MEASUREMENTS OF GAS FLOW PARAMETERS BY ABSORPTION SPECTROMETRY WITH DIODE LASERS

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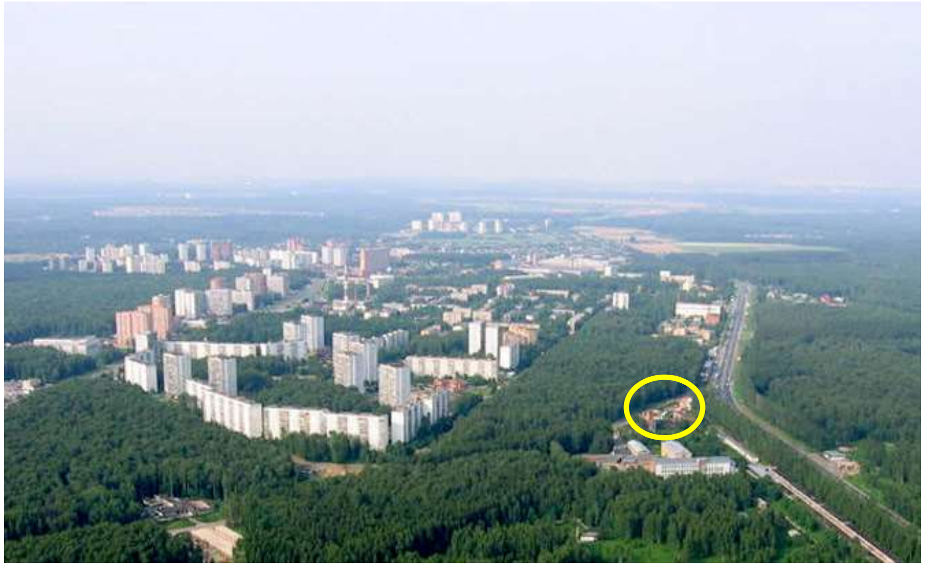
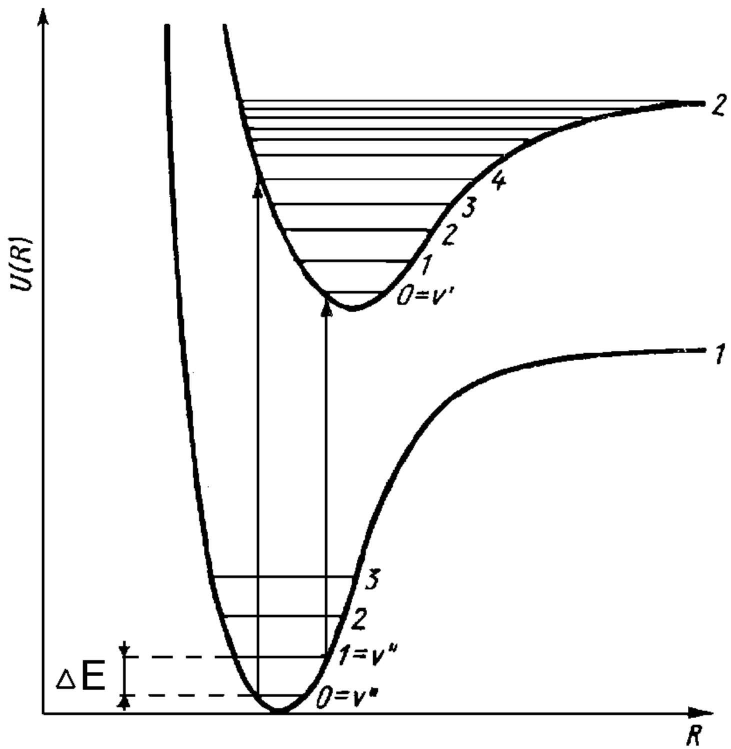


Outline for this talk

1. **Motivation & basics**
2. **Selection of analytical lines**
3. **Laboratory measurements**
4. **Optimization of the fitting model**
5. **TDLAS at the Joint Institute for High Temperatures**
6. **Imaging of experimental data**
7. **Instrumental and software improvements**
8. **Examples of *T*-measurements in combustion**

Measurements of the temperature if TDE is established



Ratio of the integral line intensities *S* for the temperature *T* is:

$$R = \left(\frac{S_1}{S_2}\right)_T = \left(\frac{S_1}{S_2}\right)_{T_0} \exp\left[-\frac{hc\Delta E}{k}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

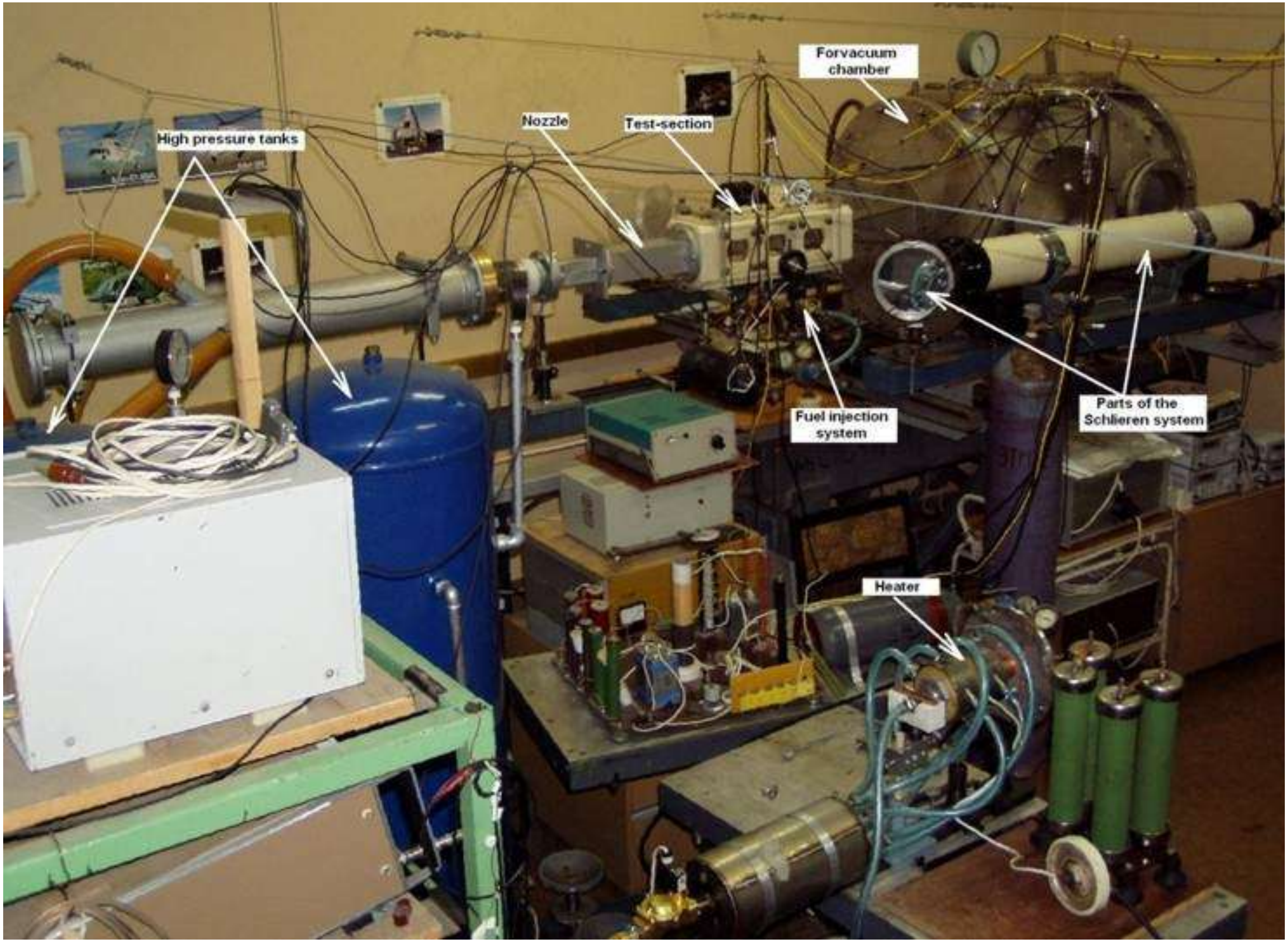
ΔE - low energies difference

Task parameters for test setup at the Joint Institute for High Temperatures (JIHT RAS)

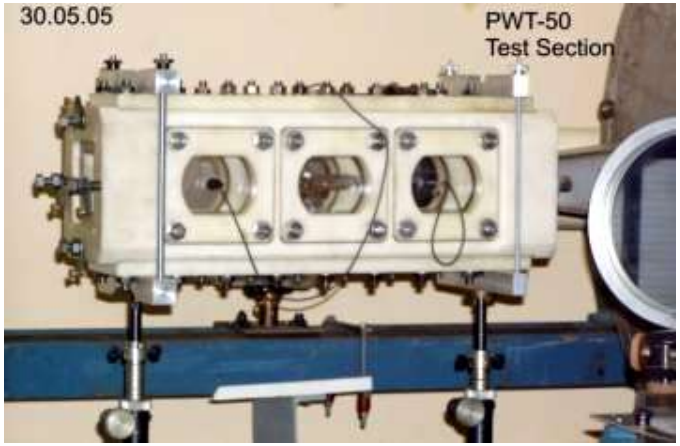
Type of combustion	plasma-assisted
Discharge	transverse filament
Fuel	H_2, ethylene
Flow velocity	M ~ 2 (supersonic flow)
Temperature	300-2000 K
Total pressure	100-300 Torr
H_2O concentrations	1-10 %
Optical length	70 mm
Duration of the run	~500 ms
Duration of the discharge	~100 ms

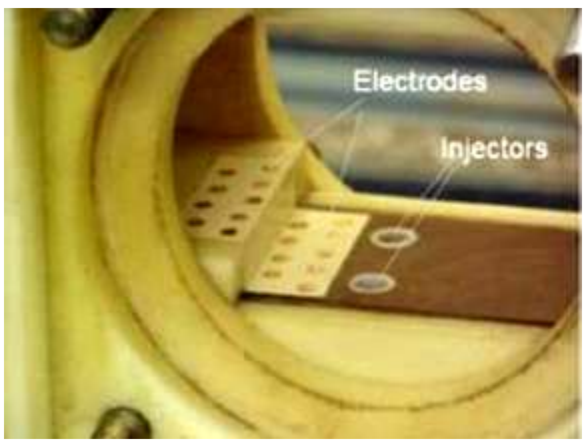
Spatially and temporally-resolved measurements are desired

Time resolution	~1 ms
Spatial resolution	~1-2 mm

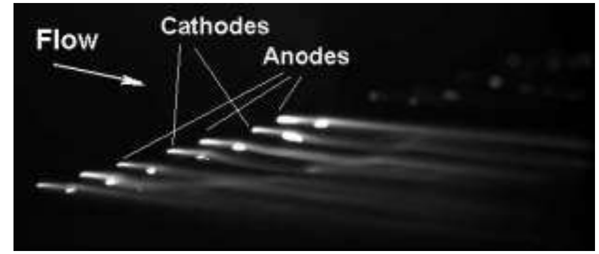

Forvacuum chamber
High pressure tanks
Nozzle
Test-section
Fuel injection system
Parts of the Schlieren system
Heater

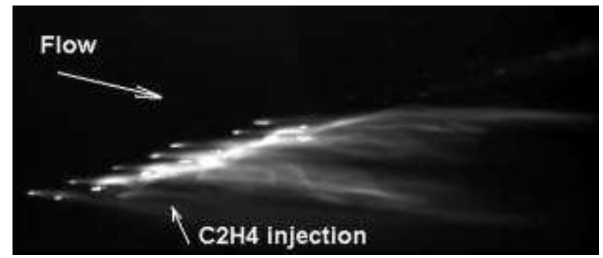
Test Section





Plasma-assisted combustion





Main problems

- Bright plasma emission
- Electrical noises
- Strong vibrations
- H_2O absorption in free-path outside the cell
- No reproducibility of baseline

Selection of analytical lines

Criteria:

- **commercially available diode lasers**
- **high sensitivity to temperature variation**
- **reasonable intensity**
- **several appropriate lines within a DL tuning range of ~ 1 cm^{-1}**
- **minimal spectral overlapping**
- **minimal experimental error :**

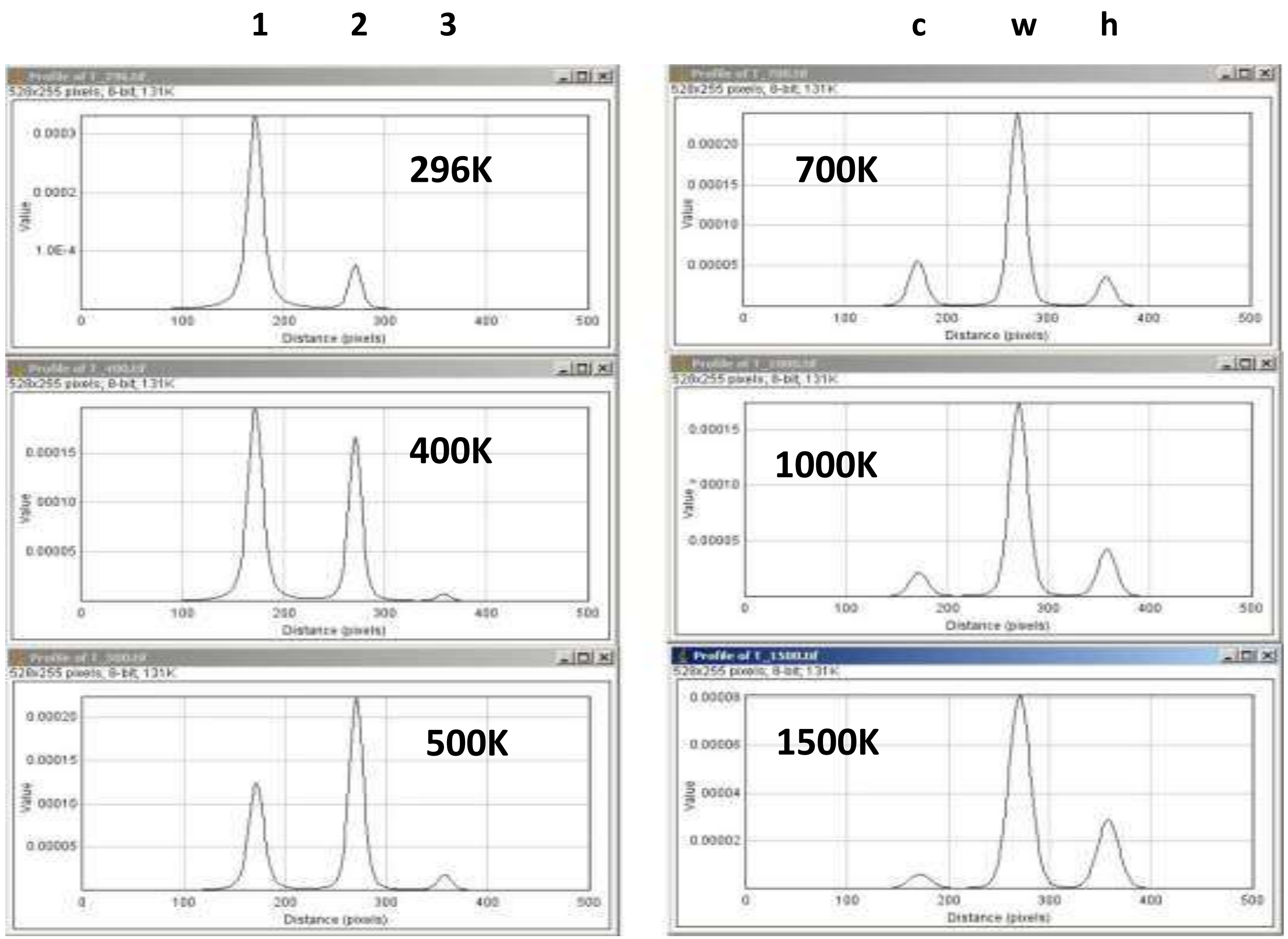
$$\frac{\Delta T}{T} = \frac{T}{T_{eff}} \left(\frac{1}{S_1^2} + \frac{1}{S_2^2}\right)^{1/2} \Delta S \qquad T_{eff} = \frac{hc\Delta E}{k}$$

The computer program was written for selection of the optimal pairs of absorption lines in the 1.3-1.4 μm region, which could provide the best signal-to-noise ratio for measurements in the temperature range 300 – 2000 K.

