Compressive Sensing for Spatial and Spectral Flame Diagnostics

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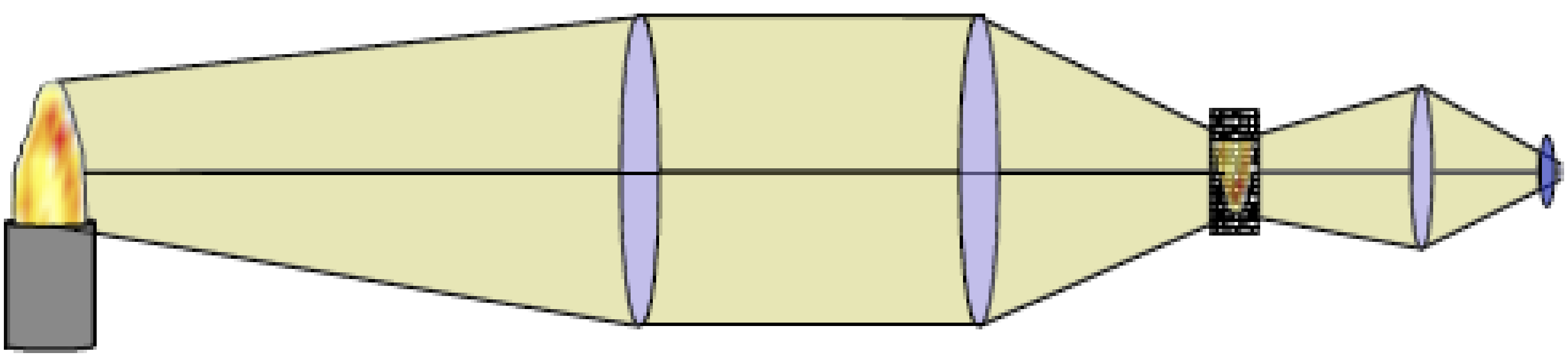


Abstract

Flame imaging is a method of recording spatial information on the combustion of a given material. This kind of imaging is very useful for gathering information on a flame's intensity, combustion efficiency, emission spectra, and more. Data compiled from flame research has applications in optics, petroleum research and alternative energy. Most of the visible light from a flame is emitted from hot soot, whereas the light from the chemical process of combustion is much dimmer. As a result, many researchers encounter an obstacle when working in this field. Currently, intensified charge-coupled devices (ICCDs) are the primary instrument used to capture and study dim flame images. However, these ICCDs are prohibitively expensive, and many smaller research institutions simply can not afford one. In our experiment, we test the viability of a less expensive alternative to ICCDs, known as compressive sensing [1]. Our experiment uses a pair of lenses to focus the image of a flame onto an array of switchable micromirrors, called a digital micromirror device. These mirrors are laid out in much the same way that pixels are laid out in a camera sensor or ICCD. The photons from the image reflects off these mirrors into another pair of lenses that focuses the light down into an optical fiber connected to a single photon detector. Using a customized Python program, we command a random pattern of mirrors to switch "on" and reflect the flame light into the fiber. On average, half of the mirrors on the array are "on", while the other half are "off" and dump the photons that hit them. We record the number of collected photons with a single photon detector from a predetermined number of patterns. We then reconstruct the original image using an algorithm developed at Rice University known as TVAL3 [2]. This algorithm converts the photon counts and patterns into what is essentially a large under-determined matrix equation, which it then solves subject to a specific constraint. Since most objects in nature do not have sharp contrasts, the matrix equation is solved for a minimized contrast gradient. The main benefit of compressive sensing over ICCD imaging is its lower cost, for which resolution is sacrificed. Our experiment was successful and performed much better than another common type of imaging, a raster scan. While the raster scan was not able to discern the image signal from shot noise, our compressive sensing scan had a high enough signal to noise ratio to provide a discernible image of the light produced by the excitation of the C-H bond in propane gas.

The Setup

We use an imaging setup that places the flame a distance away from a lens (1) equal to the lens' focal length.

This brings the diverging light rays to parallel and cuts back on light loss due to increased distance from the flame.

A second lens (2) takes the parallel light rays and images the flame onto a digital micromirror device (3).

