Application of Image Restoration Technique in Flow Scalar Imaging Experiments

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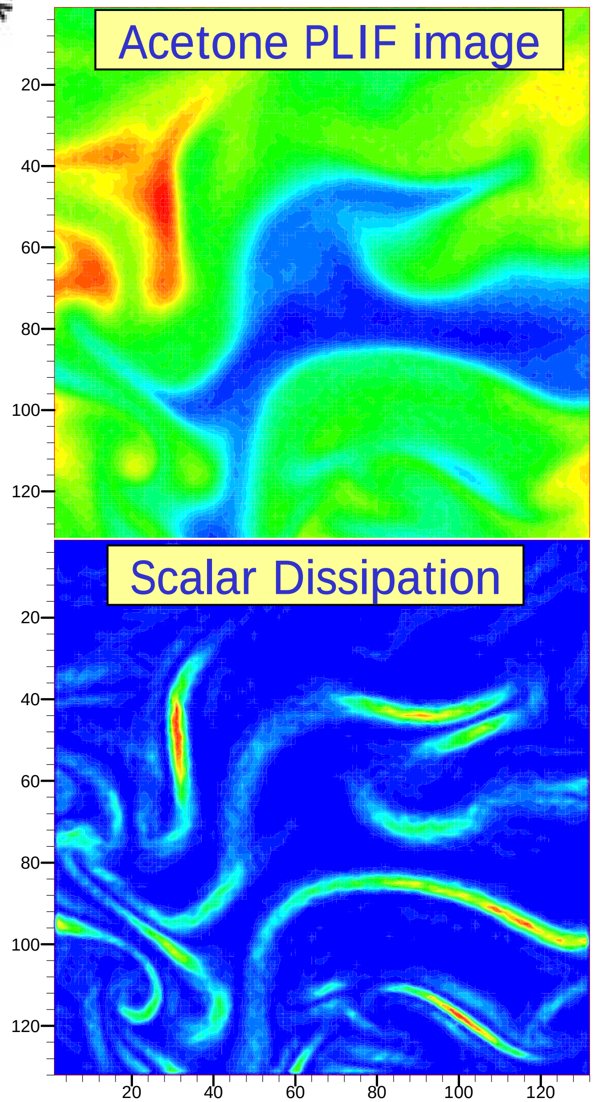
Introduction



PLIF (Planar Laser Induced Fluorescence) image $Re_{d1/2}$=9600, Sc=1.5, [Tsurikov, 2002]

Flow scalar imaging experiments

- **Resolution requirements**

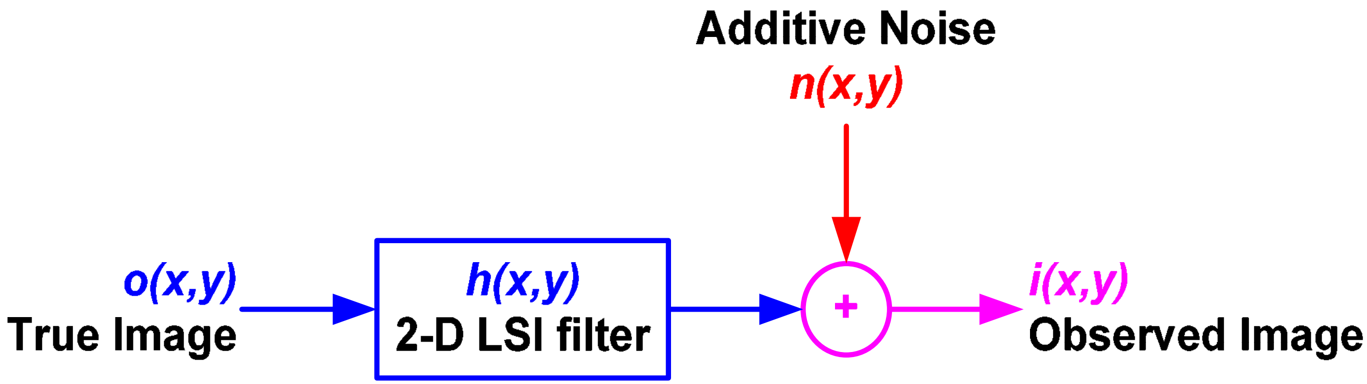
$$\lambda_V / \delta \propto \mathrm{Re}_\delta^{-3/4}$$
$$\lambda_D / \delta \propto Sc^{-1/2}\, \mathrm{Re}_\delta^{-3/4}$$

  - λ_v and λ_D: smallest local length scales

- **Resolution restrictions**
  - CCD camera pixel spacing/size;
  - Imaging system blurring effect (especially for FAST optics);

- **In this project**
  - ➔ Using image restoration technique to correct imaging system blurring effect;
  - ➔ Improve resolution and dissipation measurement accuracy;