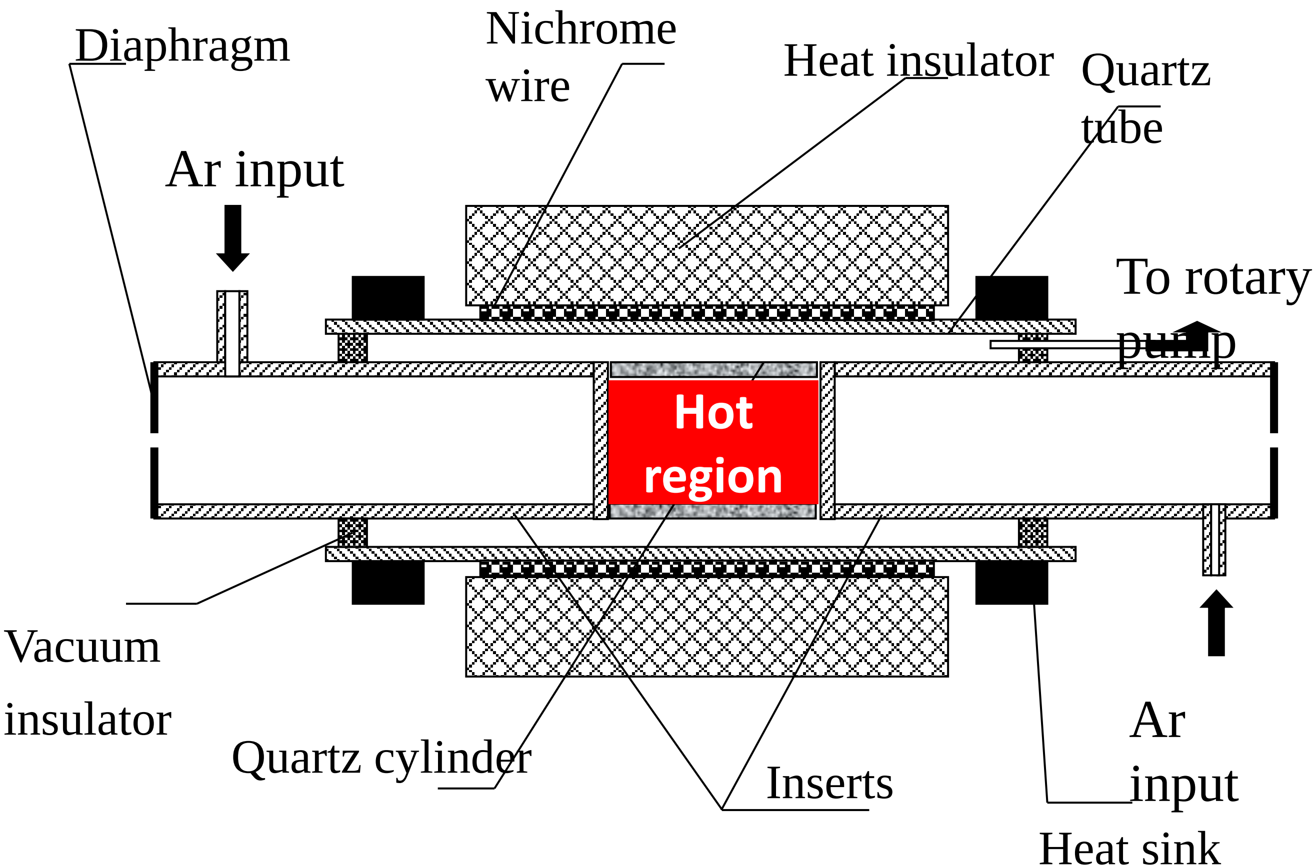
Analytical lines

	ν	*S* (cm/mol)	γ (air)	γ (H2O)	*E''* (cm^{-1})	No.	
***T* = 296 K**							
•	7189.199	1.412E-23	0.0433	0.35	1394.8142	0	
•	7189.344	6.213E-22	0.1001	0.49	142.2785	1	"cold"
•	7189.541	1.069E-22	0.0549	0.33	1255.1667	2	"warm"
•	7189.715	2.037E-24	0.0767	0.34	2004.8157	3	"hot"
***T* = 1000 K**							
•	7189.199	2.394E-22	0.0211	0.1707	1394.8142	0	
•	7189.344	1.449E-22	0.0392	0.1919	142.2785	1	
•	7189.541	1.124E-21	0.0288	0.1731	1255.1667	2	
•	7189.715	2.785E-22	0.0315	0.1398	2004.8157	3	

Modeling of absorption spectra at different temperatures



Laboratory measurements



Design of the heated cell

Details: *Appl. Phys. B*, 2010, v.100, No. 2, p.397-407

Evaluation of the probing zone parameters

Parameters of a gas medium (*T, P, C_{H2O}*) are obtained as the result of the experimental spectra fitting

$$Y_i = \alpha I_{0i} \sum_j S_j(T) g_j(\nu_i - \nu_{0,j}) \theta P L + b_i + \varepsilon_i$$

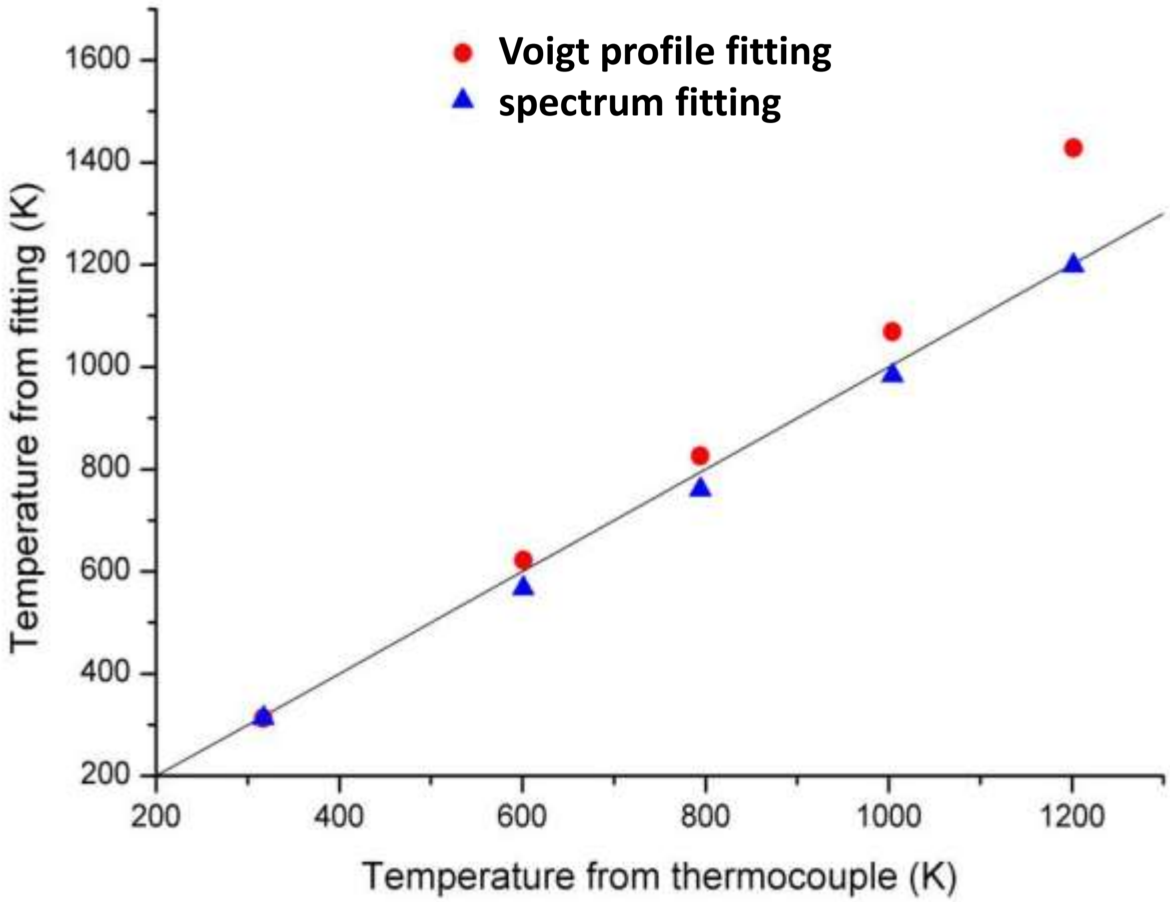
S(T)* – *line integral intensity
$g(v-v_0)$* – *line shape ,
$v_{0,j}$* – *center of j-th line,
$p = \theta \times P$* – *partial pressure of the absorbing component ,
P* – *total pressure of the gas mixture,
L* – *optical length of the absorbing layer,
α* – *amplification coefficient of the electronics,
b_i* – *baseline,
ε_i* – *residual.

Experimental spectra fitting

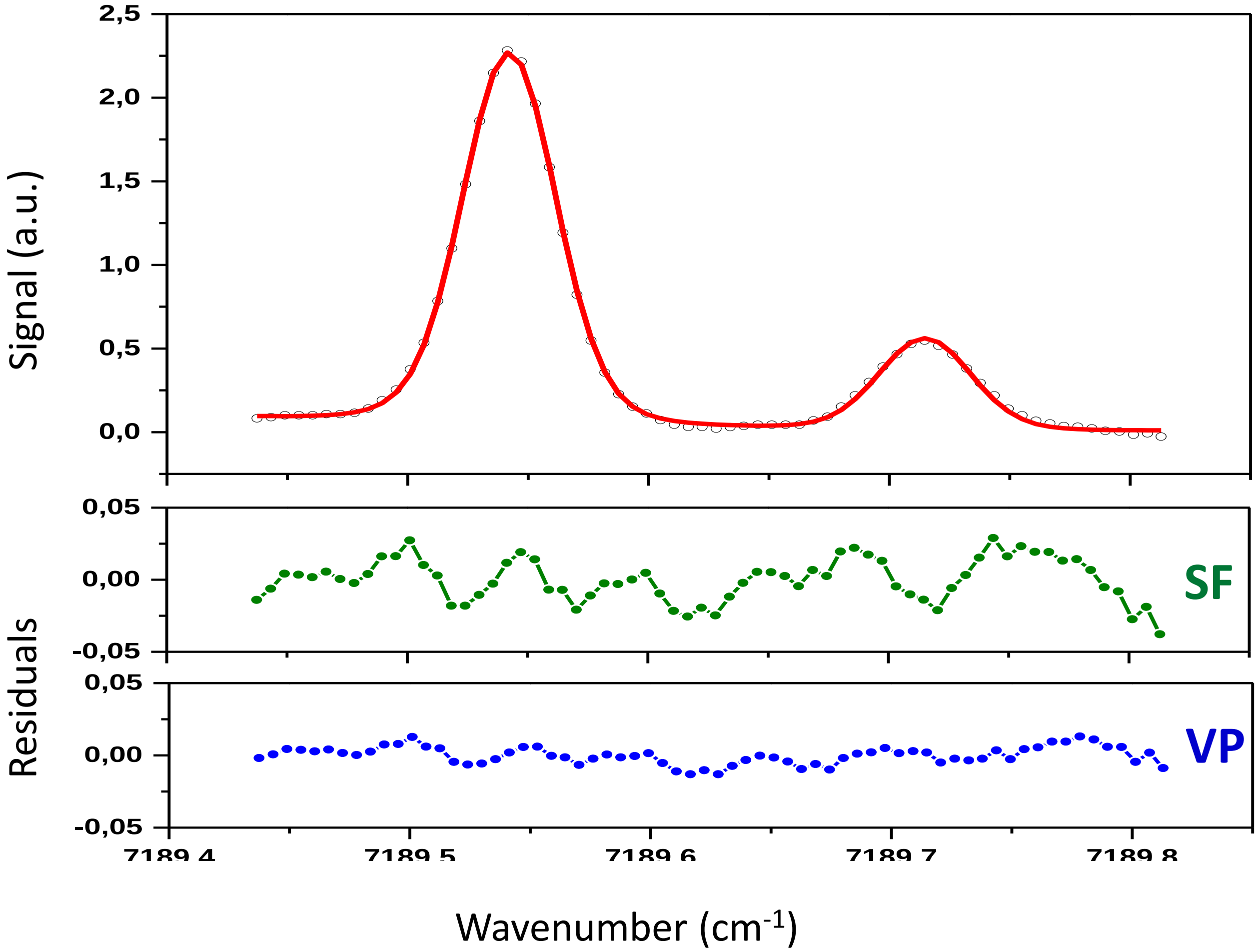
Models checked:

- **Profile fitting – Voigt profile, equal Gaussian width for both lines**
- **Spectrum fitting**
  Fitting parameters: frequency scale, temperature, gas pressure, H_2O concentration, baseline parameters. Simulated spectra have been constructed using the HITRAN and HITEMP databases.

The baseline b_i was approximated by the polynomial, linear or quadratic.



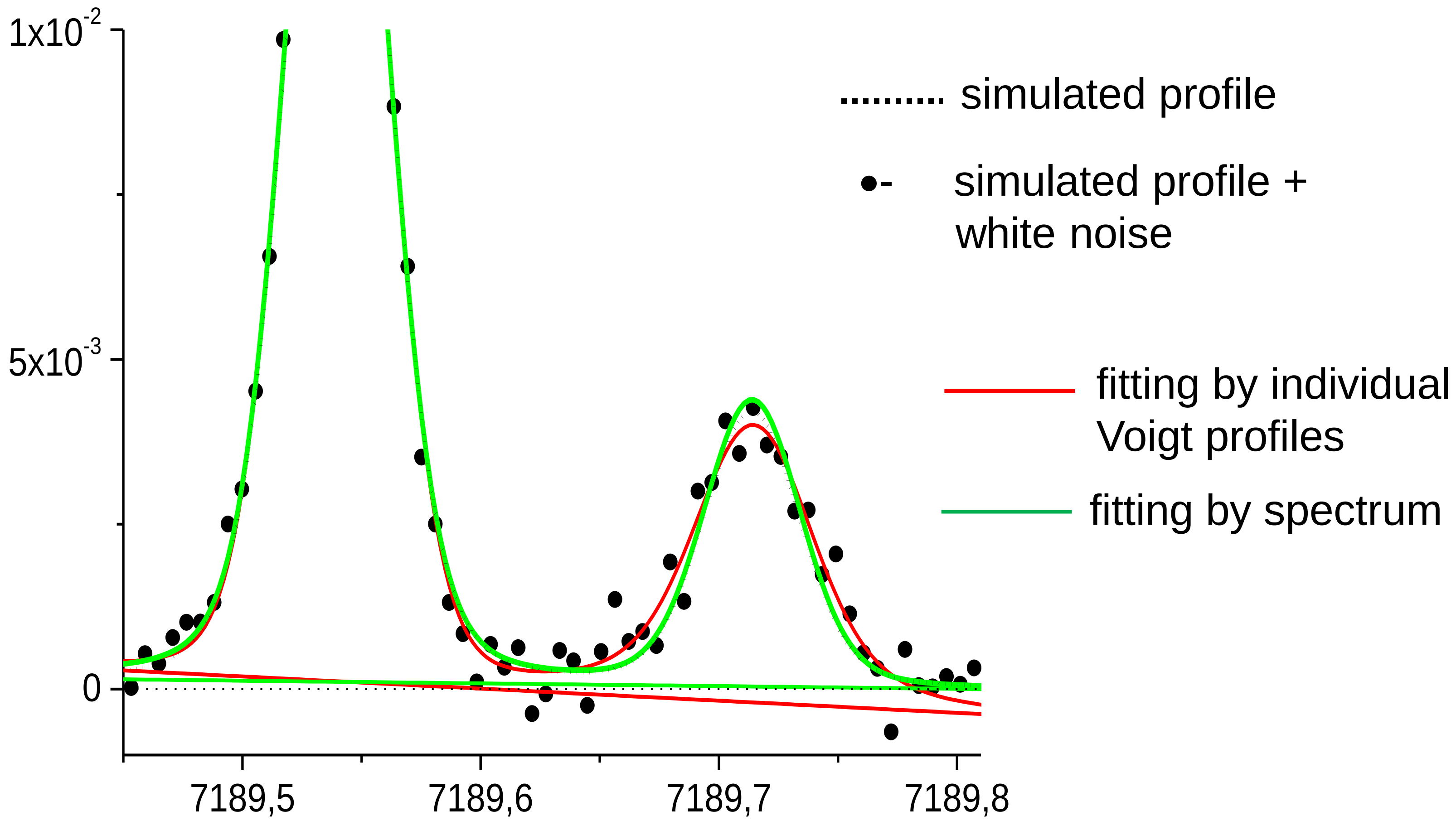
Temperature evaluated by TDLAS vs temperature measured by the thermocouple



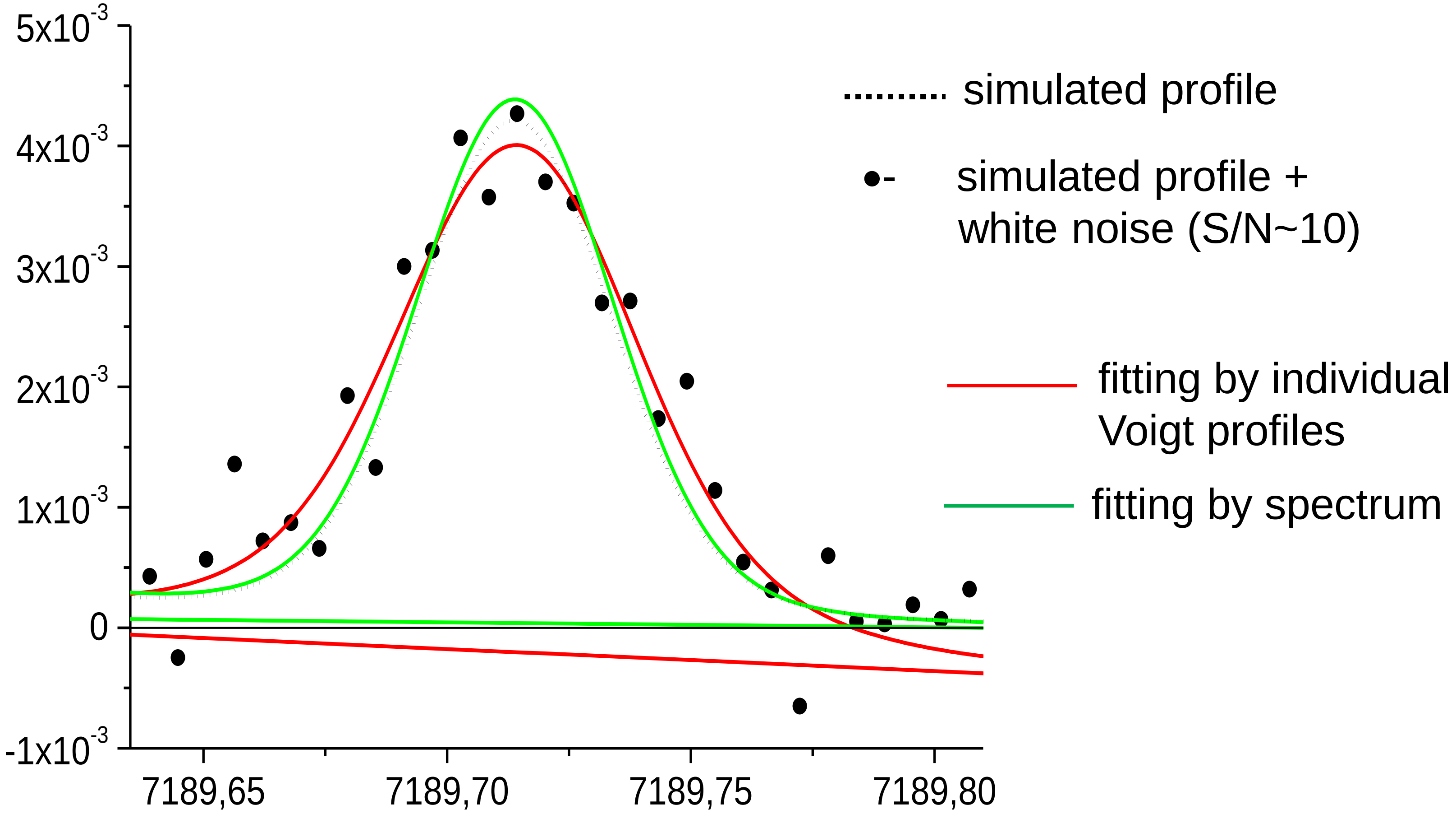
Experimental spectrum of heated water vapors at 1200 K (circles), result of spectrum fitting (red line), and residuals for spectrum fitting (SF) and Voigt profile (VP) model

