FlameMaster systems
- the modular laser imaging approach for flame imaging

Introduction

FlameMaster laser imaging systems are designed for multi-parameter measurements with high spatial and temporal resolution for combustion research supporting the following laser imaging techniques:

Laser Induced Fluorescence, LIF
Rayleigh Thermometry
Raman Imaging
Laser Induced Incandescence, LII

The **FlameMaster** application matrix below gives an overview of the imaged combustion parameter in combination with the applied laser imaging technique and **FlameMaster** system setup. For each imaged combustion parameter a dedicated set of hardware and software modules is provided offering the possibility for straightforward system upgrades. This modular nature for imaging upgrades provides full flexibility for different flame imaging applications. The highly integrated turnkey **FlameMaster** imaging systems support in a user-friendly manner the entire measurement process of hardware control, image acquisition, signal calibration and data storage and presentation keeping the operator's focus on the measurement.

Principle of laser imaging

A laser beam is formed to a light sheet (a line focus for Raman imaging) and intersects the flame at the area of interest. The resulting laser induced emission (LIF, Rayleigh, Raman or LII) from the light sheet is imaged through a filter onto a time-gated intensified camera. The conversion of the laser induced signals to meaningful concentration or temperature fields is based on calibration measurements. Each imaging application has its specific excitation (laser) and detection (filter) wavelength, its specific signal calibration process and image processing application in **DaVis**.

FlowMaster Application Matrix and System Configurations		Special Hardware	System Setup
OH-LIF with T-YAG	**OH Flame Radical Flame Front**	T-YAG Module	Multi-functional
Tracer (Fuel) LIF	**Fuel Imaging Mixture Preparation**	-	Multi-functional
Formaldehyde LIF	**Formaldehyde, HCHO**	-	Multi-functional
Rayleigh Thermometry	**Flame Temperature**	-	Multi-functional
Laser Induced Incandescence, LII	**Soot Concentration Particle Size**	-	Multi-functional
Raman Imaging	**Gas Composition Flame Temperature**	Imaging Spectrograph	Raman
Tunable LIF	**Flame Species & Radicals: OH, NO, CH, CN, CO …**	Dye-Laser	Tunable-LIF

Modular imaging concept and system setups

FlameMaster multi-functional system

The design of a customized **FlameMaster** system depends on the laser imaging techniques supported. The **FlameMaster** multi-functional system setup shown in Fig.1 supports fuel, flame temperature and soot imaging applying the laser imaging techniques Tracer-LIF, Rayleigh Thermometry and LII. For all laser imaging applications a pulsed, multi-wavelengths (532nm, 355nm, 266nm) Nd:YAG laser is the standard light source. Upgraded with a T-YAG module (intracavity etalon) this laser also supports OH-LIF imaging. The best operation with the most stable UV-output is achieved when the laser is continuously running in a stand-by mode to keep the laser optics under thermally stabilized conditions. The software controlled external laser shutter blocks the laser beam during this eye-safe stand-by mode and opens the beam path only for image recording. To monitor and correct residual pulse-to-pulse energy fluctuations the **online energy monitor** stamps each recorded image with its corresponding energy value. The software controlled **polarization rotator** is used to maximize the signal-to-noise ratio of the polarization dependent Rayleigh and Raman signals and is not needed for LIF and LII measurements. Beam delivery and sheet forming optics are dependent on experimental conditions, with the **laser guiding arm** as the most flexible solution for beam delivery. The synchronization of the laser pulse with the time-gated intensified camera and external event triggers is controlled by the Programmable Timing Unit, **PTU**. **DaVis** software offers the operator a nearly unlimited number of recording sequences executed via the **PTU**, including external device control of e. g. translation stages and synchronized AD-converter signal processing.

