Fast spectrophotometry with compressive sensing

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What are the experimental advantages of compressive sensing for spectroscopy?
Introduction

What are the experimental advantages of compressive sensing for spectroscopy?

- Standard Spectroscopy
- Compressive Sensing
- Absorption Spectroscopy
- Emission 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)
The CCD can be replaced with a scanning slit:
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But this adds to acquisition time.
Can we get the benefits of a CCD at the cost of a scanning slit?
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Can we get the benefits of a CCD at the cost of a scanning slit?

The use of compressive sensing makes this possible.
Compressive sensing is an acquisition method that takes advantage of the sparsity of the signal.
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Consider a seemingly complex signal:
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 utilizes the sparsity of an image $u$ to find a solution to a simple linear algebra problem:

$$\min_u \sum |u| \quad \text{s.t.} \quad f(M \times 1) = A(M \times N)u$$

For images, minimizing the total variation is better:

$$\min_u \sum_i ||D_i u|| \quad \text{s.t.} \quad f = A u$$
Compressive sensing utilizes the sparsity of an image $\mathbf{u}$ to find a solution to a simple linear algebra problem:

$$\min_{\mathbf{u}} \sum |\mathbf{u}| \quad \text{s.t.} \quad \mathbf{f} = \mathbf{A} \mathbf{u} \quad (1)$$

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

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

$$
\min_{\mathbf{u}} \sum \mathbf{u} \quad \text{s.t.} \quad \mathbf{f} = \mathbf{A} \mathbf{u} \quad (1)
$$

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For images, minimizing the total variation is better:

$$
\min_{\mathbf{u}} \sum_{i}||D_{i}u|| \quad \text{s.t.} \quad \mathbf{f} = \mathbf{A} \mathbf{u} \quad (2)
$$
An incoherent sampling can reproduce the image $\mathbf{u}$ with $M << N$. 
An incoherent sampling can reproduce the image $\mathbf{u}$ with $M << N$.

Original
$N = 4664$

Reconstruction
$M = 933$
12% Error

Reconstruction
$M = 2332$
6.4% Error

(this ignores the fluctuations in the image)
Previous work combining a DMD/SLM and spectroscopy:


**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
Previous work combining a DMD/SLM and spectroscopy:

*Anal. Chem. 1998, 70, 4907–4914*

**Articles**

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**Compressive Sensing Hyperspectral Imager**

Ting Sun, Kevin Kelly

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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

Previous work combining a DMD/SLM and spectroscopy:

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

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Compressive Echelle Spectroscopy

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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

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED bandwidth</td>
<td>400 - 800 nm</td>
</tr>
<tr>
<td>Max LED Power</td>
<td>500 mW</td>
</tr>
<tr>
<td>Collected LED Power</td>
<td>121 nW</td>
</tr>
<tr>
<td>Transmission Grating</td>
<td>600 lines/mm</td>
</tr>
<tr>
<td>DMD Resolution</td>
<td>608 x 684 (10.8 µm)</td>
</tr>
<tr>
<td>Si-Photodiode Detector</td>
<td>13 mm²</td>
</tr>
<tr>
<td>Time per measurement</td>
<td>0.1 s</td>
</tr>
<tr>
<td>Total integration time</td>
<td>60.8 s</td>
</tr>
</tbody>
</table>
Absorption Spectroscopy

Normalizing by LED intensity:

Dashed lines: product specification
How do these figures depend on integration time?
How do these figures depend on the number of measurements?
How do these figures depend on the number of measurements?

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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