Numerical simulation of experimental data

T = 1200 K, P = 100 Torr, c_{H2O} = 10%



Fitting of the weak line



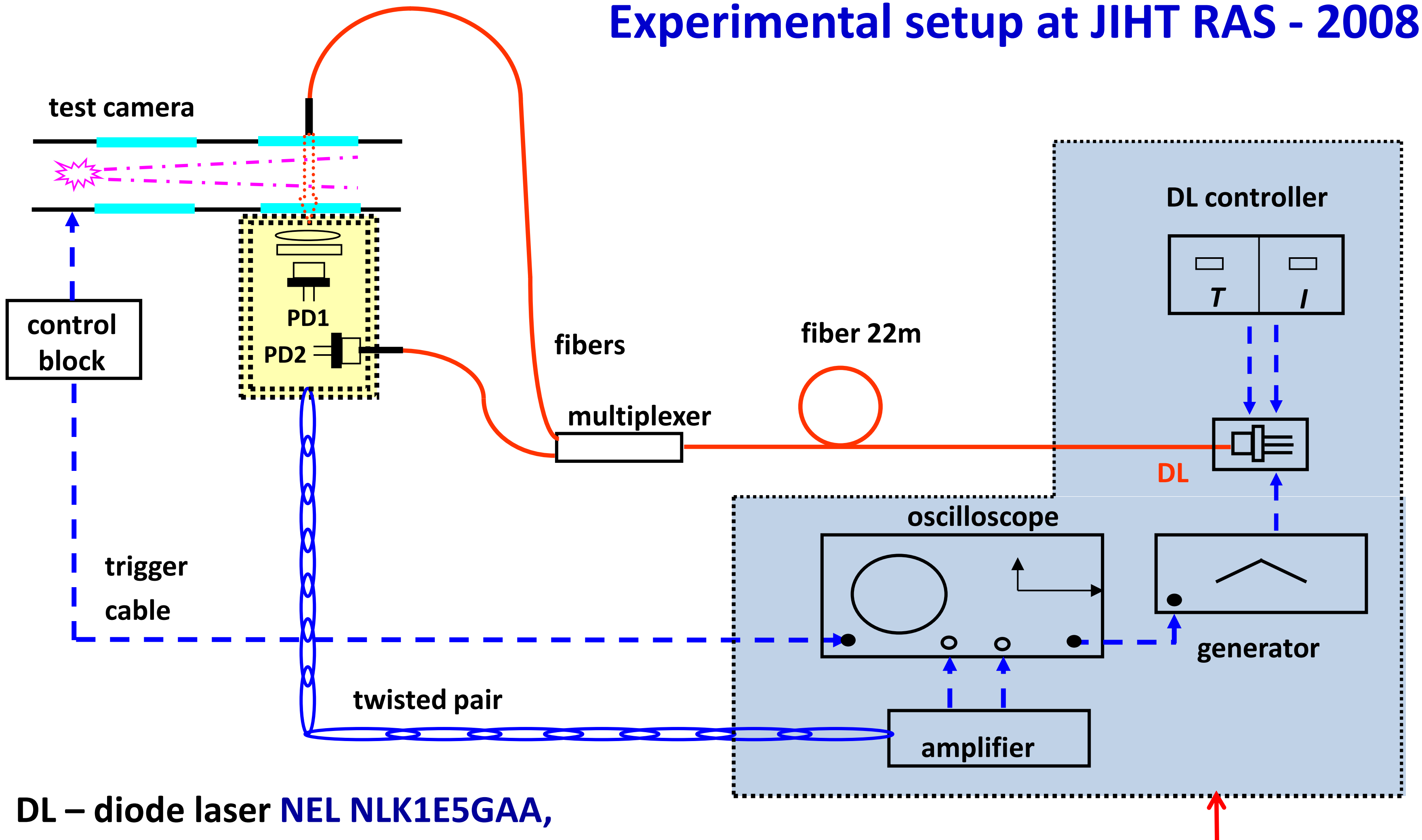
Comparison of two fitting algorithms for numerical simulation

Fitting Algorithm	S/N = 100		S/N = 10	
	T [K]	σ [K]	T [K]	σ [K]
Individual profiles	1198.7	17.8	1228	200
Spectral interval	1200.8	6.7	1210	68

Conclusions

- **Fitting of the spectra was found as good strategy for temperature evaluation.**
- **Noteworthy! Fitting of the individual line profiles can be done with lower residuals as compared to spectrum fitting.**
- **Spectrum fitting provides much better accuracy for temperature evaluation.**

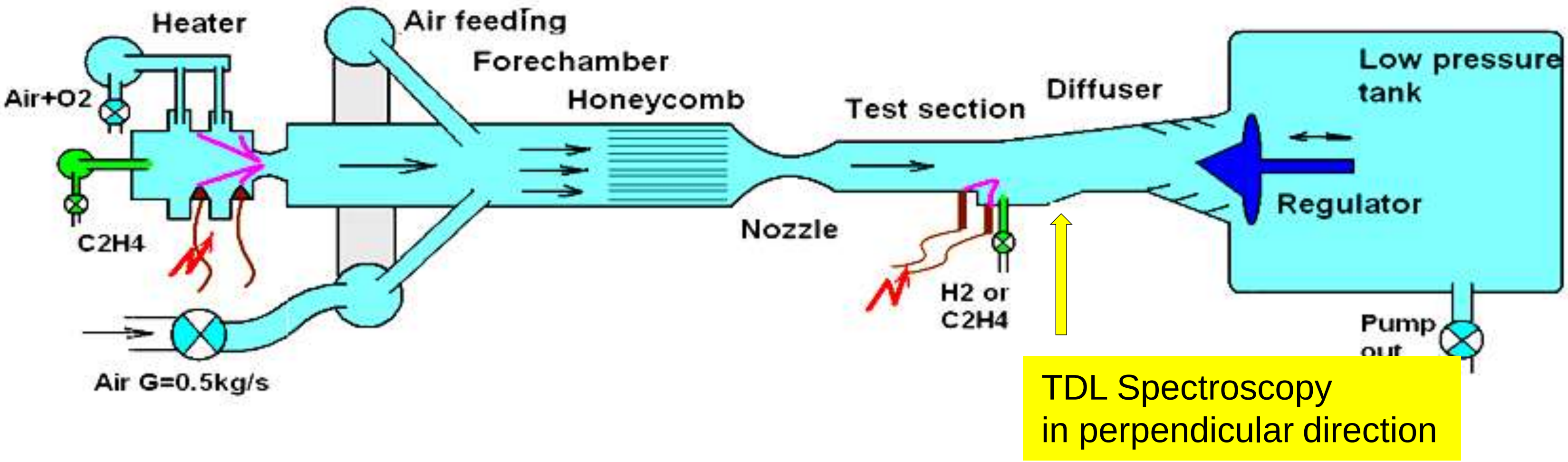
Experimental setup at JIHT RAS - 2008



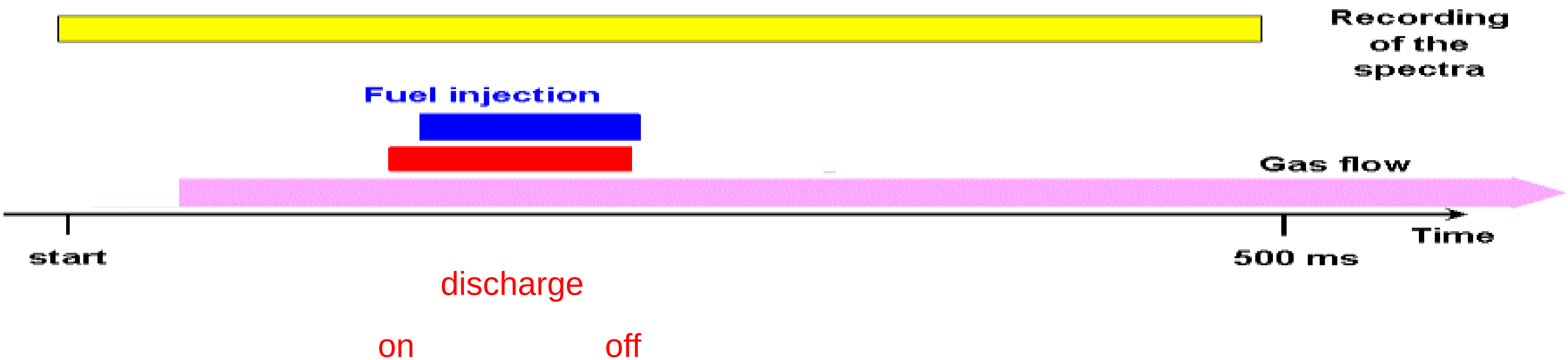
DL – diode laser NEL NLK1E5GAA,
DL controller (*T, I*) - Thorlabs TED350 and LDC202,
PD - InGaAs photodiodes Hamamatsu G8370-2,
oscilloscope - Agilent 54621A (8 bit, 2×10^6 points per channel),
generator – saw-tooth voltage generator

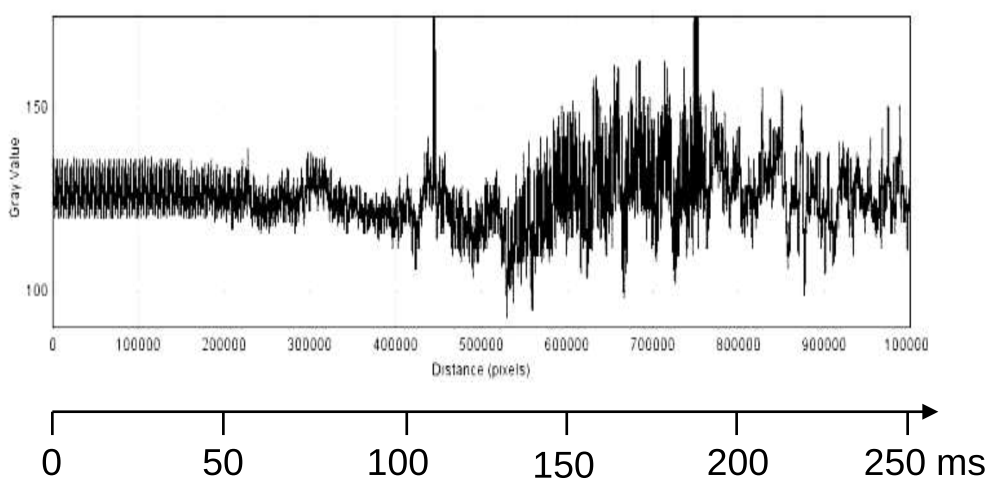
General view of the experimental chamber at JIHT RAS

Schematic diagram



Time scale of a run

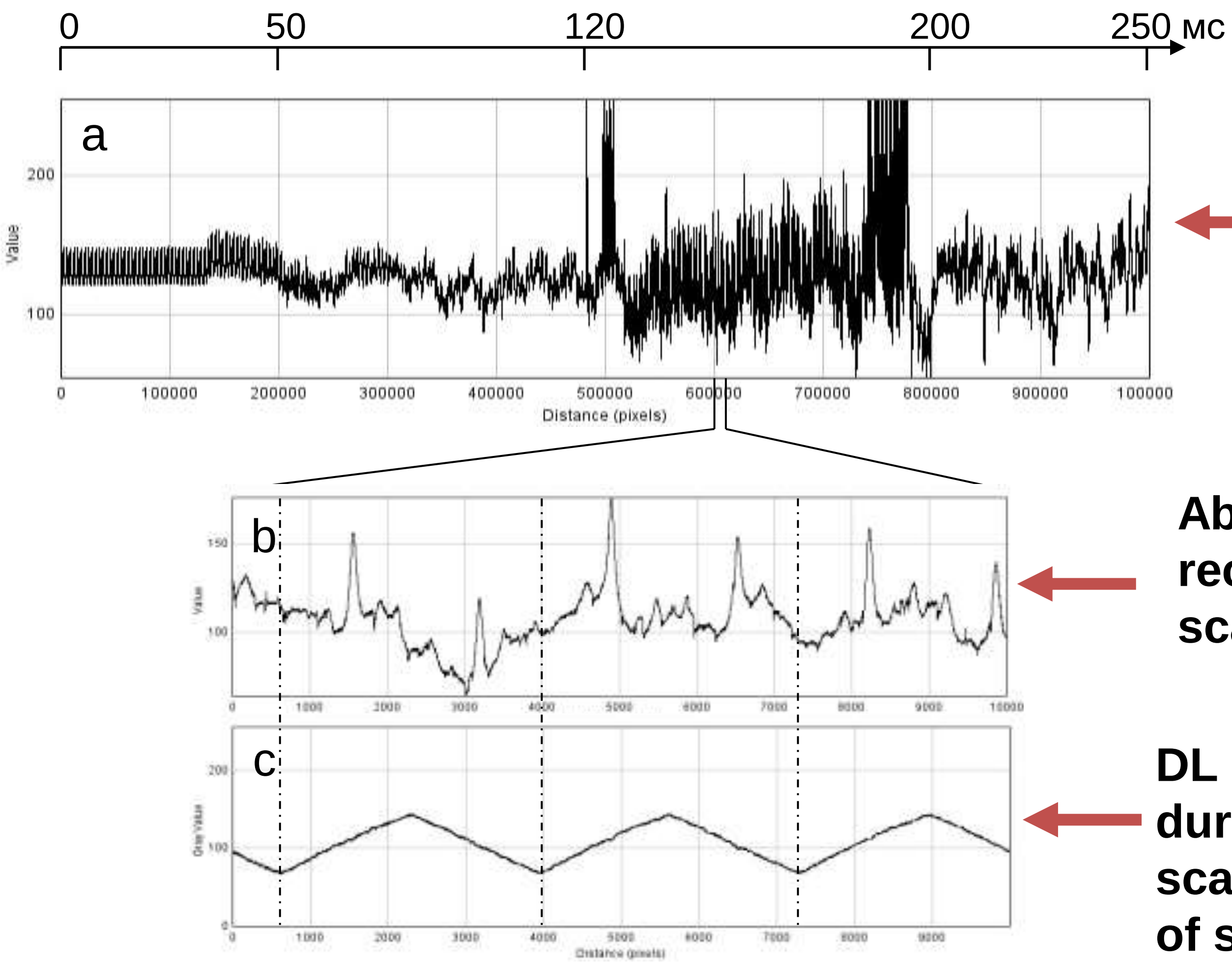




Single Run Record

10^6 points has been recorded with 8-bit ADC in 250 ms

Single run record



First 250 ms of the run (300 scans of DL)

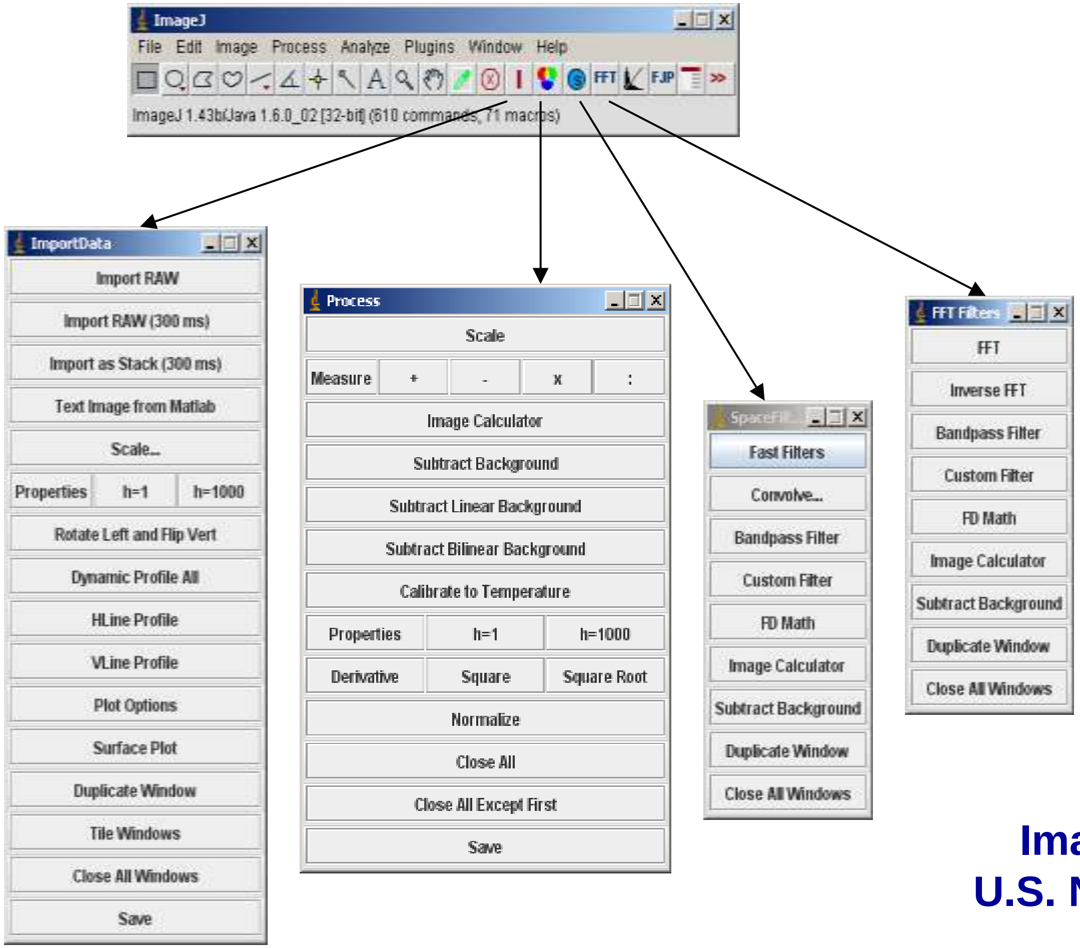
Absorption spectra recorded in 3 successive scans of DL

DL intensity variations during wavelength scanning. The frequency of saw tooth current modulation was ~1.2 kHz.