Figure 1: **FlameMaster** multi-functional system setup

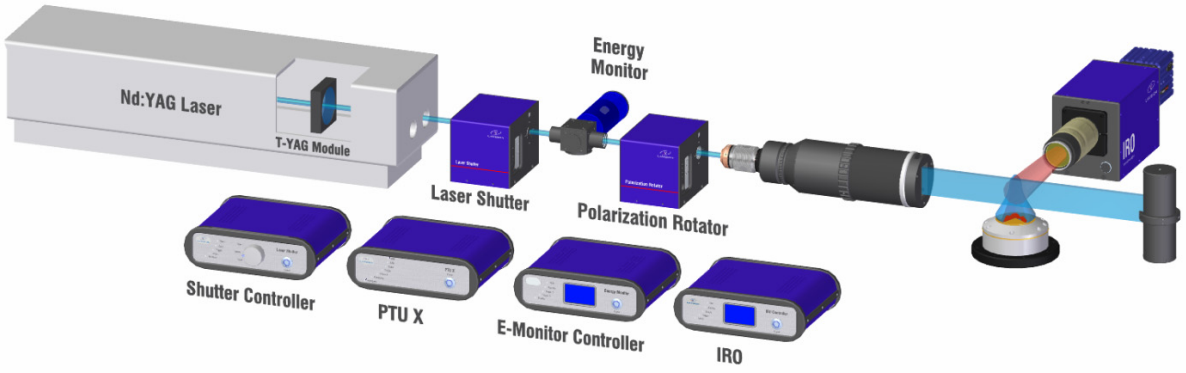


Figure 1a: Laser imaging applications in flames measured with the **FlameMaster** multi-functional system

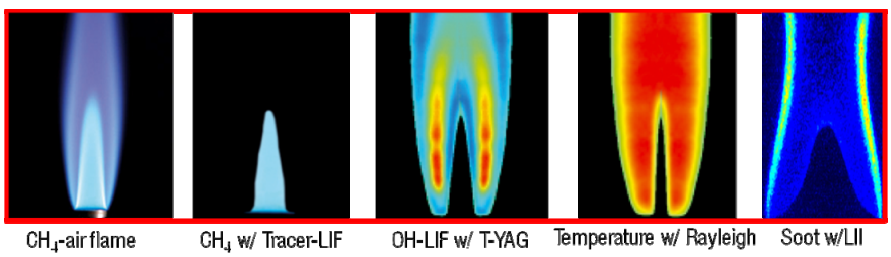
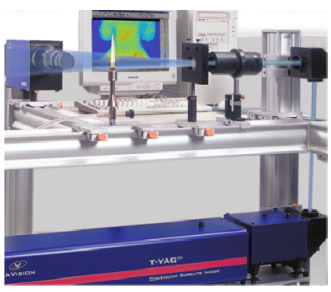
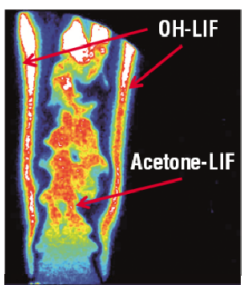


Figure 1b: **FlameMaster** with T-YAG laser for simultaneous reaction zone and fuel imaging





FlameMaster Raman system

For gas composition measurements the multi-functional **FlameMaster** system is upgraded for 1D-Raman imaging as shown in Fig. 2. Due to the weak nature of the Raman signals the light sheet is reduced to a line focus and signal averaging over multiple laser shots have to be applied. An imaging spectrograph placed between the lens and the intensified camera spectrally separates the Raman signals of the different flame species. The **FlameMaster** Raman system measures simultaneously the concentration profiles of all majority species in the flame together with the flame temperature along the line focus. Scanning the line focus over the flame generates 2D and even 3D views of the gas comosition.

