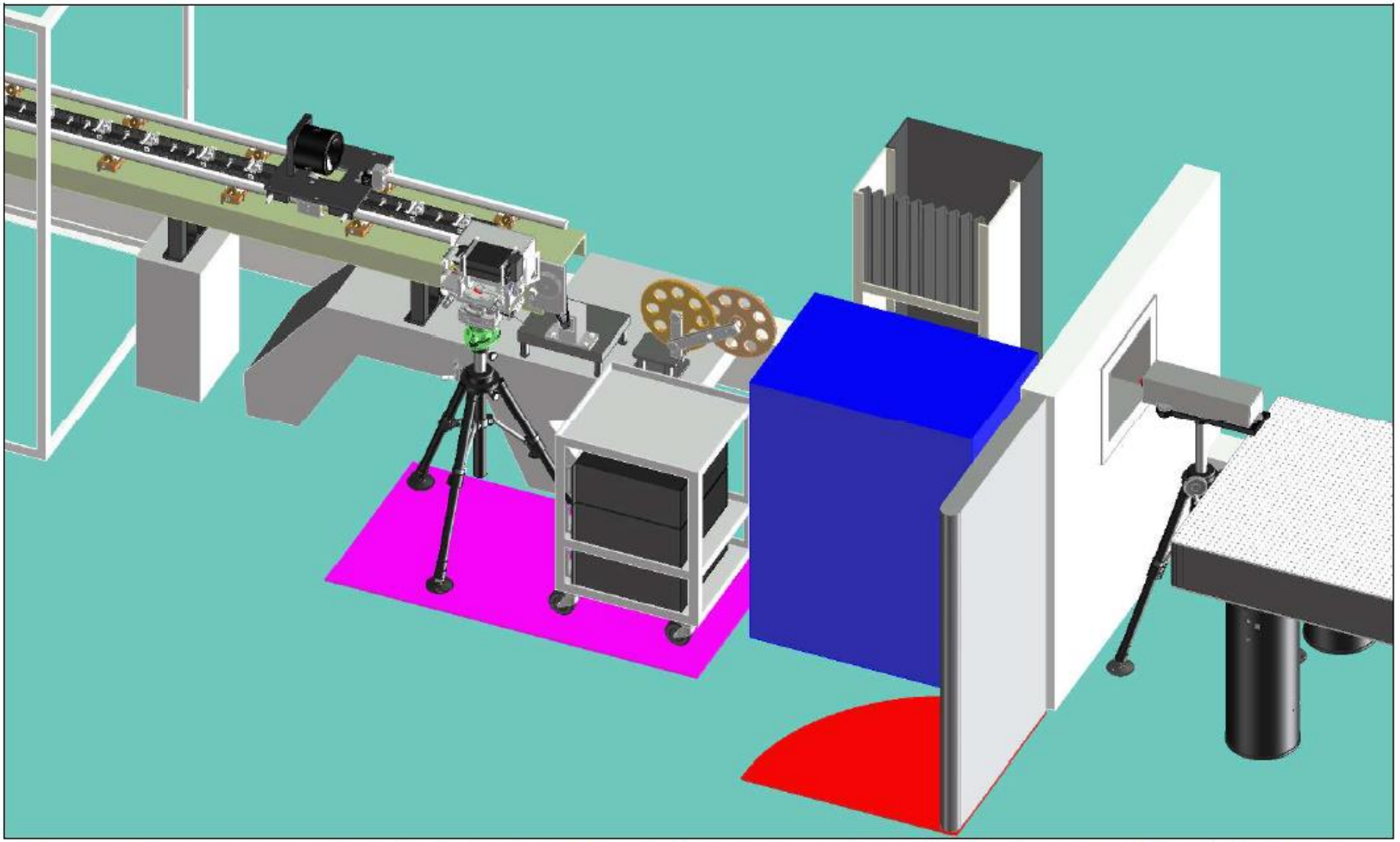




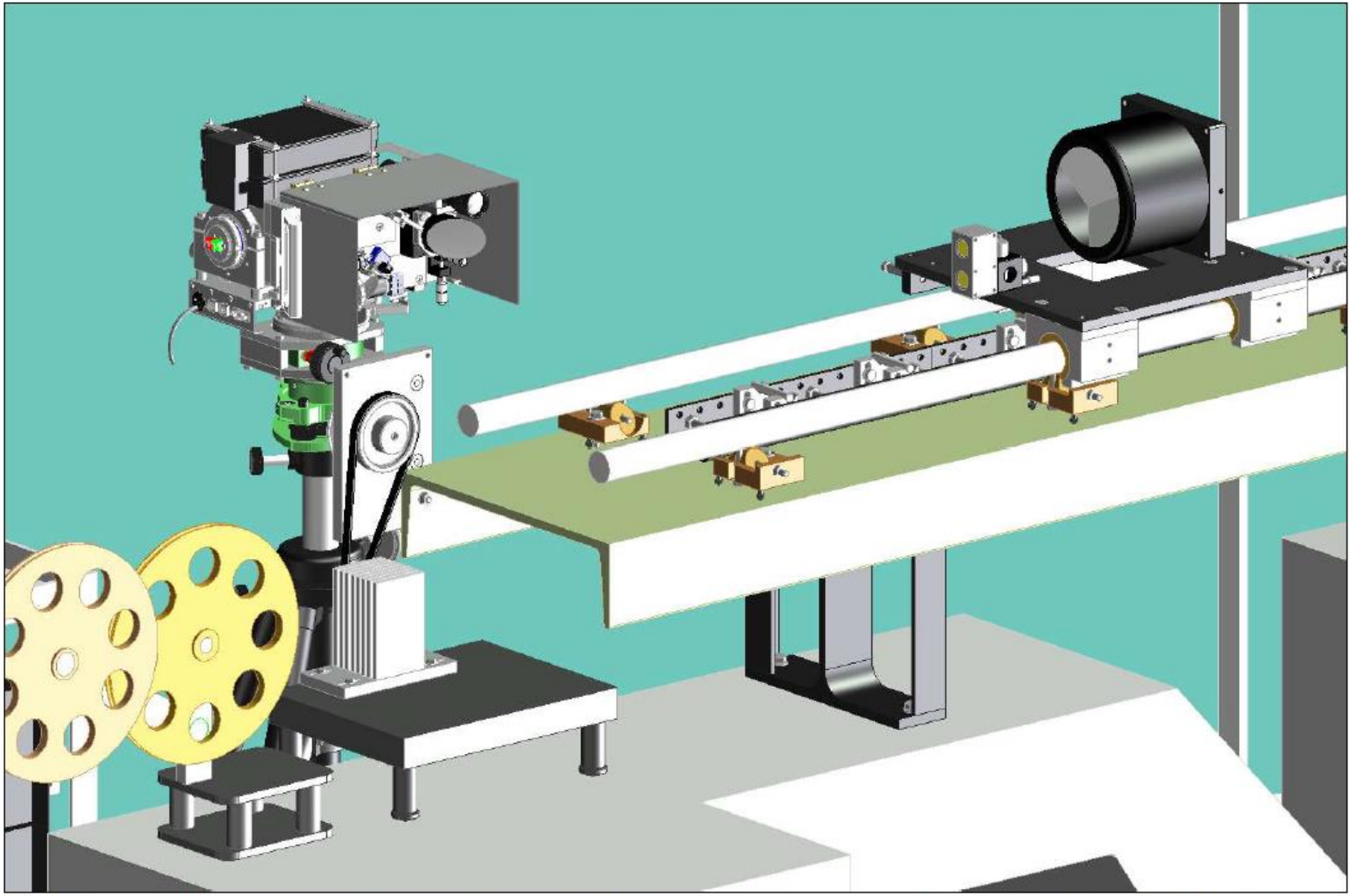