At first step of data processing the detected transient absorption spectra were transformed into 2D image. This procedure greatly simplified the general overview of data and selection of the most important periods of process evolution.

Digital processing of 2D images was based on ImageJ, the free, open source program.

ImageJ

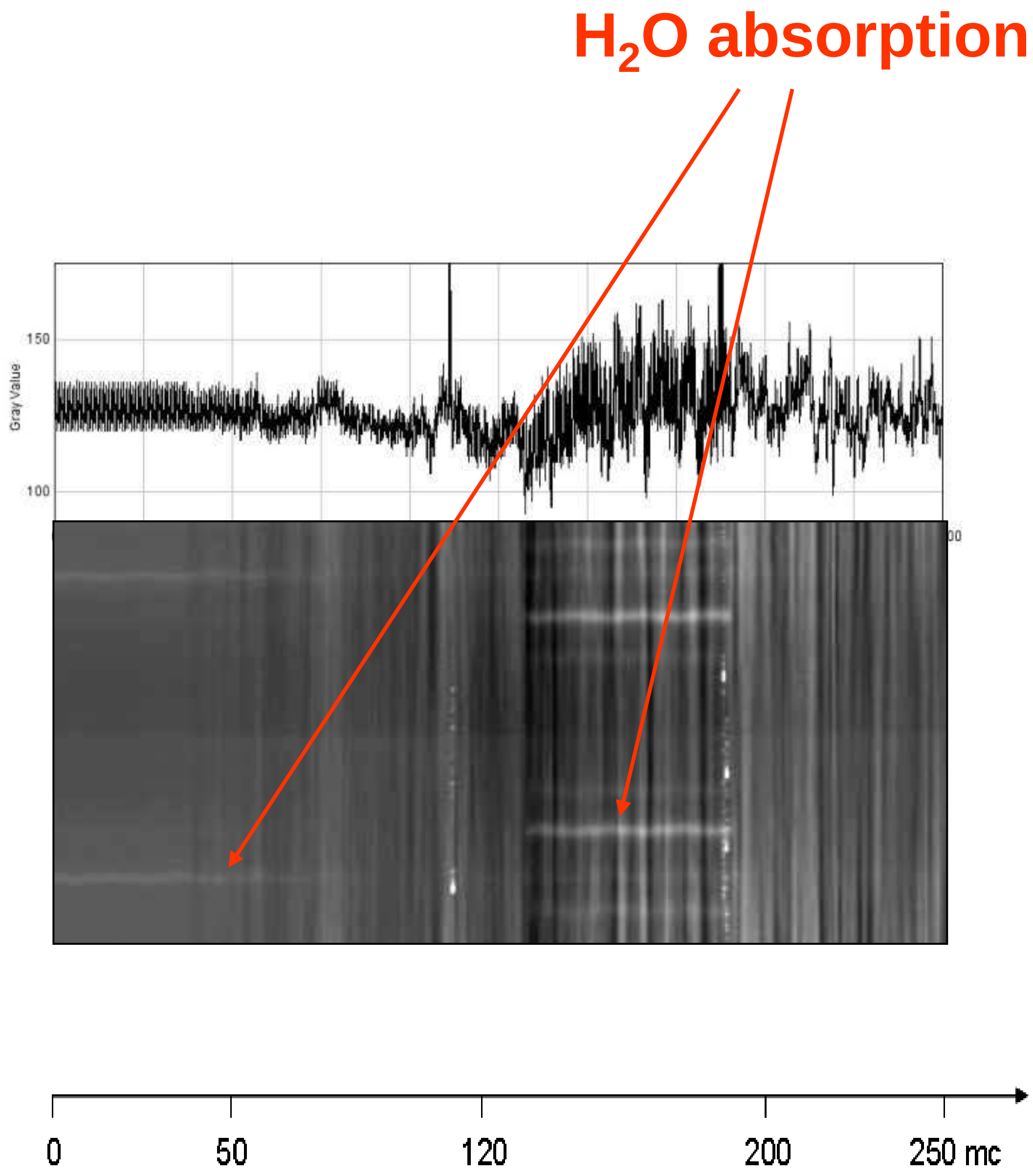


Key features:

- platform-independent, can run without modifications on Windows, Linux and MacOS;
- open many different image formats and raw data;
- extended by developing plugins and macros, more than 500 plugins and 300 macros are available;
- the world's fastest image processing software.

ImageJ author: Wayne Rasband, U.S. National Institute of Health (NIH)

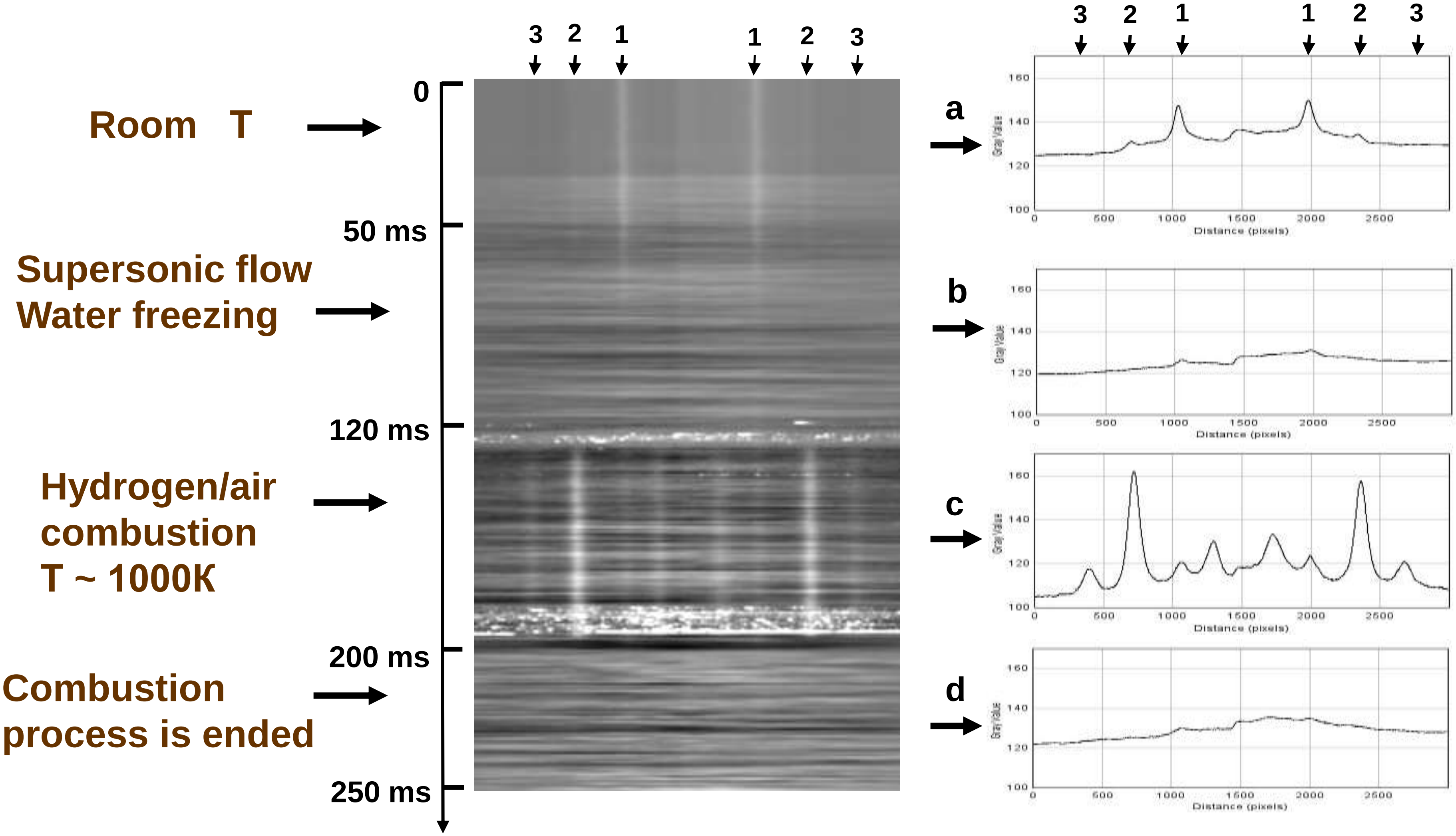
ImageJ toolbar and submenus used for TDLS data processing



upper reading – oscilloscope one-dimension trace

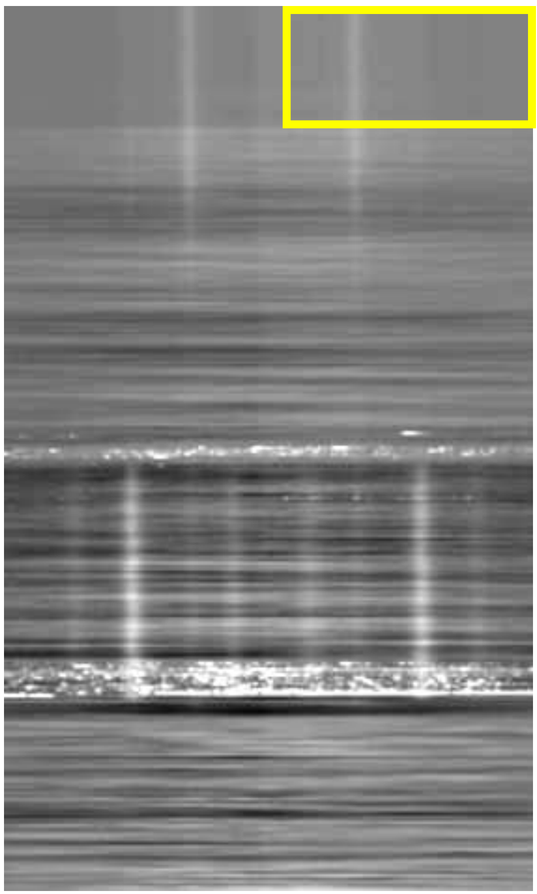
lower image – the corresponding 2D presentation

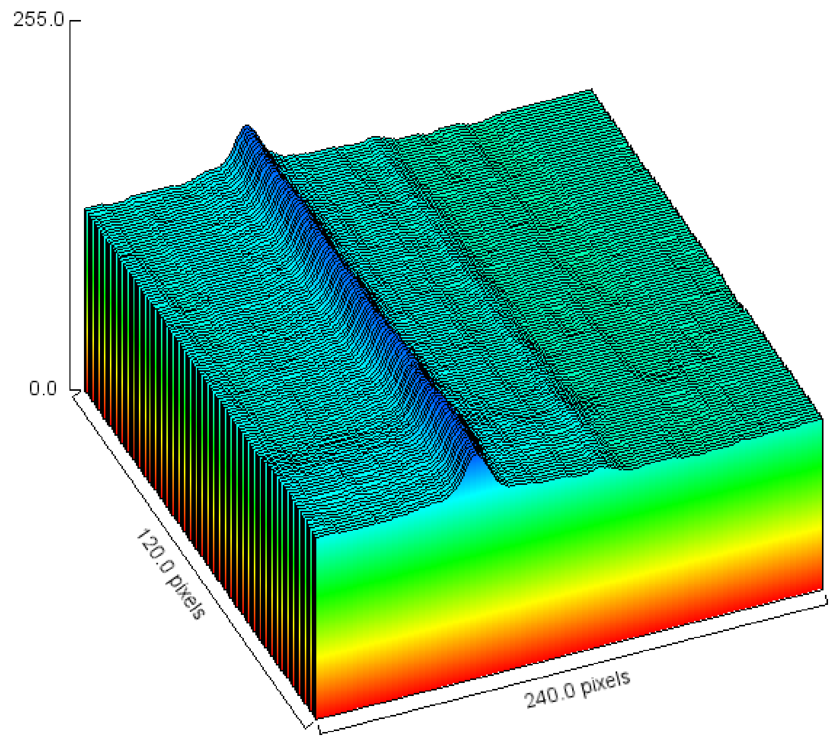
2D image of raw data
and traces integrated over 30 scans



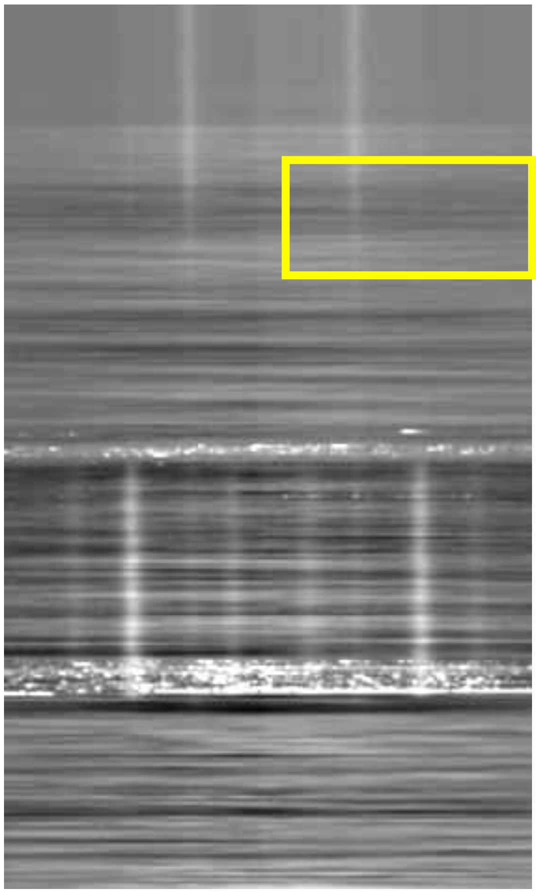
(1) – 7189.344 cm^{-1}, (2) – 7189.541 cm^{-1}, (3) – 7189.715 cm^{-1}.

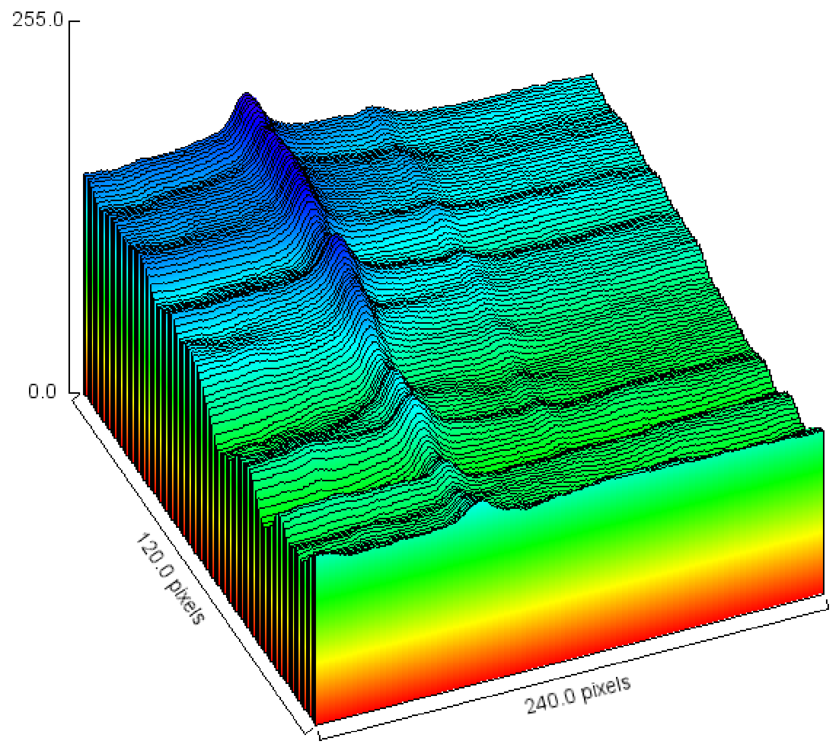
The initial stage of a run
(parameters: P_{total} ~ 0.3 atm, T ~ 20^{o}C)