Figure 2: **FlameMaster** Raman imaging setup

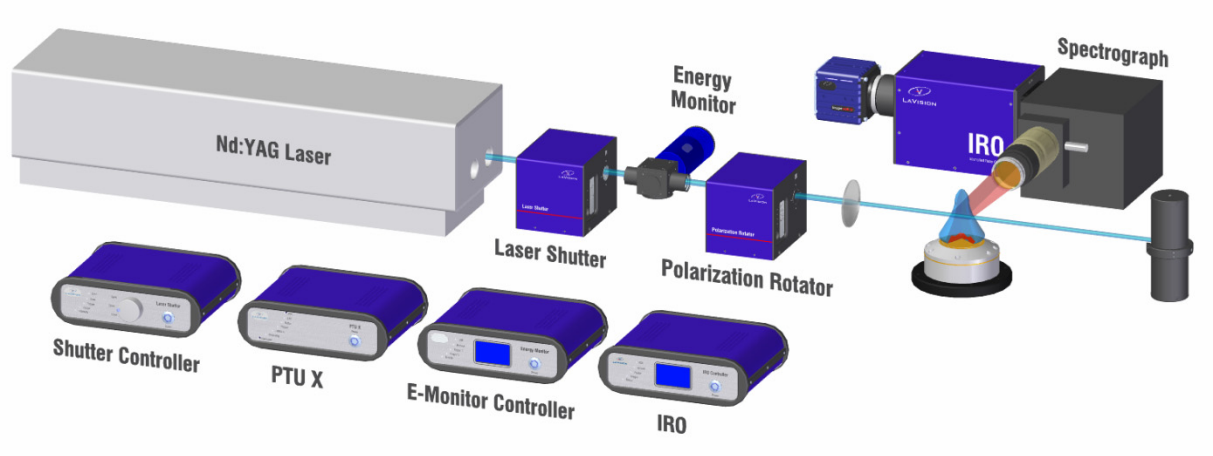
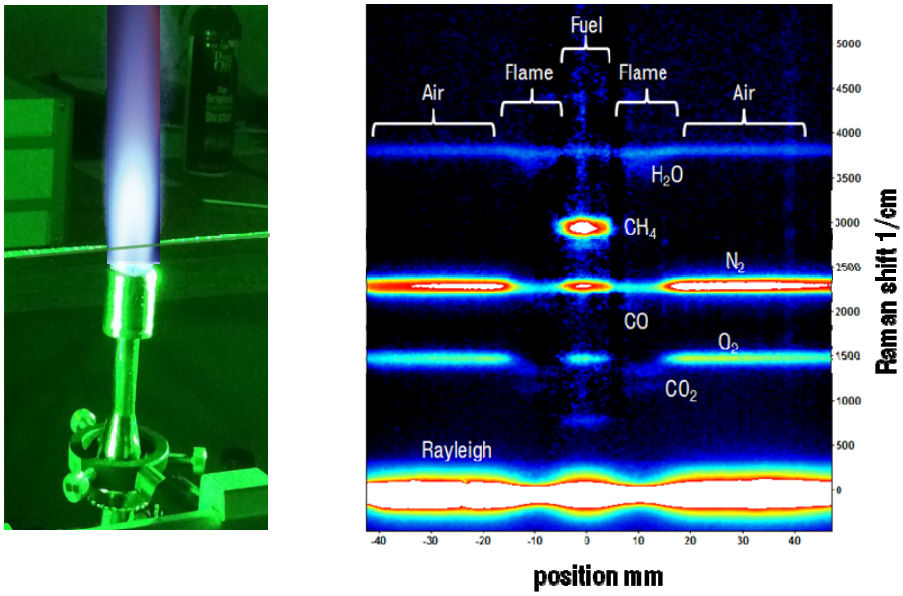


Figure 2a: Raman imaging in flames



FlameMaster tunable-LIF system

For the detection of all LIF-active diatomic flame species such as OH, NO, CH, CN, CO a dye laser is added to the multi-functional **FlameMaster** system as shown in Fig. 3. Wavelength tuning and peak finding of the selected LIF-transition is under complete **DaVis** control. Precise dye laser wavelength calibration is carried out automatically recording the LIF-excitation scan of the selected diatomic molecule. For concentration calibration of the LIF signals a calibration burner is used.

