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Simultaneous IR Spectroscopy and IR Tomography in Flames and Hot Gas Flows

Vadim Evseev, Sønnik Clausen, Alexander Fateev,
Valery Sizikov*, Karsten L. Nielsen

DTU Kemiteknik
Institut for Kemiteknik

Danmarks Tekniske Universitet

DTU

* National Research University of Information Technologies, Mechanics and Optics (University ITMO) (St Petersburg, Russia)

Motivation

- **Studying combustion phenomena**

- It is important to know essential combustion parameters such as
  - gas temperature
  - species concentrations

    – resolved temporarily and spatially and simultaneously for every point

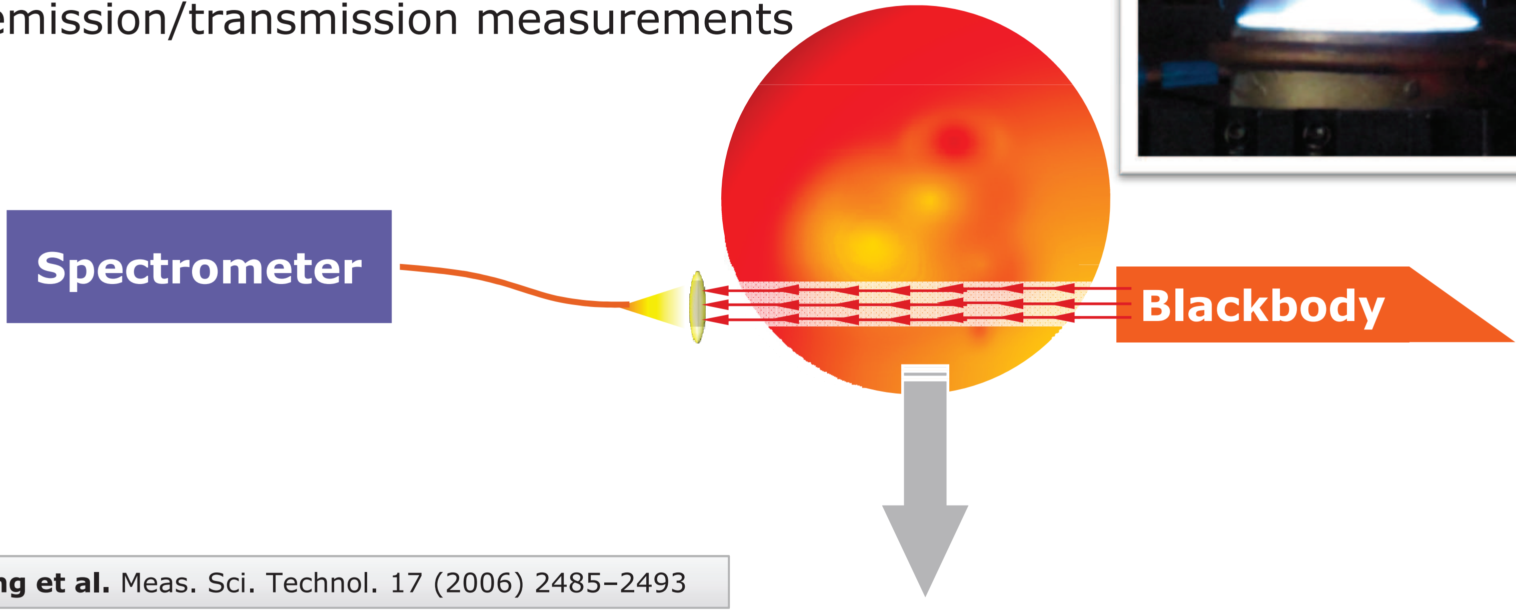
- **Objective of this work**
  - Tomographic reconstruction of
    – gas temperatures
    - in flames and hot gas flows

Outline

- **Tomographic Reconstruction of a Lab Flame Temperature Profile**
  - Measurement Schemes
  - Results on the Lab Flame
- **Equipment Suitable for Tomographic Measurements of Gas Temperatures**
  - Development
  - Application on a Large Diesel Engine
- **Towards Species Concentrations Measurements**
  - Line-by-line Modeling of Gas Spectra
  - Comparison to Experimental Data from the Hot Gas Cell

Problem Statement

- **Given** is an axisymmetric stable flame produced by a small lab-scale burner*
- The temperature profiles at a number of heights above the burner plate are known*
- **The task** is to reconstruct the temperature profile at a chosen height above the burner
  - from several optical line-of-sight spectral emission/transmission measurements



*__Hartung et al.__ Meas. Sci. Technol. 17 (2006) 2485–2493

Problem Statement: Details

- **Why optical techniques?**

They are advantageous

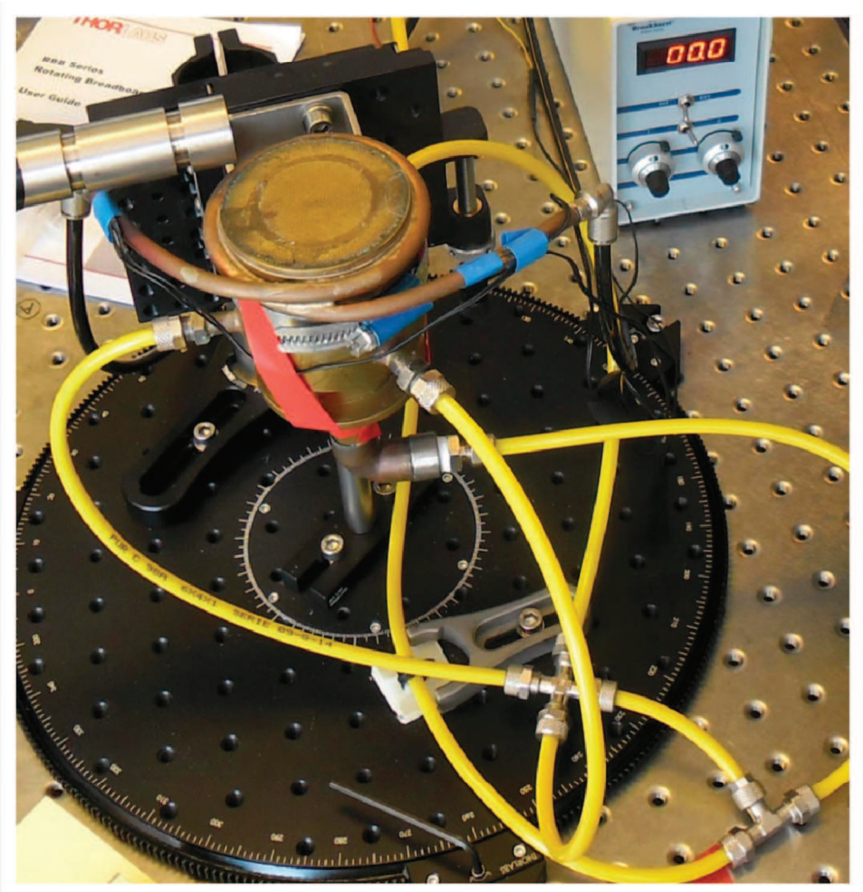
- over thermocouples due to
  - non-intrusiveness
  - high temporal resolution
- over laser-based techniques due to
  - low cost
  - wide spectral range

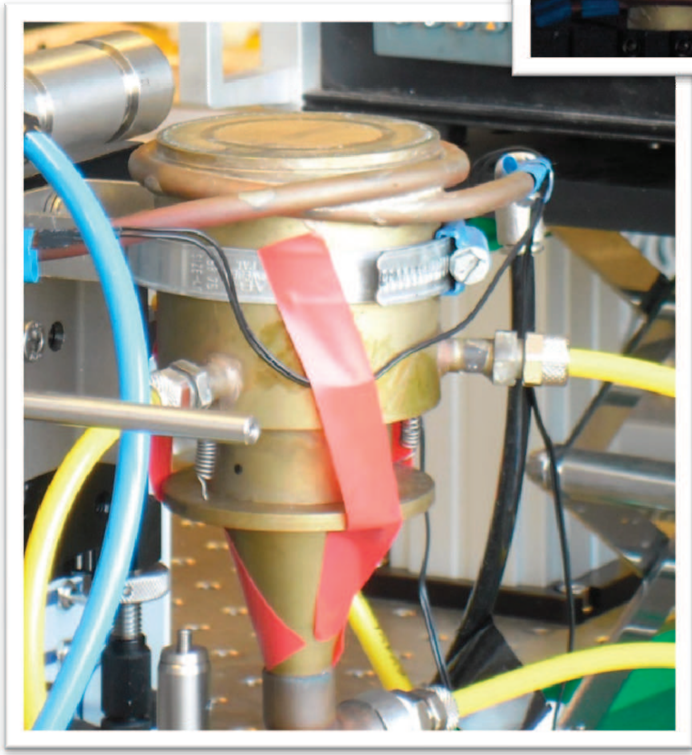
- **Why IR spectral range?**

- The major combustion species CO_2 and H_2O have strong fundamental rotational-vibrational bands in the near IR range

Equipment: Flat Flame Burner

A flat flame burner* producing
a **laminar pre-mixed CH_4/air flame**
with **known axisymmetric temperature profile***
was used for the FTIR tomographic measurements



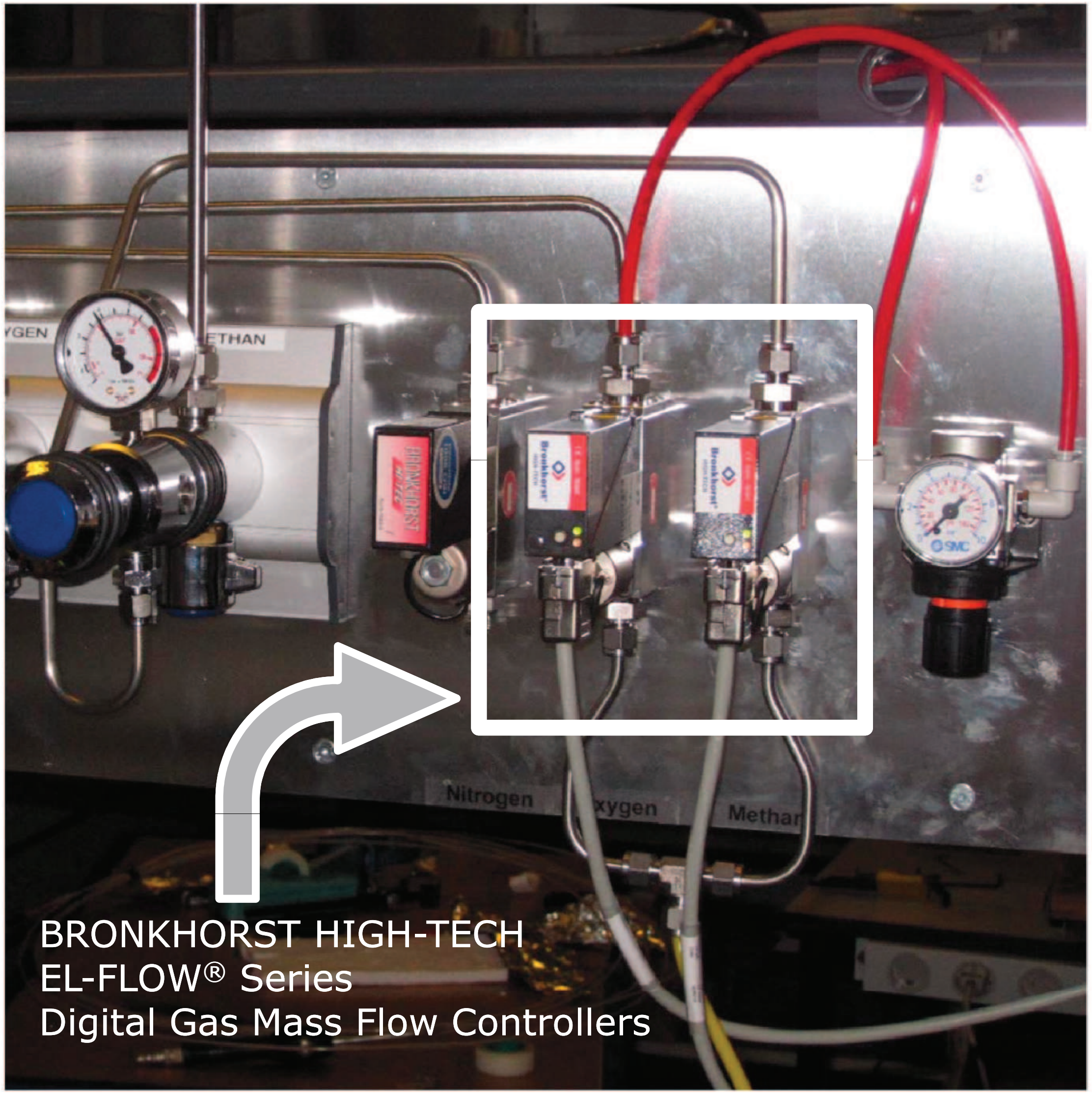


***Hartung et al.** Meas. Sci. Technol. 17 (2006) 2485–2493

Equipment: Flat Flame Burner

The system supplying the CH_4/air mixture to the burner

BRONKHORST HIGH-TECH
E-5700 Series Economical Power Supply / Readout System



BRONKHORST HIGH-TECH
EL-FLOW® Series
Digital Gas Mass Flow Controllers

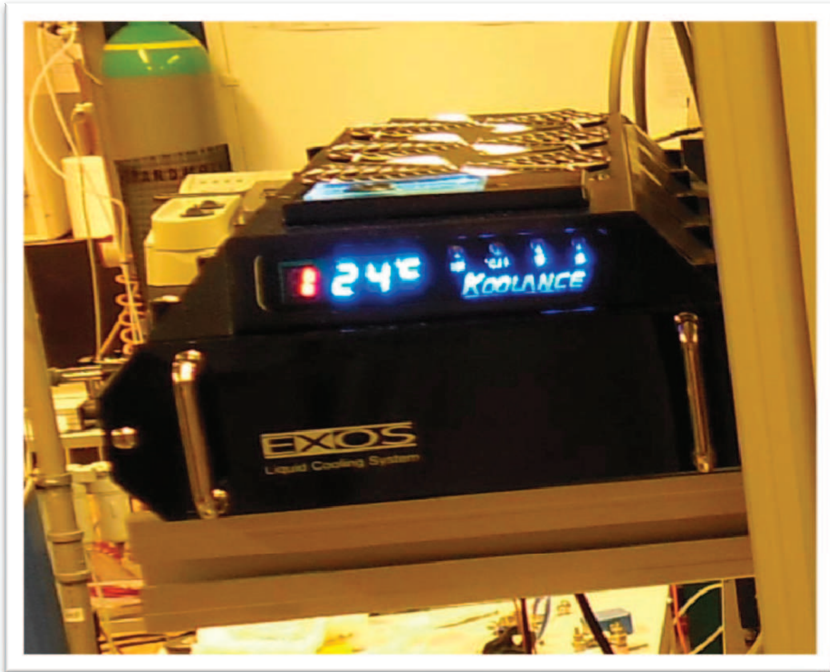
Equipment: Flat Flame Burner

The burner plate is equipped with a single water cooling loop which effectively conducts away the heat transferred to the burner plate from the flame.*

In our setup, the cooling water was supplied to the loop by a Koolance Exos-2.5 Liquid Cooling System.

The temperature of the water "leaving" the loop did not exceed 60 °C.