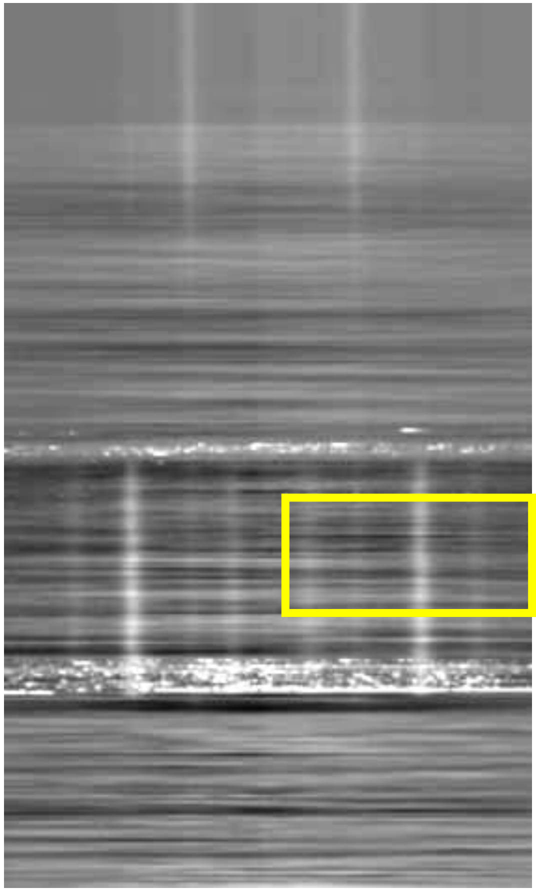


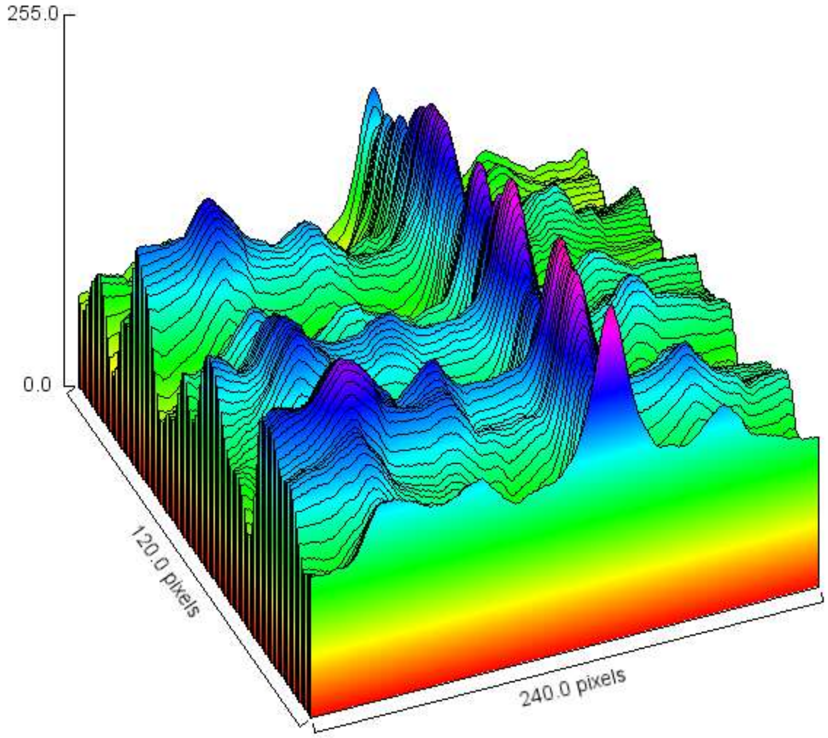
Beginning of supersonic flow



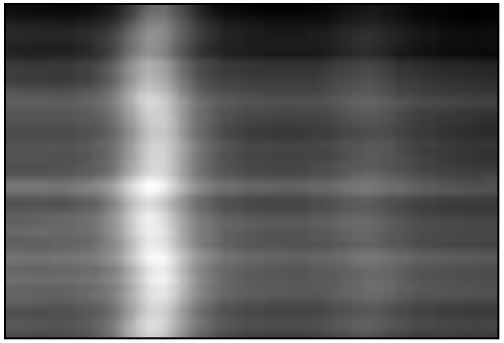


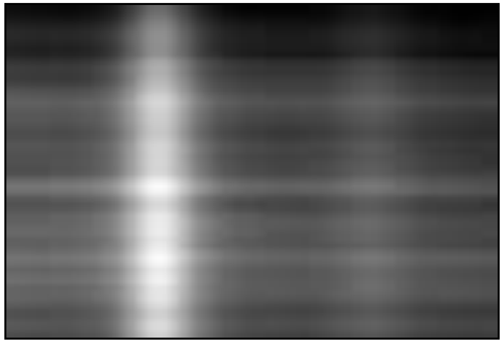
The stage of intense combustion





Jitter removing (software)



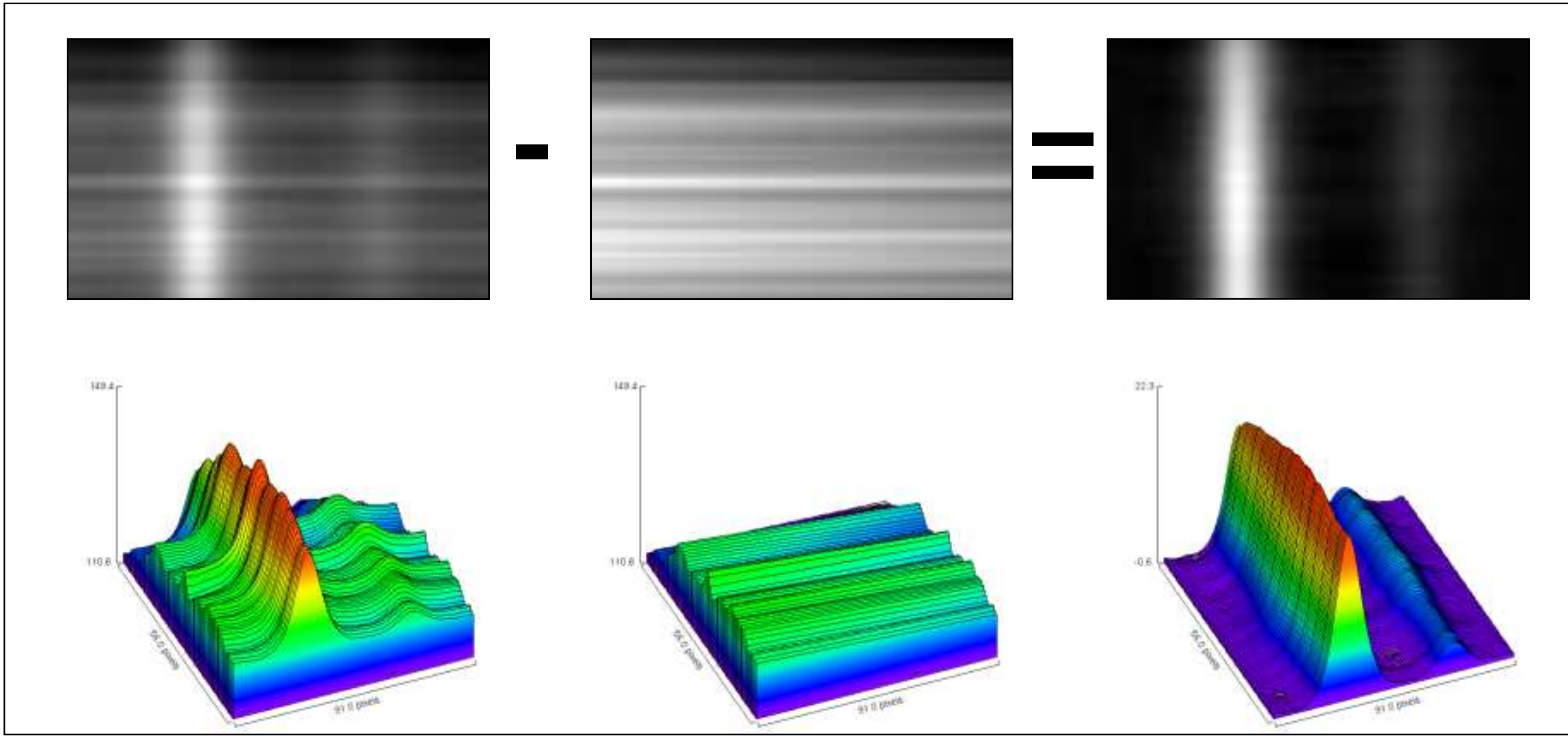


before

after

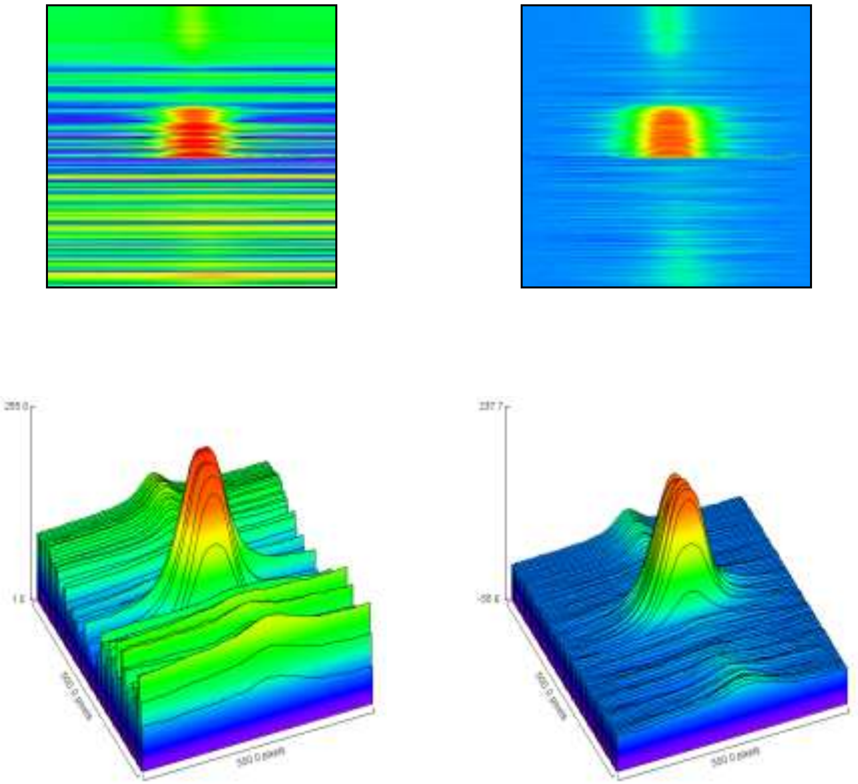
TDL frequency jitter from scan to scan is observed in image as a light twisted line. The jitter can be removed by converting image to stack consisting of images corresponding to sequential rows and using Image Stabilizer. This plugin aligns images in stack using geometrical transformations.

Background correction (software)

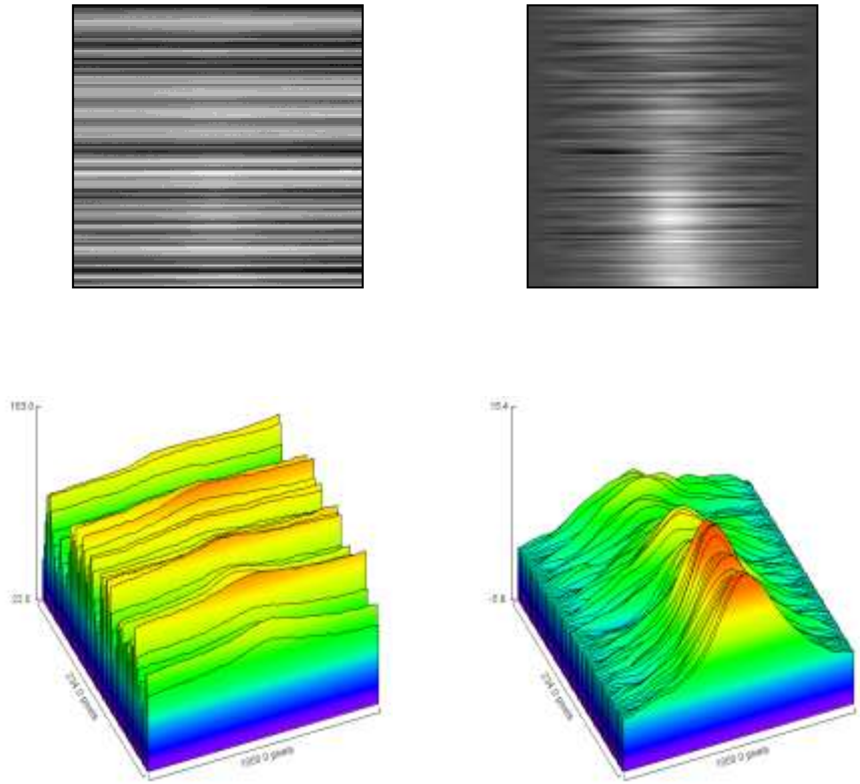


For each row in image (single TDL scan) background was constructed in the simplest way. Macros selects the first and last active points and constructs a line between them.

Background correction (software)



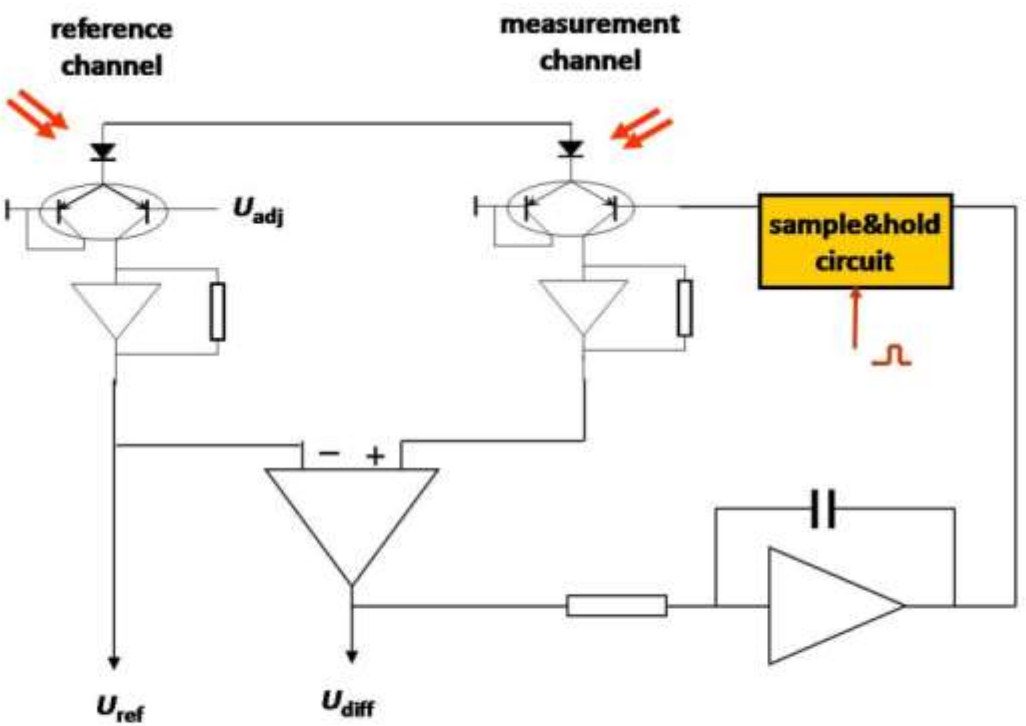
before after

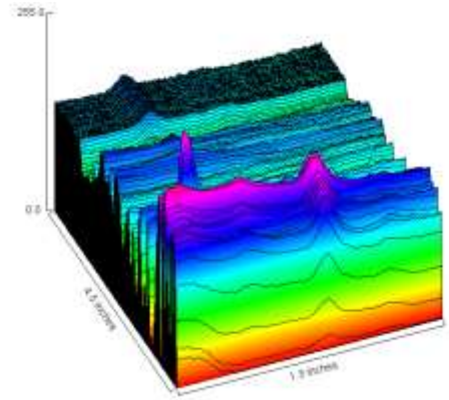


before after

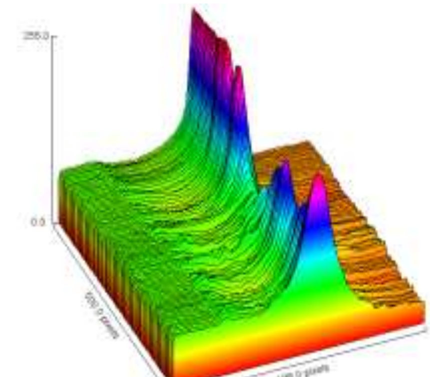
Signal-to-noise ratio increases considerably

Background correction (instrumental)
Differential detection scheme with sample & hold circuit



