Locating Fluorescence Lifetimes Behind Turbid Layers Non-Invasively Using Sparse, Time-Resolved Inversion

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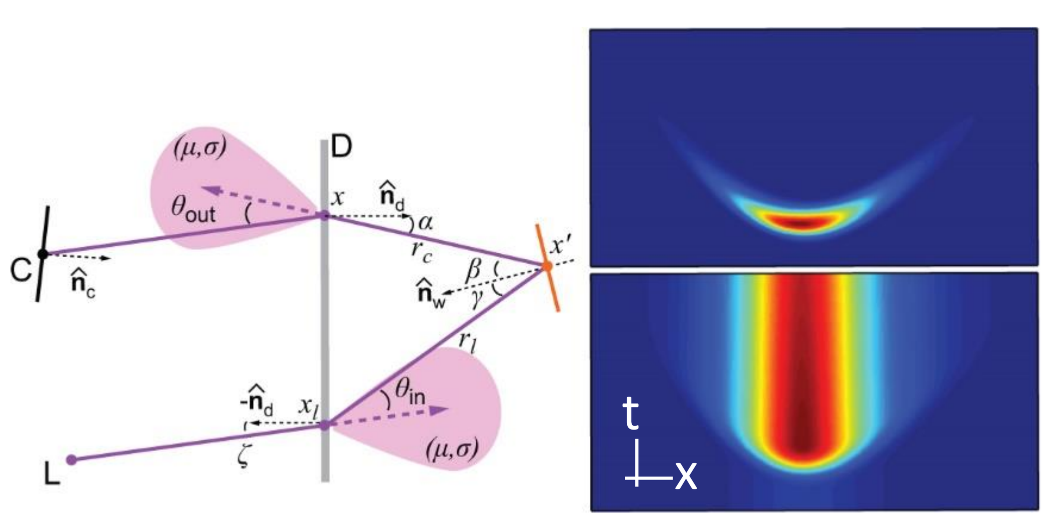
Abstract

We use time-resolved sensing and sparsity-based dictionary learning to recover the locations and lifetimes of fluorescent tags hidden behind a turbid layer. We experimentally demonstrate non-invasive target classification via fluorescence lifetimes.

Motivation

Fluorescence imaging through scattering is a pervasive problem, as scattering precludes direct image formation. Previous work [1] utilized time-resolved measurements with a streak camera, but relatively long fluorescence decay times blur the relevant temporal information. We impose a sparsity constraint to de-blur streak images to locate & classify fluorescent probes. The method is wavelength-invariant and can decouple probes with identical emission spectra.

Theory



- Illuminate point at x_l on diffuser.
- Streak camera records time resolved scattered light $I_l(x,t)$:

$$I_l(x,t) = I_0 \int g(x_l,x,x')R(x',t) *_t \delta[t - c^{-1}(r_l(x') + r_c(x'))]dx'$$

$$g(x_l,x,x') = \cos(\zeta(x_l))\, N(\theta_{in}(x')) \frac{\cos(\gamma(x'))\cos(\beta(x'))\cos(\alpha(x'))}{\pi^2 r_l^2(x') r_c^2(x')} N(\theta_{out}(x'))$$