Figure 3: **FlameMaster** tunable-LIF system

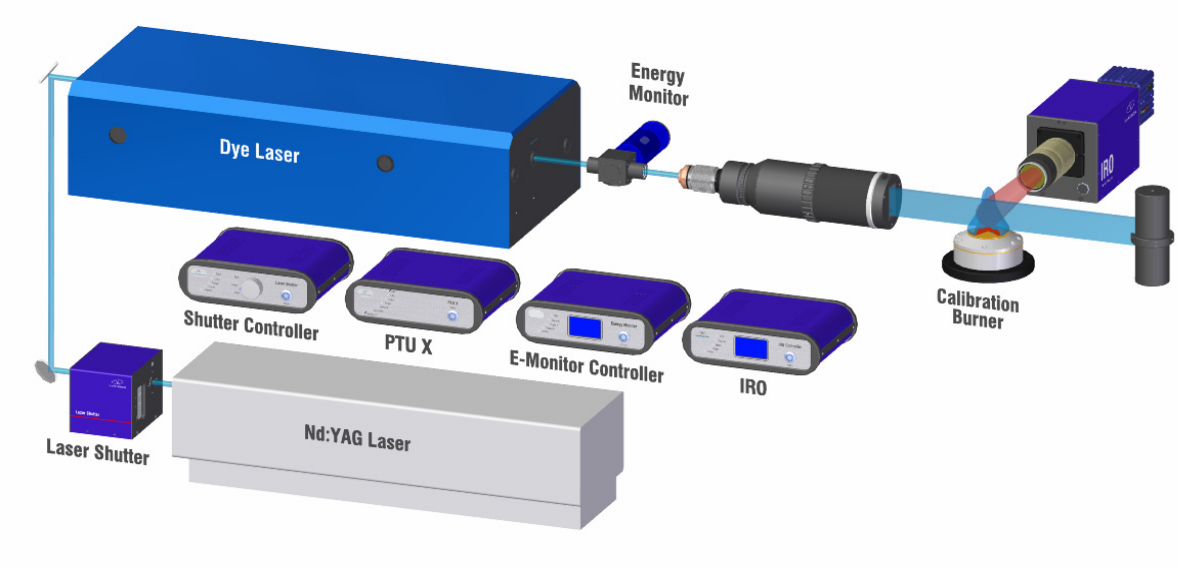


Figure 3a: Tunable-LIF imaging of flame species

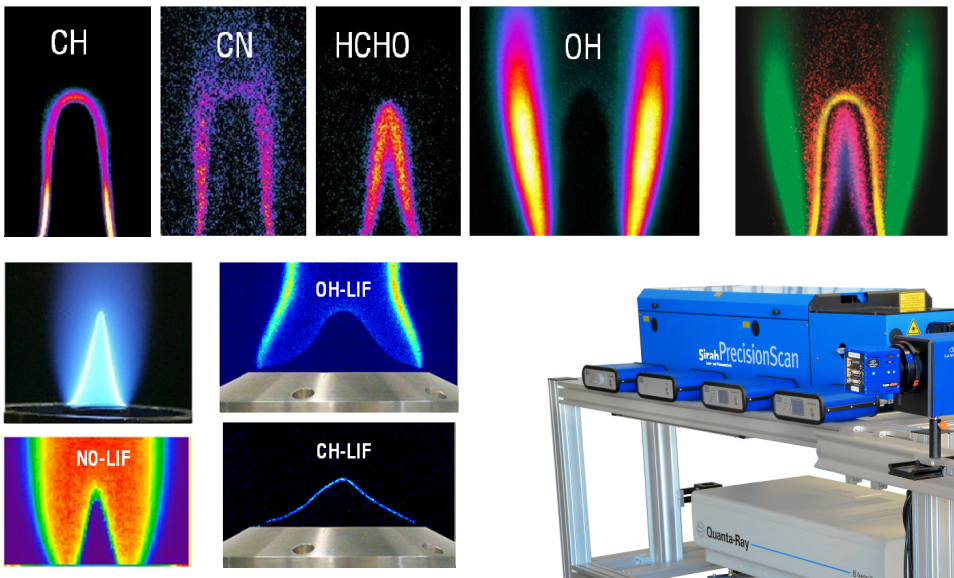


Figure 3b: Moveable **FlameMaster** tunable-LIF system mounted on a flexible rail structure (laser cradle)

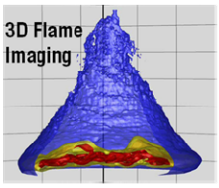
FlameMaster system features

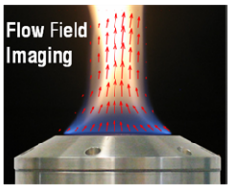
As it is shown with the three **FlameMaster** system setups all laser imaging techniques are using nearly the same hardware components creating a highly flexible and modular laser imaging system concept for combustion diagnostics. The main features of the **FlameMaster** systems are:

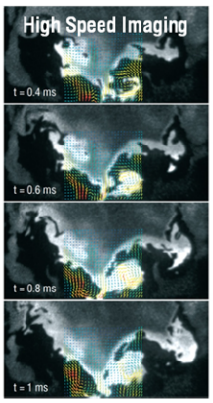
- modular system concept for multi-functional use (LIF, Rayleigh, Raman, LII)
- integrated turnkey laser imaging systems based on application matched best selection of components
- intelligent combination of laser imaging techniques supporting multi-parameter measurements
- complete hardware control using **DaVis** software
- accurate hardware and signal calibration
- laser light sheet correction incl. local laser beam absorption correction
- most efficient LIF excitation techniques with highest signal sensitivity (lowest detection limits)
- flexible beam delivery and sheet forming optics

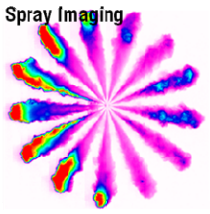
Related upgrades and imaging systems

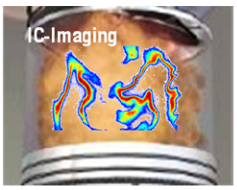
FlameMaster High Speed	Time-resolved laser imaging
FlameMaster 3D	3D flame imaging
FlowMaster	Multi-phase flow fields
SrayMaster	Laser imaging in sprays
EngineMaster	Laser imaging in engines