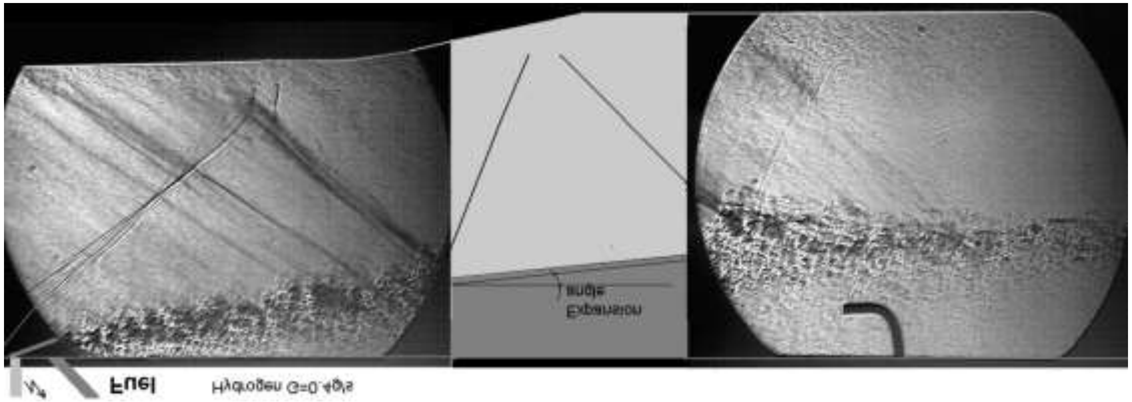


without sample&hold circuit



with sample&hold circuit

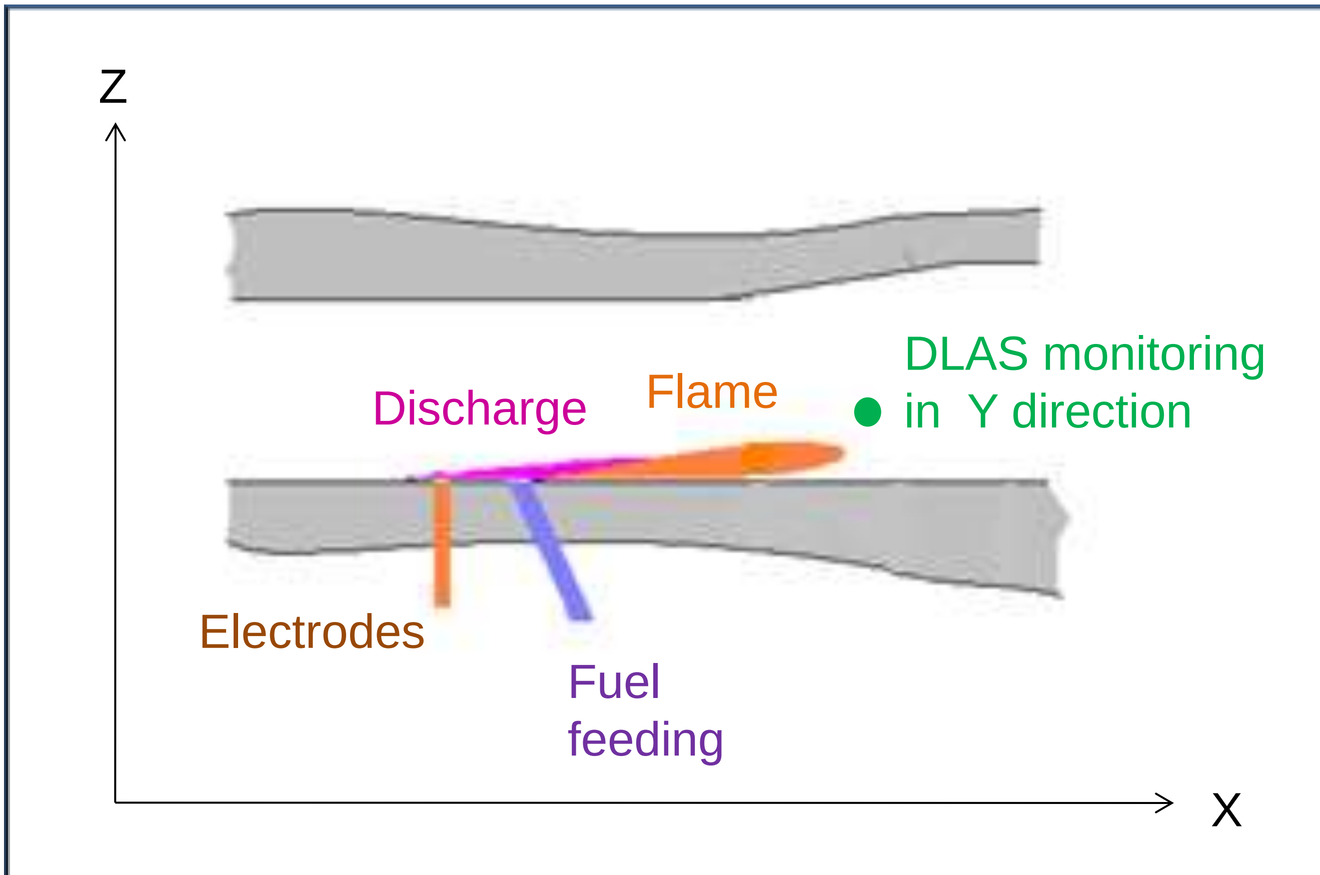
Examples of using of the developed technique in real situation of the combustion in mixing supersonic flows



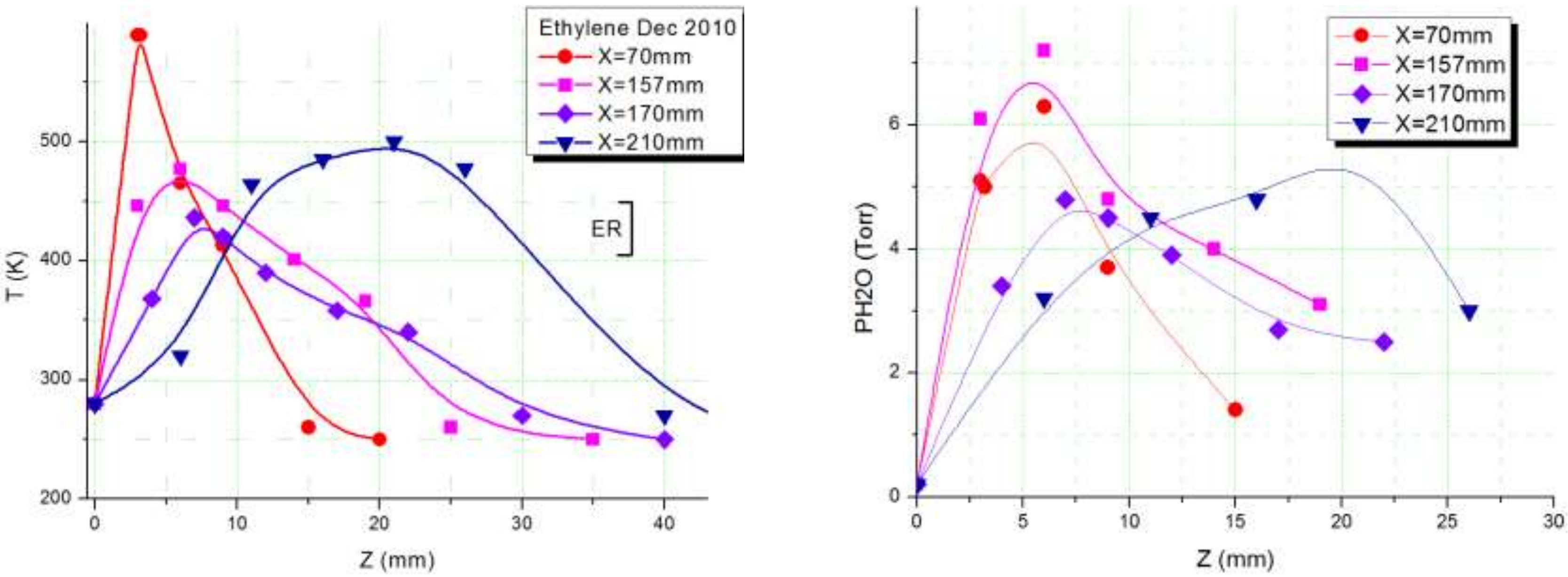
Schlieren pictures of combustion. Combination of images from two windows.

Fuel feeding

Electrodes



DLAS Measurements on H_2O Molecule in Experiments on Plasma Assisted Ethylene Combustion in Supersonic Flow (December 2010)

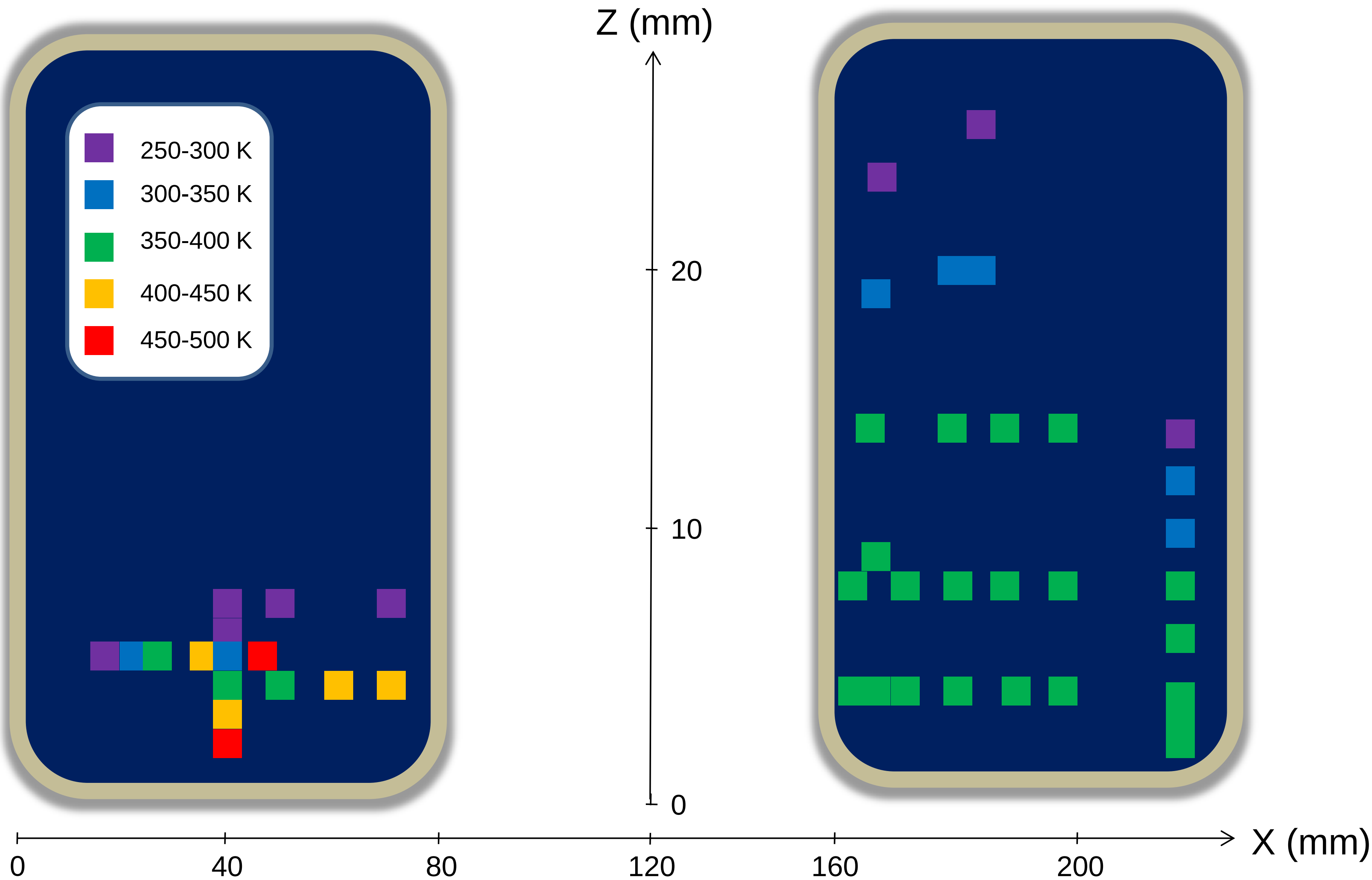


Temperature (a) and H_2O vapor pressure (b) distribution measured by DLAS in plasma-assisted combustion zone for ethylene-air pair.

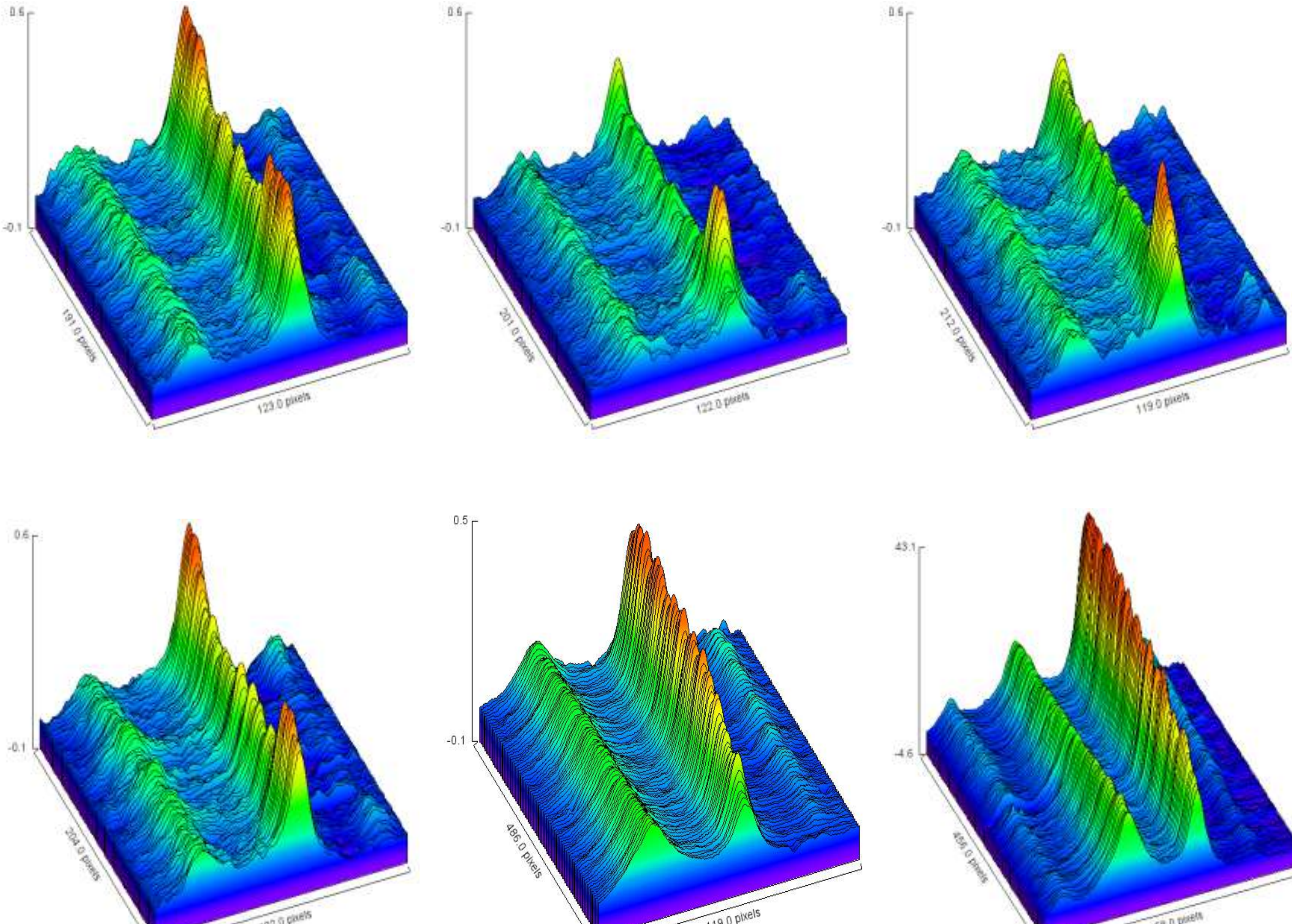
Z is the distance from the wall.
X axis is along the flow direction.

Details: *AIAA* 2012-3181, doi:10.2514/6.2012-3181

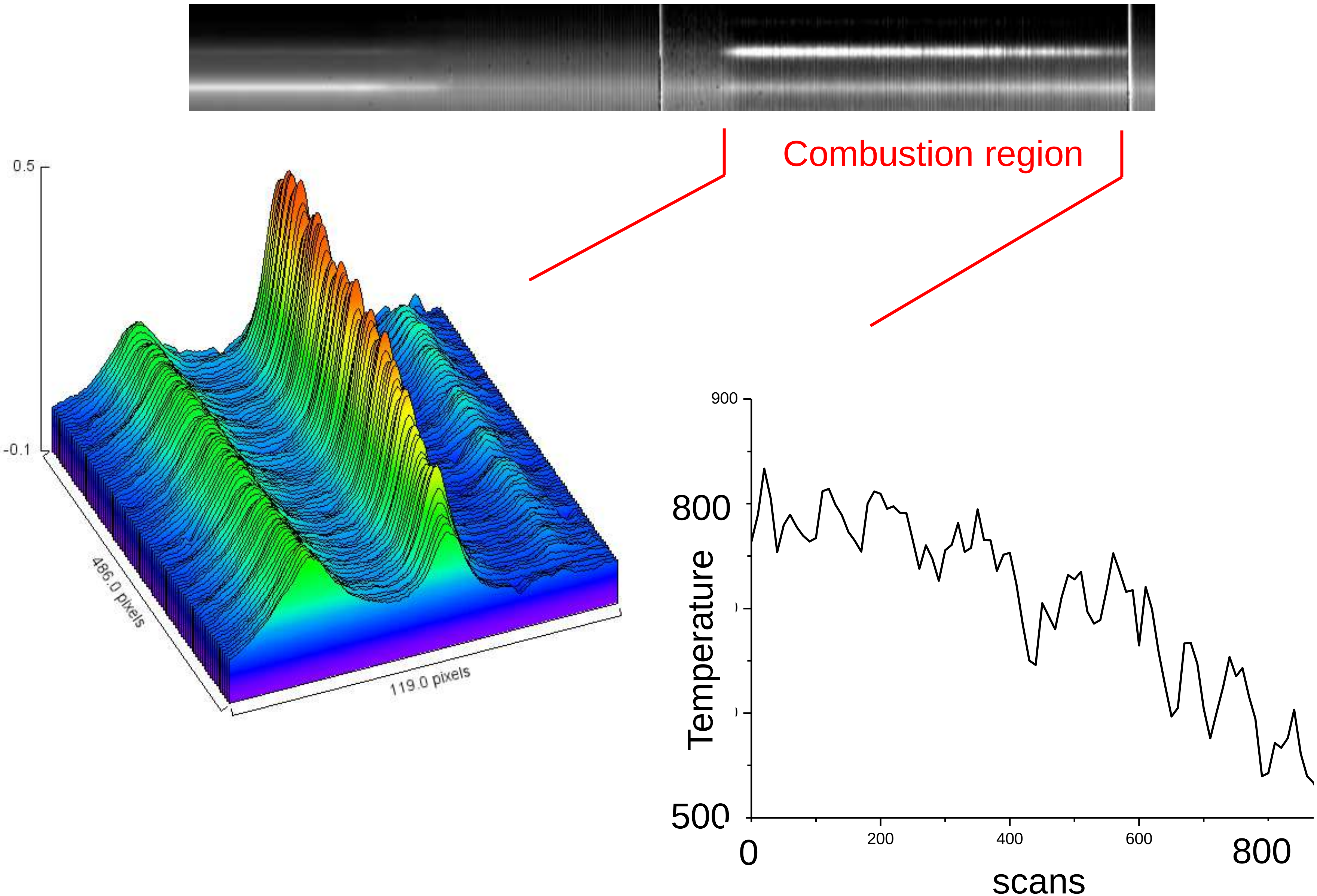
DLAS Measurements on H_2O Molecule in Experiments on Plasma Assisted Ethylene Combustion in Supersonic Flow (December 2010)