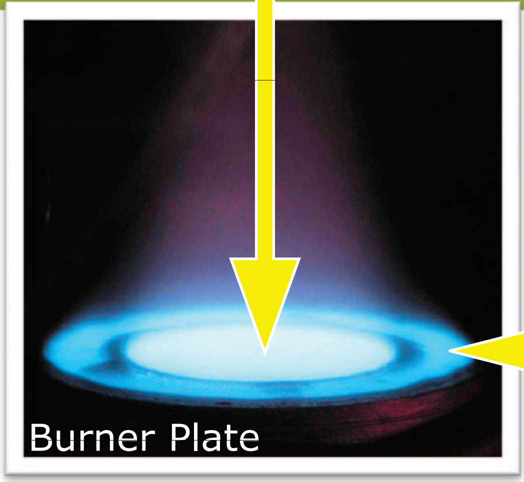
Koolance Exos-2.5
Liquid Cooling System



*Hartung et al. Meas. Sci. Technol. 17 (2006) 2485–2493

Burner Operation Parameters

The flow rates [litre/min] through the **inner** and **outer** parts of the burner plate at **φ = 1 (stoichiometric combustion)**			
Inner		**Outer**	
CH_4	**Air**	**CH_4**	**Air**
1.03	**9.84**	**1.19**	**11.37**



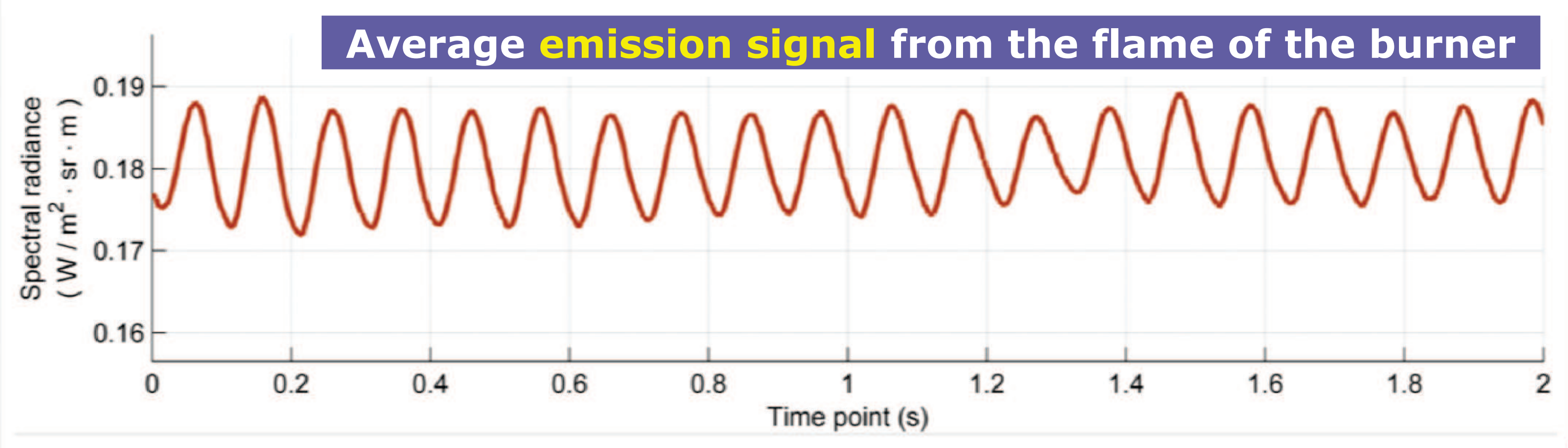
at φ = 0.8 (lean combustion)			
Inner		Outer	
CH_4	Air	CH_4	Air
1.03	12.30	1.19	14.20

Flame Fluctuations

- Although the flow rates were kept constant by flow controllers some fluctuations in the emission signal from the flame were observed.

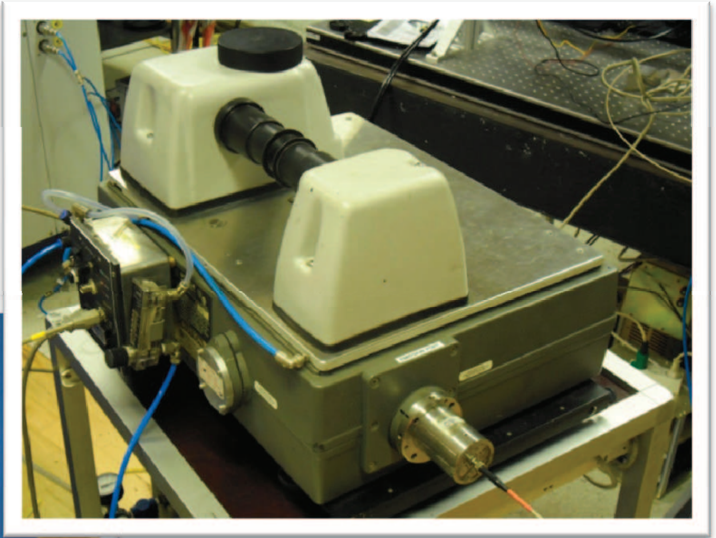
- The emission signal from the flame instead of being constant resembles
  - a **sine wave** with
    - the amplitude of about **5 %** of the mean value and
    - a frequency of about **10 Hz**.

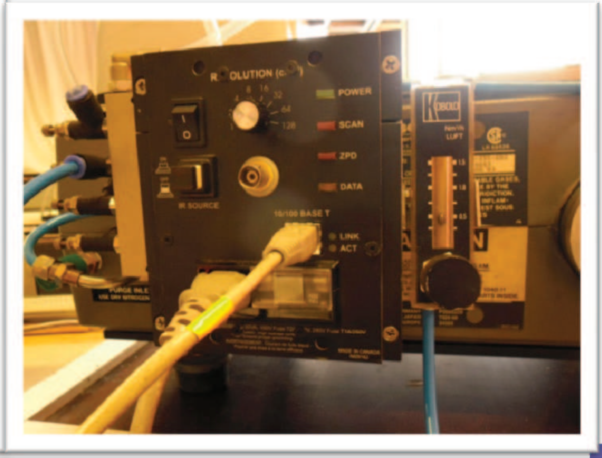
- These fluctuations are essential consequence of the phenomena related to the flame propagation dynamics taking into account buoyancy effects and convection.



Equipment: FTIR Spectrometer

Bomem/ABB model MB155 FTIR spectrometer



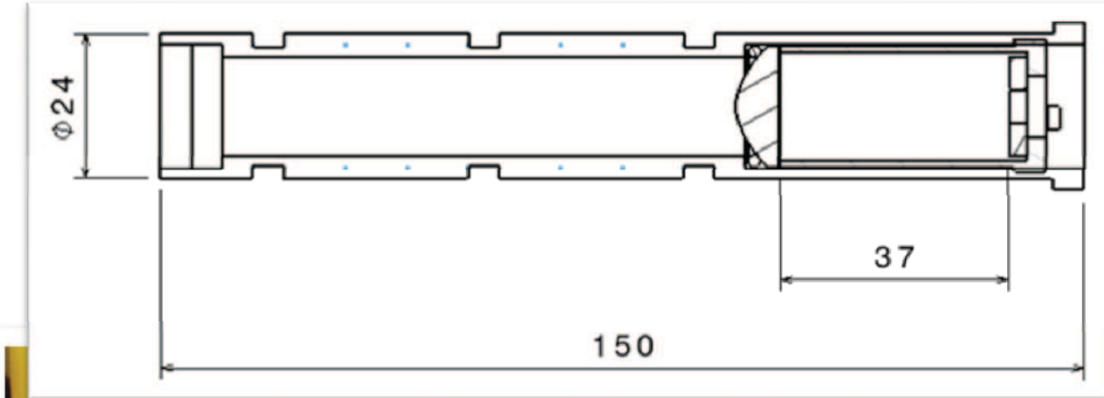


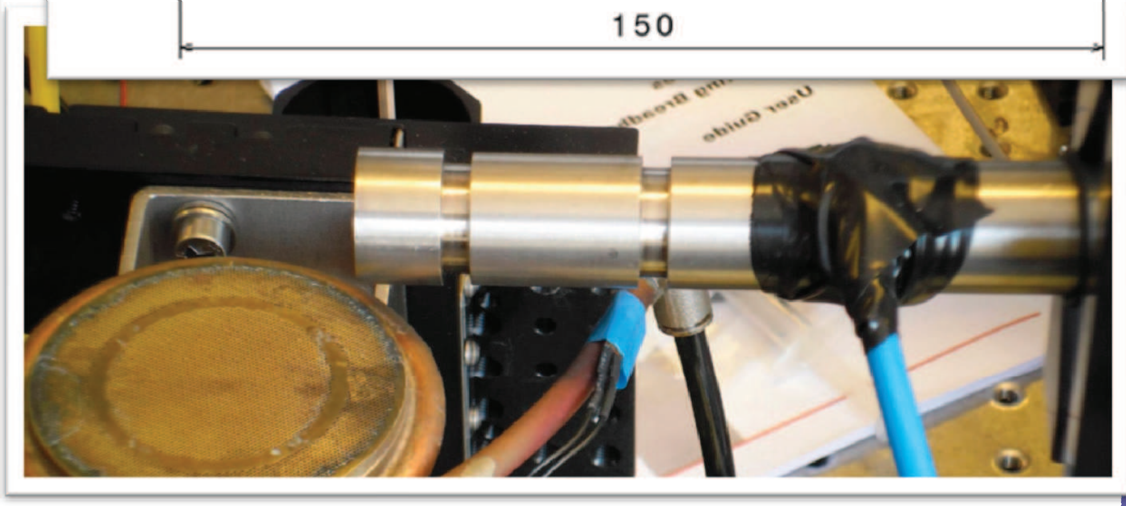
Equipment: FTIR Spectrometer

The spectrometer as well as
the other parts of the optical setup
is **purged with pressurized air**
generated by
BALSTON® 75-45
FT-IR Purge Gas Generator

Equipment: Fiber Optical Adaptor

- The fiber optical adaptor is used to focus the light onto the one end of the IR optical fiber (chalcogenide IR-glass fiber).
- The other end of the fiber is connected to the FTIR spectrometer.
- The field of view provided by the adaptor lies within a cylinder having the diameter of about 6 mm.





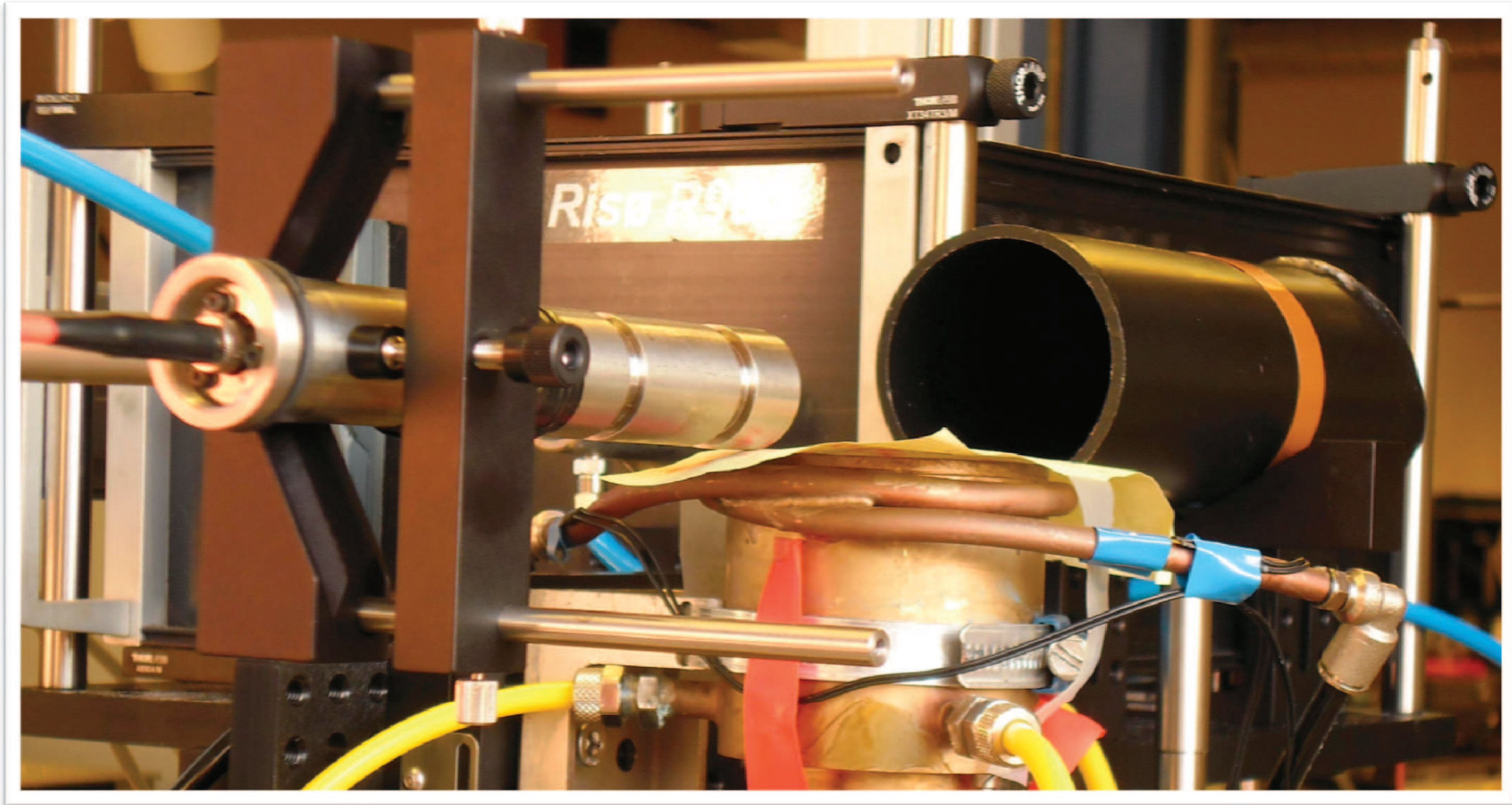
Equipment: Blackbody

- A blackbody radiation source
  with a cavity temperature of 894.4 °C (1167.6 K)
  was used for **transmission measurements**

- It is important to purge the hot cavity to remove the hot CO_2 and H_2O present inside the cavity from the ambient air

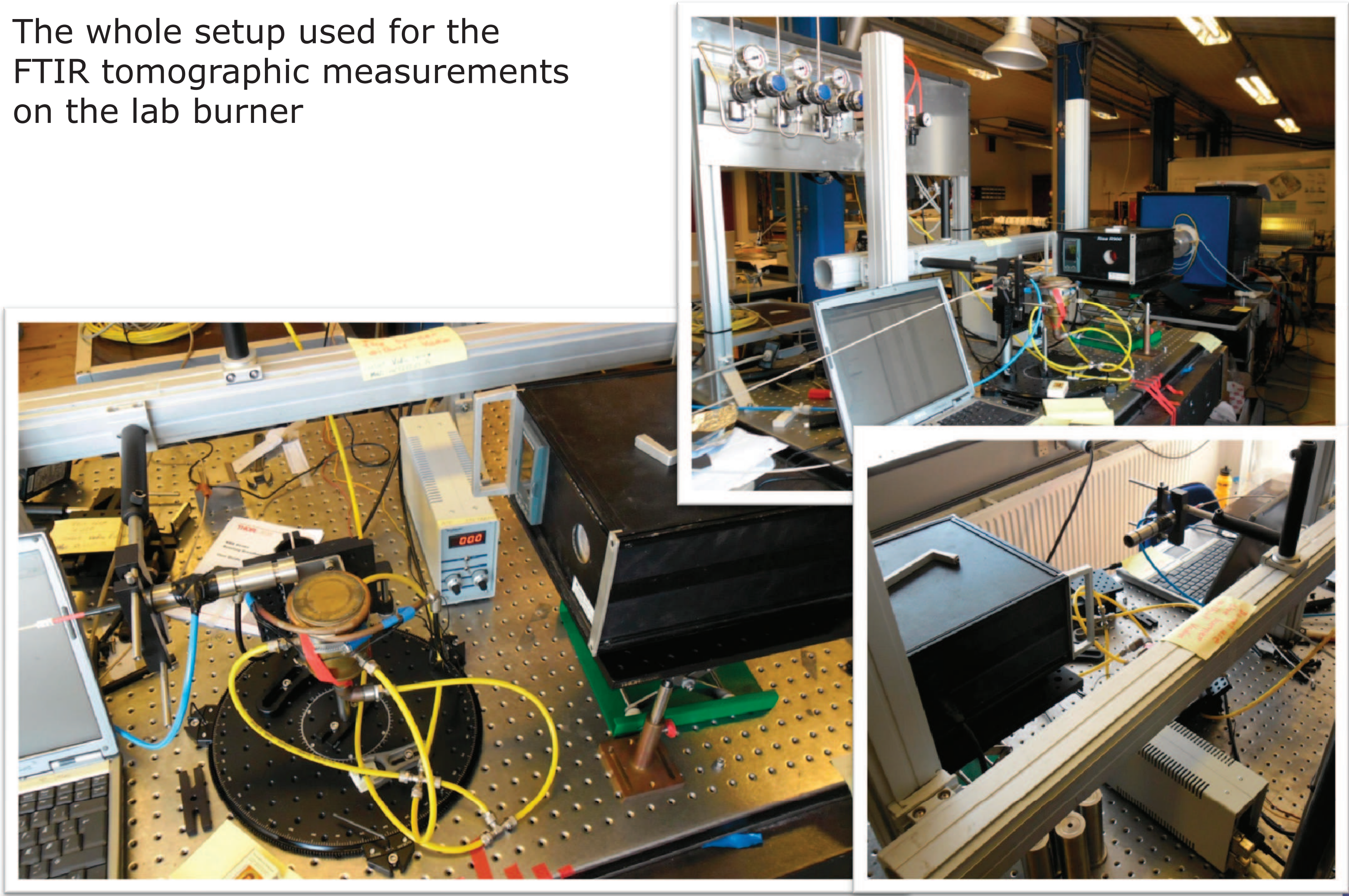
Equipment: Cold Cavity

- **Emission measurements** were performed using a cavity having ambient temperature