Related product information

- LaV. Brochure: **Focus on Combustion**
- LaV. Application Notes: **Laser Imaging for Combustion Species**
  Laser Imaging for Flame Temperature

System Components

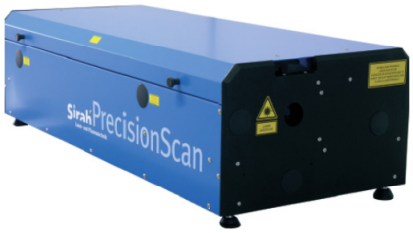
High energy pulsed Nd:YAG laser

Features:

- high energy pulsed laser
- excellent beam quality and stability
- used to pump the dye laser
- **T-YAG module** for OH-LIF

All laser imaging signals are increasing with laser pulse energy (LII needs a threshold value for a given light sheet height). Therefore, high pulse energies with a good beam quality are beneficial for laser imaging applications. With the **T-YAG module** placed in the laser cavity OH-LIF is possible.

Pulsed dye laser

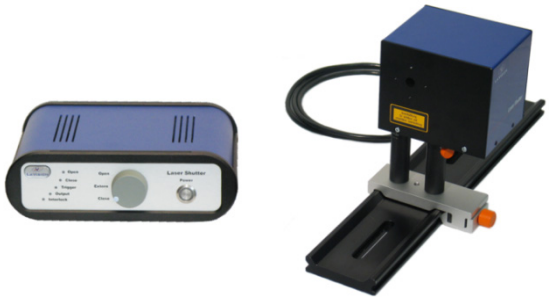


Features:

- tuning range: 350 - 610nm
  220 - 350nm w/ frequency conversion unit
- high conversion efficiencies
- good spectral match of laser line width with absorption lines

Reliable work horse for the generation of narrowband and tunable UV-radiation. Maximum conversion efficiency for each dye for highest energy outputs. Wavelength tuning and calibration using excitation scan recording under **DaVis** operation w/o beam steering effects.

Laser shutter



The external laser shutter blocks the Nd:YAG laser beam to realize stable UV-operation and an extended lifetime of laser dyes. **DaVis** controls its operation and opens the beam path for image recording or on demand.

Features:

- allows stable UV operation of Nd:YAG lasers
- extended operation times of laser dyes
- shutter operation under **DaVis** control

Laser energy monitor

For each recorded image the online energy monitor measures the relative laser pulse energy to increase the measurement accuracy. The correction for these pulse-to-pulse energy fluctuations is performed online or during image post processing.

Features:

- correction of pulse-to-pulse energy fluctuations
- dynamic range better than 1:500
- spectral working range: 245 – 900nm

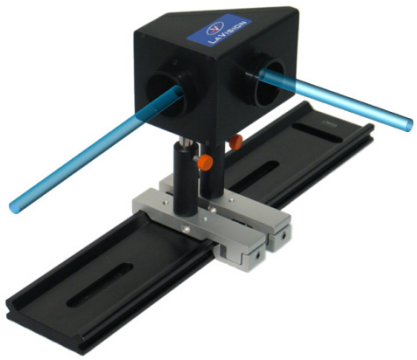
Polarization rotator

Rayleigh as well as Raman signals keep the polarization of the Nd:YAG laser. Their dipole radiation is maximized in the direction of the detector with the polarization rotator controlled by **DaVis**. Unpolarized stray light can be separately detected and subtracted from the signal.

Features:

- controls laser beam polarization orientation
- unpolarized stray light is separated
- operation under **DaVis** control

Laser beam delivery optics

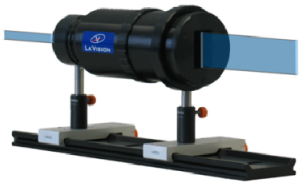


High reflection mirrors are used for fixed wavelength operation and prisms for tunable operation. Precise laser beam steering in two directions is carried out with fine adjustment screws w/o touching the optical elements.

Features:

- free adjustable laser beam steering units
- eye-safe housings and beam tubing
  also for dust protection

Sheet optics

The light sheet projection onto the measurement plane is carried out with a set of sheet optics. While the standard sheet optics produces a divergent light sheet with adjustable parameters (focal length and angle), it generates in combination with the collimator a parallel light sheet up to 50mm height.

