Buoyant Jet Mole Fraction Measurements using Rayleigh scattering Technique

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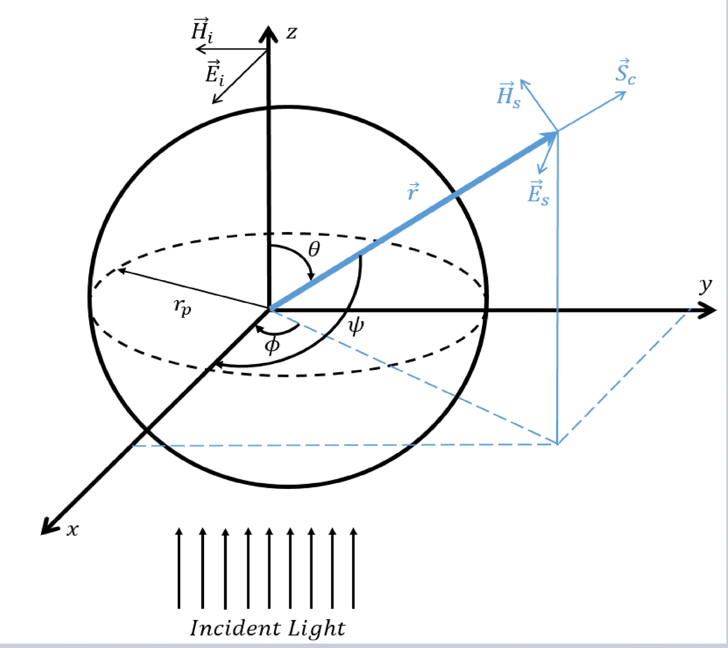
INTRODUCTION

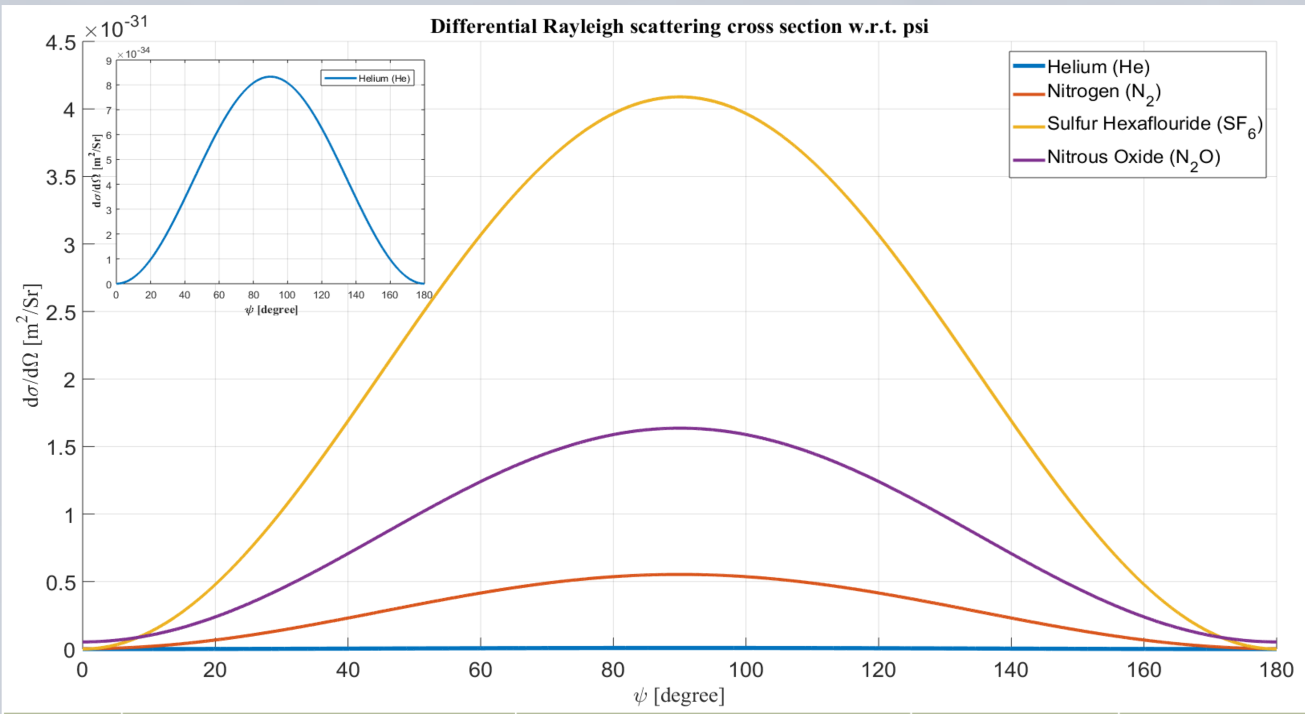
- In flow studying, it is very important to obtain the most possible information about the flow physical behavior.
- Rayleigh scattering technique has the advantage of measuring the density, temperature and velocity without any disturbances to the flow and there is also no need to seed the flow with particles (PIV) or gas phase tracer e.g. acetone (PLIF).
- This technique involves the elastic interaction of the incident laser light with the gas molecules which results the scattered light and the laser to have the same central wavelength.