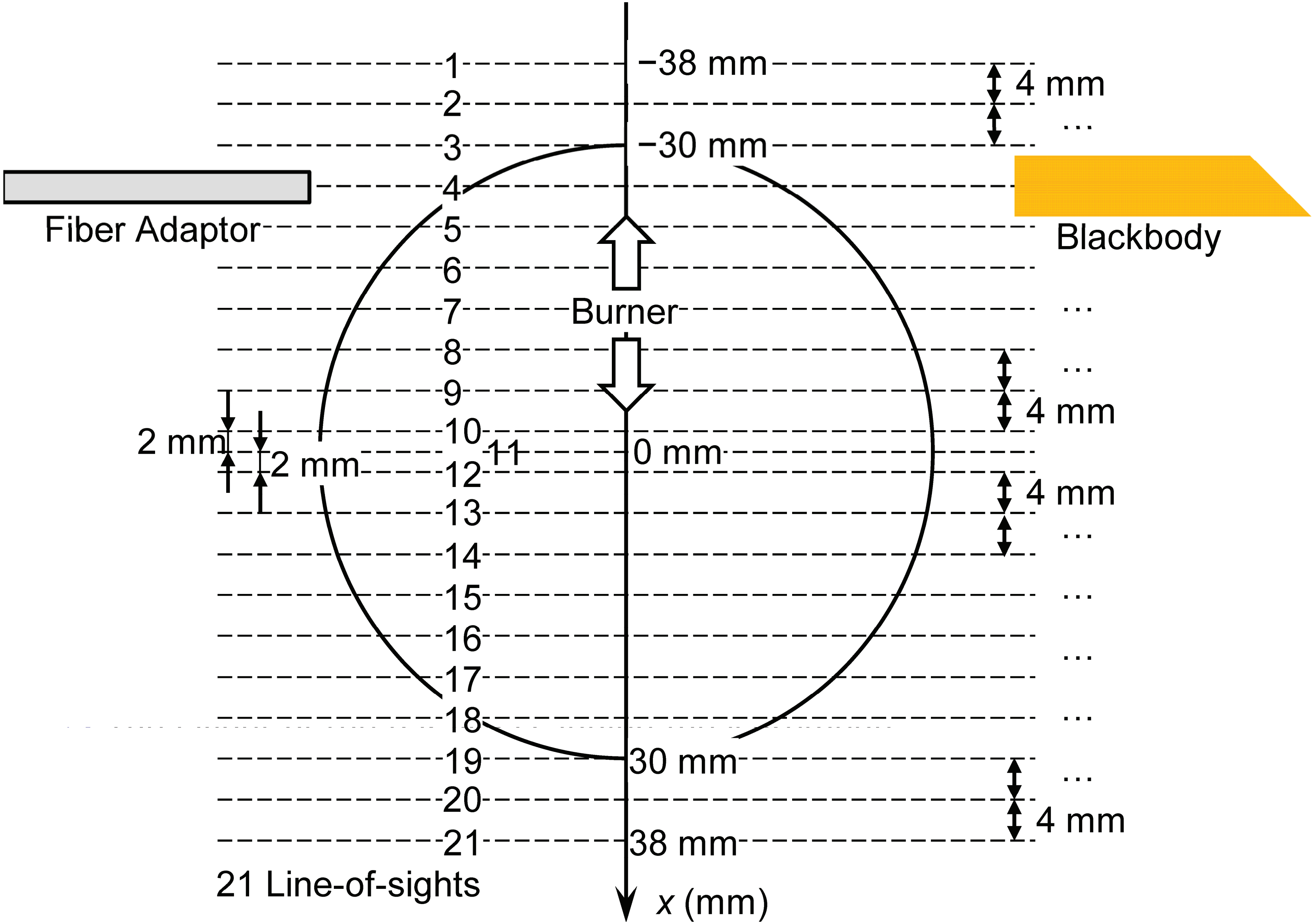


Equipment

The whole setup used for the FTIR tomographic measurements on the lab burner

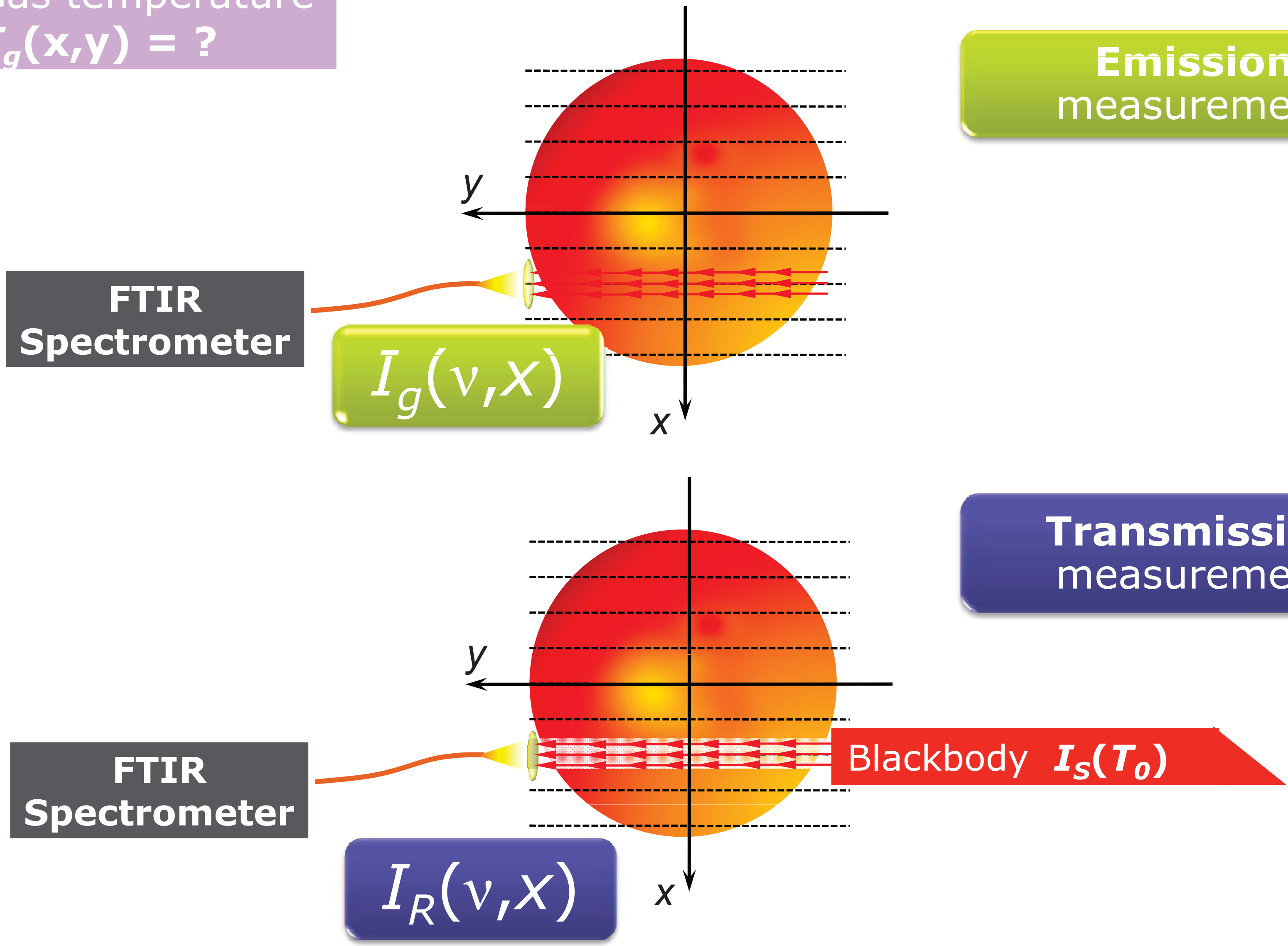


Parallel Scanning



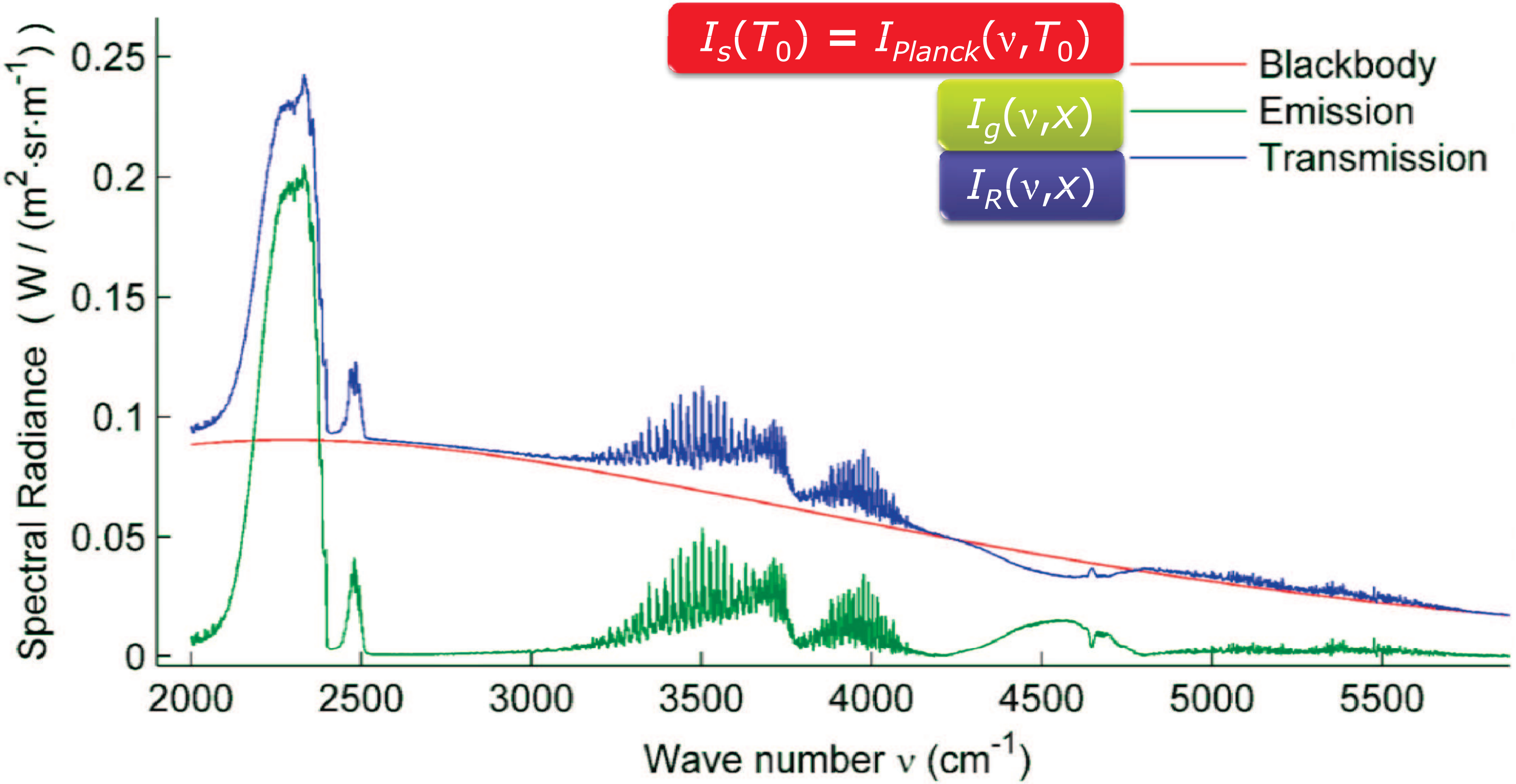
Parallel Scanning

Gas temperature
$T_g(x,y) = ?$



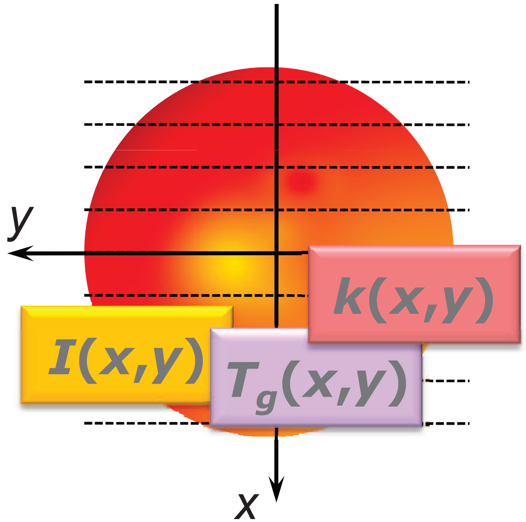
Parallel Scanning

- Examples of the **blackbody radiation** (the Planck radiation law at T_0 = 894.4 °C (1167.6 K)), **emission** and **transmission** spectra for the
  - **central line-of-sight (x = 0 mm)**,
  - height above the burner plate of 12 mm,
  - **stoichiometric combustion** (equivalence ratio **φ = 1**).



Parallel Scanning

Gas temperature
T_g(x,y) = ?