If a given pixel is "on" the photons hitting it reflect into a lens (4) that brings the diverging image light back to parallel.

Collimated light reflects off a mirror (5) and is focused by a lens (6) into a fiber optic cable (7). A narrowband blue filter is fitted over the fiber to pass 434 nm light.

Photons travel down the fiber to be detected by a single photon counting module (not shown).

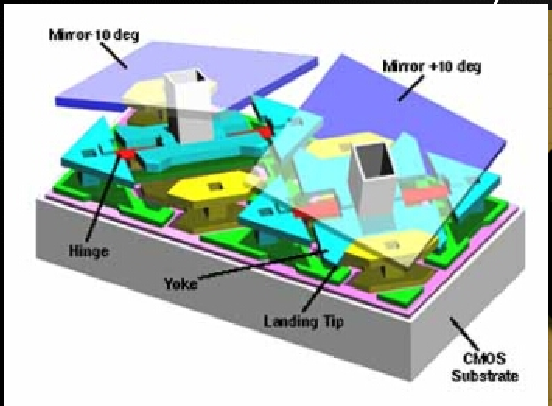
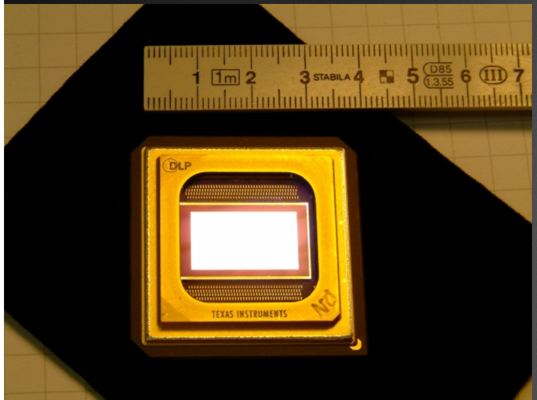
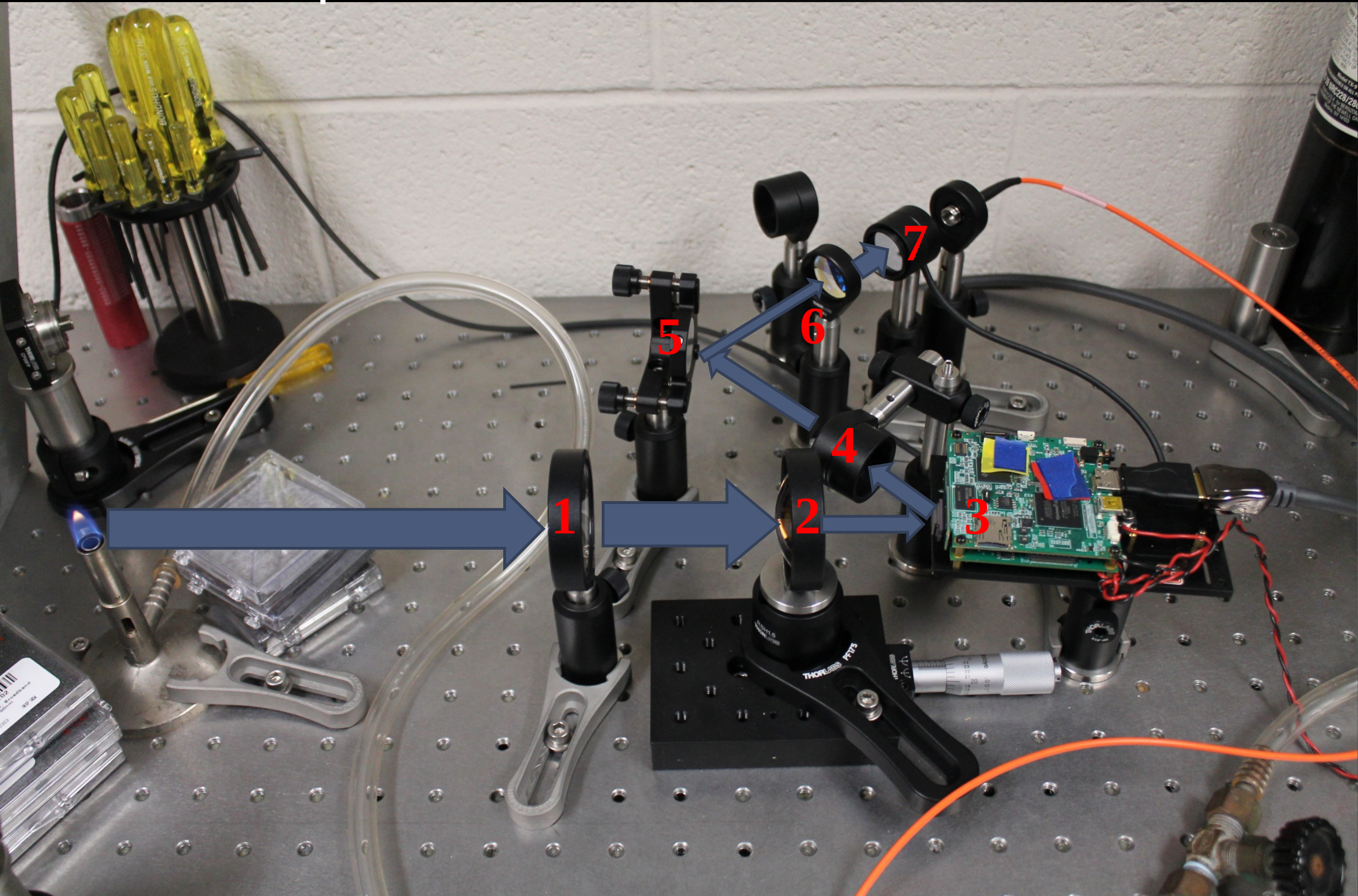