Rayleigh scattering geometry

$$I_S = I_i N L_s \Omega \frac{d\sigma}{d\Omega}$$

$I_S \equiv$ Rayleigh scattering signal intensity $[W.m^{-2}]$, $I_i \equiv$ incident laser intensity $[W.m^{-2}]$, $N \equiv$ species number density $[m^{-3}]$, $L_s \equiv$ length of probe volume $[m]$, $\Omega \equiv$ solid angle for detection $[Sr]$, $\frac{d\sigma}{d\Omega} \equiv$ differential Rayleigh scattering cross section species mixture $[m^2.Sr^{-1}]$.



Species	Scattering cross section $\sigma \times 10^{33}\ [m^2]$	Differential scattering cross section $\frac{d\sigma}{d\Omega} \times 10^{34}\ [m^2.Sr^{-1}]$	Refractive Index $(n-1) \times 10^6$	Polarization value $\rho_p \times 10^4$
He	6.97	8.32	34.9	0
N_2	476	552	283.8	104
N_2O	1610	1630	483.4	618
SF_6	3420	4080	732.8	2

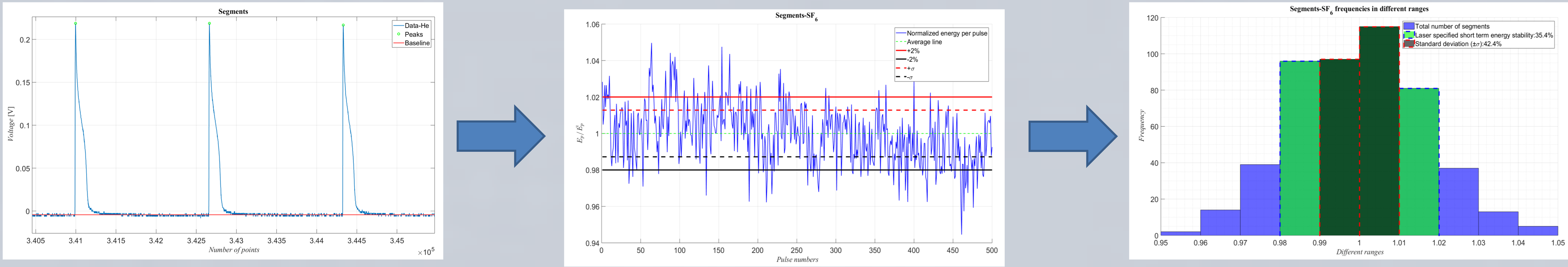
METHODOLOGY

- Raw image definition [Clemens, N. T. (2002)]: $\boxed{S(i,j,t_i,t_{ro}) = w(i,j)[L(i,j)\, S_R(i,j) + S_{back}(i,j,t_i)] + S_{dark}(i,j,t_{ro})}$

With $S \equiv$ total detected Rayleigh scattering signal $[pixel-count]$, $(i,j) \equiv$ vertical and horizontal pixel locations, $t_i \equiv$ Exposure time, $t_{ro} \equiv$ array readout time, $w(i,j) \equiv$ white-field response function, $L(i,j) \equiv$ Laser intensity distribution, $S_R \equiv$ the actual jet and coflow Rayleigh scattering signal $[pixel-count]$, $S_{back} \equiv$ background signal $[pixel-count]$, $S_{dark} \equiv$ camera dark current $[pixel-count]$.