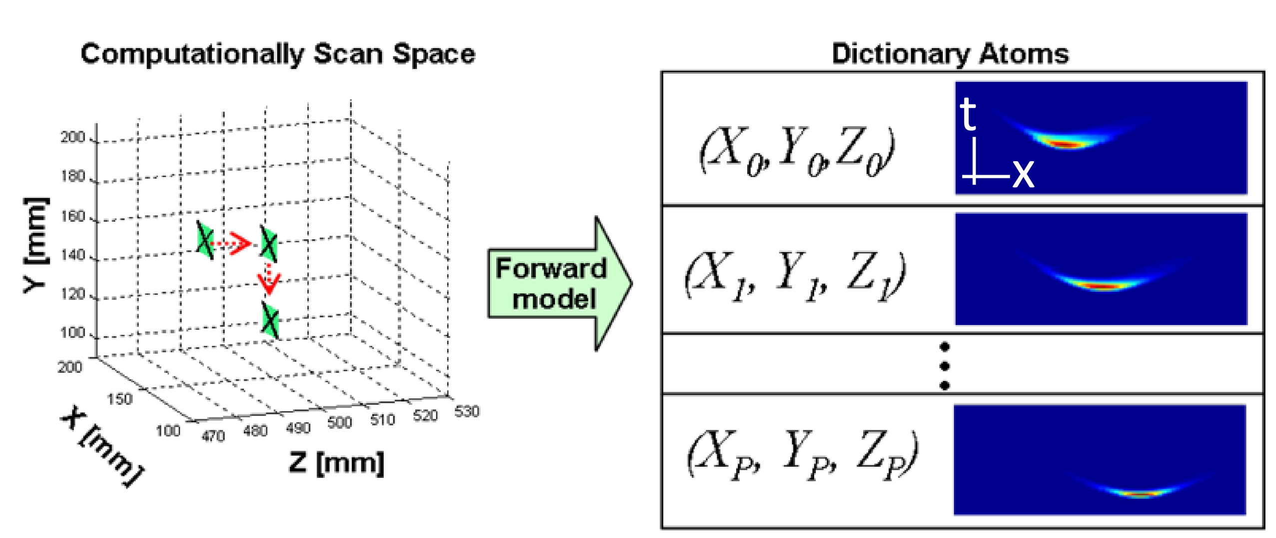
- Fluorescent markers provide space-time response $R(x',t)$:

$$R(x',t) = \underbrace{\rho(x')}_{\text{Efficiency}}\tau^{-1}(x')e^{-\frac{t}{\underbrace{\tau(x')}_{\text{Lifetime}}}}u(t)$$

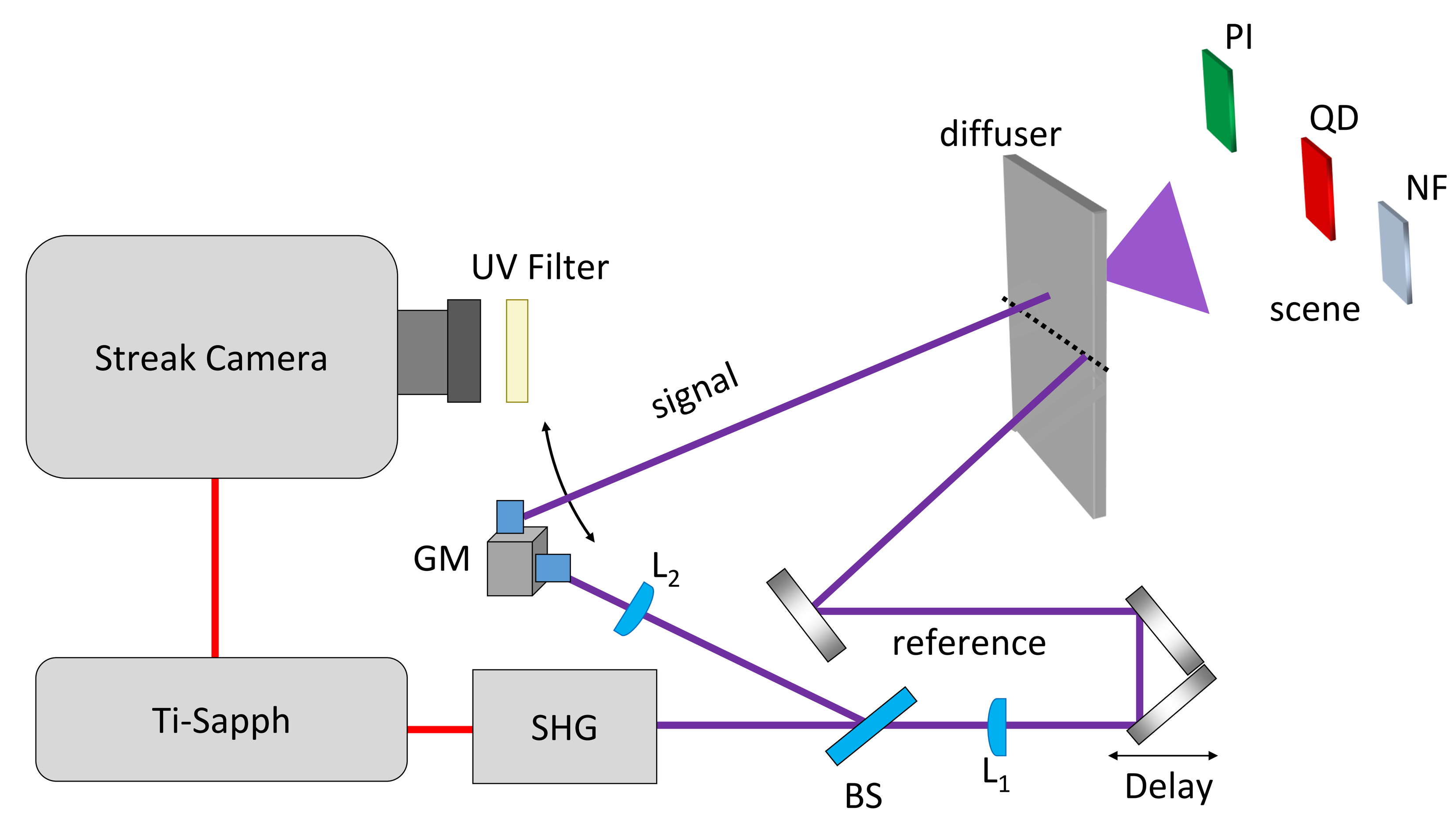
- Vectorize $I_l(x,t) \rightarrow \boldsymbol{I}_{meas}$, and high-pass filter.
- Create dictionary $\boldsymbol{D}$ containing streak images of non-fluorescent markers.
- Find locations via sparse optimization (orthogonal matching pursuit [2]):