Image Credit: opticalsciences.com



DMD close up

The Setup



Testing Procedure

We used a propane gas cylinder to supply fuel to a small Bunsen burner with an adjustable air flow valve.

The DMD is wired into the computer as a second monitor.

A custom written Python program is executed through Command Prompt.

We specify how long to take each data point and how many data points to take.

physicslab.py

```
########################################
###### Open the DMD Window #############
########################################

########################################
# Important Note!!!
#   2 pixels in the x direction is twice as far (10.8 um) than 2 pixels in the y direction (5.4 um)
#   For this reason, a "square" big pixel must be something like 50x100 smaller pixels
########################################

if testtype in ['r', '1', '1c', 'c', 'b']:
    xstart = 0*1280 #Moving it over 1280 puts the display on the second monitor of the lab computer
    ystart = 0
    Rx = 608 #Resolution
    Ry = 684
    start = (0,0) # Where to start the scan (0 is first pixel)
    end = (Rx,Ry) # Where to end the scan
    pixelnum = 16   # Number of big pixels in either direction
    pixelsize = int((end[0]-start[0])/pixelnum) # How many little pixels in the big one, rounded down (note: y w
    ypixelnum = min(pixelnum,int((end[1]-start[1])/(2*pixelsize))) #The box may not be "square" if there's not e

    zerosarray = [[0 for x in range(Ry)] for x in range(Rx)]

    filename = str(raw_input('Filename?\n'))        # This has the (x,y) pixel location and the measurement
    pygame.init()
    os.environ['SDL_VIDEO_WINDOW_POS'] = "%d,%d" % (xstart,ystart)
    main_surface = pygame.display.set_mode((Rx,Ry),NOFRAME)

    count(2) # Just to get the FPGA going and so that I can leave the room if needed


########################################
###### 1D Raster #####################
########################################

if testtype == '1':
    filenamebeamfinder = filename + '_1DR.csv'
    f = open(filenamebeamfinder, 'w')
    f.write("coincidences, accidentals, singles1, singles2, efficiency, total counts 1, total counts 2, integrat

    for xscan in range(0,pixelnum):
        print str(round((xscan/float(pixelnum))*100,1)) + "% - Time remaining: " + str(round(2*(pixelnum-xscan)*
        randomarray = [[255 for x in range(Ry)] for x in range(Rx)]
```