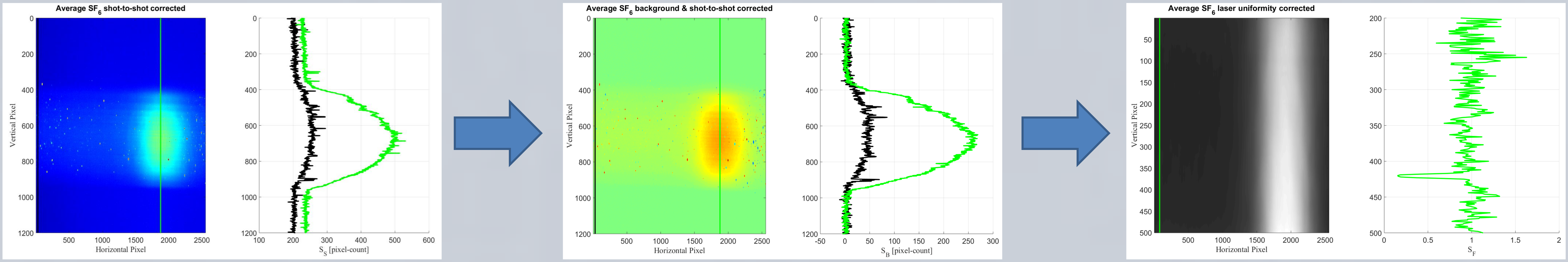
Image correction process → Shot-to-shot correction → Background and dark current correction → Laser non-uniformity correction

- Shot-to-shot correction: using photodiode and oscilloscope to capture each laser pulse (total 500 pulses).