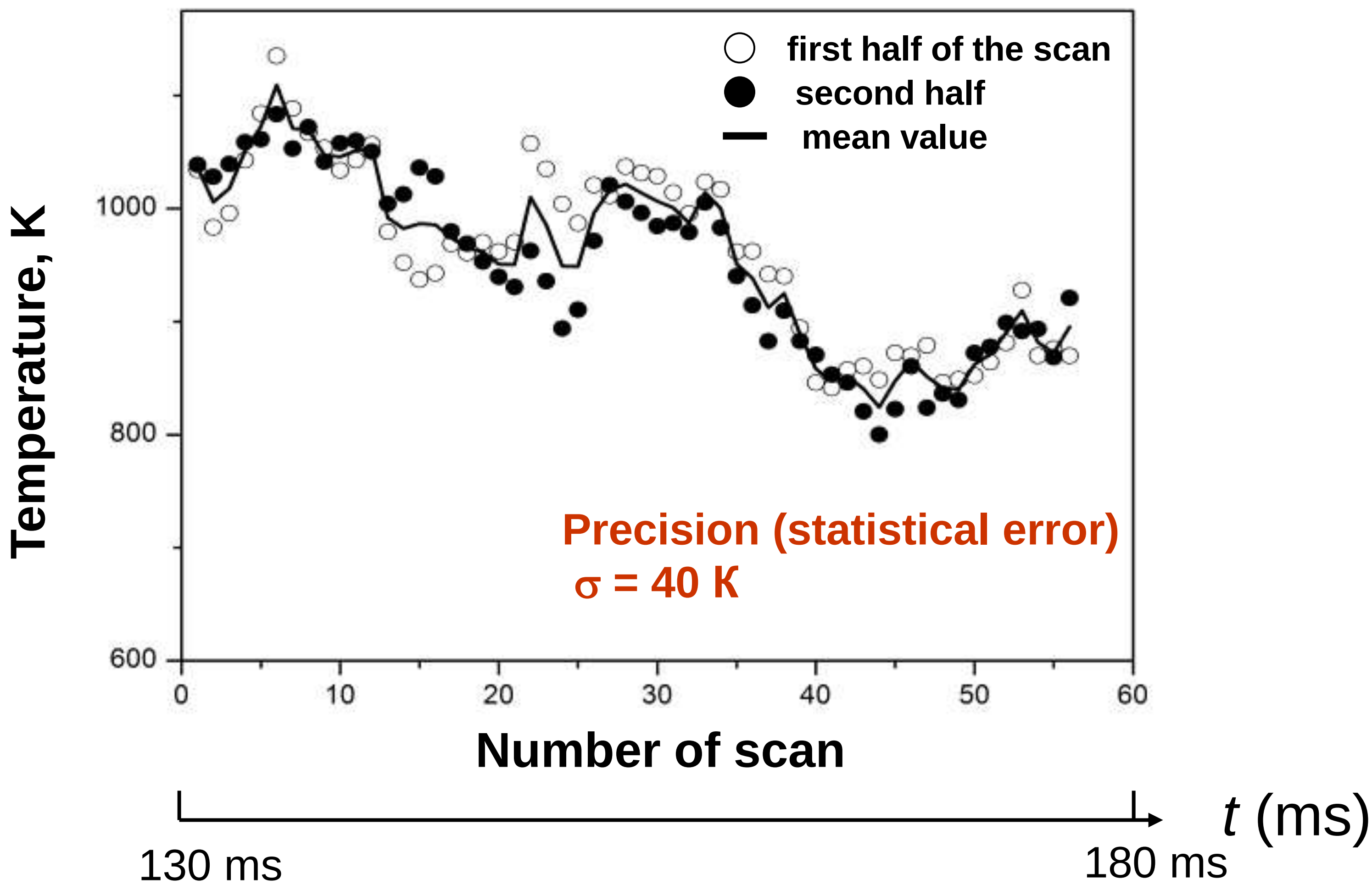
01.06.2011. Section Window 2, x = 130mm.
Ethylene Long Combustion. *T*=800-500 K



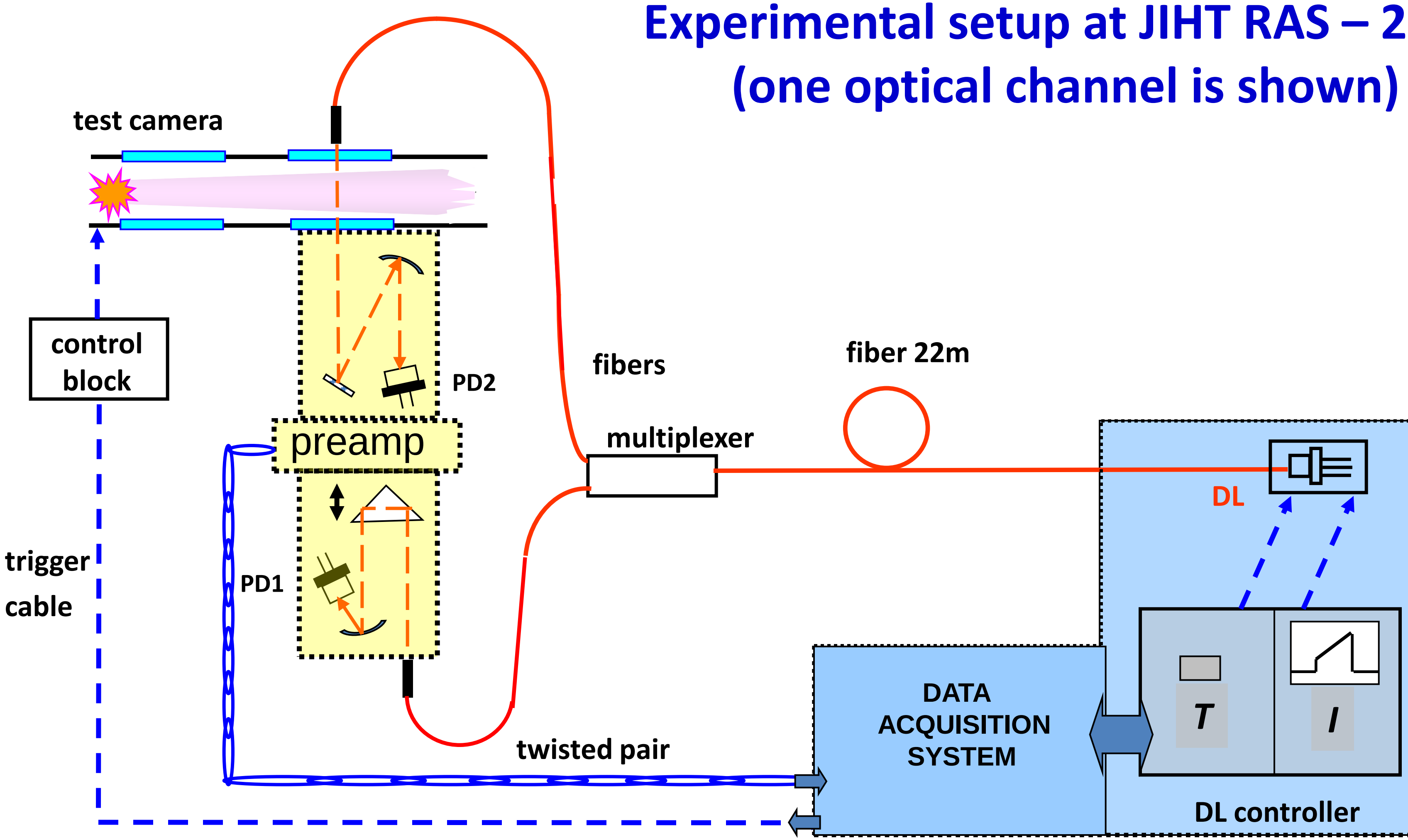
01.06.2011; Run 10; Section Window 2; x = 130mm.
Ethylene Long Combustion. Temporal Behavior. *T*=800-550 K



Dynamics of the probing zone temperature

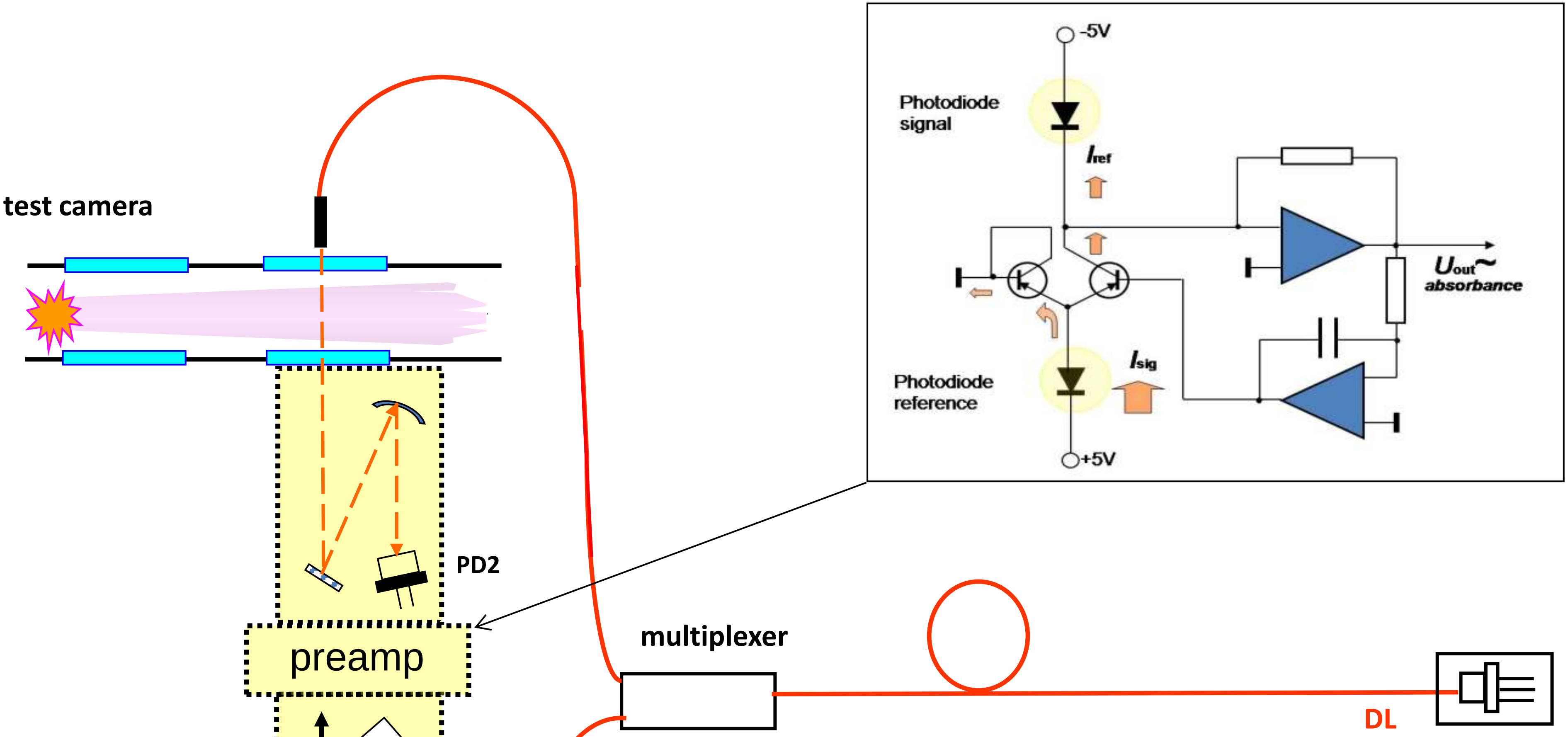


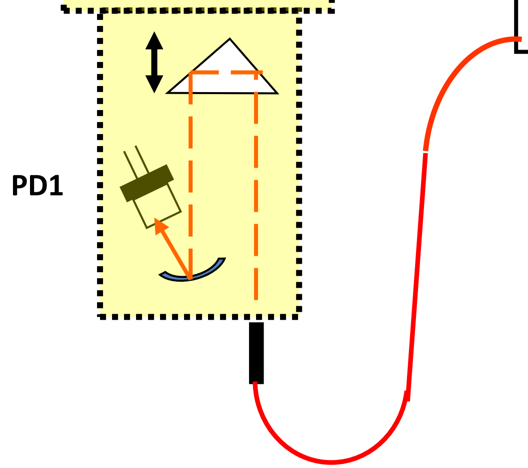
Experimental setup at JIHT RAS – 2012 (one optical channel is shown)



Instrumental improvements:

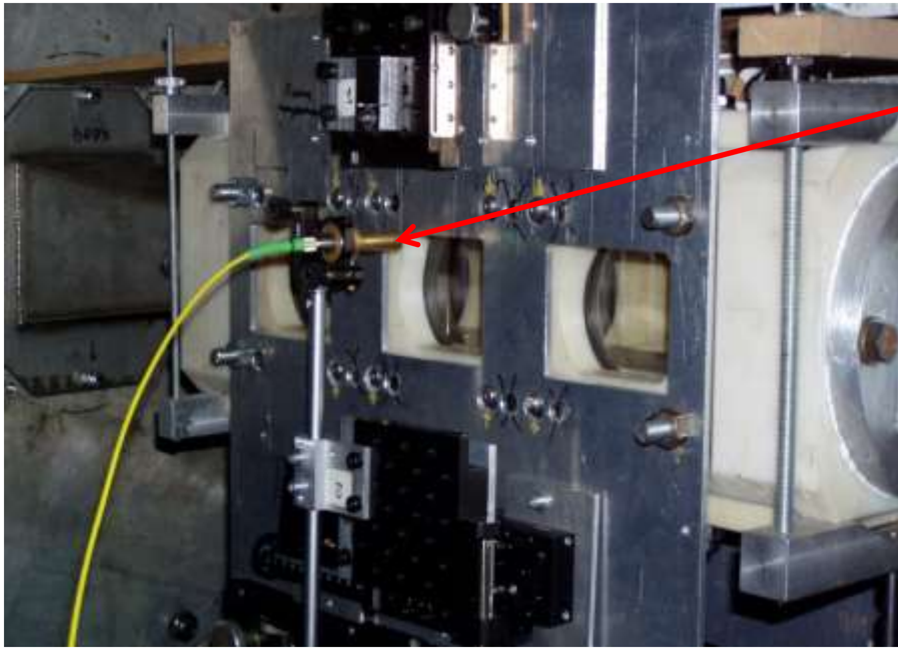
Data Acquisition System - NI USB-6351 (16-bit resolution),
DL and DAS controller – GPI TDLS complex





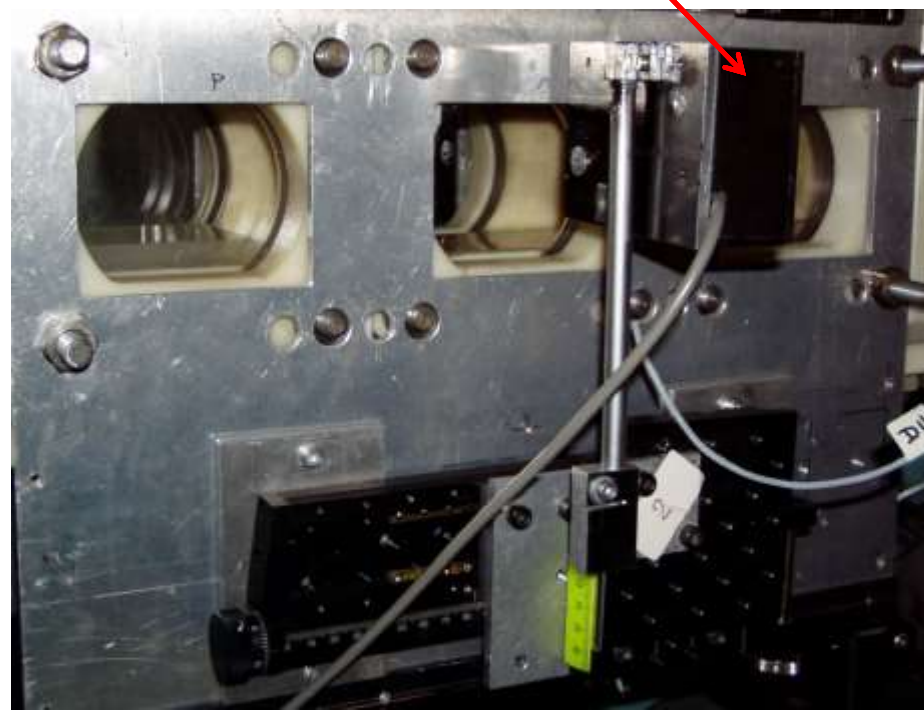
Instrumental improvements:

- big aperture, mirror optics,
- compensation of absorption in a free-path,
- signal optimization,
- new differential scheme