D. Truong drawings



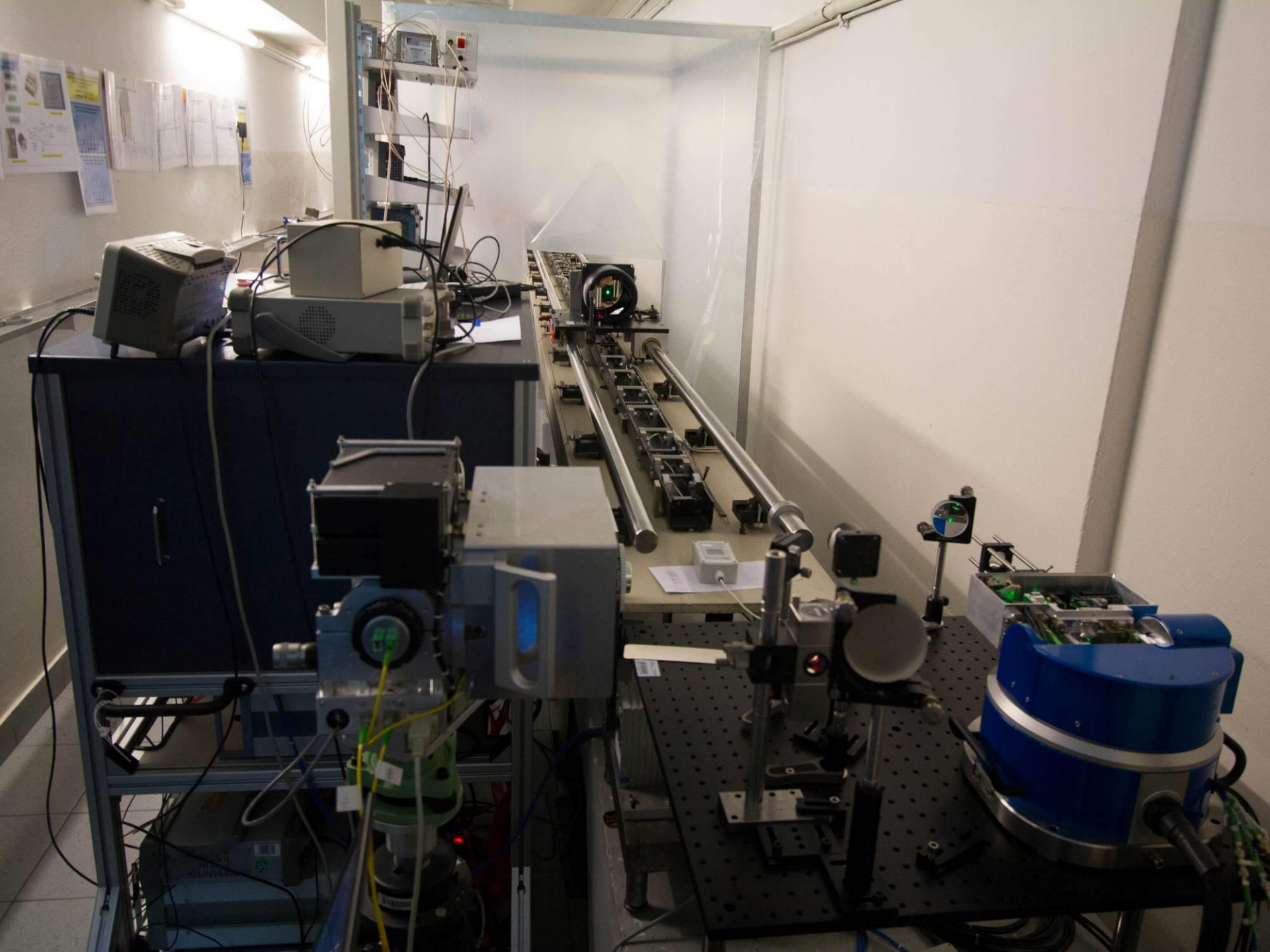
The GUM 50 m tape bench with its two heating volumes, seen from the interferometer end.