Blurring Model



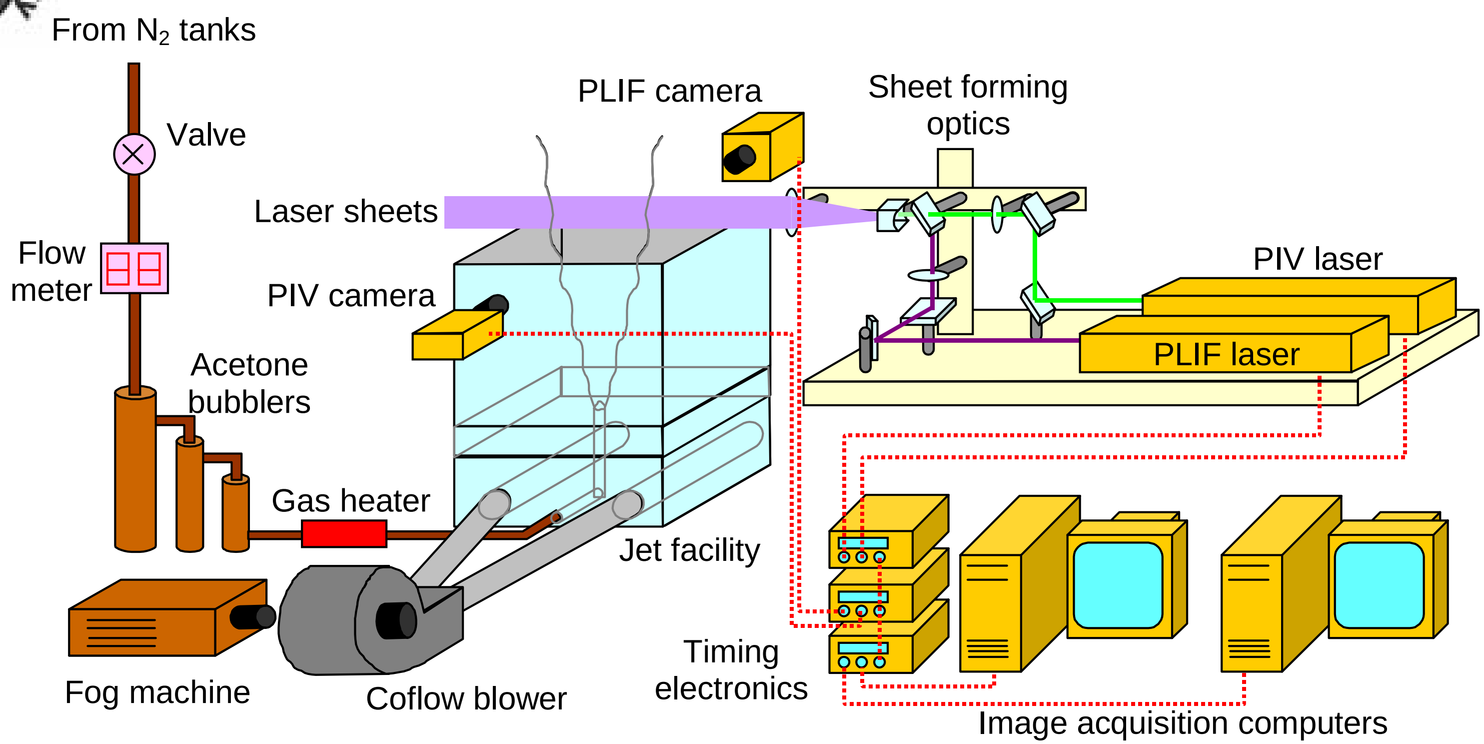
- Blurring model — $o(x,y) = i(x,y)**h(x,y) + n(x,y)$
- True image *o(x,y)* — ***Flow Scalar field***
- LSI Filter *h(x,y)* — ***Point Spread Function (PSF) of imaging system***
- Noise *n(x,y)* — ***Additive noise, i.e. CCD camera readout noise***

Inverse problem:

- Known ***i(x,y)*** and PSF ***h(x,y)***
- Prior knowledge of ***o(x,y)*** and ***n(x,y)***

→ How to get ***o(x,y)*** ?