- The spectral irradiance $I(x,y)$ by a beam of monochromatic radiation at a wavenumber ν varies according to*

$$dI(x,y) = \underbrace{-k(T_g)\, I(x,y)\, dy}_{\text{Lambert's Law}} + \underbrace{k(T_g)\, I_{Planck}(T_g)\, dy}_{\text{Kirchhoff's Law}}$$

The monochromatic **radiative transfer equation** without scattering

- $T_g = T_g(x,y)$ – gas temperature
- $k(T_g) = k(T_g(x,y)) =$
  $= k(x,y)$ – the absorption coefficient
- $I_{Planck}(T_g)$ – the Planck function at T_g

* **Tourin et al.** Applied Optics 4 (2) (1965) 237–242

Parallel Scanning

- The radiative transfer equation is a **differential equation** with respect to $I(x,y)$
- It's solution is a complex **integral equation** with respect to $T_g(x,y)$ and $k(x,y)$:

Transmission measurement

$I_R(x)$ =

$$= I_S(T_0)\exp\left(-\int_{y_1(x)}^{y_2(x)} k(x,y)\,\mathrm{d}y\right) + \quad I_T(x)$$

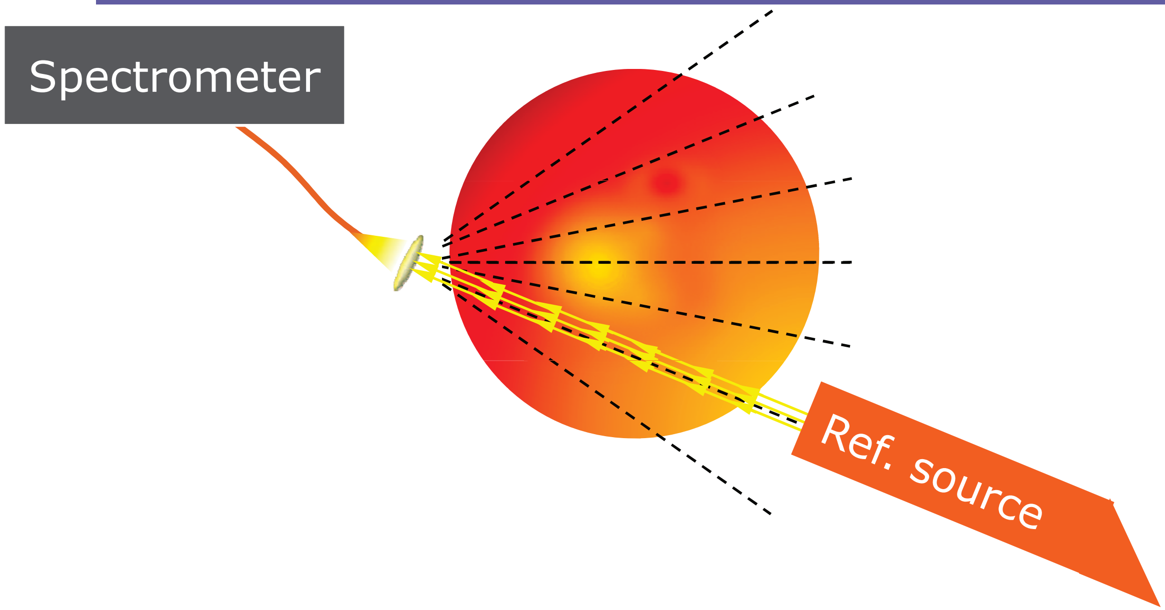
$$+ \int_{y_1(x)}^{y_2(x)} k(x,y)\, I_{Planck}(T_g(x,y)) \exp\left(-\int_{y}^{y_2(x)} k(x,y')\,\mathrm{d}y'\right)\mathrm{d}y \quad I_g(x)$$

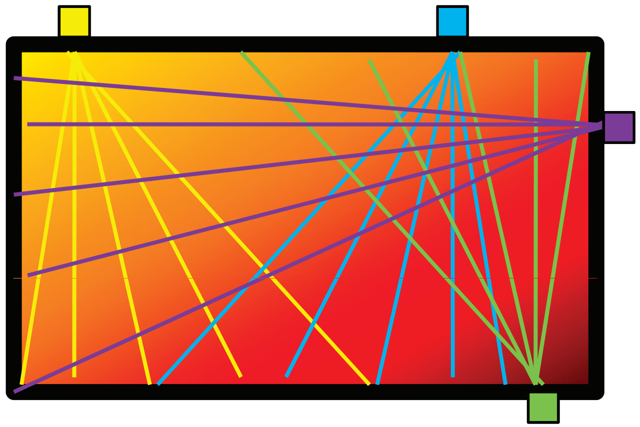
Emission measurement

$$I_T(x) = I_R(x) - I_g(x)$$

→ $k(x,y)$ → $T_g(x,y)$

Sweeping Scanning

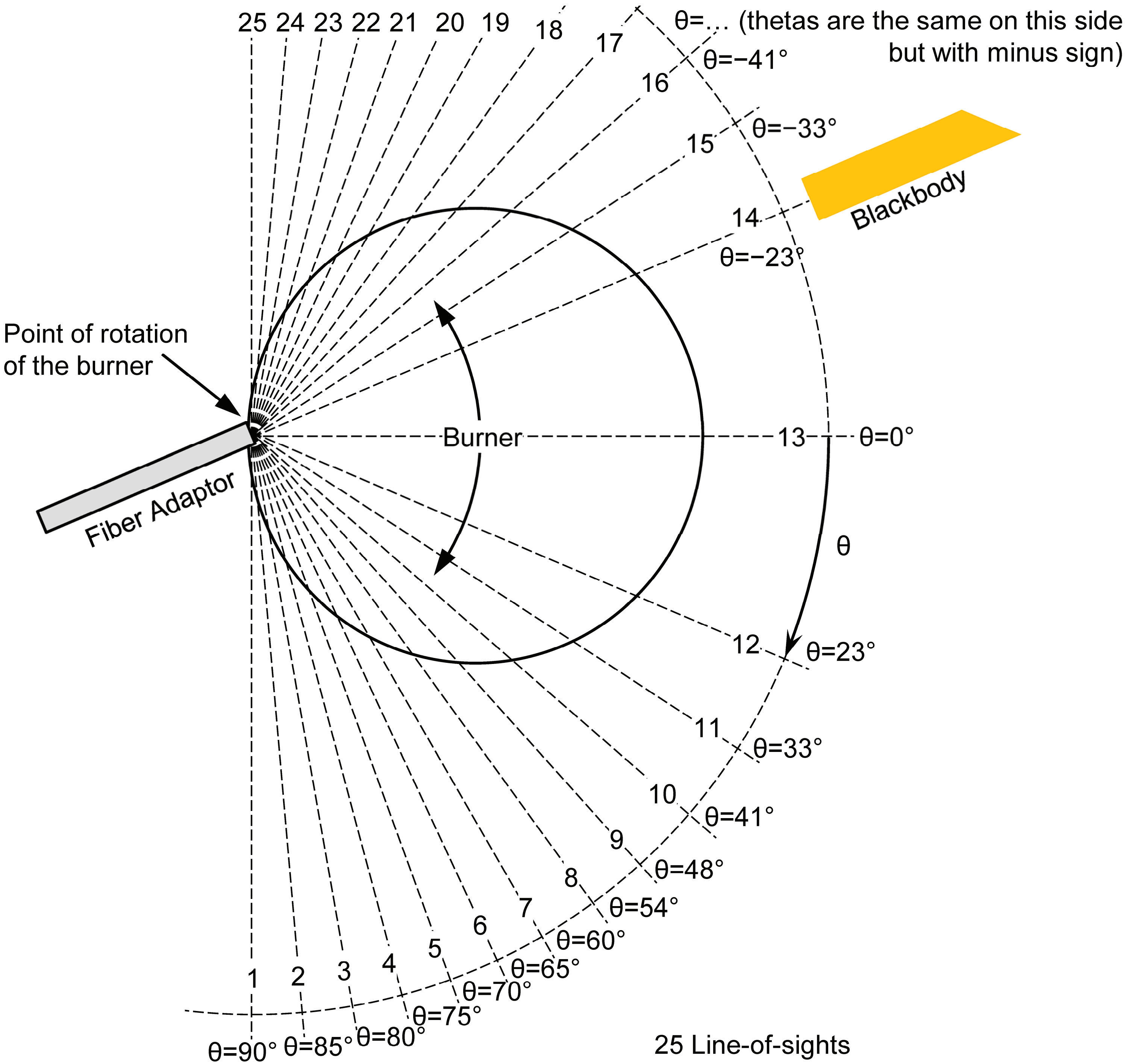




- **Advantage**
  - More practicable with respect to the real conditions of an industrial scale
    - The idea is to use several synchronized spectrometers with the sweeping scanning
    - The walls of a boiler can be used as a reference source

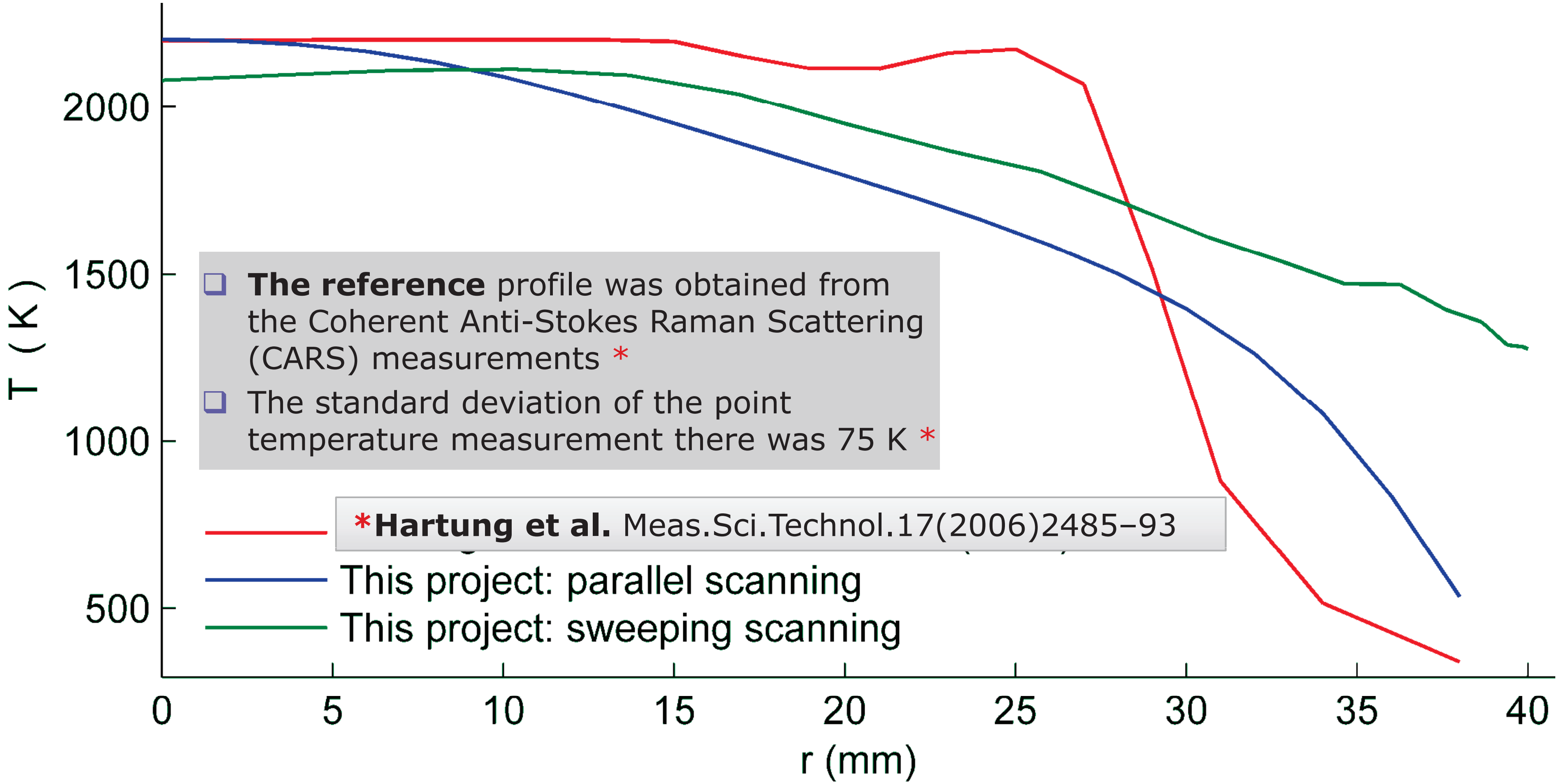
- **Equations**
  - The same as in the parallel case but just converted to polar coordinates

Sweeping Scanning



Tomography Results at φ = 1

- **Burner temperature profile** as a function of the distance from the center of the burner plate, r [mm] (r = 30 mm is the edge of the burner plate), corresponding to the height above the burner plate 12 mm.

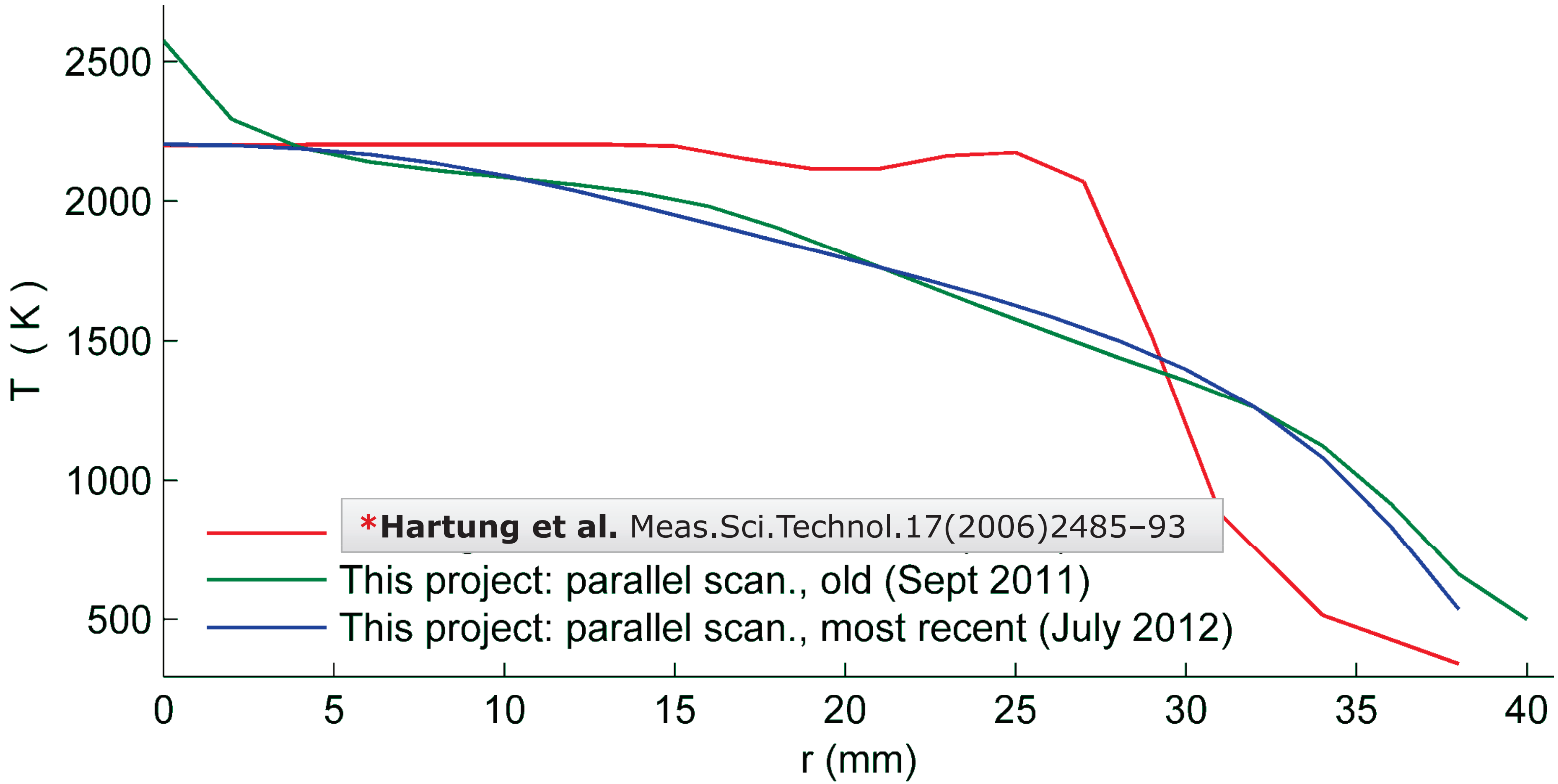


- **The reference** profile was obtained from the Coherent Anti-Stokes Raman Scattering (CARS) measurements *
- The standard deviation of the point temperature measurement there was 75 K *

***Hartung et al.** Meas.Sci.Technol.17(2006)2485–93

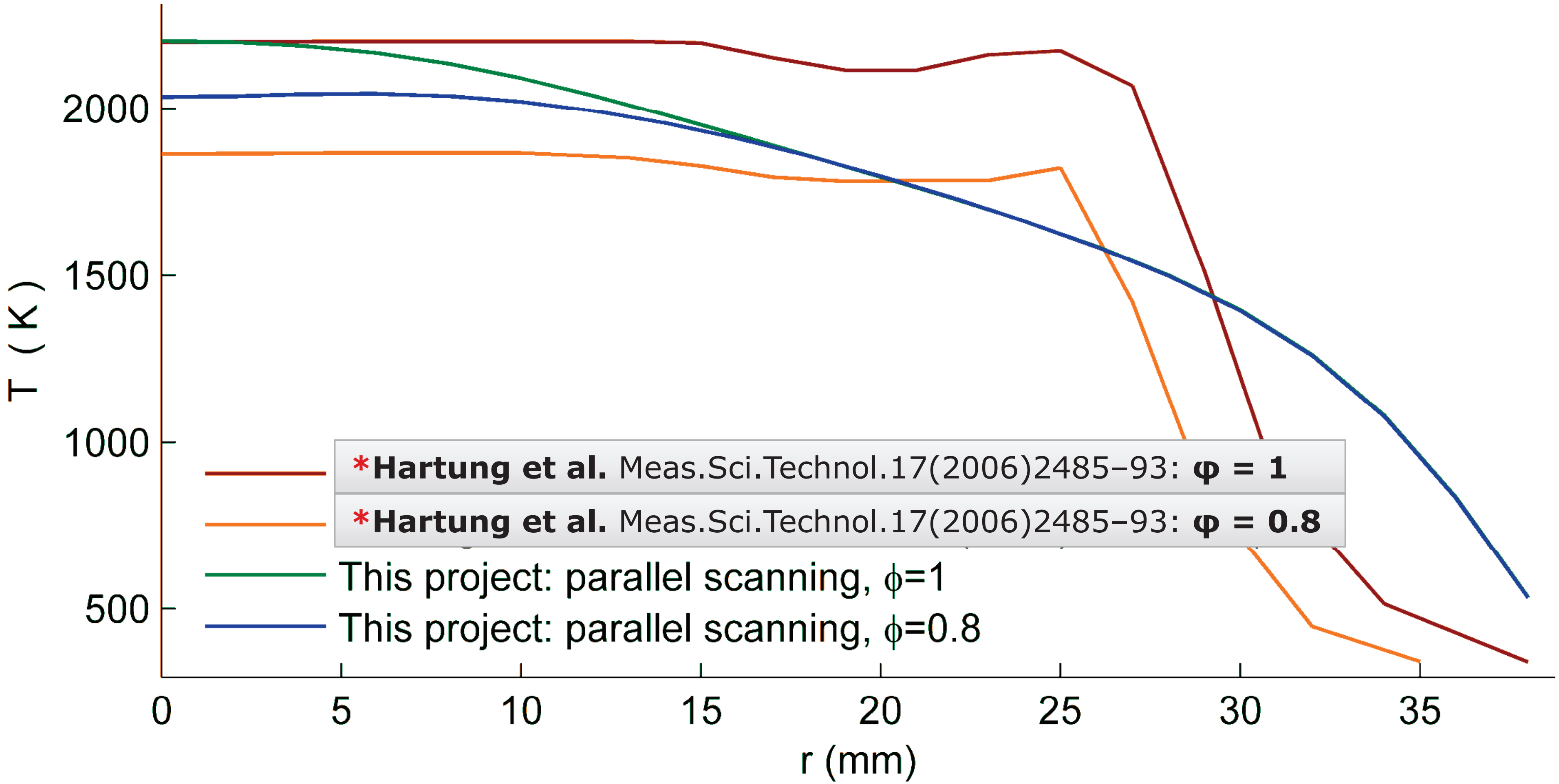
Tomography Results at φ = 1

- Some remarkable consistency between the temperature profiles obtained in the different measurement sessions in this project can be observed.