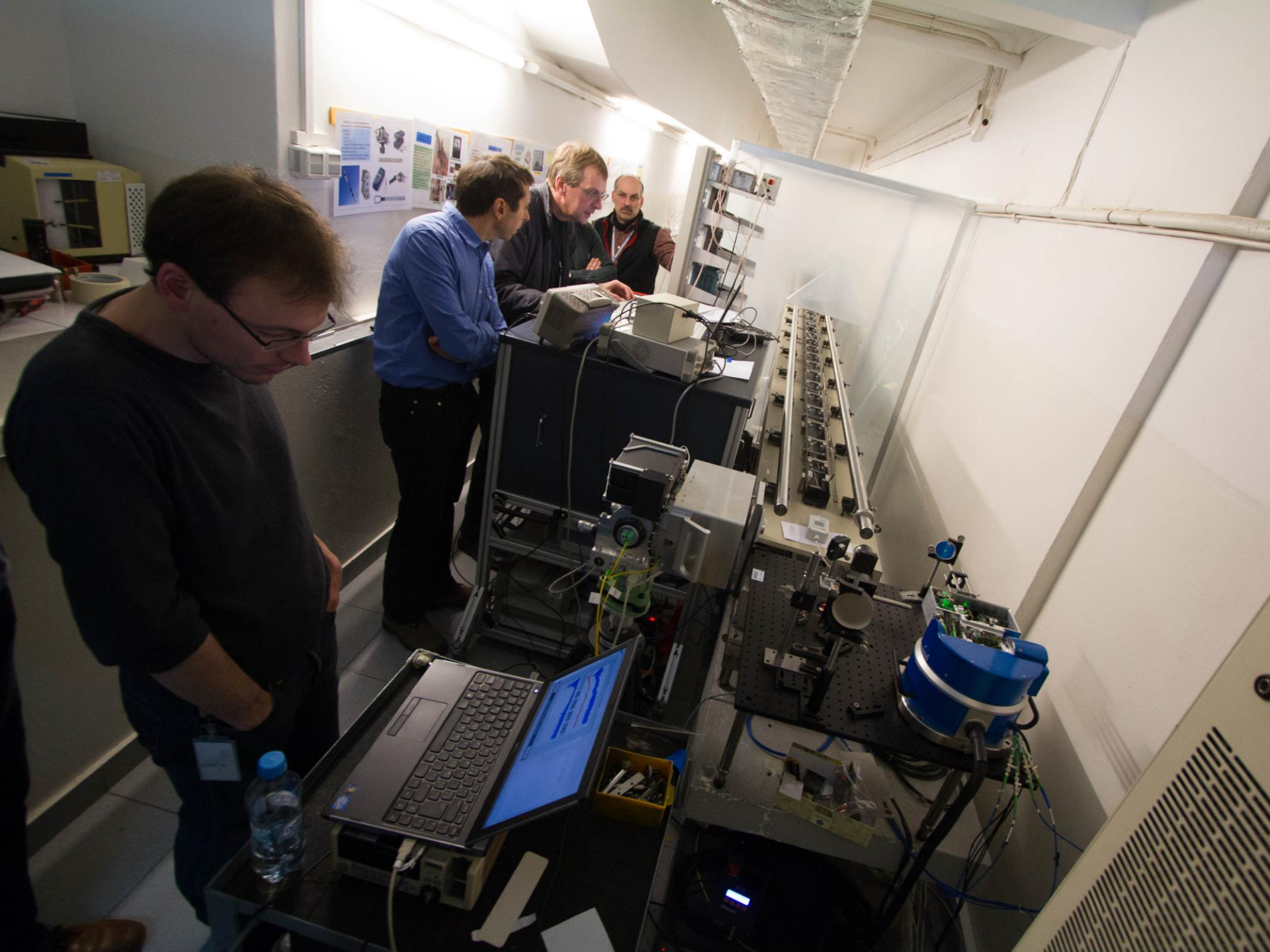


The GUM 50 m tape bench with the CNAM ADM in purple and PTB ADM in blue (90x60x118 volume in cm). The door path is underlined in red.