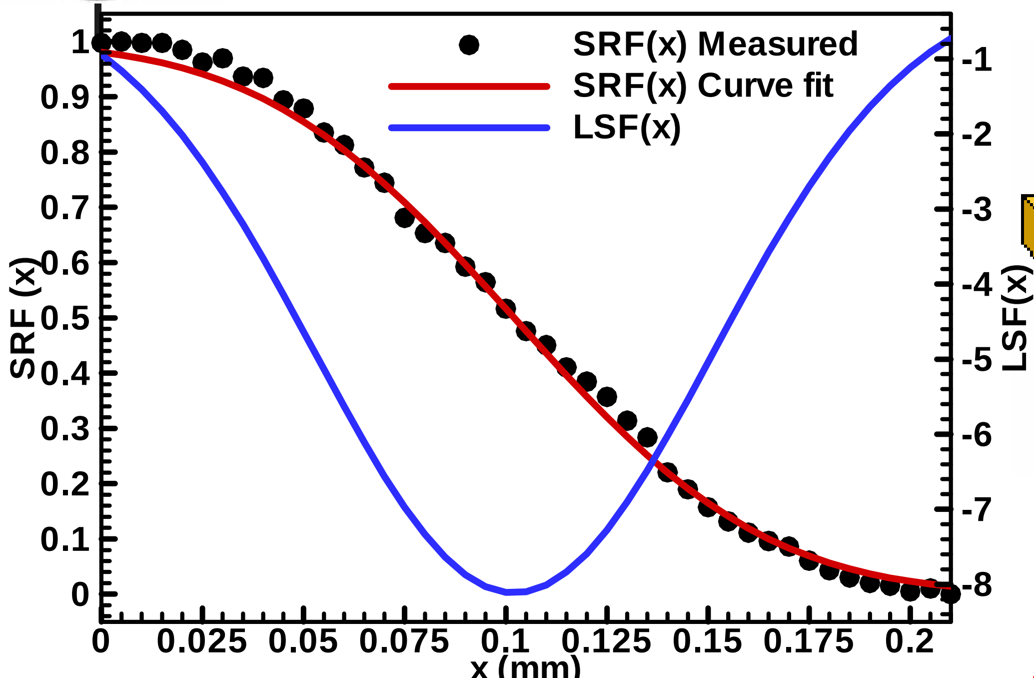
Prior Knowledge of the PLIF Image



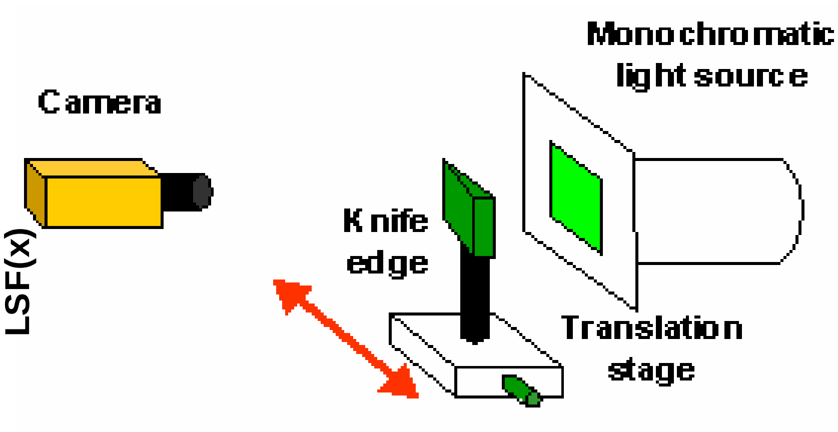
PLIF (Planar Laser Induced Fluorescence) Experiment Setup [Tsurikov, 2002]

- For acetone PLIF, differential cross section is ***10^{-24} cm²/sr***
- High signal ➔ Photon counting statistics noise is dominant;
- True image ***o(x,y)*** ➔ *Shot-noise limited;*
- *Poisson noise = Shot-Noise limited*

Point Spread Function (PSF) Measurement



Measured **SRF**, curve-fitted **SRF_{cf}** and **LSF** for a Nikon 105mm f/2.8 [Tsurikov, 2002]



Scanning knife edge technique

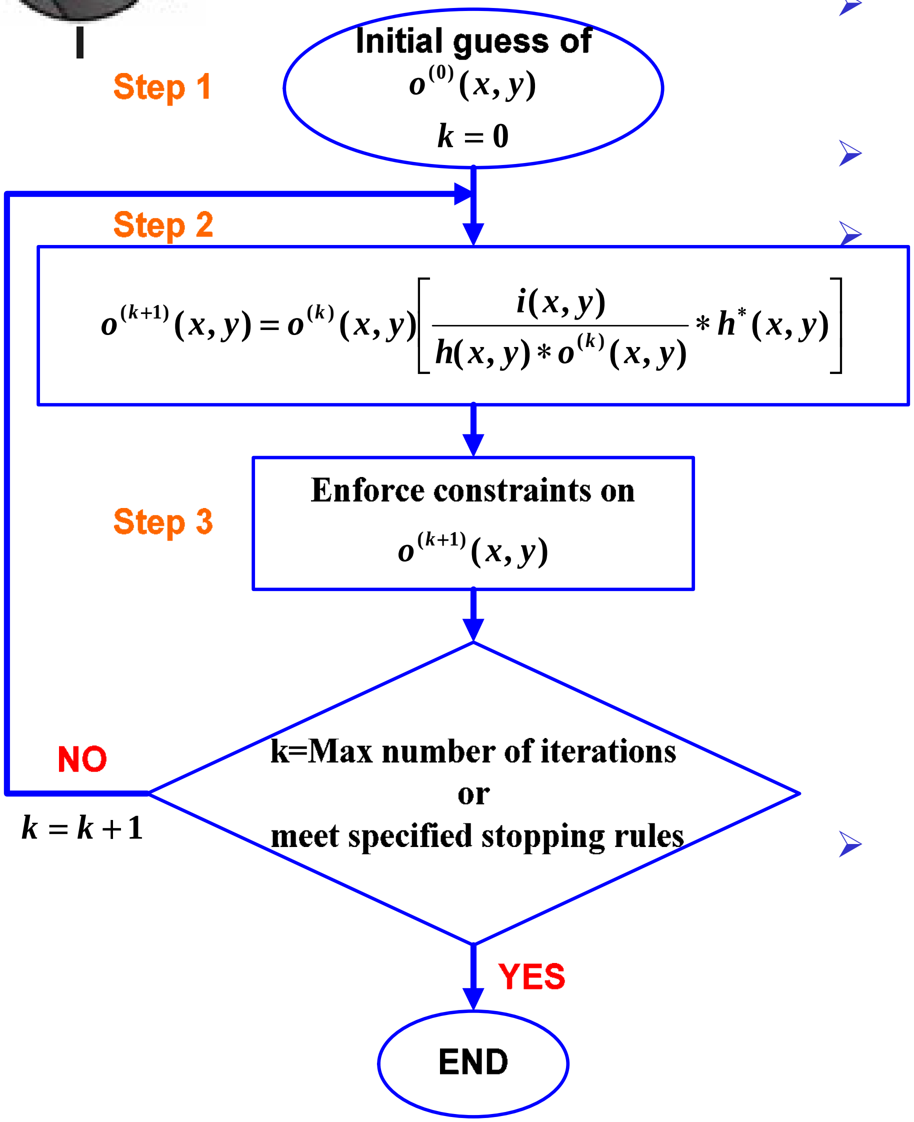
References:

- N.T. Clemens (2002)
- W.J. Smith (2000)
- T.L. Williams (1999)

- **SRF_m & SRF_{cf}:** Measured & Curve-fitted Step Response Function
- **LSF:** Line Spread Function
- **PSF:** Point Spread Function
- **MTF:** Modulation Transfer Function

$$SRF_m \xrightarrow{\text{curve fit}} SRF_{cf} \xrightarrow{d/dx} LSF \xrightarrow{\text{Isotropic}} PSF \xrightarrow{\text{Fourier transform}} MTF$$

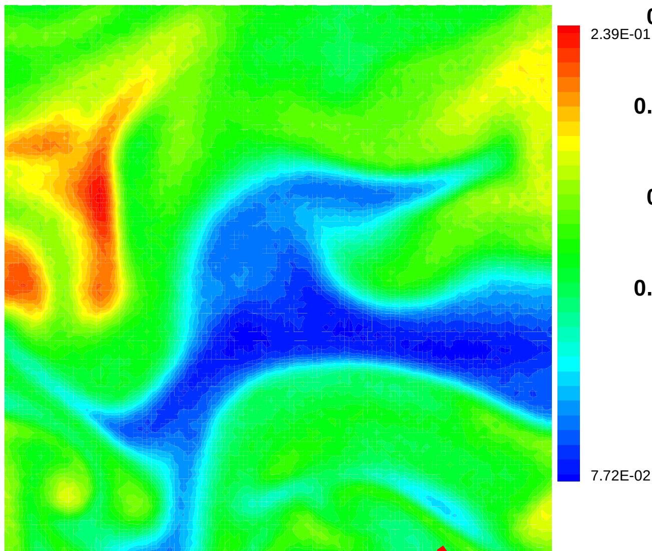
R-L-EM Algorithm



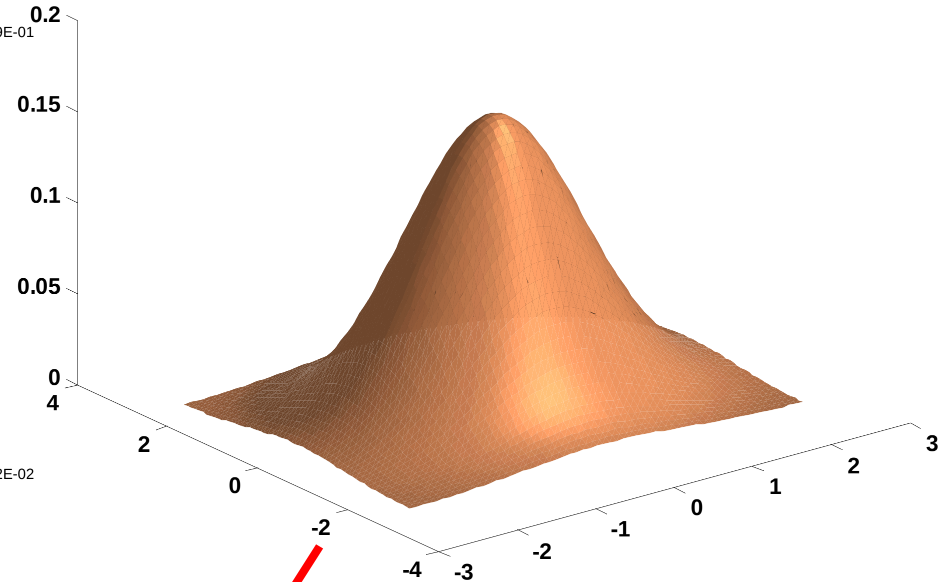
- Richardson-Lucy Expectation Maximization (R-L-EM)
- Richardson (1972) and Lucy (1974)
- Well developed in 1990's for HST (Hubble Space Telescope) image restoration
  - It converges to the Maximum Likelihood (ML) solution for Poisson statistics in the image;
  - The restored image is non-negative and flux is conserved at each iteration;
  - The restored image is robust against small errors in the PSF;
- Constraints:
  - Non-negativity;
  - Total-Flux conserved;
  - Finite spatial support;
  - Band-limited;

