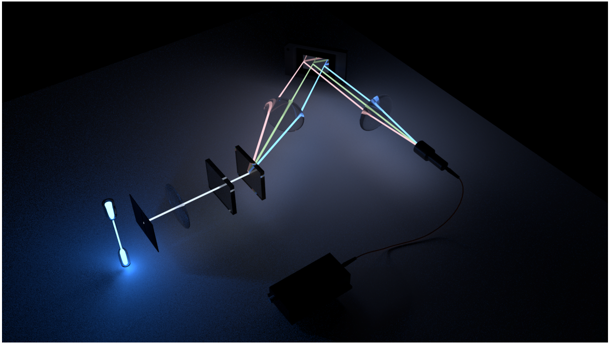
Fast spectrophotometry with compressive sensing



David J. Starling Gregory Howland
Joseph Ranalli Ian Storer

Penn State University - Hazleton Campus

March 6, 2015

Introduction

What are the experimental advantages of compressive sensing for spectroscopy?

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What are the experimental advantages of compressive sensing for spectroscopy?

- Standard Spectroscopy
- Compressive Sensing
- Absorption Spectroscopy
- Emission Spectroscopy

Spectroscopy

A good spectrograph balances the need for high photometric precision, high spectral resolution, high speed and low cost.

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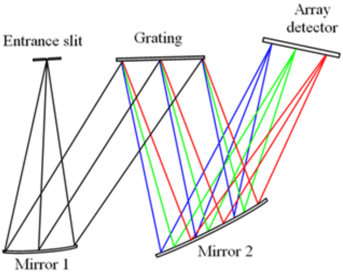
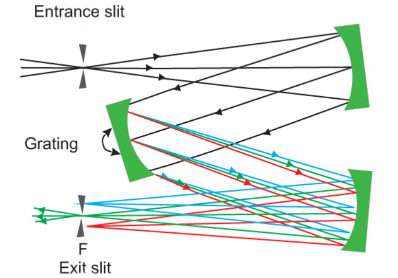
The Czerny-Turner spectrograph is the standard design for many applications.



(image source: bwtek.com)

Spectroscopy

The CCD can be replaced with a scanning slit:



(image source: zeiss.com)

Spectroscopy

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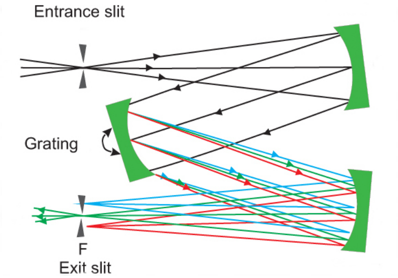

(image source: zeiss.com)

But this adds to acquisition time.

Spectroscopy

Can we get the benefits of a CCD
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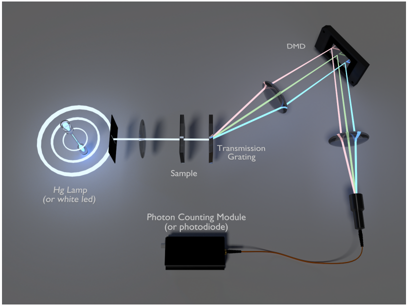

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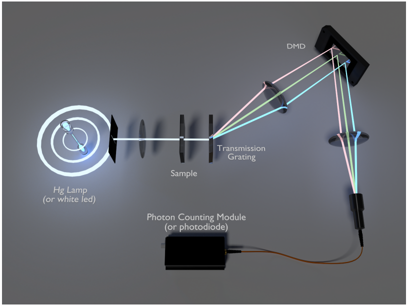

The use of compressive sensing makes this possible.

Compressive Sensing

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

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Consider a seemingly complex signal:

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

Compressive Sensing

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

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

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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 $\mathbf{u}$ with $M << N$.