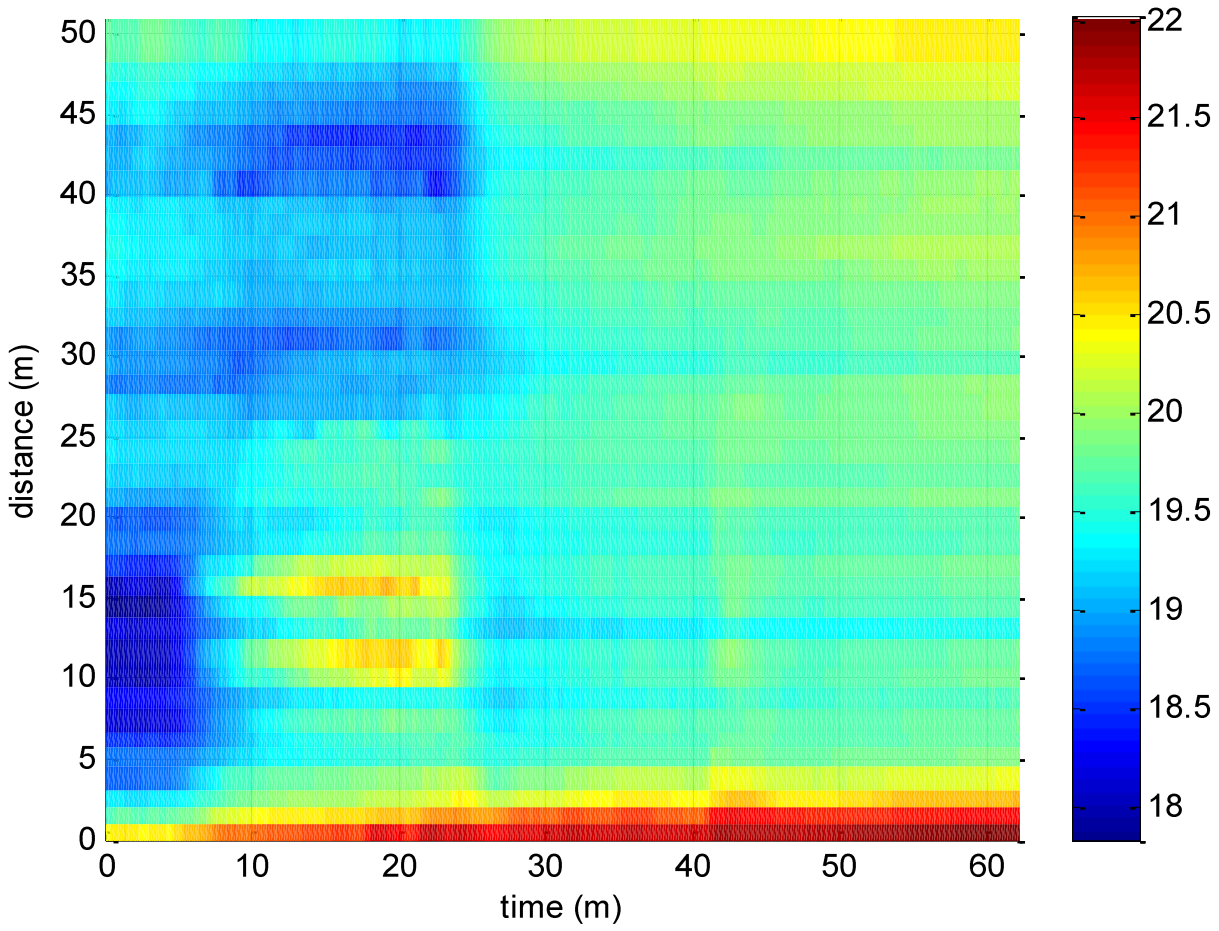


Detail of the corner cube positioned on the carriage (not yet fixed) and the CNAM ADM.