Results – Initial conditions

Observed Concentration field



Measured PSF



Noise Handling → **R-L-EM Deconvolution** ← **Stopping Rules**

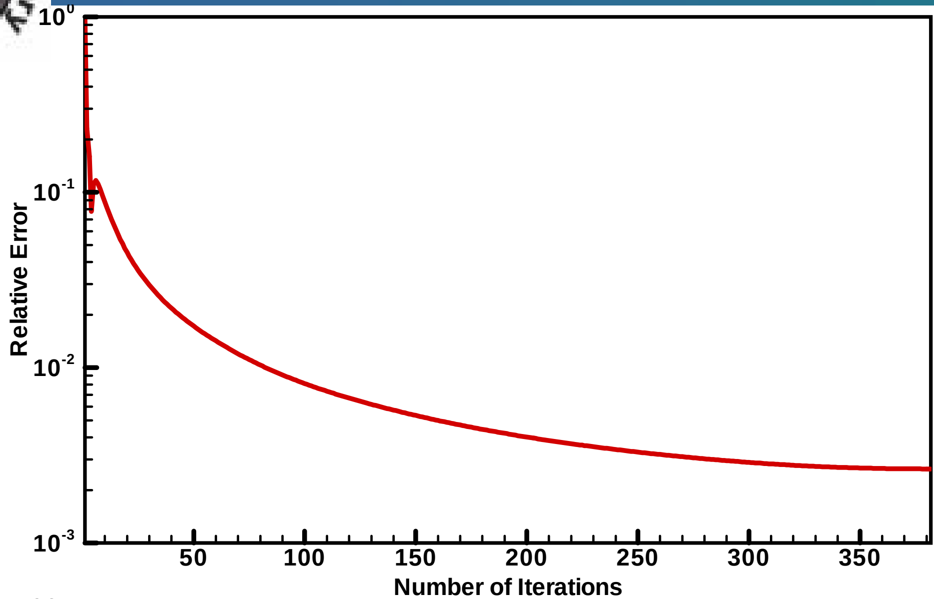
O(x,y)

Starck, Pantin and Murtagh (2002)

Molina, Nunez, Cortijo and Mateos (2001)

Hanisch, White and Gilliland (1997)

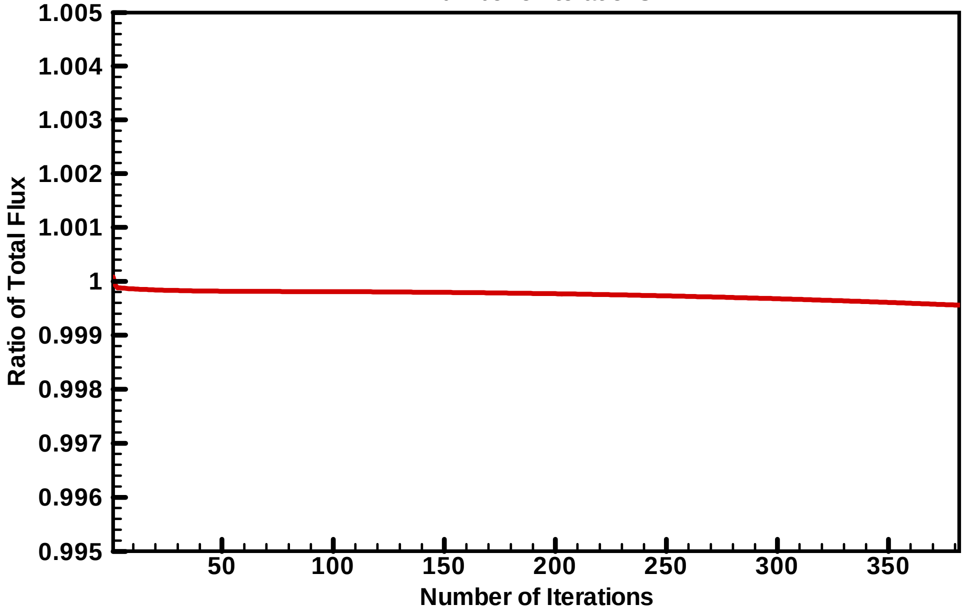
Results – Convergence and Conservation



$$\frac{\left\| o^{(k+1)}(x,y) - o^{(k)}(x,y) \right\|}{\left\| o^{(k)}(x,y) \right\|} \le \varepsilon$$

Where ε is a small number

- V. M. R. Banham and A. K. Katsaggelos (1997)