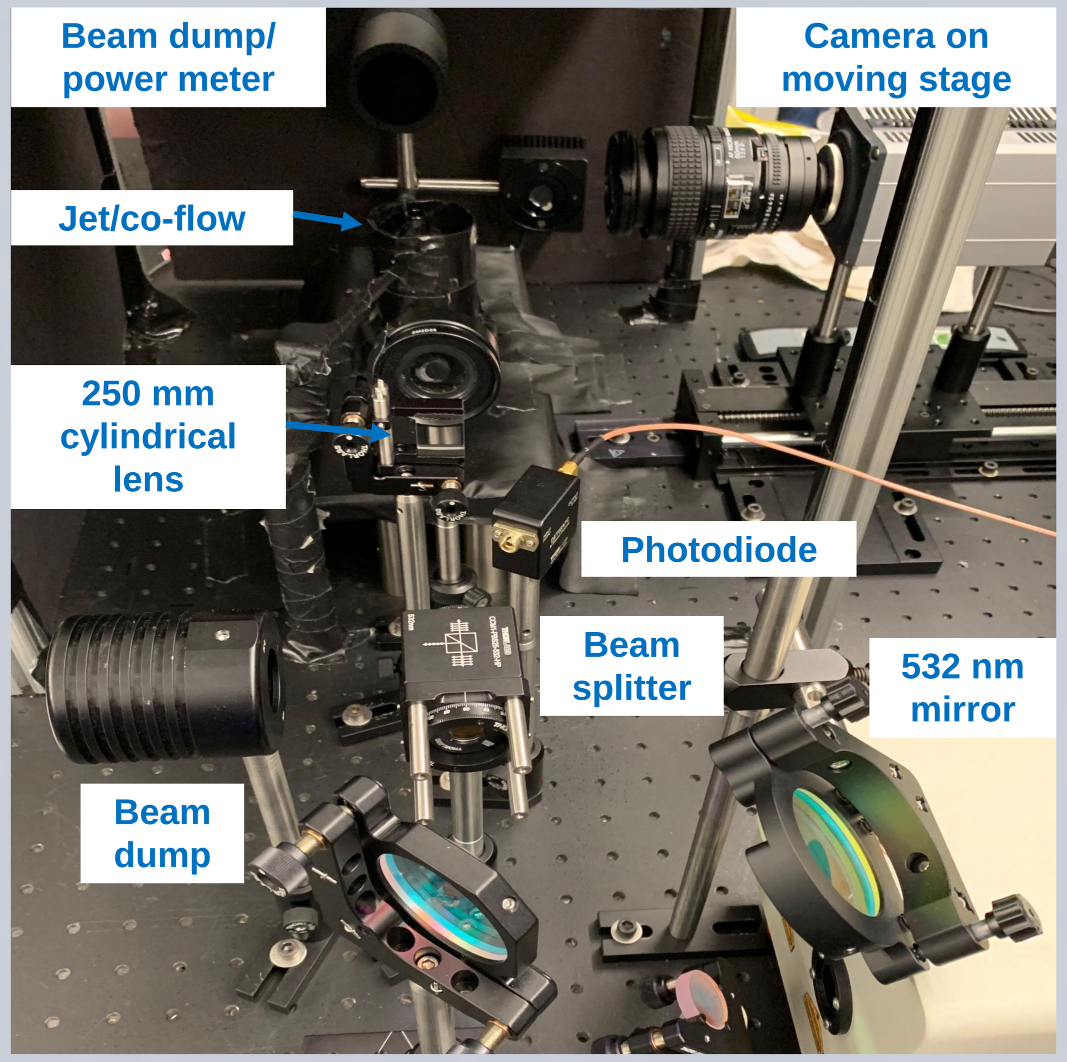


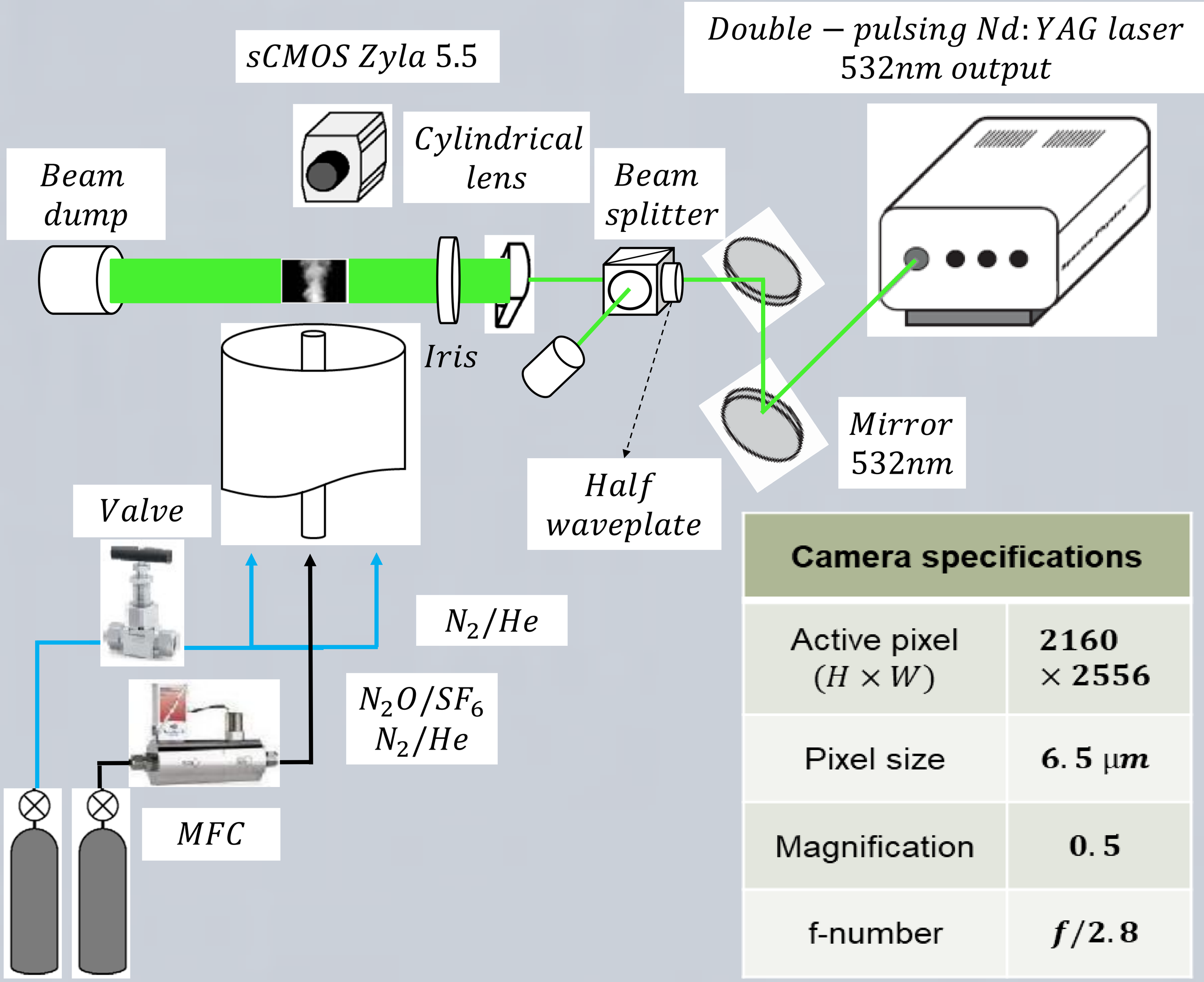
- Background and dark current correction:

$$Background(i,j) = Background_{He}(i,j) - \left(\frac{\frac{d\sigma_{He}}{d\Omega}}{\frac{d\sigma_{N_2}}{d\Omega} - \frac{d\sigma_{He}}{d\Omega}}\right)[Background_{N_2}(i,j) - Background_{He}(i,j)]$$



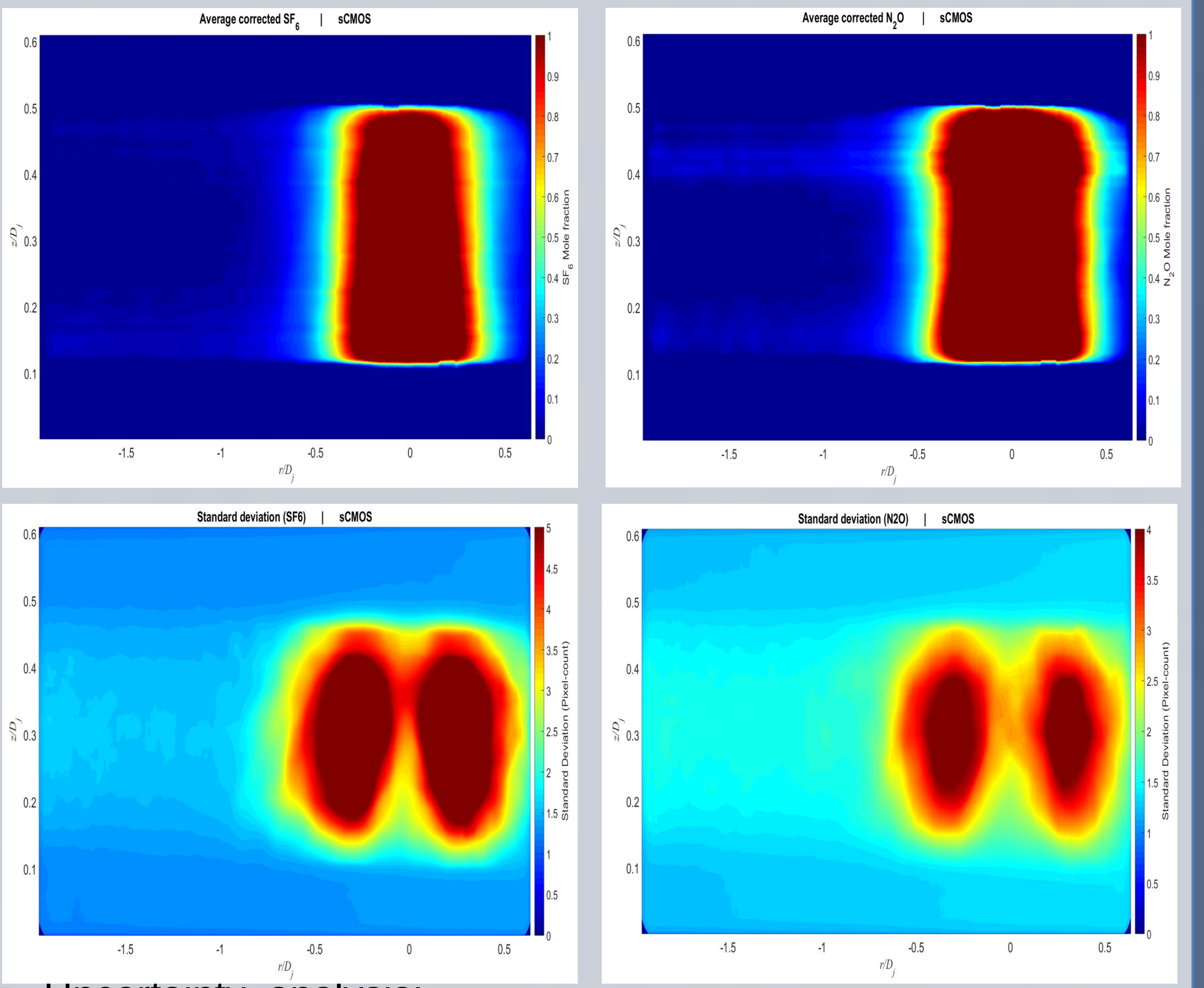
EXPERIMENTAL SETUP





Camera specifications	
Active pixel $(H \times W)$	2160×2556
Pixel size	$6.5\ \mu m$
Magnification	0.5
f-number	$f/2.8$

RESULTS + UNCERTAINTY ANALYSIS



- Uncertainty analysis:

$$I_S = R\frac{P\Omega E_i}{T\lambda_i^4} \rightarrow T = R\frac{P\Omega E_i}{I_S\lambda_i^4}$$

$$\Delta T = \sqrt{\left(\frac{\partial T}{\partial I_S}\Delta I_S\right)^2 + \cancelto{0}{\left(\frac{\partial T}{\partial P}\Delta P\right)^2} + \cancelto{0}{\left(\frac{\partial T}{\partial \lambda_i}\Delta \lambda_i\right)^2} + \left(\frac{\partial T}{\partial \Omega}\Delta \Omega\right)^2 + \left(\frac{\partial T}{\partial E_i}\Delta E_i\right)^2}$$

$$\Delta N = \sqrt{\cancelto{0}{\left(\frac{\partial N}{\partial P}\Delta P\right)^2} + \left(\frac{\partial N}{\partial T}\Delta T\right)^2}$$

$\Delta I_S \equiv$ shot noise numbers of photoelectrons (Poisson statistics) $= (I_S)^{\frac{1}{2}}$, $\Delta P \equiv$ negligible for thermometry measurements, $\Delta\lambda_i \equiv$ negligible for R.S. (only for FRS), $\Delta\Omega \equiv$ beam pointing stability $= \pm 3.14 \times 10^{-8}\ [Sr]$, $\Delta E_i \equiv$ Incident energy uncertainty.

Temperature uncertainty	Concentration uncertainty	sCMOS (Zyla 5.5)
$\left(\frac{\Delta T}{T}\right)_{SF_6}$	$\left(\frac{\Delta N}{N}\right)_{SF_6}$	1.66%
$\left(\frac{\Delta T}{T}\right)_{N_2O}$	$\left(\frac{\Delta N}{N}\right)_{N_2O}$	1.90%

Future Work

- Filtered Rayleigh scattering (FRS) is the atomic/molecular vapor filter which is placed in front of camera and will improve qualitative flow visualizations.
- FRS will be used to remove more precisely the wall/dust reflections from Rayleigh scattering signal to improve accuracy of the image analysis for flow temperature measurements.