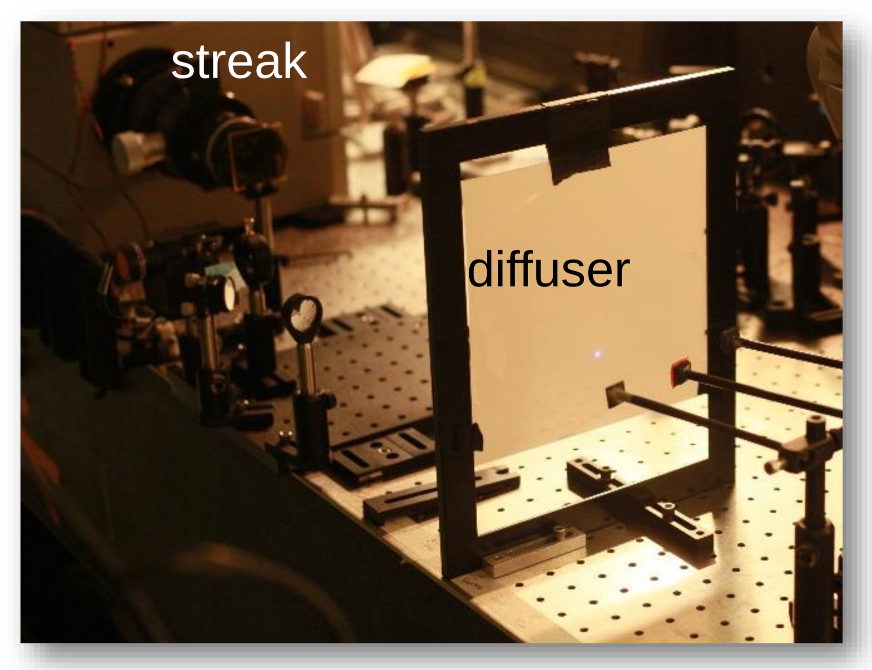
$$\text{minimize } \|\boldsymbol{\rho}\|_0 \text{ subject to} \|\boldsymbol{I}_{meas} - \boldsymbol{D\rho}\|_2 < \epsilon$$