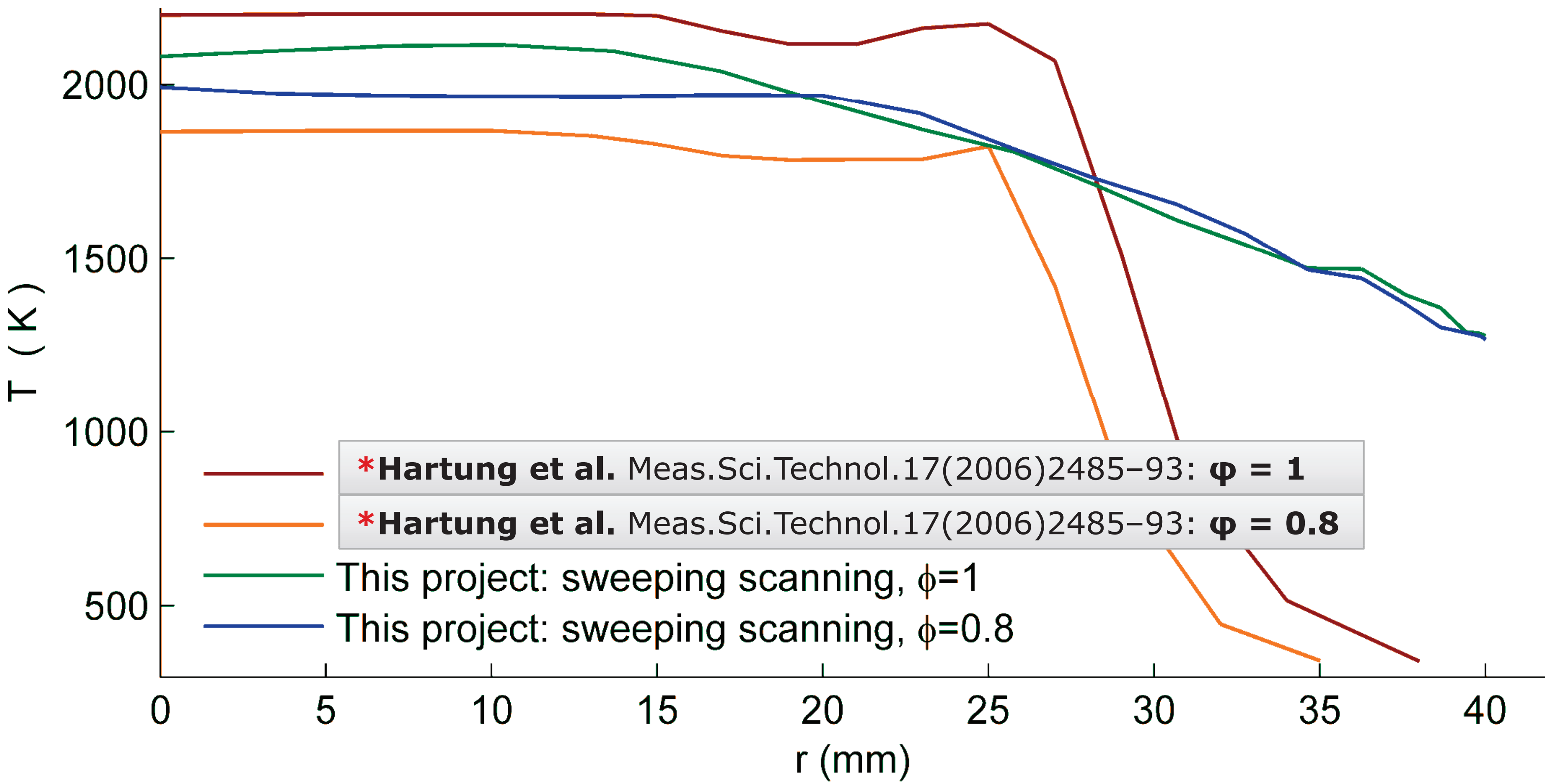
Tomography Results at φ = 0.8

- for **parallel scanning** in comparison with the results at **φ = 1:**



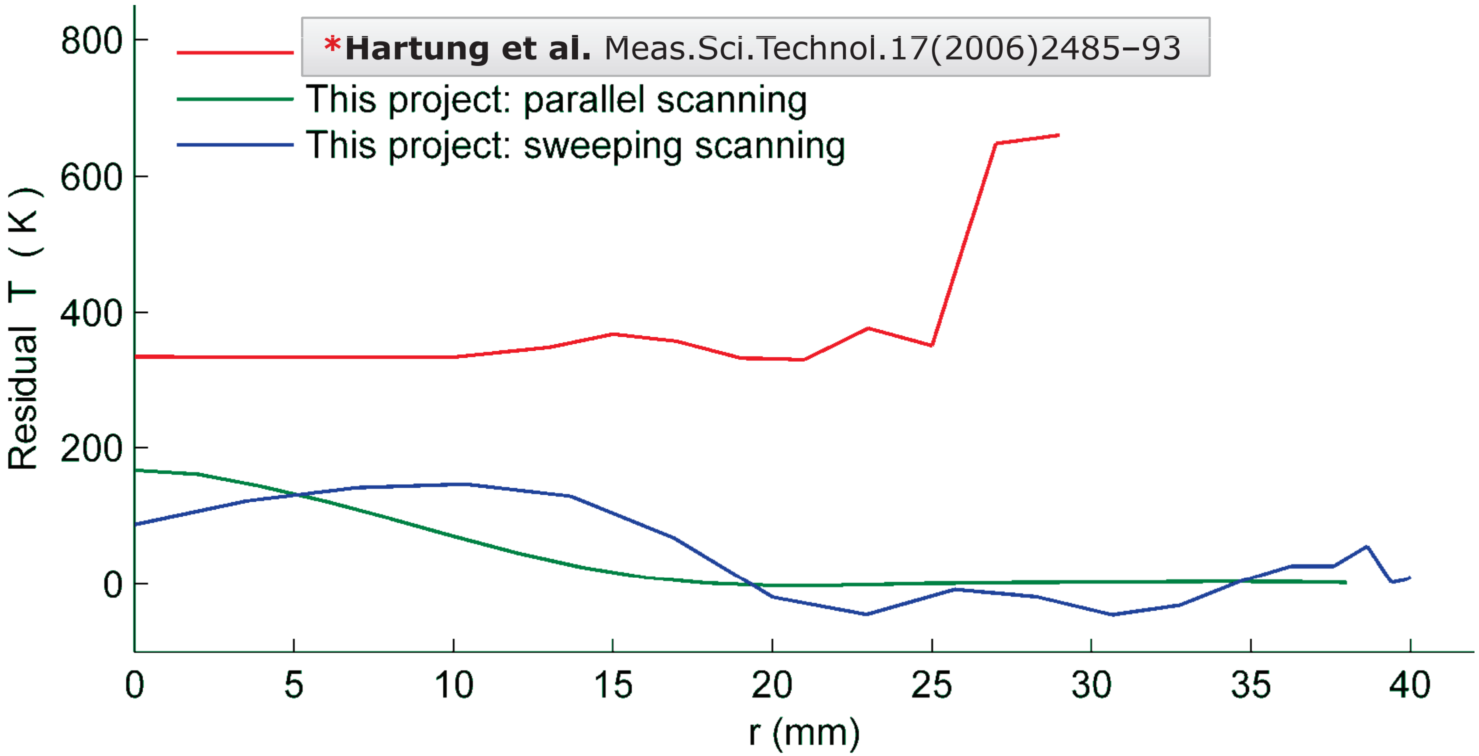
Tomography Results at φ = 0.8

- for **sweeping scanning** in comparison with the results at **φ = 1:**



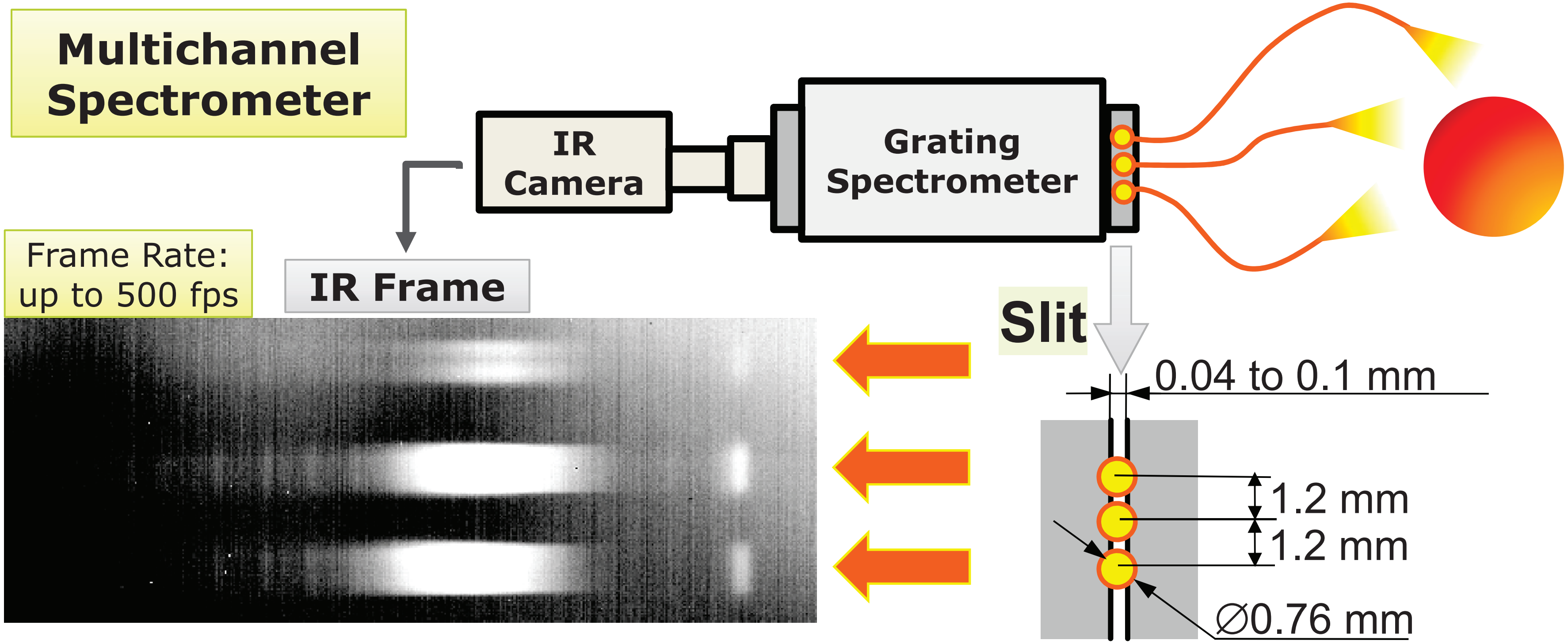
Tomography Results: Discussion

- The difference between the profiles for φ = 1 and φ = 0.8 is about 70-167 K at r < 10 mm for both parallel and sweeping scanning (i.e. independent) measurements performed in this project
- whereas the corresponding difference between the reference profiles for φ = 1 and φ = 0.8 is about 335 K. *
- Fig. below shows the residuals between the respective temperature profiles for φ = 1 and φ = 0.8 (e.g. the olive curve is the profile for φ = 1 minus the profile for φ = 0.8 both obtained from the parallel scanning measurements in this project).



Towards the Equipment for Tomography

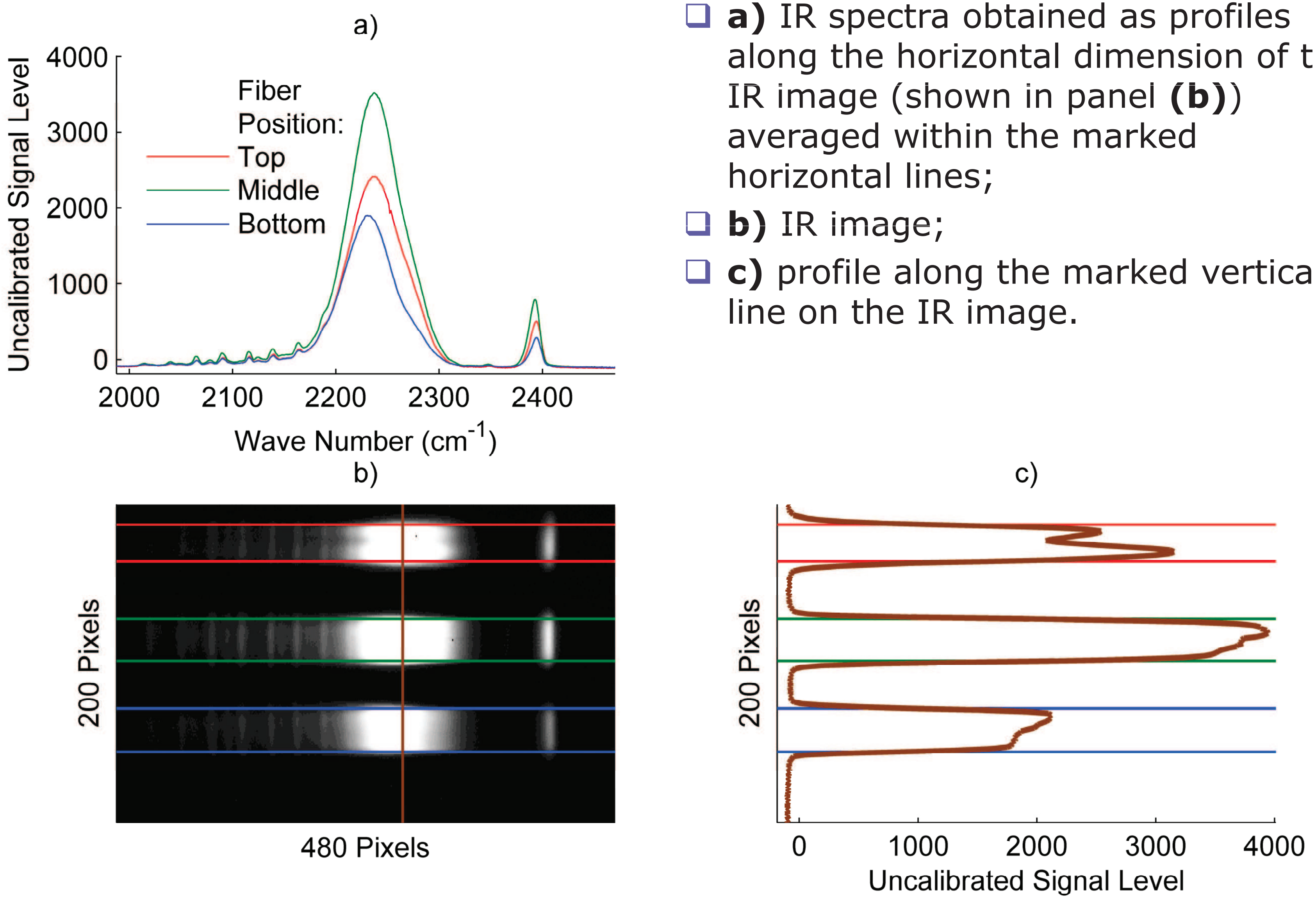
- **Objective**
  - It is essential for tomography to have simultaneous spectral measurements from several lines of sight
- **Approach**
  - Several optical fibers + grating spectrometer + IR camera



Fast simultaneous spectral measurements

Three fibres is not a limit!