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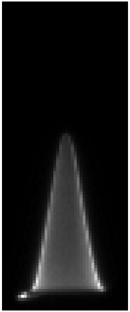
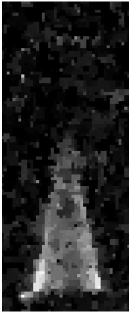
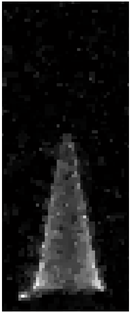


Original
N = 4664



Reconstruction
M = 933
12% Error

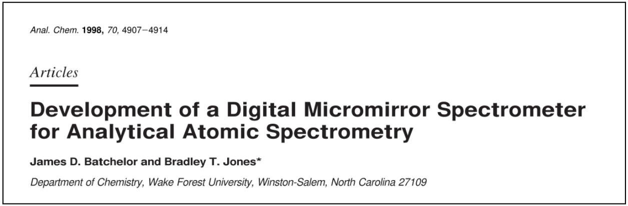


Reconstruction
M = 2332
6.4% Error

(this ignores the fluctuations in the image)

Compressive Sensing

Previous work combining a DMD/SLM and spectroscopy:



Anal. Chem. **1998,** *70,* 4907−4914

Articles

Development of a Digital Micromirror Spectrometer for Analytical Atomic Spectrometry

James D. Batchelor and Bradley T. Jones*

Department of Chemistry, Wake Forest University, Winston-Salem, North Carolina 27109

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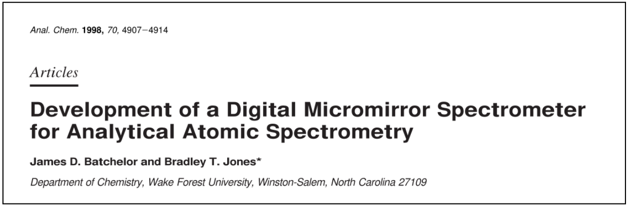

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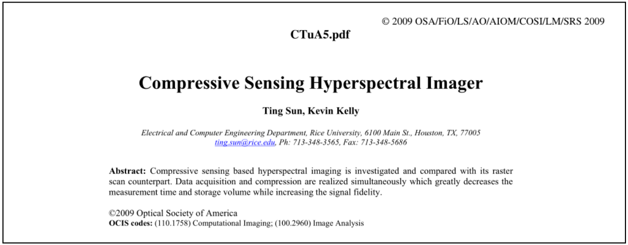

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Compressive Sensing Hyperspectral Imager

Ting Sun, Kevin Kelly

Electrical and Computer Engineering Department, Rice University, 6100 Main St., Houston, TX, 77005
ting.sun@rice.edu, Ph: 713-348-3565, Fax: 713-348-5686

Abstract: Compressive sensing based hyperspectral imaging is investigated and compared with its raster scan counterpart. Data acquisition and compression are realized simultaneously which greatly decreases the measurement time and storage volume while increasing the signal fidelity.

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OCIS codes: (110.1758) Computational Imaging; (100.2960) Image Analysis

Compressive Sensing

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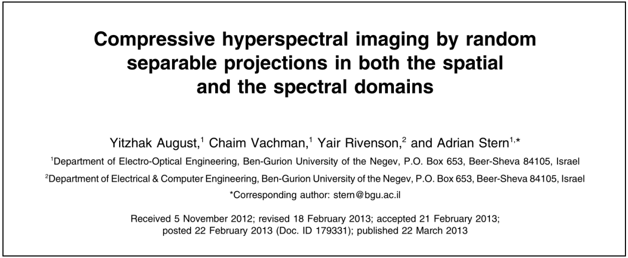

Compressive hyperspectral imaging by random separable projections in both the spatial and the spectral domains

Yitzhak August,[1] Chaim Vachman,[1] Yair Rivenson,[2] and Adrian Stern[1,*]

[1]Department of Electro-Optical Engineering, Ben-Gurion University of the Negev, P.O. Box 653, Beer-Sheva 84105, Israel

[2]Department of Electrical & Computer Engineering, Ben-Gurion University of the Negev, P.O. Box 653, Beer-Sheva 84105, Israel

*Corresponding author: stern@bgu.ac.il

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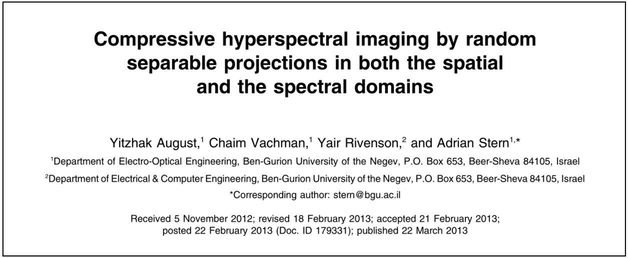