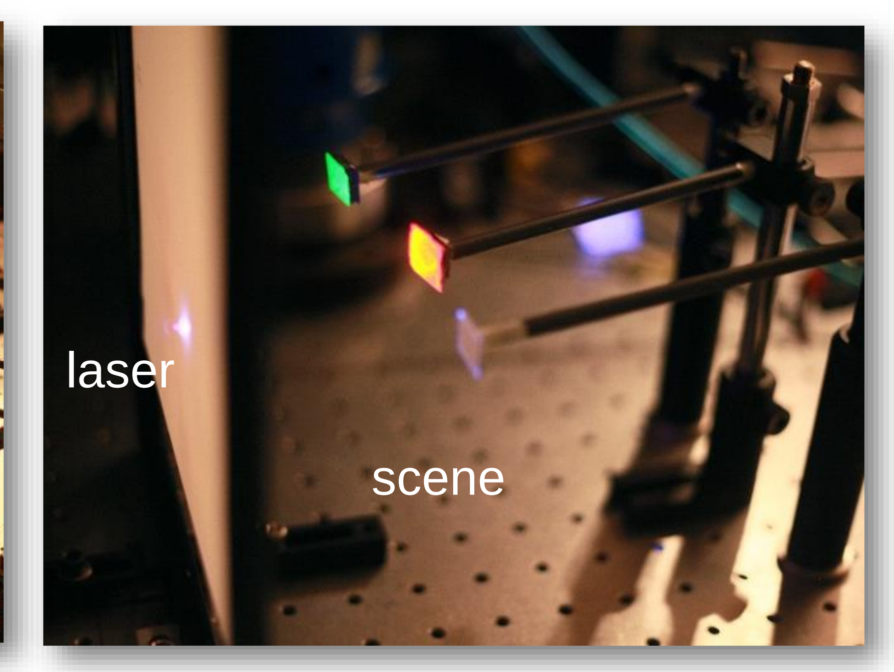
- Use fluorescence data to classify probes via lifetimes.