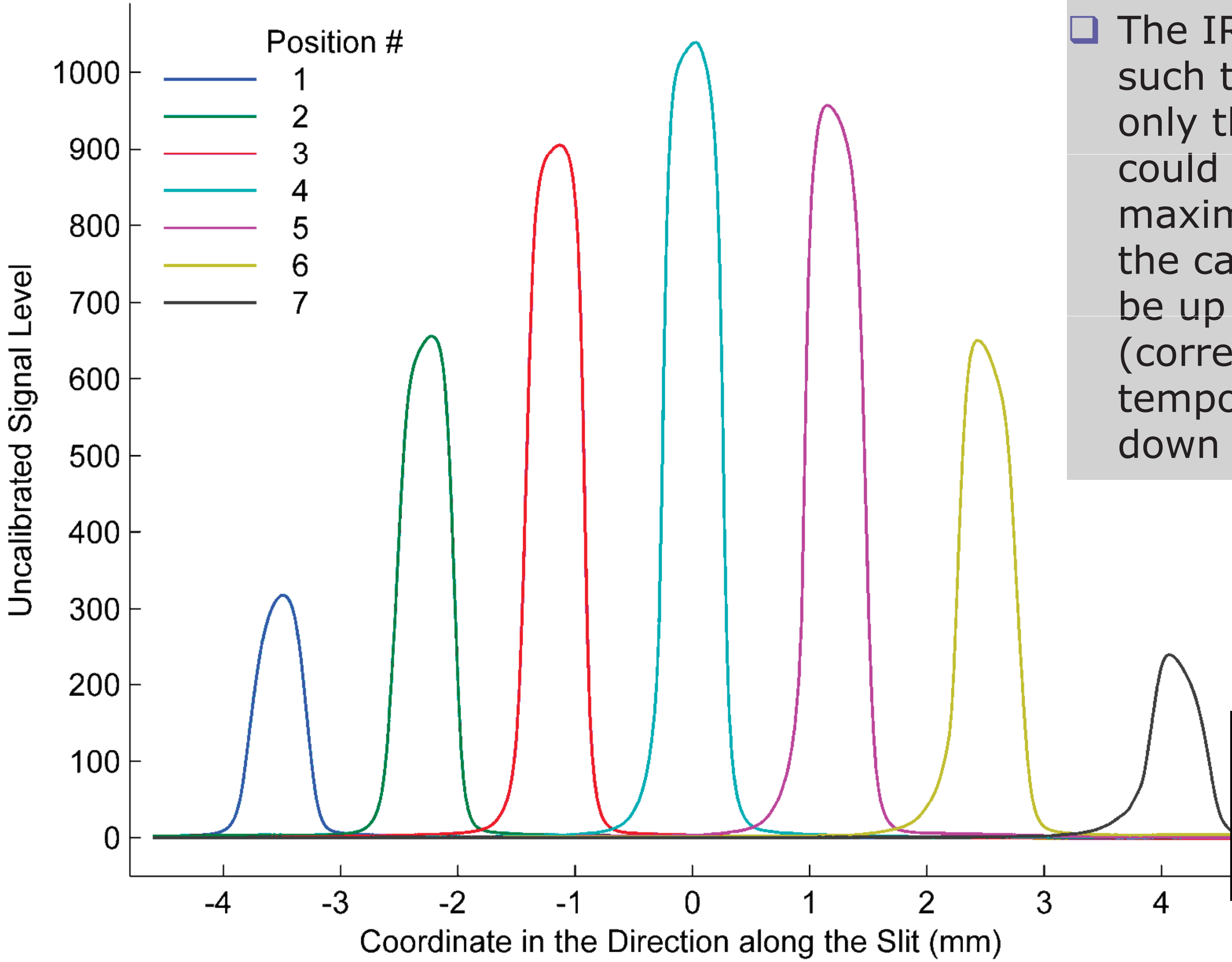
Multichannel Spectrometer



- **a)** IR spectra obtained as profiles along the horizontal dimension of the IR image (shown in panel **(b)**) averaged within the marked horizontal lines;
- **b)** IR image;
- **c)** profile along the marked vertical line on the IR image.

Multichannel Spectrometer

Number of Fibers Coupled onto the Entrance Slit and Time Resolution

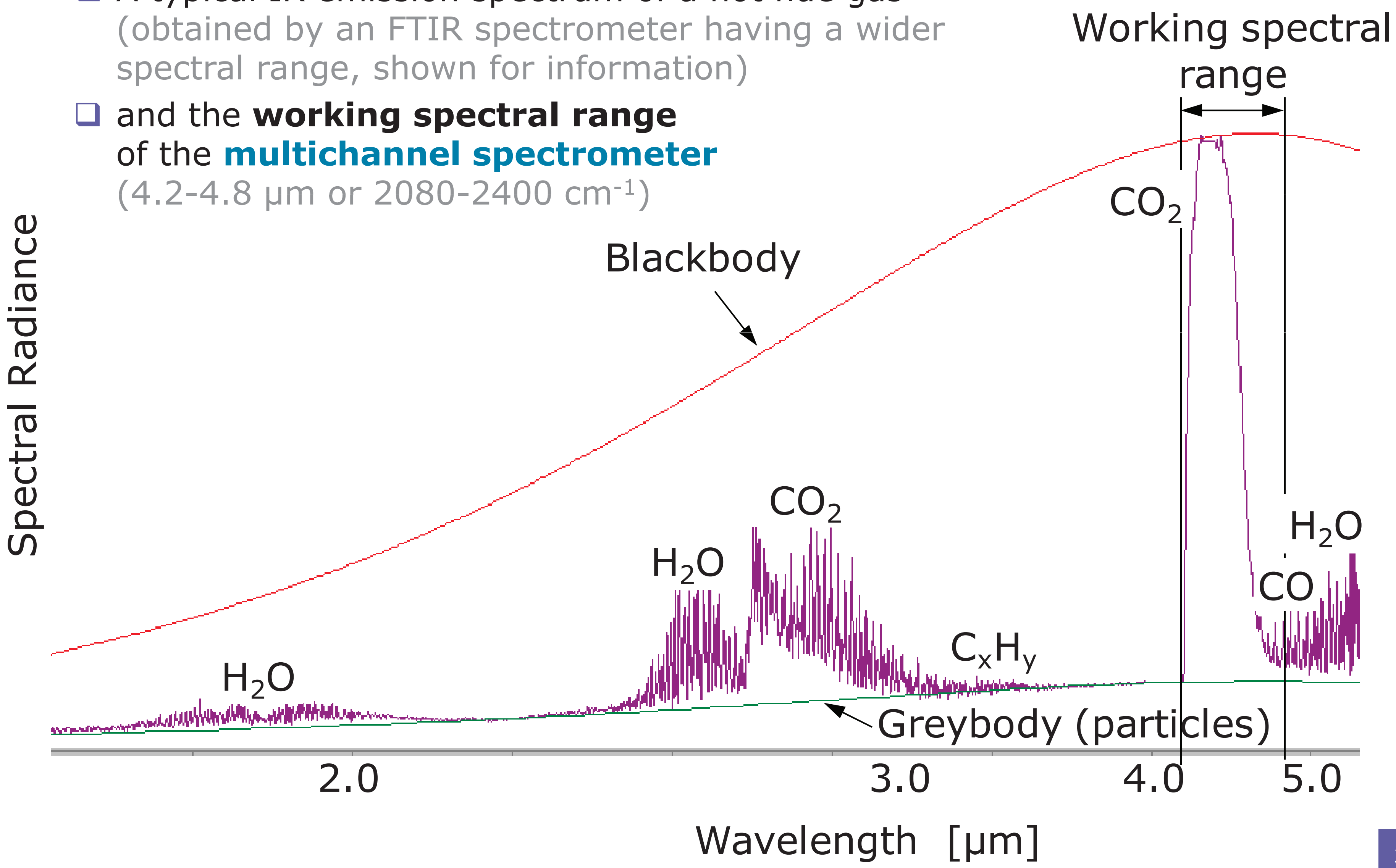


- The IR image was trimmed such that the signal from only the 3 central positions could be detected to maximize the frame rate of the camera which can then be up to 500 fps (corresponding to the temporal resolution of down to 2 ms).

The signal from a fiber at 7 positions in front of the entrance slit of the spectrometer

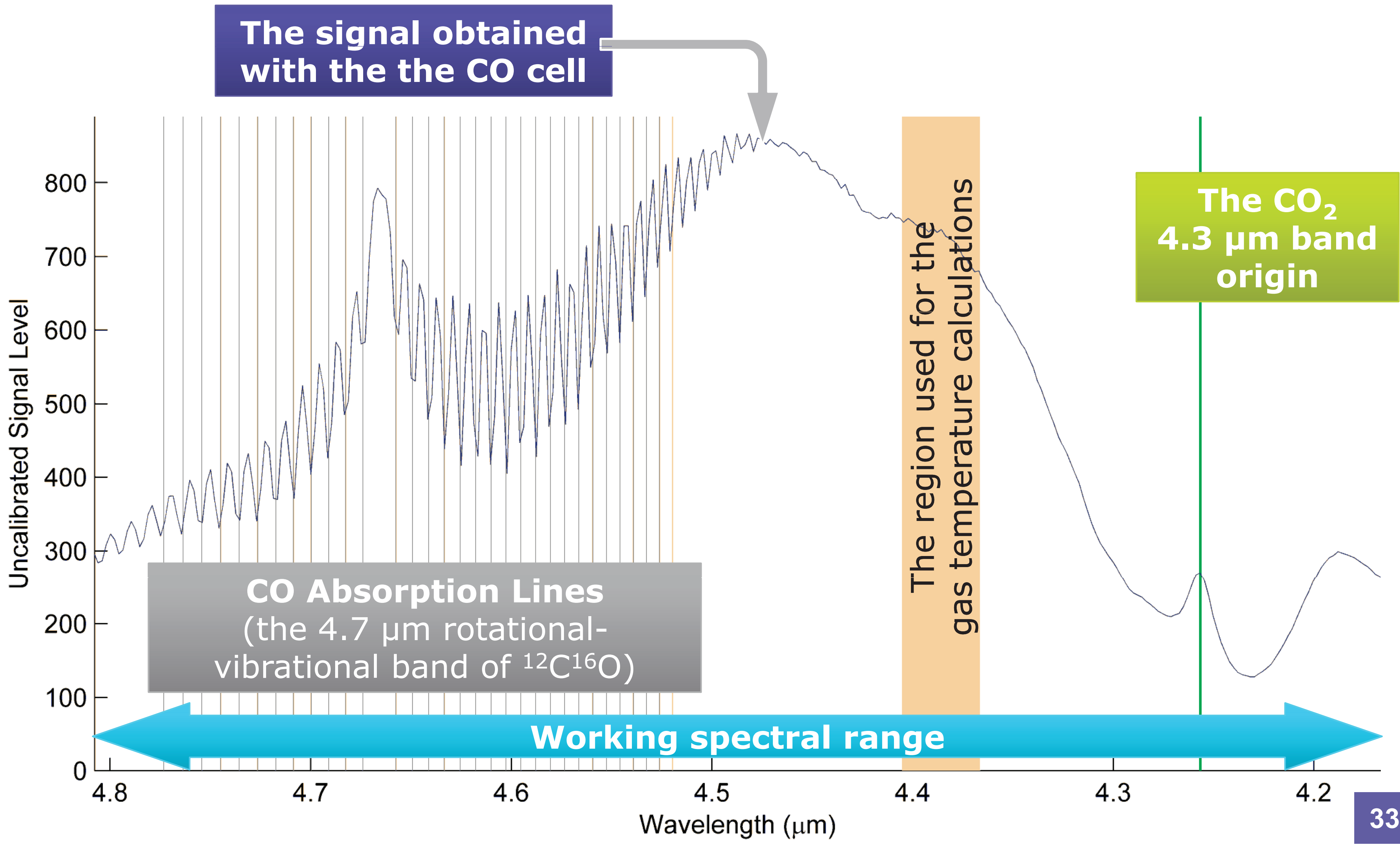
Multichannel Spectrometer

- A typical IR emission spectrum of a hot flue gas (obtained by an FTIR spectrometer having a wider spectral range, shown for information)
- and the **working spectral range** of the **multichannel spectrometer** (4.2-4.8 μm or 2080-2400 cm^{-1})



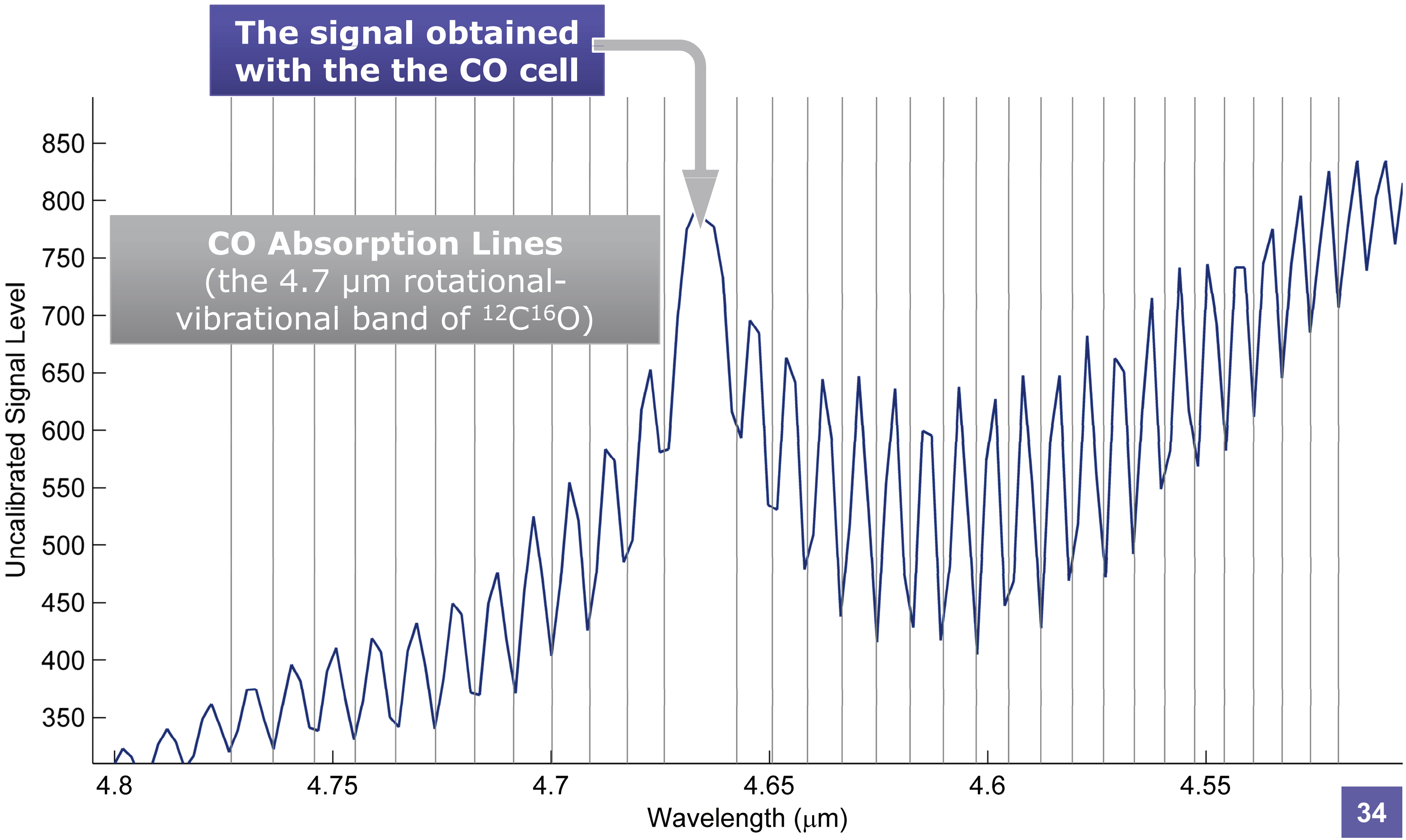
Multichannel Spectrometer

Calibration of the x-axis (wavelength axis)