Features:

- adjustable divergent sheet geometries
- parallel light sheets up to 50mm in combination with the collimator optics
- optics for all wavelengths

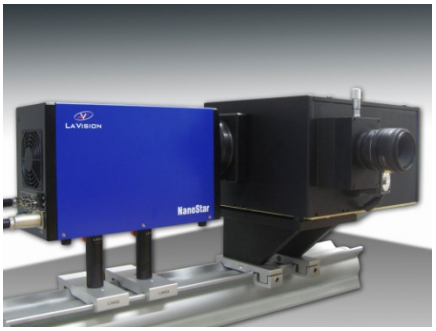
Camera lens and filter


Nearly all laser induced emissions are in the UV spectral range and their signal strength is limited by the number of collected photons, i.e. by photon statistics. Due to these reasons, UV-lenses with high light collection efficiencies are used. For each applied imaging technique a dedicated filter with a high peak transmission is mounted in front of the UV-lens.

Features:

- high quality UV-lenses with different f/#
- application specific filters with maximum transmission and spectral background suppression

Imaging spectrograph



The line focus of the Raman beam is imaged onto the entrance slit of the spectrograph, which spectrally separates the Raman signals of the different flame species. Together with the intensified camera it acts like a highly sensitive 1D multi-channel detector for multi-species flame analysis along the line focus.

Features:

- high performance imaging spectrograph
- ultra sharp 1D-imaging
- multiple grating turret under DaVis control

Intensified camera

The intensified camera is required for signal amplification, short gates and UV sensitivity. The camera is lens coupled to the image intensifier using high quality relay lens optics (IRO). Intensifier with high quantum efficiencies and high spatial resolution are used for signal detection.

Features:

- high resolution camera w/ highest sensitivity
- lens coupling for optimized image quality
- complete operation under **DaVis** control

Synchronizer and timing unit PTU

The entire measurement process of hardware control, device triggering and synchronization, image and data recording is managed by the PTU. Together with the **DaVis** software it is the brain of the measurement system.

Features:

- generation of complex trigger sequences
- highly accurate timing on multiple outputs (up to 16 independent channels)
- available as PCI board or stand alone USB device

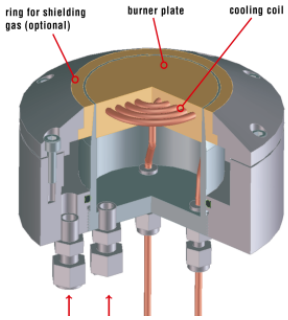
Moveable system cradle

The moveable system cradle is a rail structure accommodating all system components. Its rail structure supports all mounting requirements for laser imaging experiments in a very flexible way and is easily expandable.

Features:

- moveable system setup
- rail structure support for flexible setups
- modular design and therefore expandable

Calibration burner setup



The calibration burner is used for concentration calibration of flame species and flame temperature. Beside other stable flames (e. g. Bunsen burner) it is used for excitation scan recording, i.e. precise wavelength calibration of the dye laser. An annular co-flow of shield gas isolates the flame from ambient air. Flow controllers are used for flame conditioning.

Features:

- calibration standard for laser imaging in flames
- stable, shielded premixed flame
- flow controllers are used for flame tuning

Software

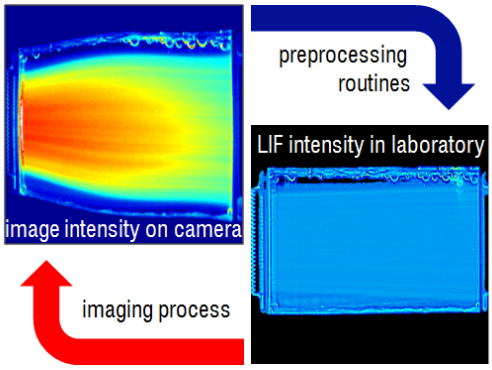
DaVis application modules

DaVis is the state-of-the-art software platform for laser imaging applications. **DaVis** manages the entire measurement process of hardware control, image acquisition, signal calibration, image processing and data handling.