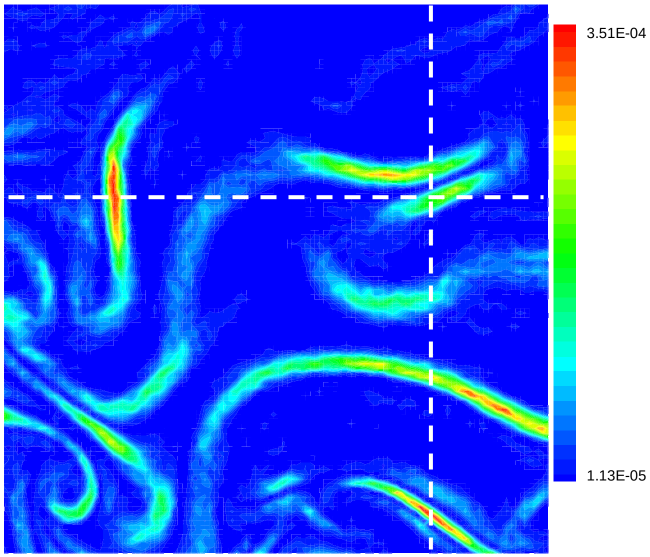


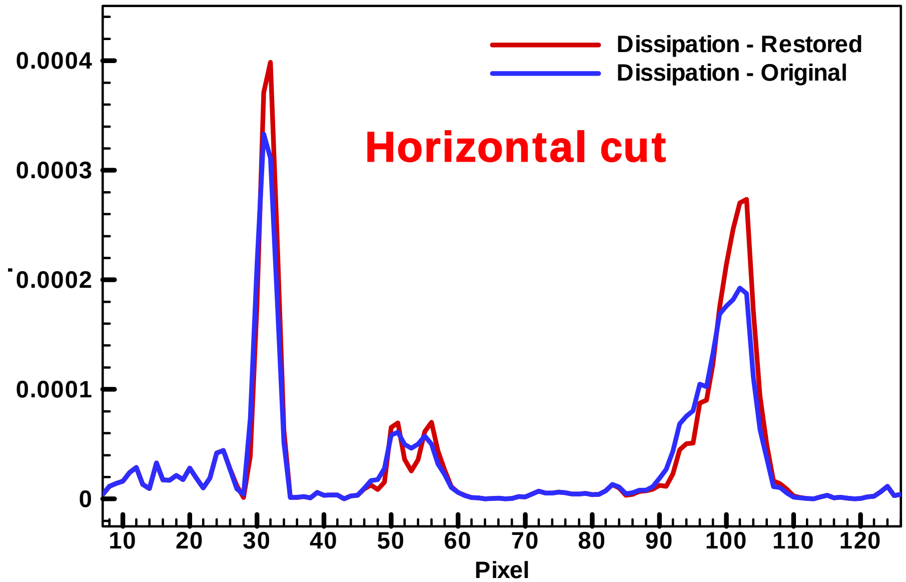
$$Total\ \ Flux\ \ Ratio = \frac{\sum_{x,y} o^{(k)}(x,y)}{\sum_{x,y} i(x,y)}$$

The blurring should not alter the total number of photons detected.