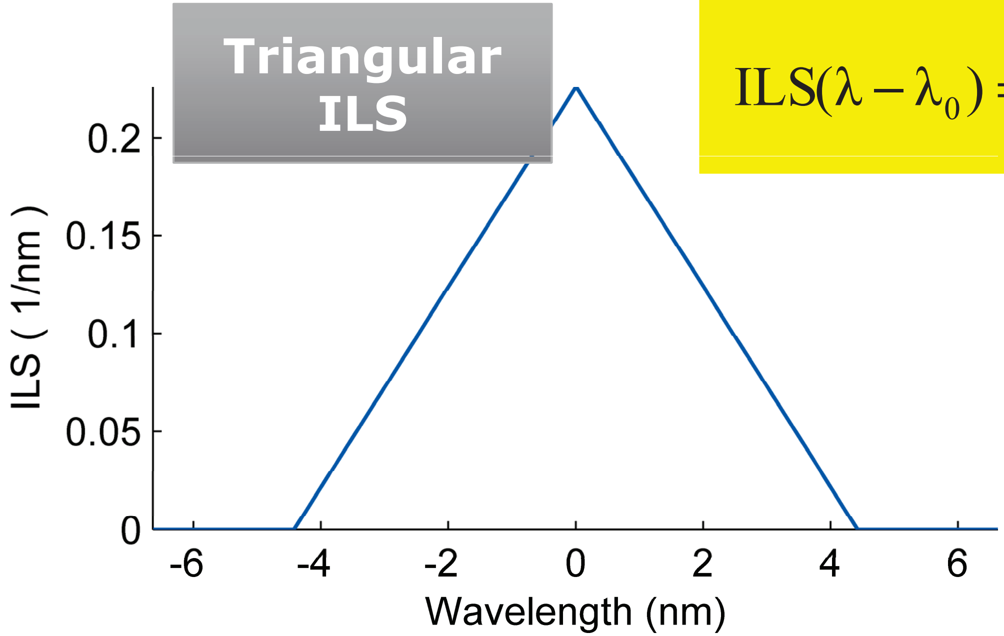
Multichannel Spectrometer

Calibration of the x-axis (wavelength axis)



Multichannel Spectrometer

Instrument Line Shape Function (ILS) ,
Spectral Resolution (R) and Entrance Slit Width (W)



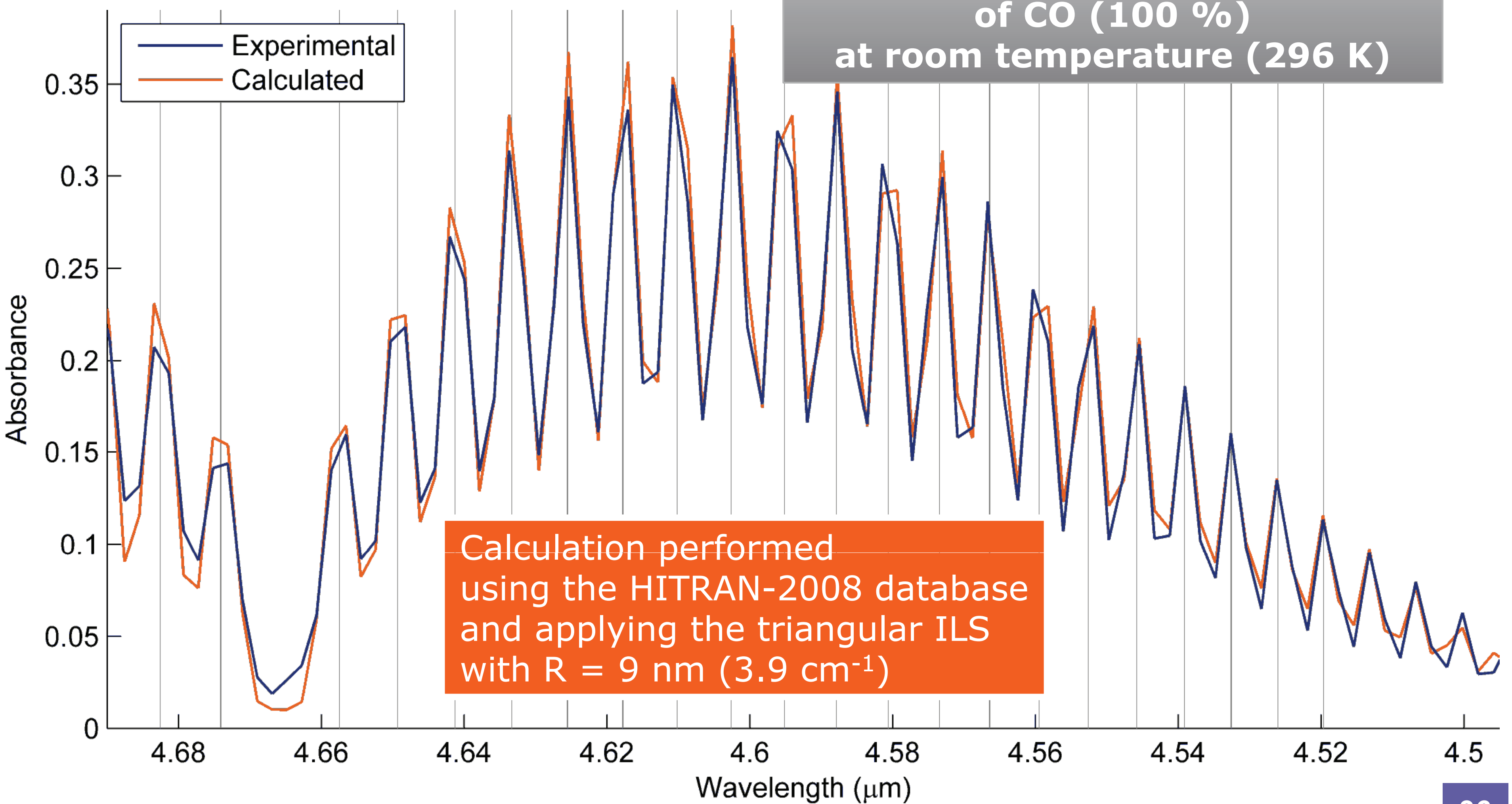
$$\mathrm{ILS}(\lambda-\lambda_0)=\frac{1}{0.5R}\left(1-\frac{|\lambda-\lambda_0|}{0.5R}\right),\quad |\lambda-\lambda_0|\le 0.5R$$

Setup	R		W
	nm	cm^{-1}	µm
The setup for the x-axis calibration (the CaF_2 lens with *f*=50.8mm is used instead of the fiber)	**9**	3.9	**40**
The multichannel setup with the 3 fibers	**23**	12	**100**

Multichannel Spectrometer

Instrument Line Shape Function (ILS) and Spectral Resolution (R)

Absorbance of the 4.7 µm band of CO (100 %) at room temperature (296 K)

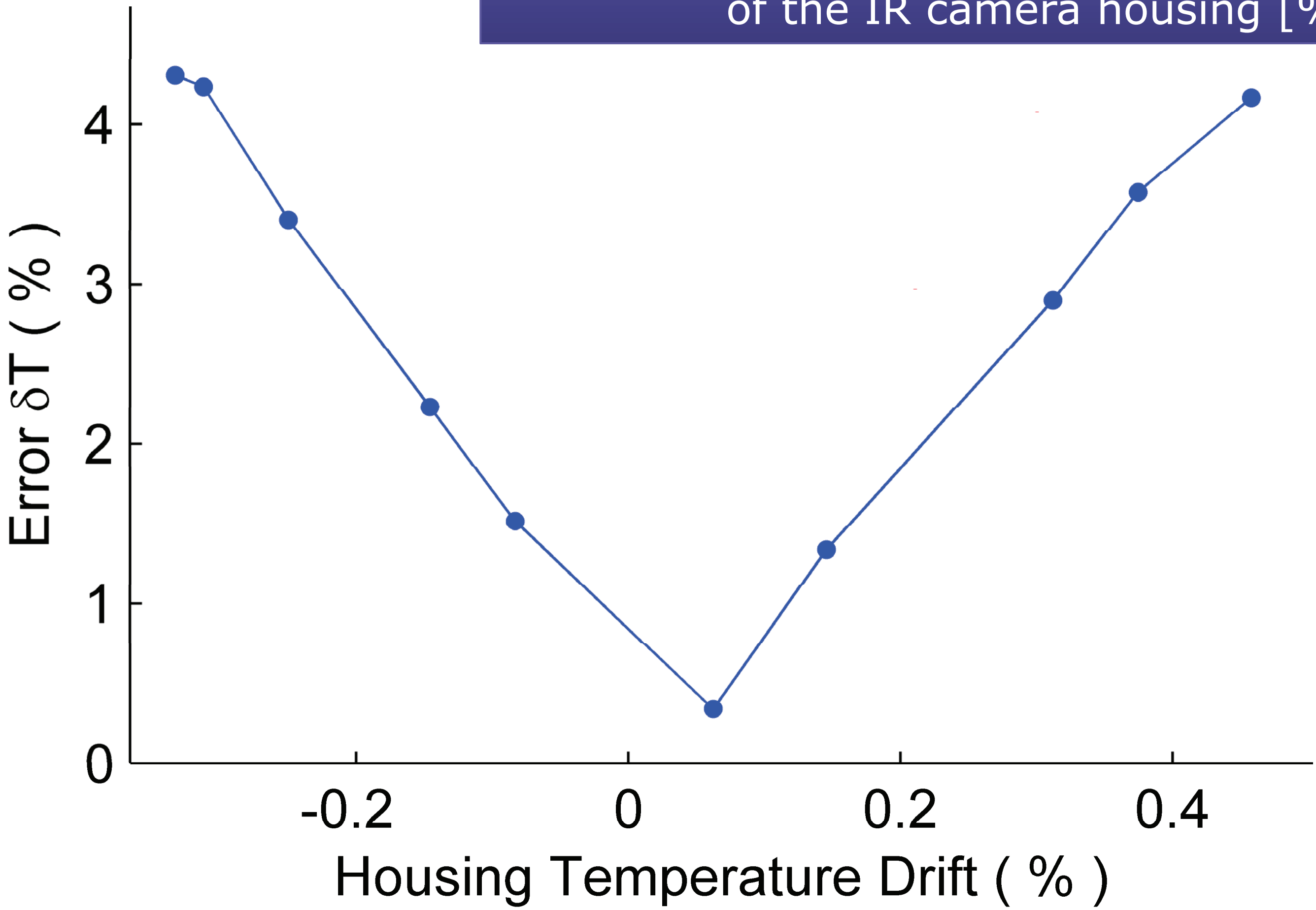


Calculation performed using the HITRAN-2008 database and applying the triangular ILS with R = 9 nm (3.9 cm^{-1})

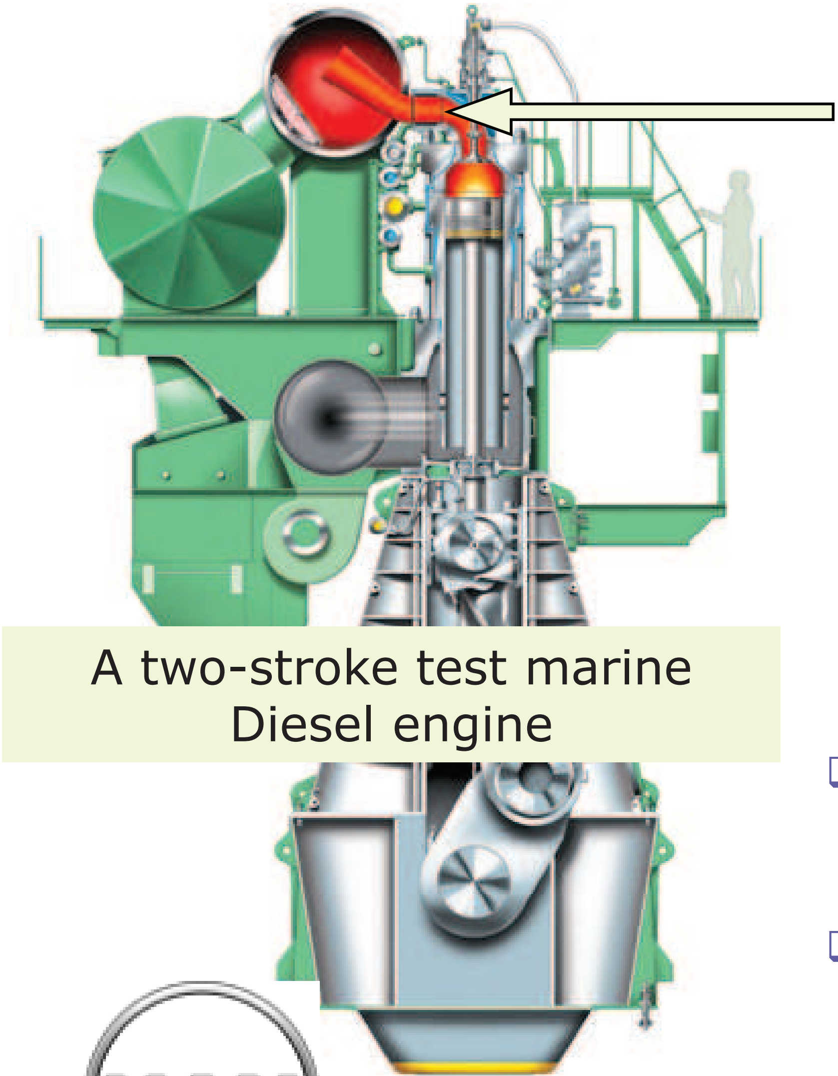
Multichannel Spectrometer

Thermal Stability of the System

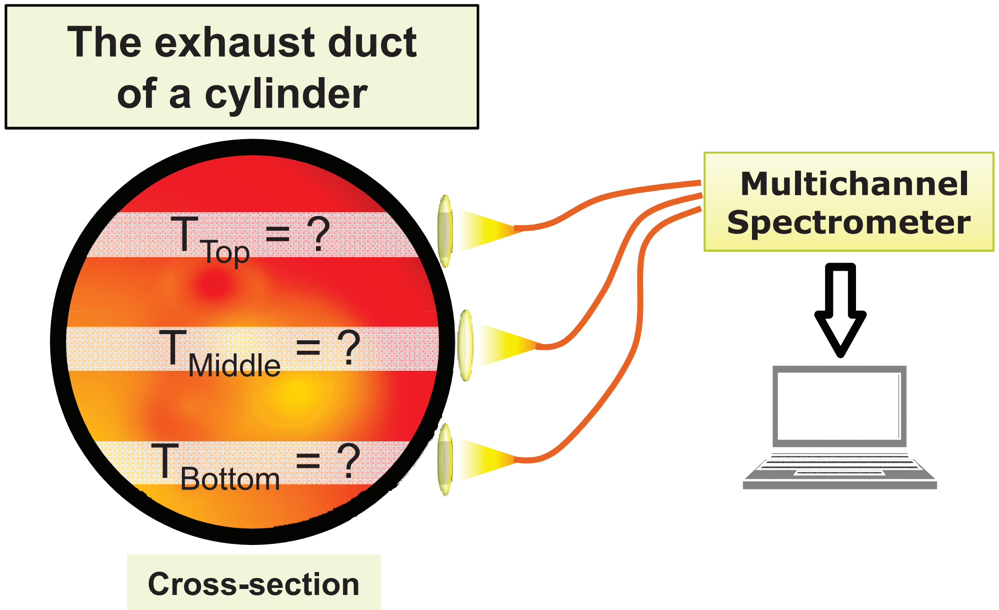
The relative error **δ*T* [%]** of the blackbody temperature measurement as a function of the temperature drift of the IR camera housing [%]



