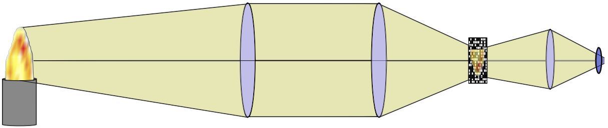
Compressive sensing for spatial and spectral flame diagnostics



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Introduction

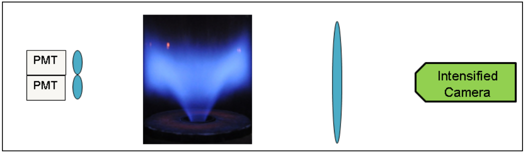
How can modern low light level imaging techniques be used for flame diagnostics?

- Flames Diagnostics
- Compressive sensing (review)
- Spatial imaging (chemiluminescence)
- Species and temperature measurement

Flame Diagnostics

Emissions, efficiency and safety are the primary concerns in combustion research.

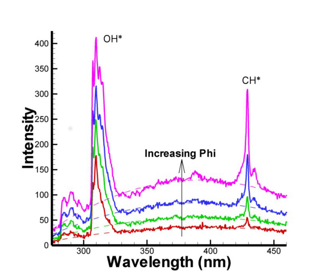
However, flame diagnostics often require low-intensity optical measurements.

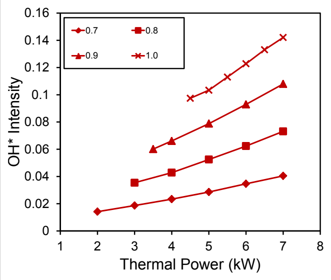


- Photomultiplier tubes used for single point data
- Intensified CCDs used for spatially resolved data

Flame Diagnostics

Hydrocarbons produce well known spectra with features associated with different species.



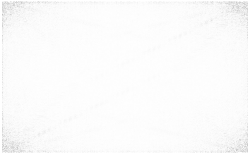


- Excited radical emission correlates to thermal power
- Used to detect spatial heat release rate

Compressive Sensing

Compressive sensing is an acquisition method that takes advantage of the sparsity of the signal.

Consider a seemingly complex signal:



But, in the fourier domain... (inverted for clarity)

Compressive Sensing

Compressive sensing utilizes the sparsity of an image $\mathbf{u}$ to find a solutions to a simple linear algebra problem:

$$\min_{\mathbf{u}} \sum |\mathbf{u}| \quad \text{s.t.} \quad \underset{(M\times 1)}{\mathbf{f}} = \underset{(M\times N)}{\mathcal{A}} \underset{(N\times 1)}{\mathbf{u}} \tag{1}$$

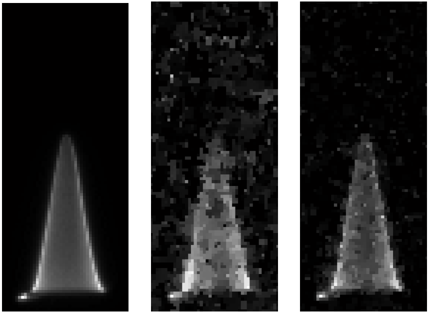
- $\mathbf{f}$ is a vector of M measurement results
- $\mathcal{A}$ is an incoherent $M \times N$ measurement matrix

For images, minimizing the total variation is better:

$$\min_{u} \sum_{i} ||D_i u|| \quad \text{s.t.} \quad \mathbf{f} = \mathcal{A}\mathbf{u} \tag{2}$$

Compressive Sensing

An incoherent sampling can reproduce the image **u** with $M << N$.



Original
N = 4664

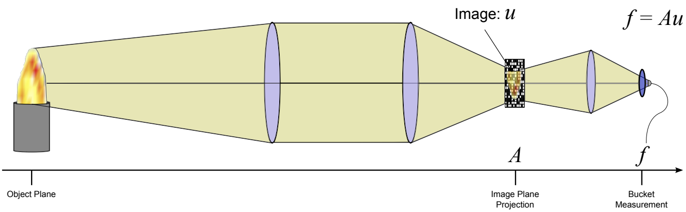
Reconstruction
M = 933
12% Error

Reconstruction
M = 2332
6.4% Error

(this ignores the fluctuations in the image)

Spatial imaging

We image a propane (C_3H_8) flame onto a DMD array:

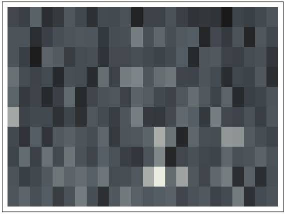


The collection optics include steering mirrors, lenses, spectral filtering and a multimode fiber with a 50 μm core.

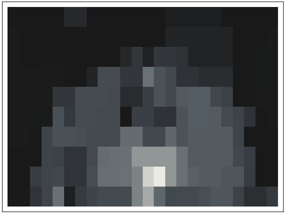
Spatial imaging

Flame size	1 cm $\times$ 1.5 cm
Image size	300 μm $\times$ 450 μm
Photon Flux (434 nm)	6,000 counts/s
Dimensions N	24 $\times$ 28
Measurements M (max)	672
Time per measurement	1 s

Raster Scan

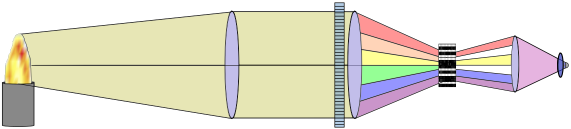


100 % Measurement



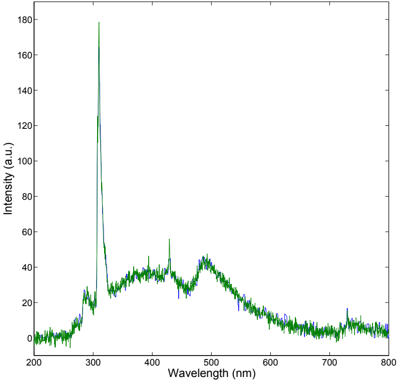
Species and temperature measurement

To measure the spectrum of the flame with limited signal, we can again use CS.



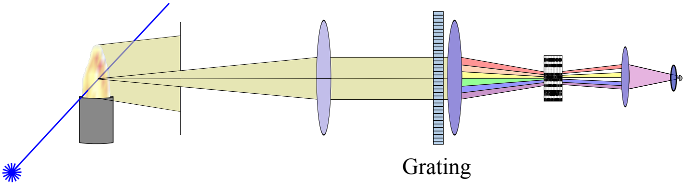
Species and temperature measurement

Bin Width (spectral)	0.361 nm
Dimensions N	2047
Measurements M	409 (20%)
Relative Error	12%



Species and temperature measurement

For Raman scattering, a "weak" CW beam can be used due to the increased sensitivity.



Results

For dim flames, compressive sensing can:

(a) improve SNR or reduce integration (cf. raster scan);

(b) reduce cost of imaging systems (cf. intensified CCDs);

(c) allow for Raman spectroscopy with a CW pump;

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