Features:

- extensive number of application modules for laser imaging in flames
- recording sequences for nearly all applications
- batch processing
- command language for customized solutions

Image preprocessing routines

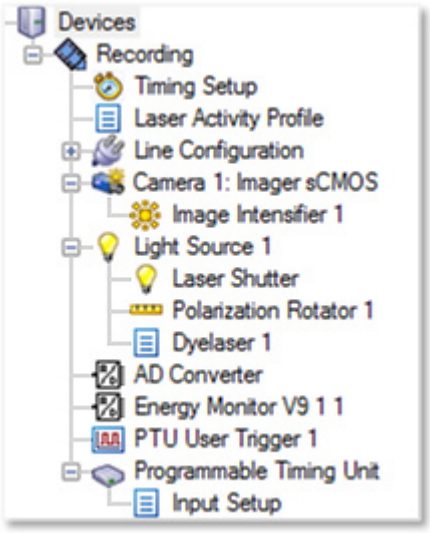


The FlameMaster software contains all necessary routines to compensate for image artifacts. The integrated **image preprocessing routines** account for background offset, variations in signal gain, laser sheet intensity distribution, laser pulse-to-pulse fluctuations, vignetting and image distortion. The result of these image preprocessing routines is a cleaned up 2D image of the laser induced signal.

Features:

- correction of all image artifacts
- batch processing routines for automated correction

Hardware integration and management

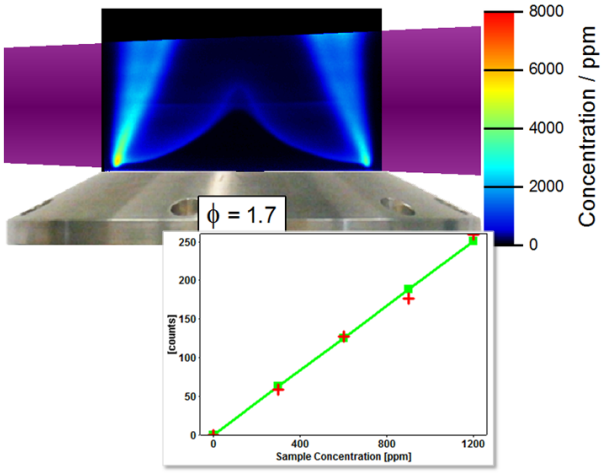


DaVis takes control over proper synchronization and data readout of all hardware components. Cameras and short-gate intensifiers perfectly match the laser pulse with a minimum of operator interaction. Polarization control, laser energy monitor, spectrograph, laser and camera shutter and more accessories are all implemented in **DaVis**. Image data from the cameras are combined with laser energy readout, A/D-converter data and device settings to a fully traceable data set for each measurement.

Features:

- fully integrated cameras, lasers, intensifiers, translation stages, A/D-converter and more
- precise automatic timing control
- large variety of triggering and timing schemes
- on-chip integration for improved S/N-ratio

Calibration module for physical units

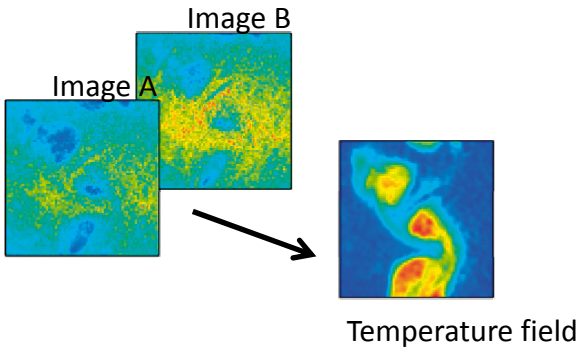


This FlameMaster software package transfers signal intensities into the desired physical unit such as temperature, mixing ratio, tracer concentration, fuel or oxygen content and more. Different fitting models like linear, exponential or splines can be applied to match the physical model describing the relation between camera signal and measured flame parameter.

Features:

- calibrates signal intensities in units of the measured quantity (ppm, K,…)
- various fitting functions
- 1-step recalibration for different imaging setups