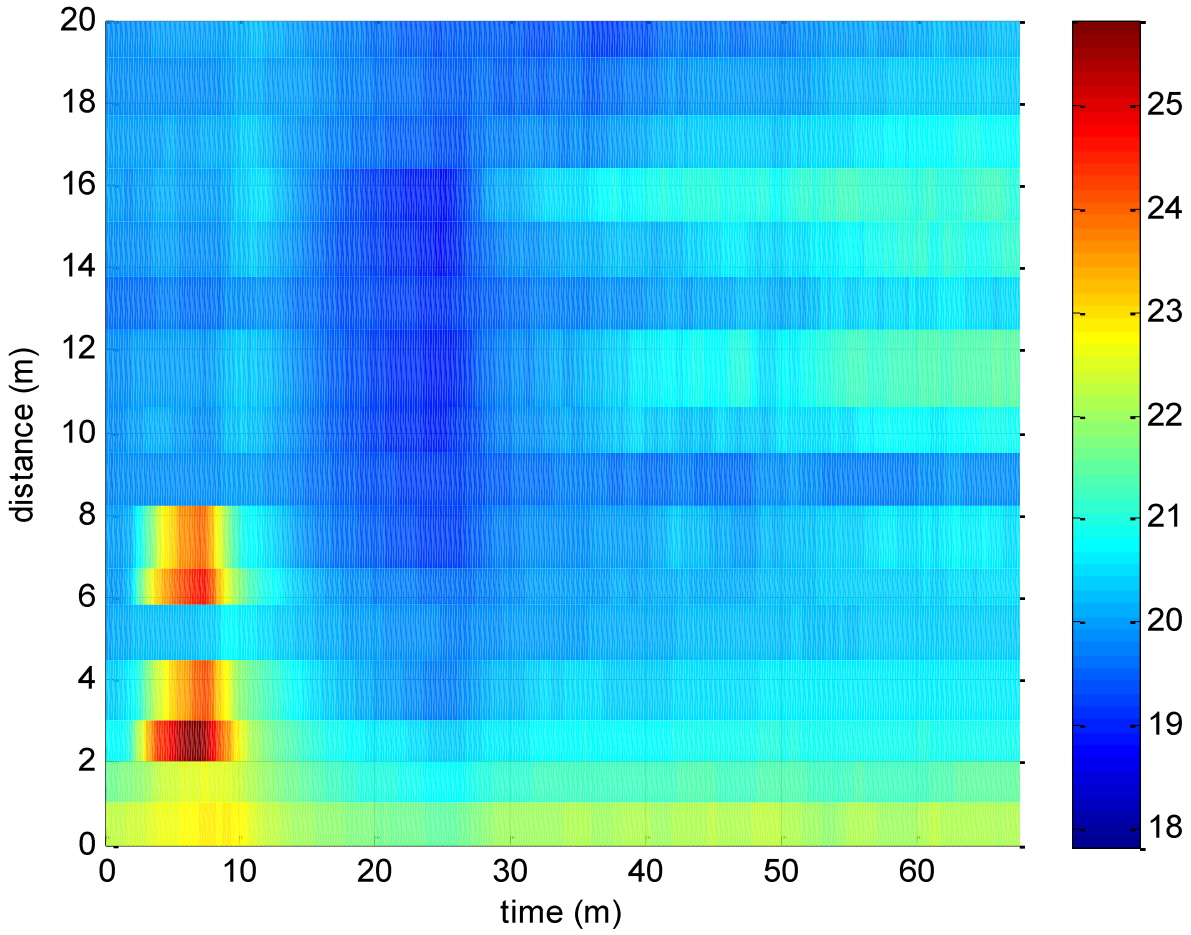




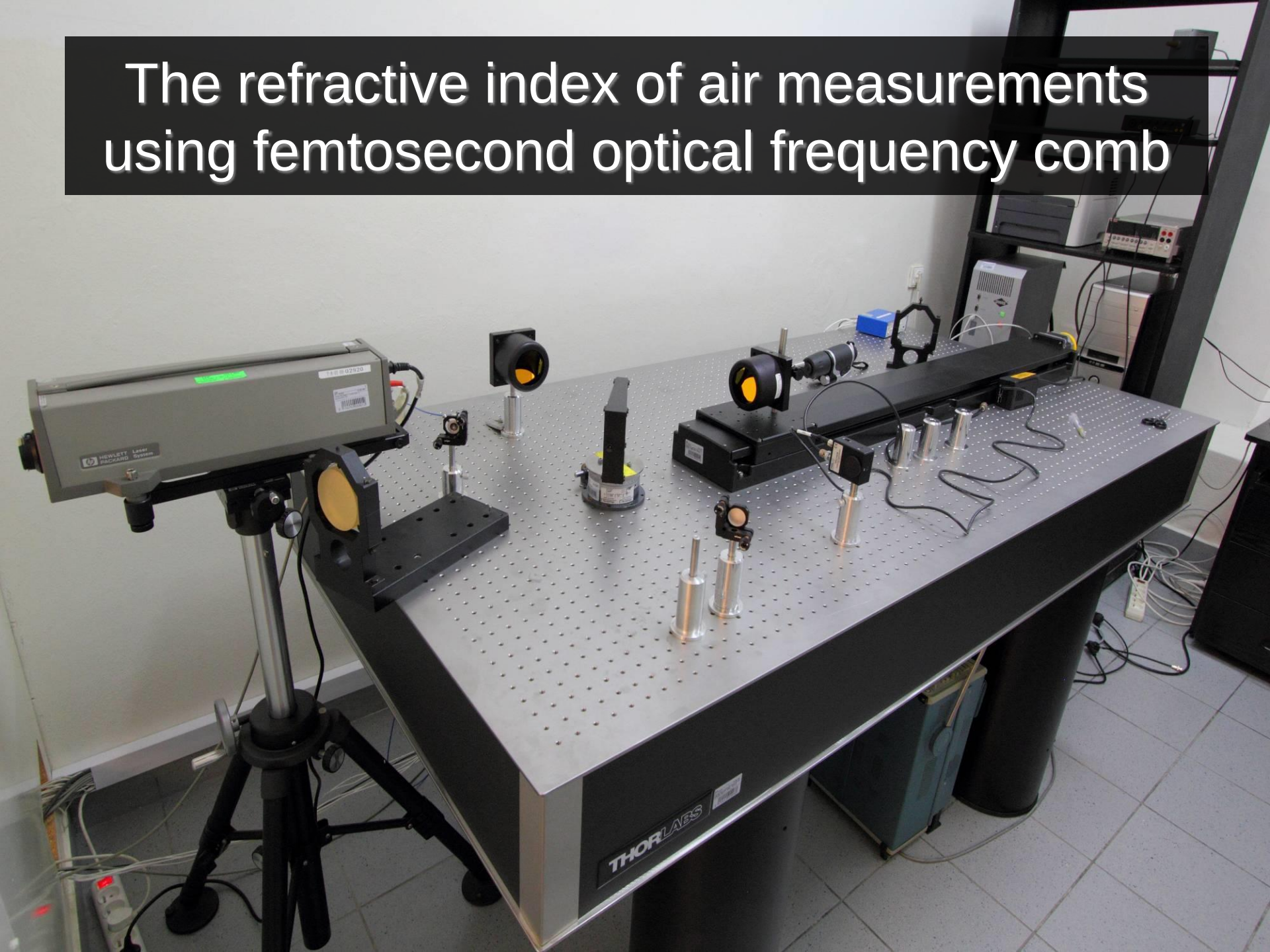
Verification of CNAM and PTB devices



Verification of CNAM and PTB devices



The refractive index of air measurements using femtosecond optical frequency comb



The refractive index of air measurements using femtosecond optical frequency comb

- The second method based on interferometric measurements using Michelson interferometer with femtosecond optical frequency comb. The aim of this method is to calculate the refractive index of air using different wavelengths during the differential measurements along the same path.

An upgraded 50 m 1D facility with refractive index monitoring

Summary

- Environmental monitoring
  - 40 thermistors
  - 5 termohigrometers
  - 1 barometer
  - Estimation: $\boldsymbol{u(n) = 4.2\ 10^{-7}}$ for 50 m tape bench
- Simulation of Industrial gradients:
  - Stable 1 °K
  - AC regulation 3.8 °K
  - Heaters 8 °K

Simulation of industrial environment in Large Volume Metrology

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Introduction

The Central Office of Measures (GUM) is taking part in EMRP project JRP IND53 LUMINAR „Large Volume Metrology In Industry". Aim of LUMINAR project is to find innovative technical solutions for performing accurate measurements of the size, position, location, and shape of objects of large size, assembly of large objects, and machines. The task of project is development of the innovative measurement systems capable of providing a measurement uncertainty of 50 microns in volume (10 × 10 × 5) m in industrial conditions and measurement systems to determine the absolute distance (ADM) with environmental conditions compensation. The computer simulations of thermal variations in sizes and shapes of large structural elements will be carried out.

During last phase of the LUMINAR project the GUM laboratory will be used for verification of the effectiveness of the measurement systems developed during the project by CNAM and PTB. The laboratory room, with the tape bench with controlled environment, has been prepared to simulate the harsh conditions typical for the production hall.

The monitoring system

The monitoring system which consist of 40 air temperature sensors type YSI 44031 (10kΩ), 5 relative humidity sensors and one air pressure sensor was used for determination of environmental conditions on the 50 m interferometric comparator. Sensors were placed in regular distances to cover 50 m range.

All sensors were calibrated before simulation for wide range of possible environmental conditions. The parameters of the characteristic has been estimated. The software for real time recording and data analysis of all parameters was developed.