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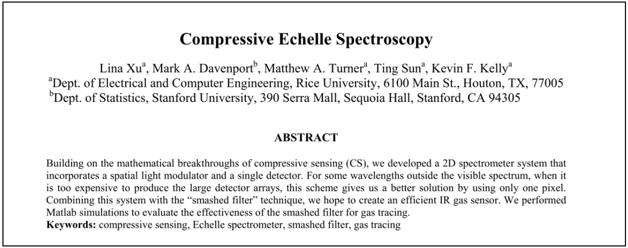


Compressive Echelle Spectroscopy

Lina Xu[a], Mark A. Davenport[b], Matthew A. Turner[a], Ting Sun[a], Kevin F. Kelly[a]
[a]Dept. of Electrical and Computer Engineering, Rice University, 6100 Main St., Houton, TX, 77005
[b]Dept. of Statistics, Stanford University, 390 Serra Mall, Sequoia Hall, Stanford, CA 94305

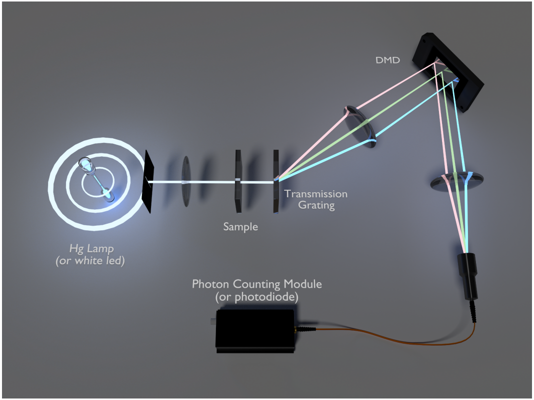
ABSTRACT

Building on the mathematical breakthroughs of compressive sensing (CS), we developed a 2D spectrometer system that incorporates a spatial light modulator and a single detector. For some wavelengths outside the visible spectrum, when it is too expensive to produce the large detector arrays, this scheme gives us a better solution by using only one pixel. Combining this system with the "smashed filter" technique, we hope to create an efficient IR gas sensor. We performed Matlab simulations to evaluate the effectiveness of the smashed filter for gas tracing.

Keywords: compressive sensing, Echelle spectrometer, smashed filter, gas tracing

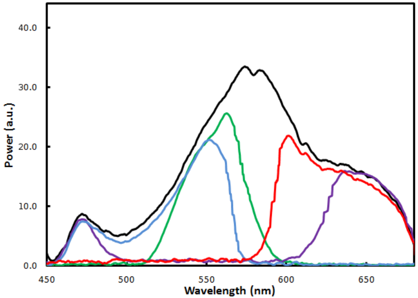
Absorption Spectroscopy

We start with a broadband LED as the light source, and a small DMD for the random projections.



We tested the absorption of a variety of broadband interference filters.

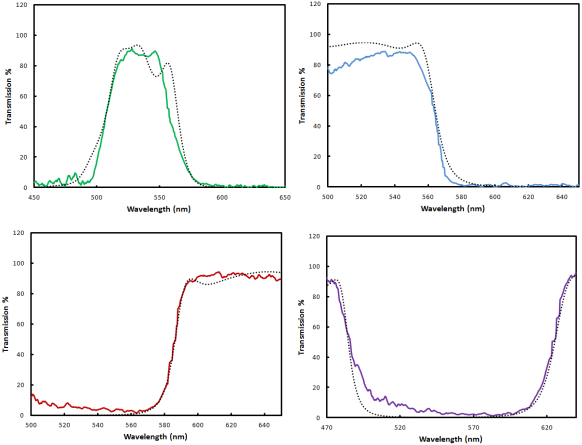
Absorption Spectroscopy



LED bandwidth	400 - 800 nm
Max LED Power	500 mW
Collected LED Power	121 nW
Transmission Grating	600 lines/mm
DMD Resolution	608 x 684 (10.8 μm)
Si-Photodiode Detector	13 mm^2
Time per measurement	0.1 s
Total integration time	60.8 s

Absorption Spectroscopy

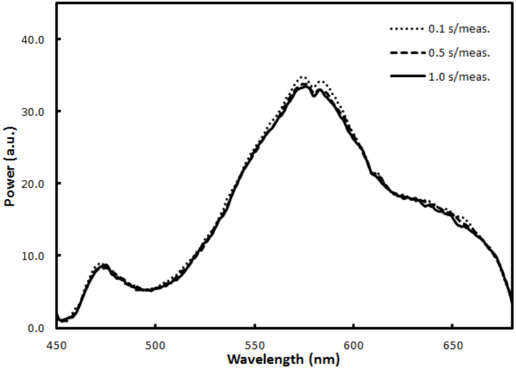
Normalizing by LED intensity:



Dashed lines: product specification

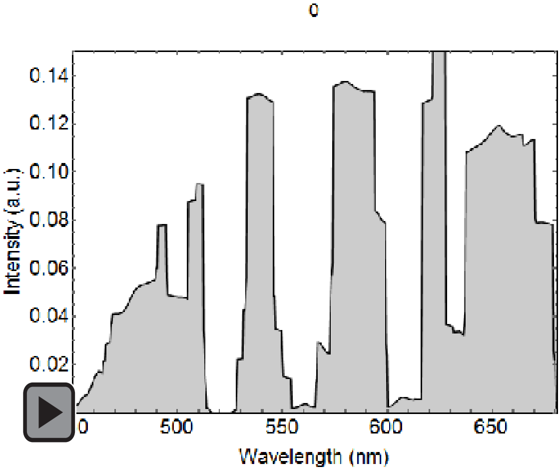
Absorption Spectroscopy

How do these figures depend on integration time?



Absorption Spectroscopy

How do these figures depend on the number of measurements?



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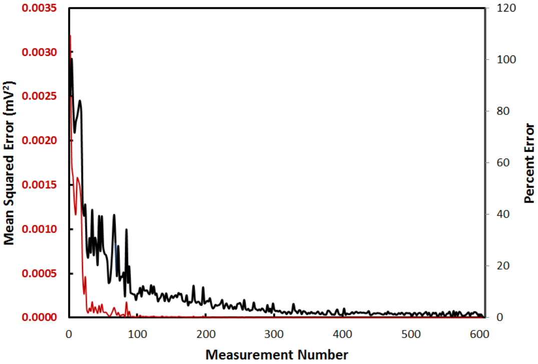
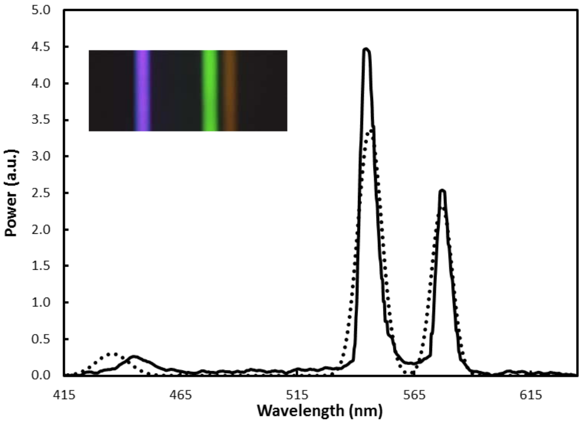


We only need 17% (100 measurements) at 0.1 s each to reproduce the spectrum.

Emission Spectroscopy

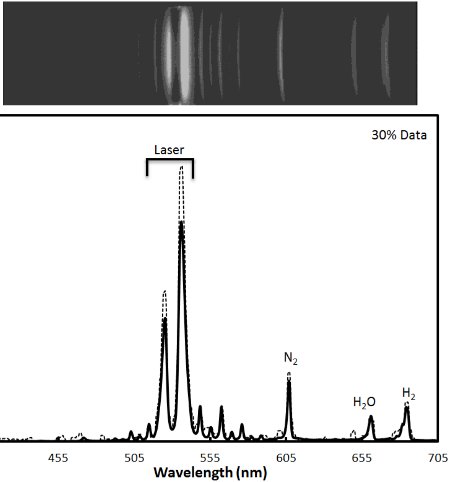
Using a standard low pressure mercury lamp:



The dashed line is a linear fit to calibrate wavelength.

Emission Spectroscopy

We can apply these results to Raman spectroscopy



Hydrogen flame: 512 px, reconstructed from 150 images

Conclusion

CS spectroscopy:

(a) 0.38 nm resolution over 230 nm

(b) only 10 s required

(c) data on the fly (watch spectrum emerge)

(d) very low cost ($<$\$1000)

(e) can be used for very dim objects (120 nW)

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Contact Information:

- David J. Starling
- email: `starling@psu.edu`
- website: `www.david-starling.com`