Ratiometric imaging – temperature measurements

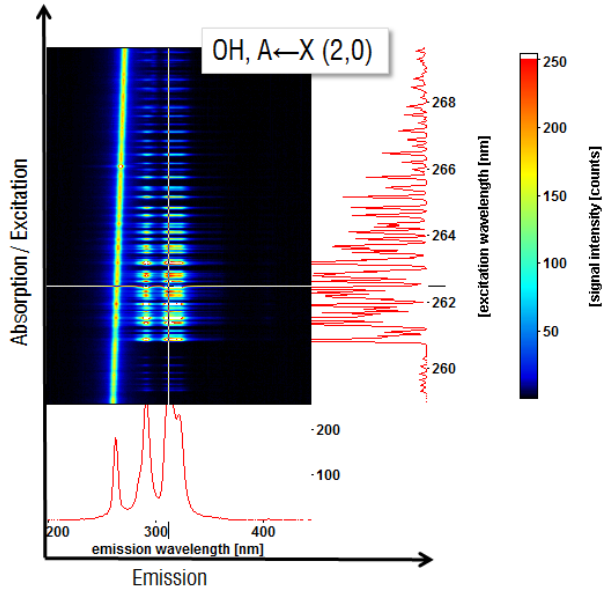


The **ratiometric imaging** approach makes the measurement of a physical property independent of the laser illumination situation. The so called 2-color ratiometric LIF method measures the intensity ratio of 2 LIF emissions which is then not affected by any local laser light intensity fluctuations caused by deflection, absorption or attenuation. For this approach a homogeneous tracer concentration is not needed.

Features:

- 2-color LIF image ratio
- laser imaging w/o laser sheet and intensity variations
- precise pixel-by-pixel matching of both images
- processing routine for ratio calculation
- best practice for temperature measurements

Dye-laser operation for tunable LIF

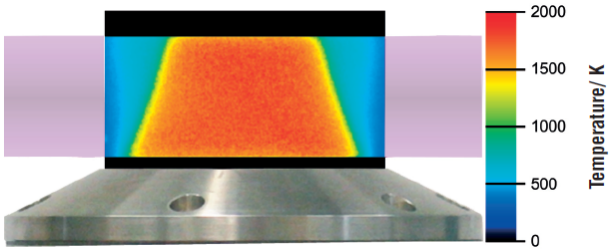


DaVis supports the wavelength scan functionality of the dye-laser including precise wavelength calibration. For planar laser imaging the peak finding routine automatically tunes the dye-laser for maximum LIF signal intensities. A detailed spectral analysis can be achieved recording a complete excitation-emission spectrum in combination with a spectrograph.

Features:

- **DaVis** control of dye-laser tuning
- automated peak finding for max. LIF signal

Rayleigh thermometry

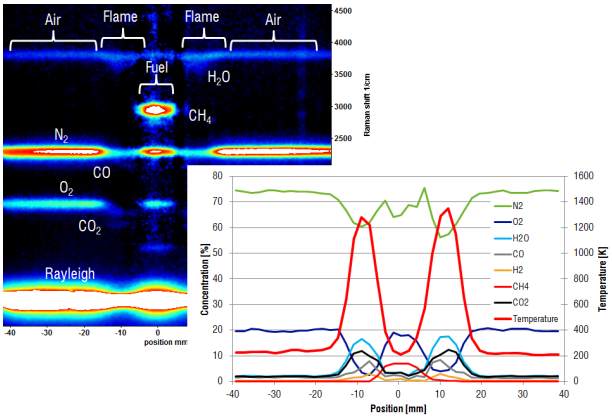


Features:

- polarization rotation technique for improved temperature imaging
- ratiometric imaging
- automatically detects and corrects for locally different gas composition
- integrated data base for Rayleigh cross sections

The **Rayleigh thermometry** package supports recording of images using the polarization rotation technique for improved temperature measurements. The ratiometric imaging approach for Rayleigh thermometry makes the system independent of the laser beam profile and laser sheet geometry. A built-in data base assist to correct for the influence of the gas mixture composition to the Rayleigh signal. The automated detection of regions with different gas compositions is supported.

Raman imaging

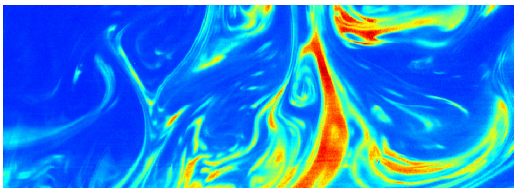


Features:

- polarization rotation technique
- build-in Raman data base
- batch-processing Raman analysis

Raman imaging measures simultaneously gas composition (major species) and flame temperature. The Raman package supports recording of images using the polarization rotation technique to improve the signal to noise ratio. A built-in Raman data base for different flames are used in the analysis process. A wizard guides through the calibration process using calibration gases.

Absorption correction



Features:

- true concentration fields without artifacts from absorption
- real physical absorption model for the ray-tracing algorithm

While the laser is guided through the measurement section, each part of the beam is differently attenuated by a locally inhomogeneous tracer mixture. The **absorption correction** module compensates for locally absorbed laser intensities. The result is a tracer-LIF image cleaned up for laser beam absorption effects.