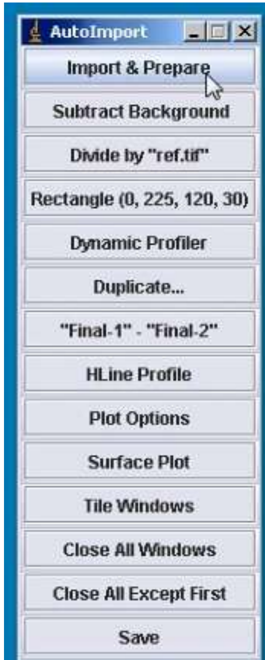
Laser output collimator

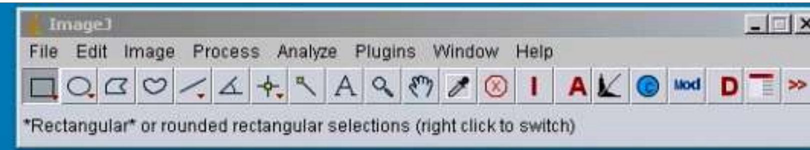
Mirrors set & photodiode



Instrumental improvements:

- precise manual translational stages

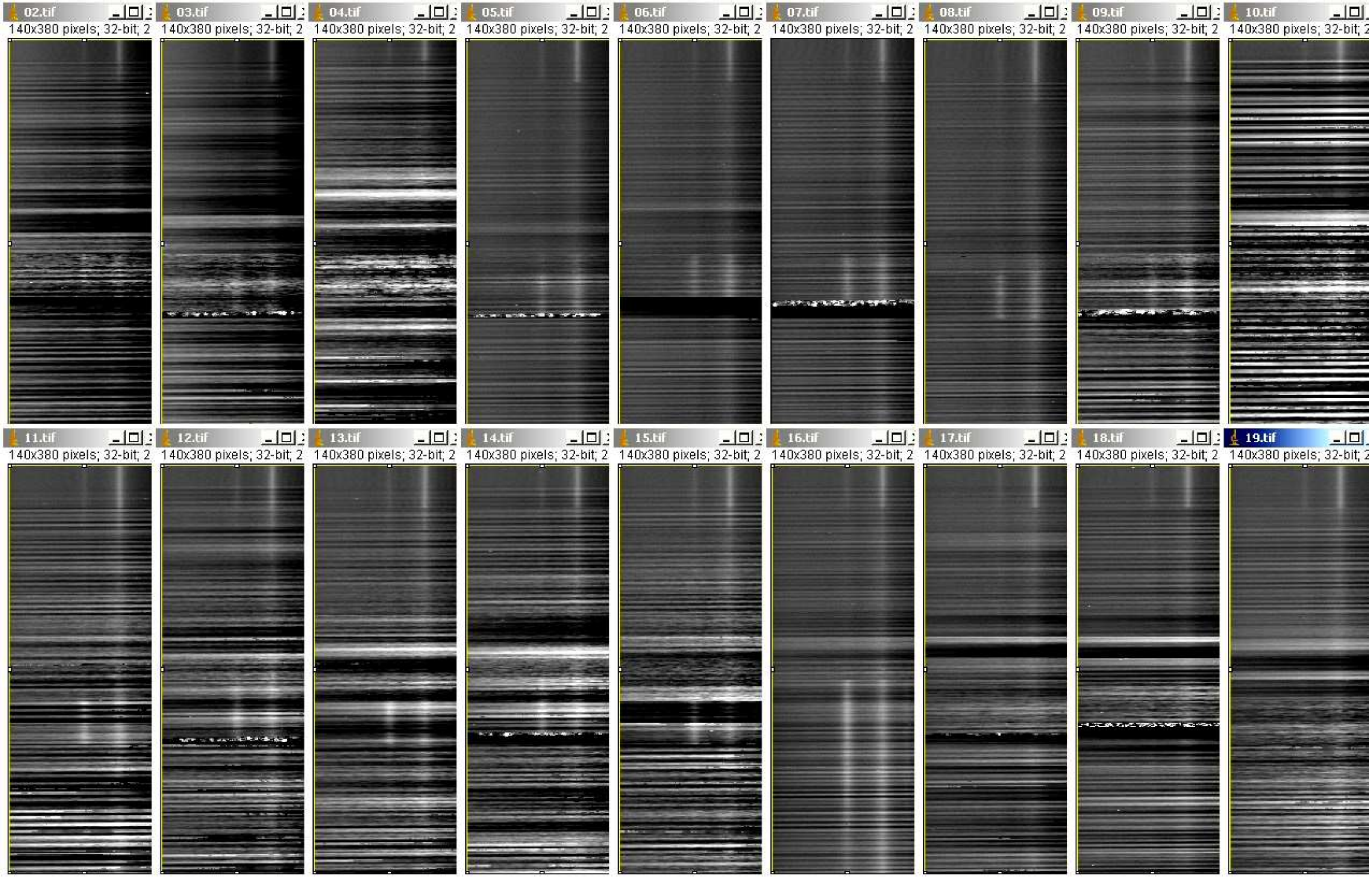




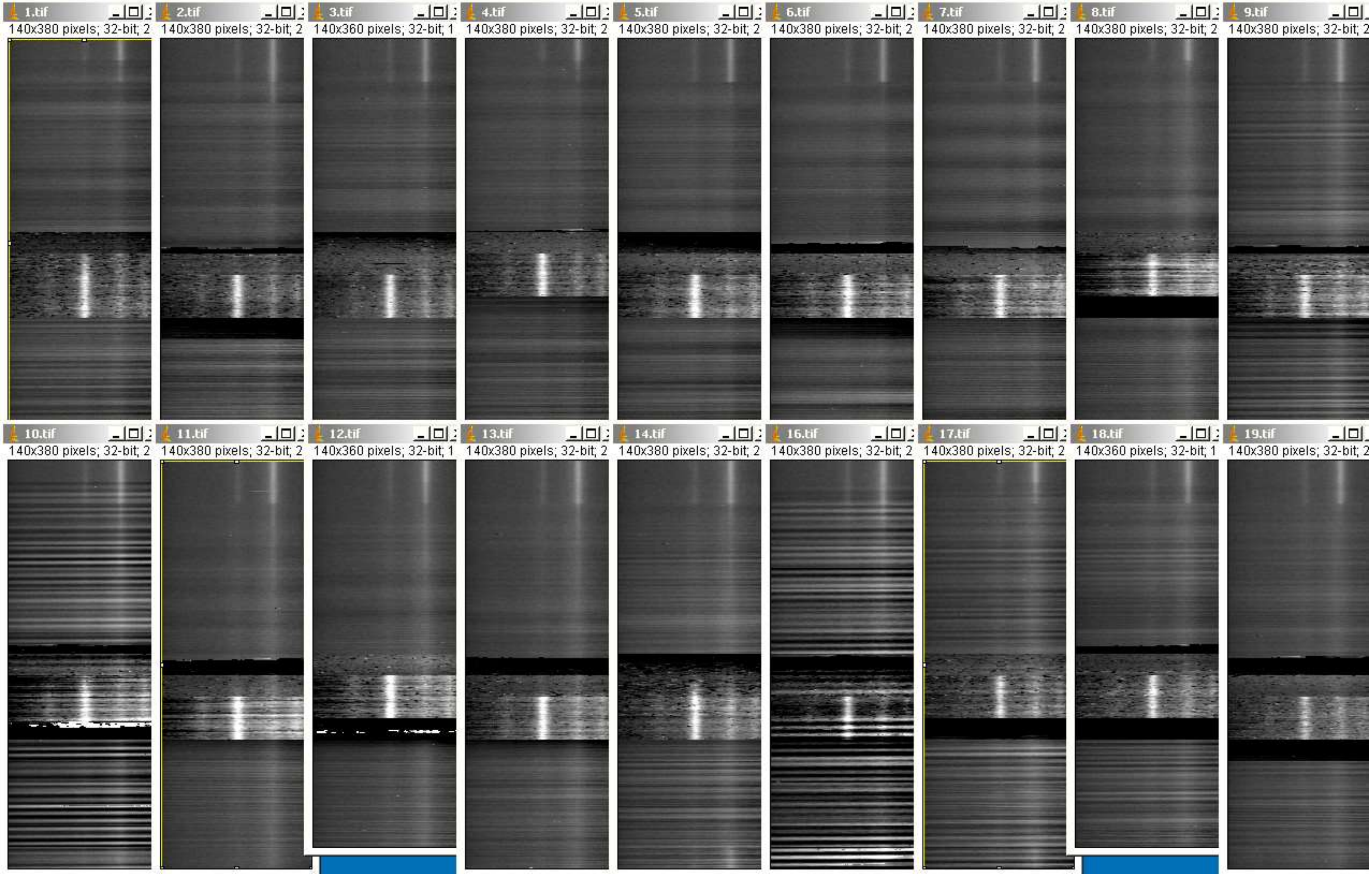
Semi-automatic data processing

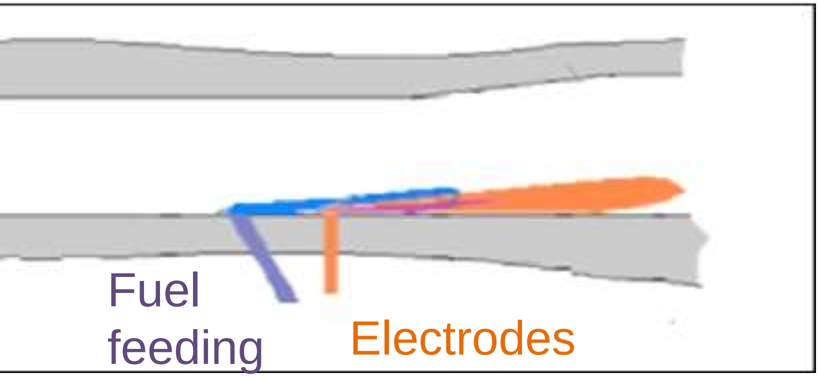
- Import Raw Data
- Delete Outliers
- Set Brightness & Contrast
- Correct Background
- Divide by Laser Intensity
- Select Region of Interest
- Subtract Water Freezing Region
- Compare with Model Spectra

Ethylene combustion. Choice of combustion parameters:
mass of injected fuel, initial air temperature, discharge parameters

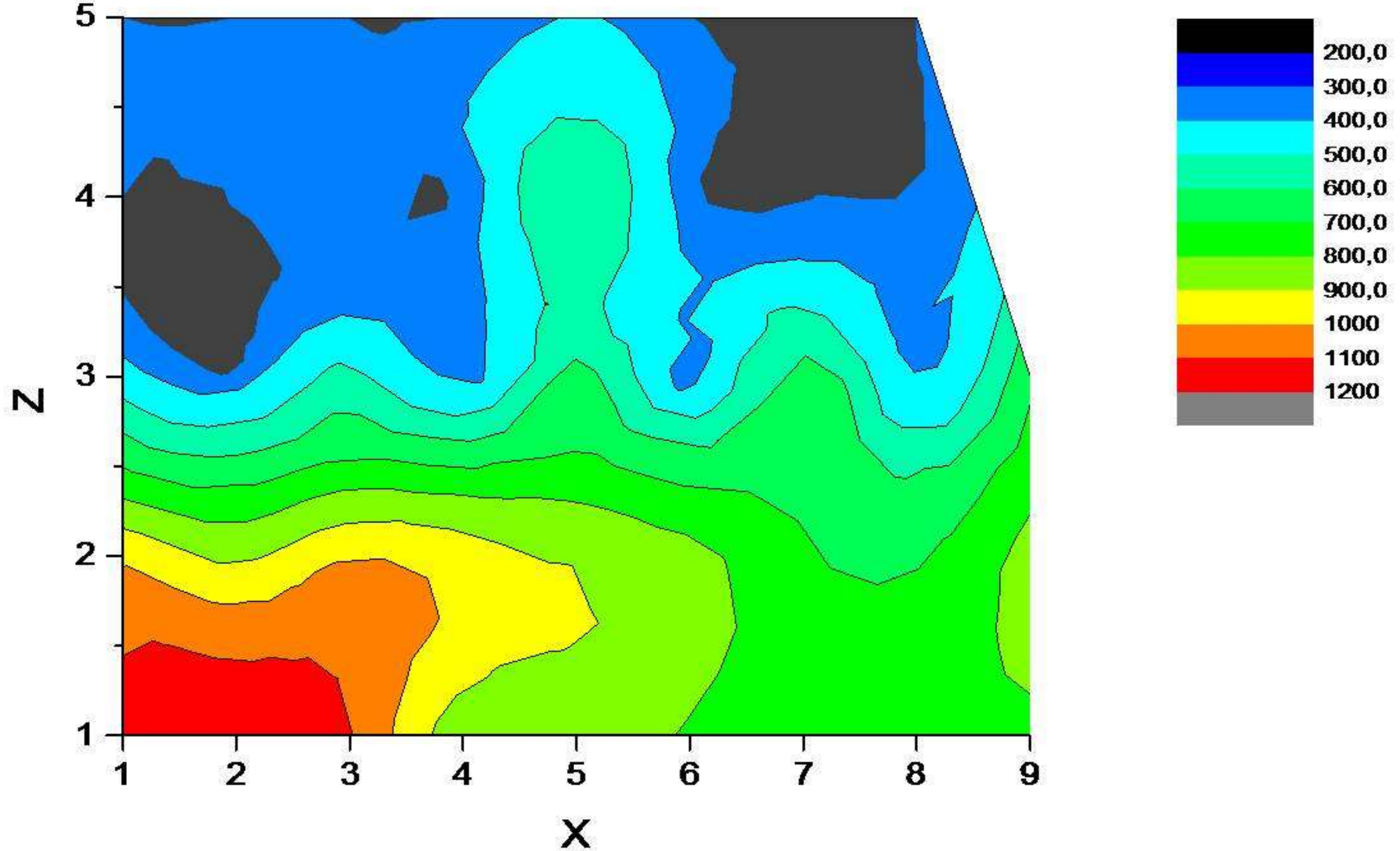


DLAS Measurements on H_2O Molecule in Experiments on Plasma Assisted Ethylene Combustion on the Plane Wall in Supersonic Flow 30.05.2012





Temperature Map
from TDLAS Measurements
in Plasma Assisted Ethylene Combustion
30.05.2012



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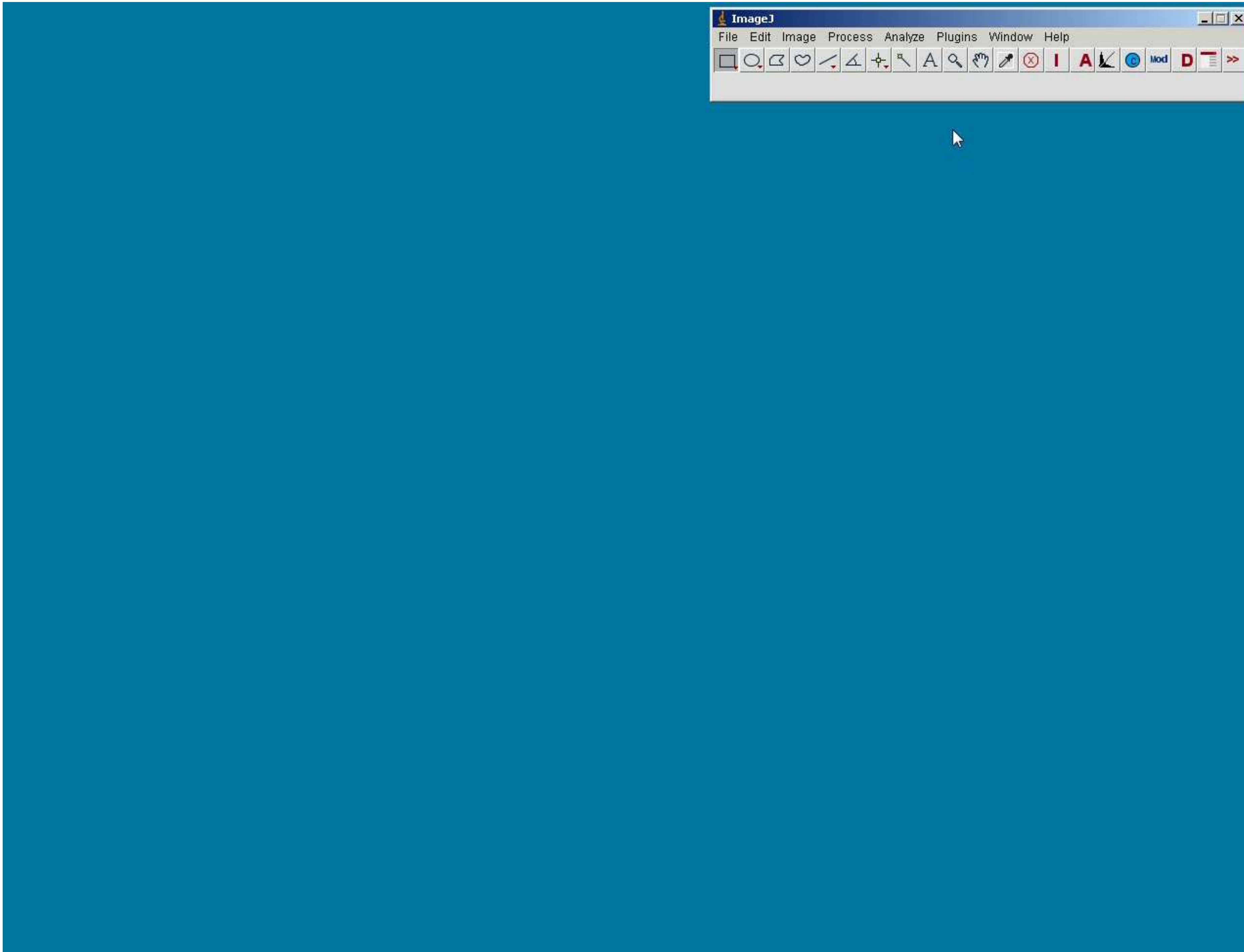
Thank you for attention!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