Large Diesel Engine



A two-stroke test marine Diesel engine

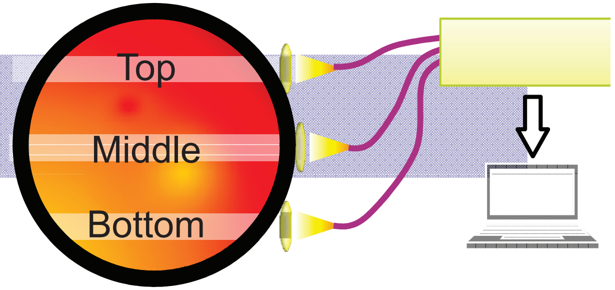


MAN Diesel & Turbo
Copenhagen
R&D Department

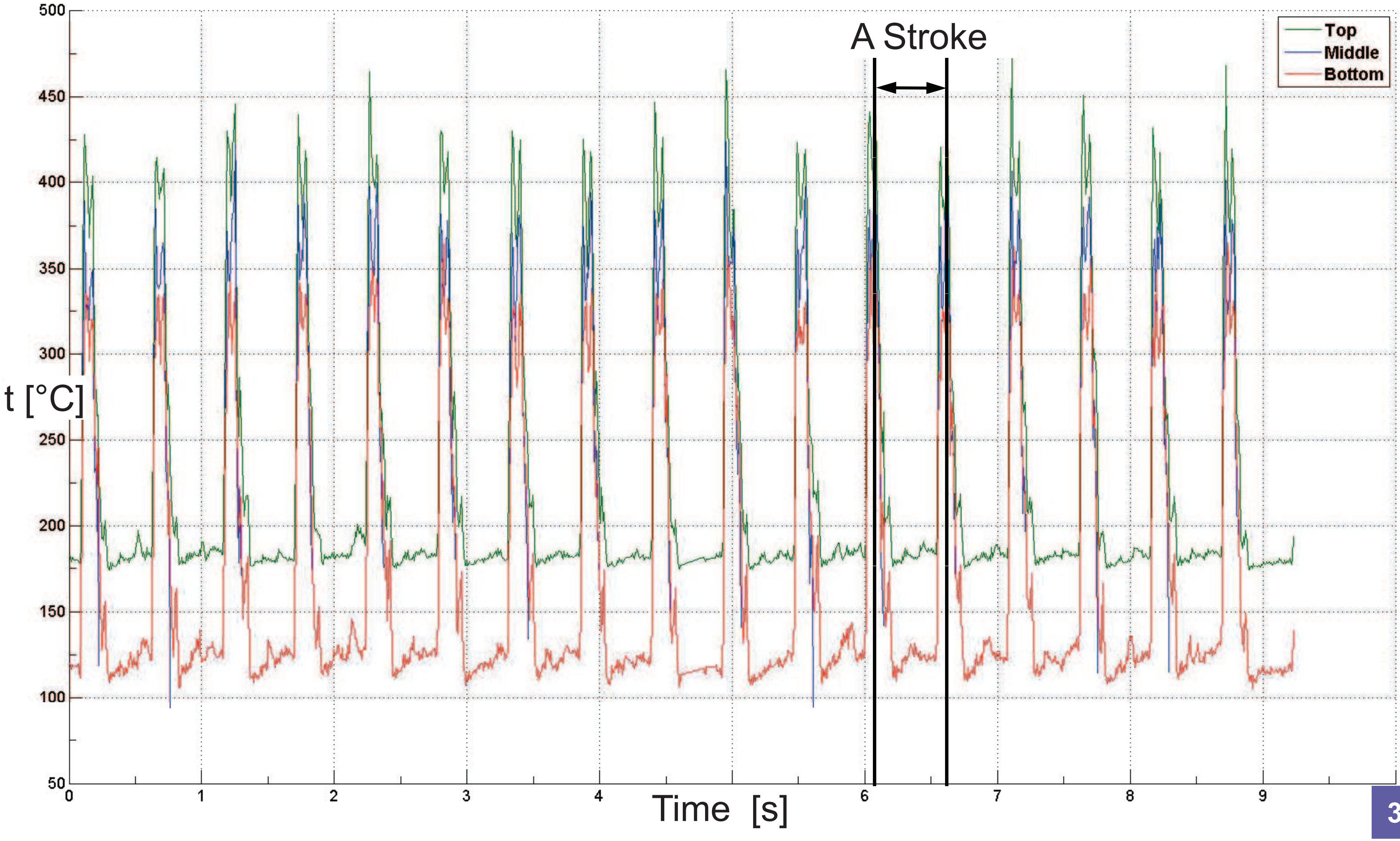
- **The system was successfully tested under real conditions**

- **The objective** was to measure gas temperature simultaneously in the three optical ports
  - measurements were synchronized with the encoder of the main shaft

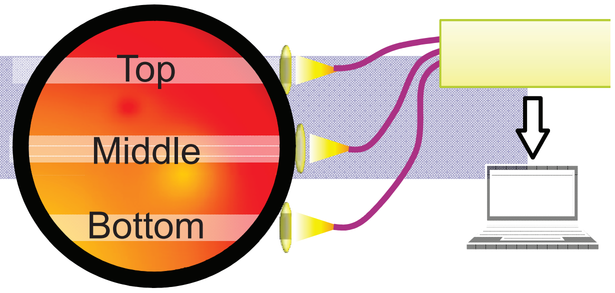
Gas Temperature vs Time



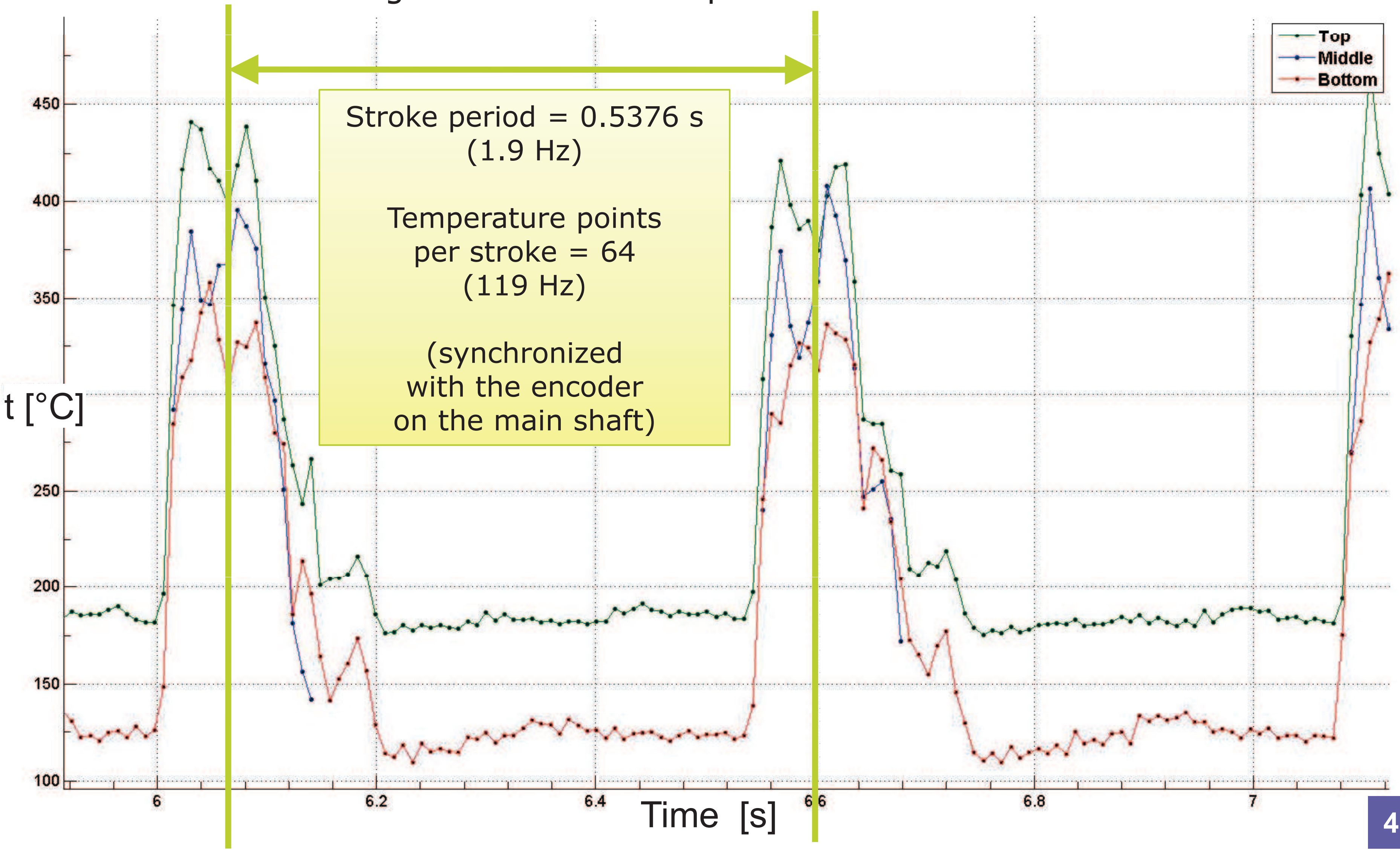
- Temporal resolution 119 Hz (64 points per stroke)



Gas Temperature vs Time



- Gas temperature is not homogeneous
  - It is increasing from bottom to top



Gaseous Species Concentrations

- Calculations are based on **Line-By-Line** modeling of spectra*
  - which uses spectroscopic databases HITRAN, HITEMP, CDSD

Measured

•Gas temperature [K]	T_g
•Total pressure [atm]	p
•Absorption path length [cm]	L
•**Mole fraction of the species [%]**	$\boldsymbol{c}$
•Instrument Line Shape Function	$ILS(\nu,\nu_c)$
•**Measured transmittance**	$\boldsymbol{\tau_m(\nu)}$

Database parameters for the *i* th transition*

•Spectral line transition frequency [cm-1]	ν_0
•Air-broadened pressure shift [cm-1/atm]	δ
•Air-broadened HWHM [cm-1/atm]	γ_{air}
•Self-broadened HWHM [cm-1/atm]	γ_{self}
•Coefficient of temperature dependence of γ_{air} and γ_{self}	n
•Spectral line intensity [cm-1/(molecule cm-2)]	S_0
•Lower state energy of the transition [cm-1]	E_0

Calculated*

•Pressure-shift correction of line position [cm-1]	$\nu_0{}^*(p)$
•Temperature and pressure correction of line HWHM [cm-1]	$\gamma\,(p,T_g)$
•Lorentz profile [1/cm-1]	$f\,(\nu,\,T_g,\,p)$
•Temperature correction of line intensity [cm-1/(molecule cm-2)]	$S\,(T_g)$
•Monochromatic absorption coefficient [1/(molecule cm-2)]	$k_i\,(\nu,\,T_g,\,p)$
•**Calculated transmittance**	$\boldsymbol{\tau_{clc}(\nu)}$

- The idea is to compare measured and calculated transmittances
- The mole fraction can then be obtained from the best match between the transmittances

* **Rothman et al.** J. Quant. Spectrosc. Radiat. Transfer 60 (5) (1998) 665–710

Line-By-Line Modeling

Evseev et al. J. Quant. Spectrosc. Radiat. Transfer 113 (17) (Nov.2012) 2222-33

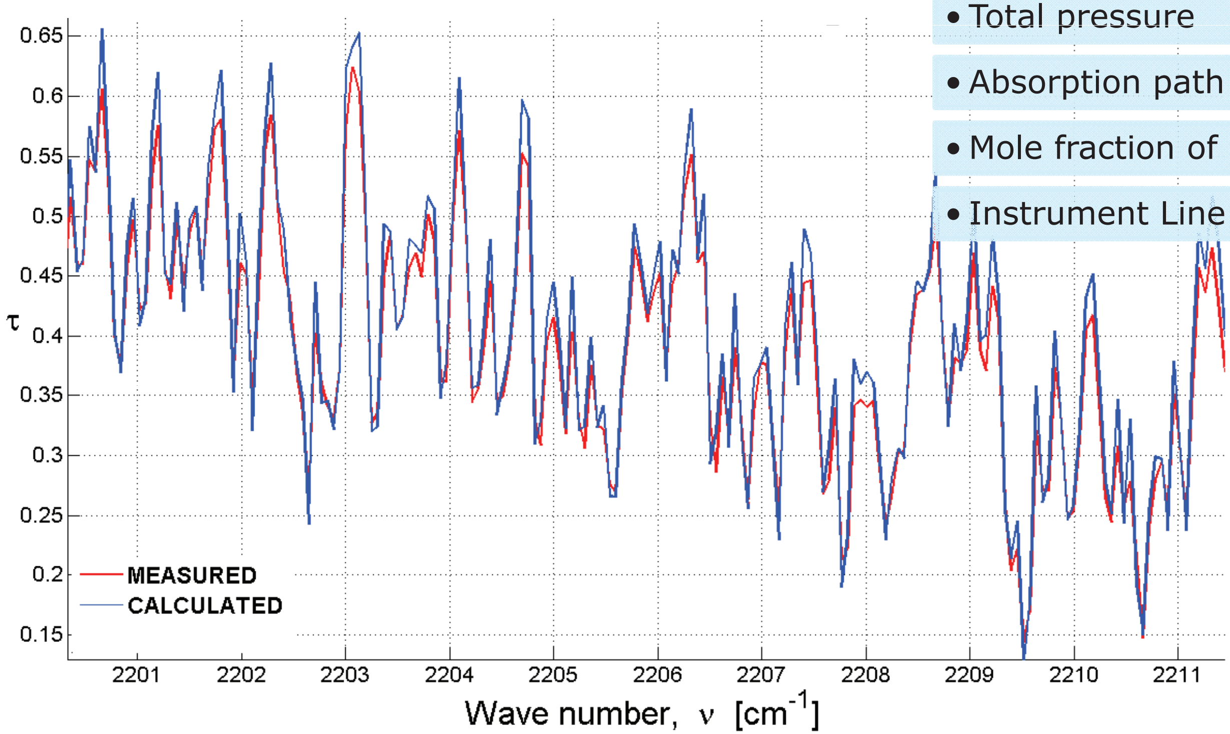
CO_2 Transmittance

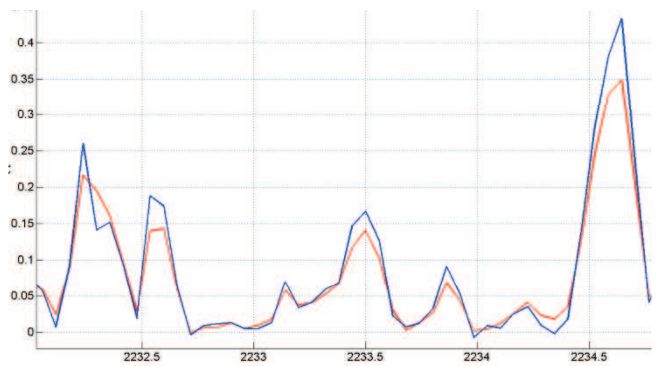
- **Measured** in the high-temperature flow gas cell developed at *DTU Chemical Engineering* *(before 1 January 2012 Risø DTU, Optical Diagnostics Group)*

  Vs

- **Calculated** using the HITEMP 2010 database

• Gas temperature	1000 K
• Total pressure	1 atm
• Absorption path length	53.3 cm
• Mole fraction of CO_2	10 %
• Instrument Line Shape Function	*sinc*





Summary

- **Tomographic reconstruction of gas temperatures**
  - Axisymmetric case
    - Parallel scanning
    - Sweeping scanning

- **Tomography equipment**
  - Multichannel spectrometer
    - Optical fibres + grating spectrometer + IR camera
    - Successfully applied on the large Diesel engine
      - Simultaneous temperature measurements in the three optical ports of the exhaust duct

- **Concentration calculations**
  - Measurements in the hot gas cell are compared with the line-by-line modeling results
    - Excellent agreement in a wide spectral range

Thank you for your attention!