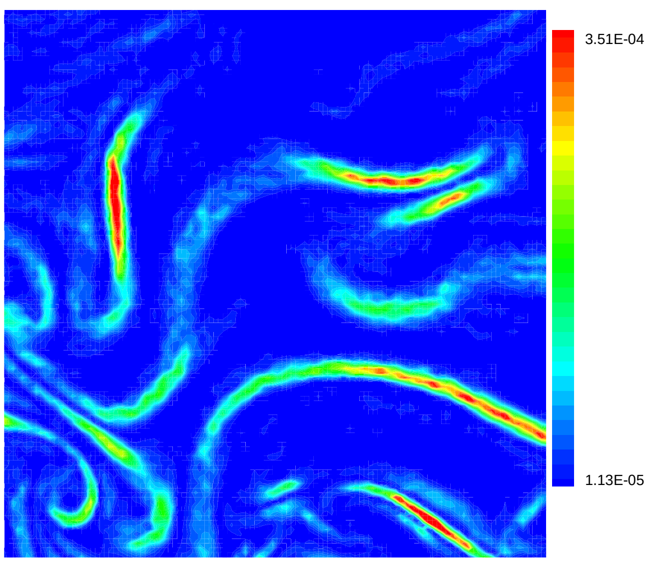
Results – Dissipation fields

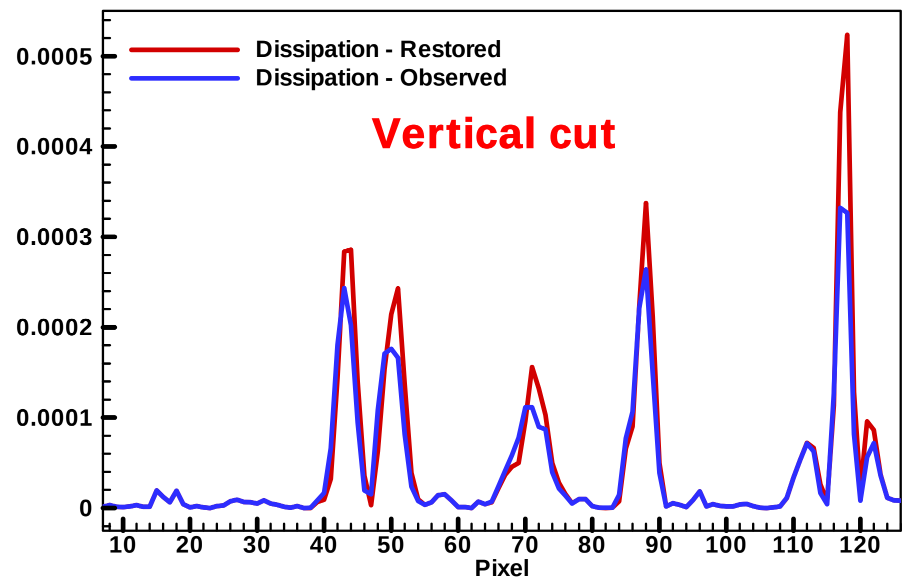
Observed
Dissipation field





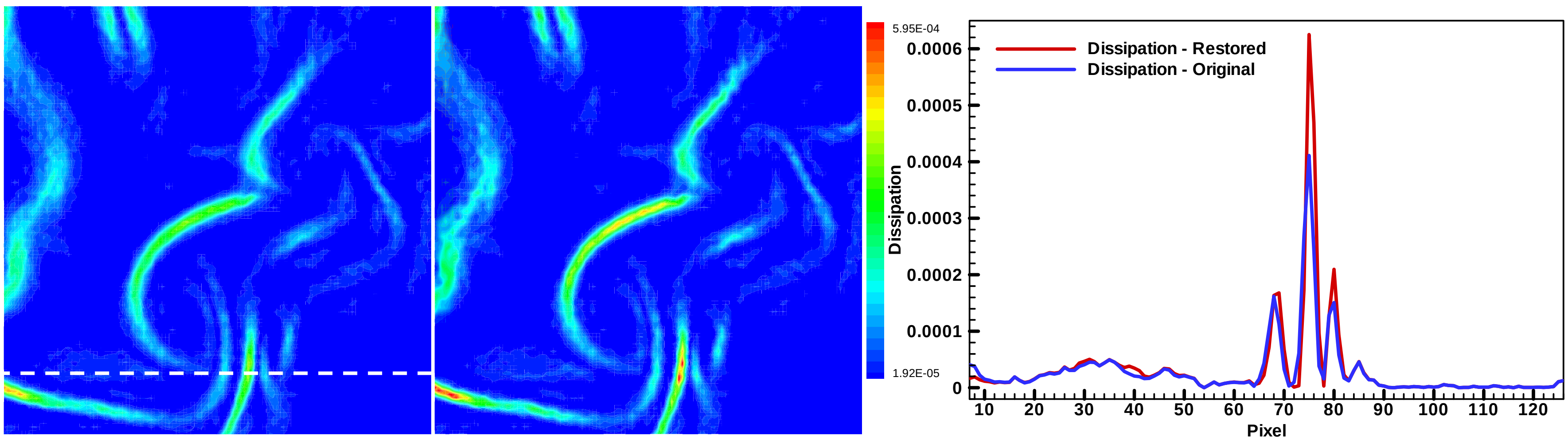
Restored
Dissipation field

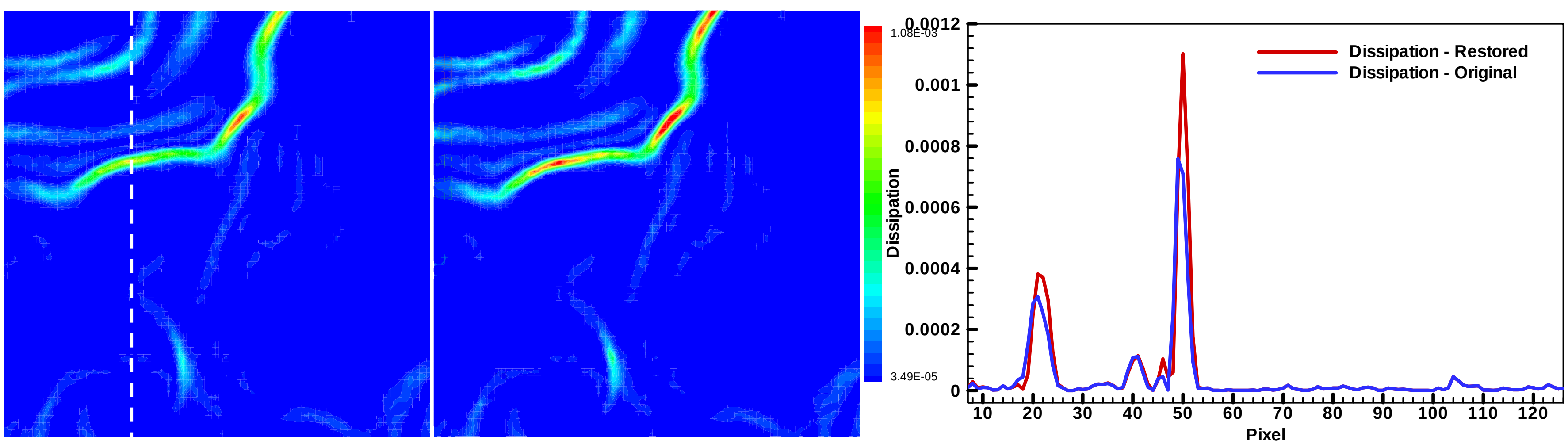




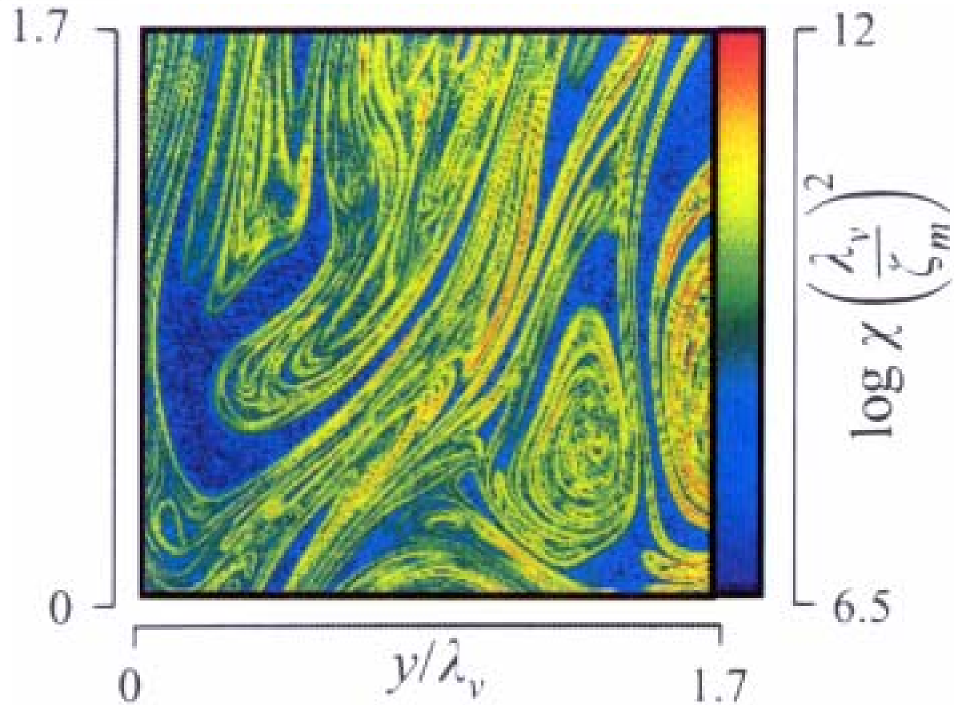
Results – Dissipation fields

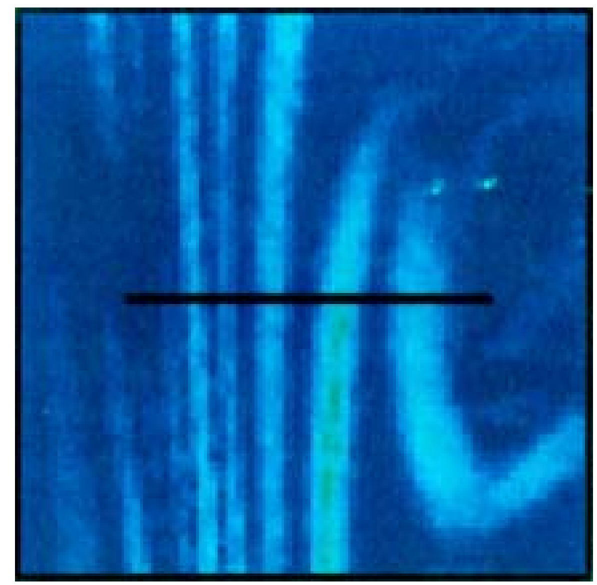
Observed | **Restored** | **Cross-cut profile**

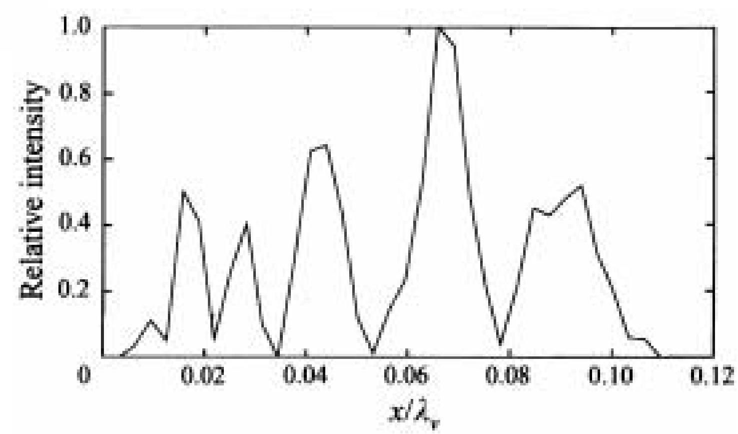




What is the impact?







Buch and Dahm (1996), Sc=2075, Re= 2100, Fig.13 and Fig.28(b)

Conclusions and Future Work

- R-L-EM algorithm works well for PLIF image restoration
  - PLIF image is shot-noise limited (Poisson noise);
  - Measured PSF by scanning knife edge technique;
- Preliminary PLIF image restoration results show:
  - Peak dissipation rate is affected most, especially for thin and clustered dissipation layers;
- Image restoration techniques can be used to
  - Improve resolution and dissipation measurement accuracy;
  - Especially for thin and/or clustered dissipation layers;
- Future work
  - Multi-Channel blind deconvolution ➔ better PSF
  - Multi-Level deconvolution (i.e. wavelet-Lucy) ➔ better noise handling;
  - Stopping rules ➔ utilizing 2D scalar structure information;