Experimental Setup

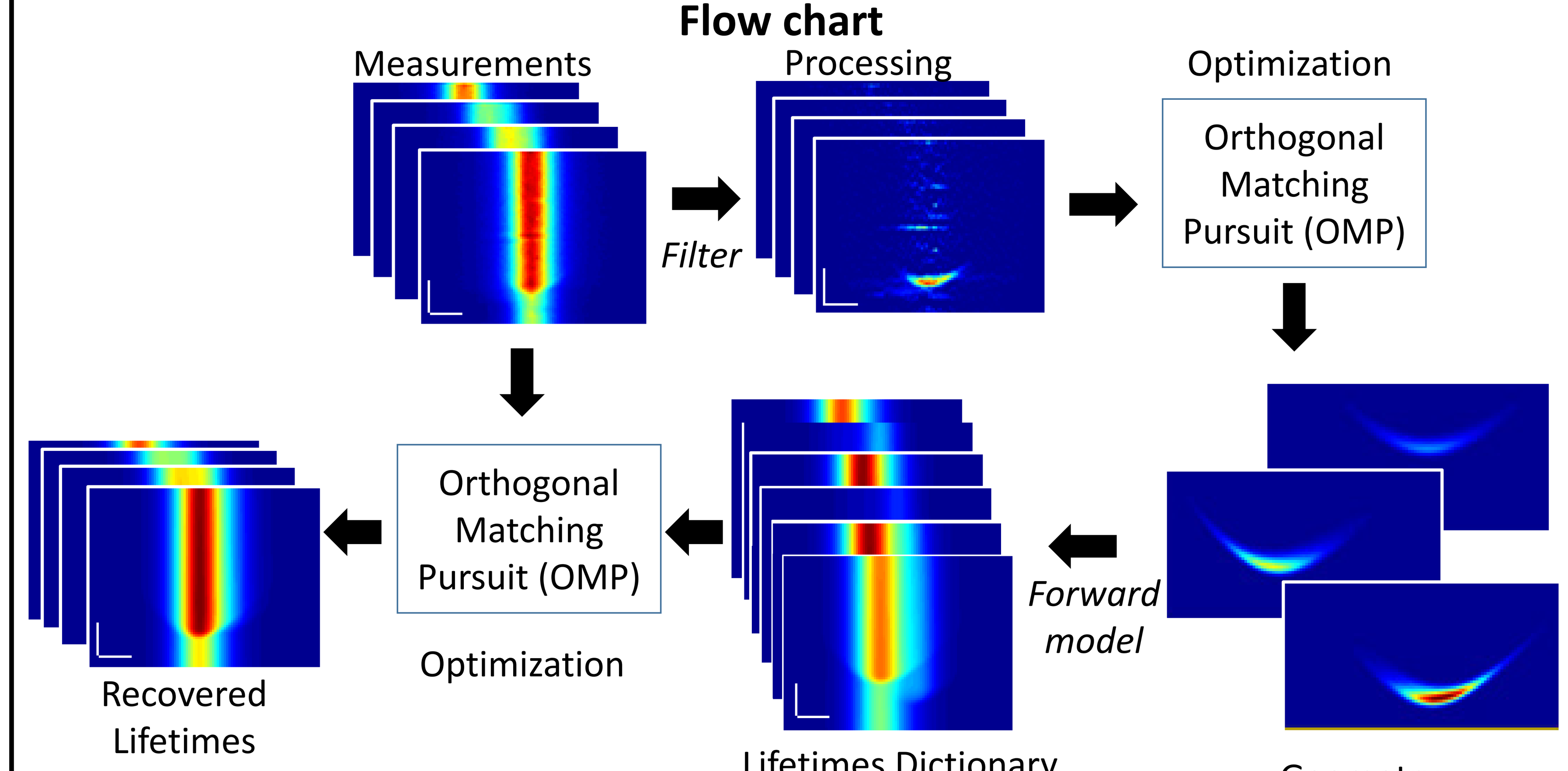




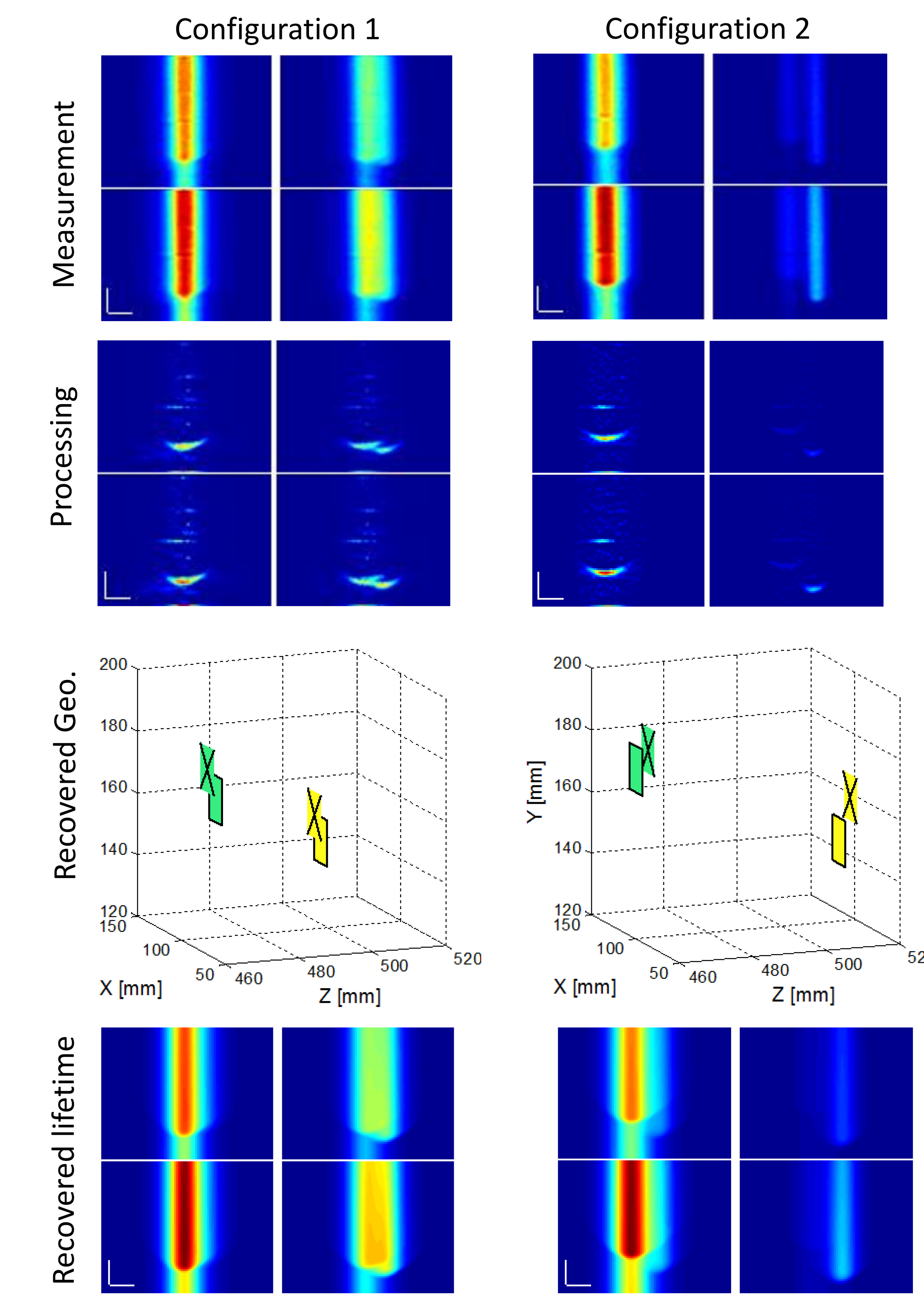


- System: streak camera synchronized to Ti:Sapph laser.
- Laser scatters from polycarbonate holographic diffuser.
- Record fluorescent streak image for 12 different incident laser positions.
- Scene comprises three patches of different lifetimes locations:
  - Non-fluorescing patch (NF, $\tau = 0$).
  - Quantum dot (QD, $\tau = 32ns$) [3].
  - Phosphorous ink (PI, $\tau = 5ns$).

Flow chart



Experimental Results



	Config. 1			Config. 2		
Patch	$\Delta X_\perp$ [mm]	ΔZ [mm]	$\Delta\tau$	$\Delta X_\perp$ [mm]	ΔZ [mm]	$\Delta\tau$
QD (yellow)	9.9	1.6	0	9.9	1.6	0
PI (green)	12.3	1.7	0	14.5	2.1	0

Conclusions

Using a sparse optimization with time-resolved measurements, we have demonstrated the location and classification of fluorescent markers through turbid layers. Our inversion, which is wavelength-invariant, can overcome the temporal blurring due to long lifetimes and shows promise for applications in remote sensing through turbulence and diffuse fluorescence tomography.

References

[1] A. Velten, et al., "Recovering three-dimensional shape around a corner using ultrafast time-of-flight imaging," Nat. Commun. 3, 745 (2012).
[2] D. L. Donoho, et al., "Stable recovery of sparse overcomplete representations in the presence of noise," IEEE Trans. Information Theory 52, 6-18 (2006).
[3] O. Chen, et al., "Compact high-quality CdSe–CdS core–shell nanocrystals with narrow emission linewidths and suppressed blinking," Nat. Mat. 12, 445-451 (2013).