Table 1. Sensors of the monitoring system

Sensor type	No.of sens.	Sensor uncertainty
temperature	40	± 0,05 °C
Humidity	5	± 0,2 %
air pressure	1	± 1,0 hPa
CO_2	1	± 47 ppm

Results of the simulation

Adjustments of the operating parameters of two independent air conditioners (AC) were used to obtain large gradients along the test bench and rapid changes in local conditions. The AC were located at the both ends of 50 m comparator and use common pipe to distribute air. The AC were set to work in three states: N-Normal, standard temperature 20 °C for calibrations; C-Cooling to 15 °C; H-Heating to 25 °C. Measurements was made 2 hours after changing AC settings.

A combinations of cooling, heating and normal state was examined. Achieved gradients of temperature and humidity are presented on Figure 2 and 3. During preliminary tests the air temperature gradient on the level of 4 °C and relative humidity gradient on the level of 11% for distance of 50 m were achieved. The highest gradient of temperature was achieved for heating on the beginning and cooling at the end of 50 m comparator (H-C state). Additional test are needed to increase gradients for 10 m range.

The vertical gradients perpendicular to comparator corridor were examined and presented on Figure 4.

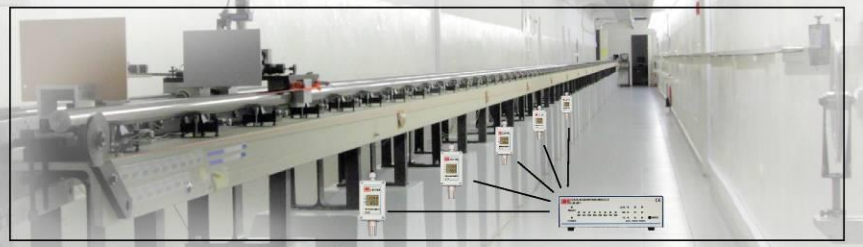

Figure 1. The 50 m interferometric comparator and the schematic of the monitoring system

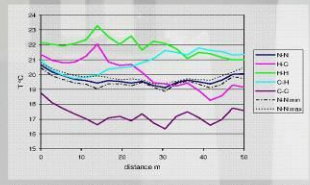

Figure 2. Gradients of temperature for combinations of cooling (C), heating (H) and normal (N) state of two air conditioners.

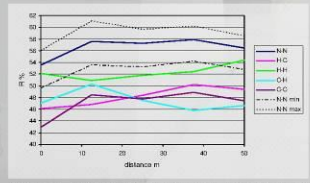

Figure 3. Gradients of humidity for combinations of cooling (C), heating (H) and normal (N) state of two air conditioners.

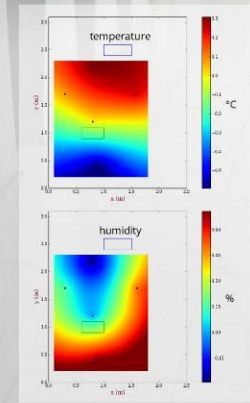

Figure 4. Relative vertical gradients of humidity and temperature perpendicular to comparator corridor

Estimation of the refractive index uncertainty

Measurements of temperature, humidity, air pressure, and CO_2 from the monitoring system of the environmental conditions and the Edlen equation was used for calculation of refractive index of air *n*.

The uncertainty of the measuring system was estimated using Monte Carlo method. 400 series of raw data collected in N-N state was used. 1000 measurements was randomly generated for each of series, with assumption of uncertainties of the sensors given in Table 1.

Correlation between amplitude of changes of temperature and humidity was observed. This fact was used to estimate uncertainty of mean humidity calculation. Results of 40 temperature sensors was compared with 5 humidity sensors. Uncertainty of mean humidity was estimated on 0,4 %.

Differences between *n* value calculated using raw and randomly generated data was used to estimate uncertainty of the system. The uncertainty was estimated on $u(n) = 4{,}2\ 10^{-7}$. This level of uncertainty fulfils requirements for the verification of the CNAM and PTB measurement systems planed in LUMINAR project.

The second method for refractive index of air measurement is under development. It will be based on interferometric measurements using Michelson interferometer with signals from femtosecond optical frequency comb. Procedure and data processing for this method will be developed in next phase of project.

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Thank you