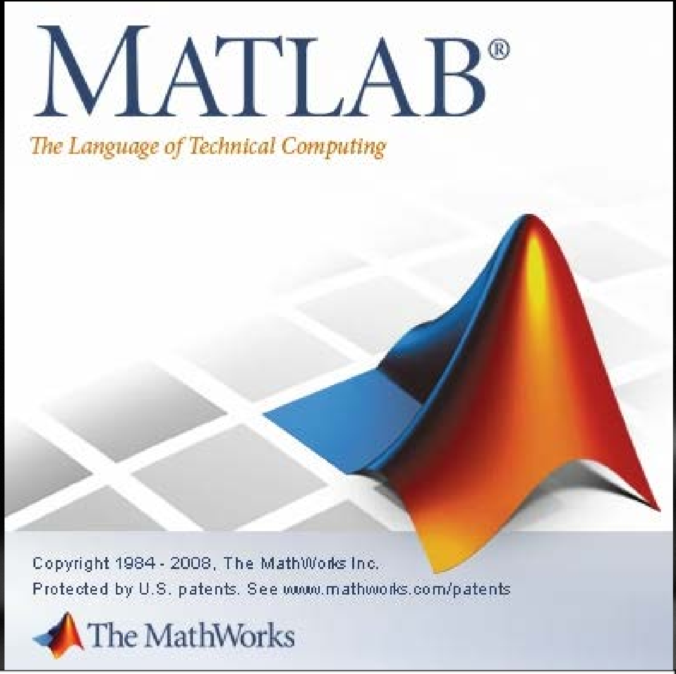
Code credit: Dr. David Starling and Blake Burger

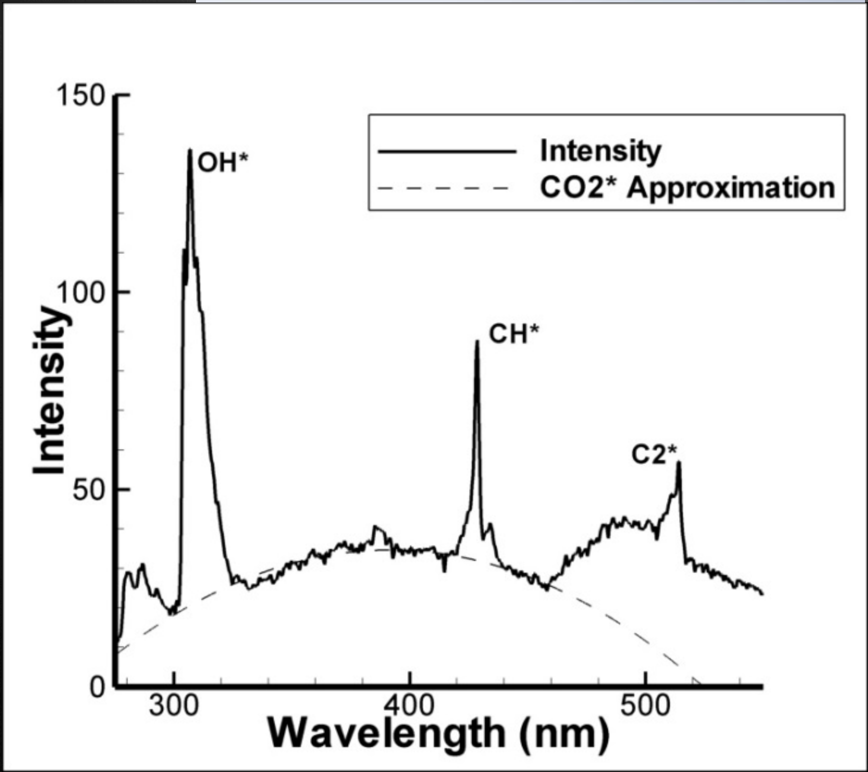
Testing Procedure

After data collection, we use an algorithm written in Matlab by a team at Rice University [2] to reconstruct the original image.

The same flame is then tested using the standard raster scan technique.

The raster scan turns on one pixel (or group of pixels) at a time and records light gathered.





Right: Our experiment focused on recording the light produced by the CH* excitation, emitting photons of 434 nm (blue- violet)

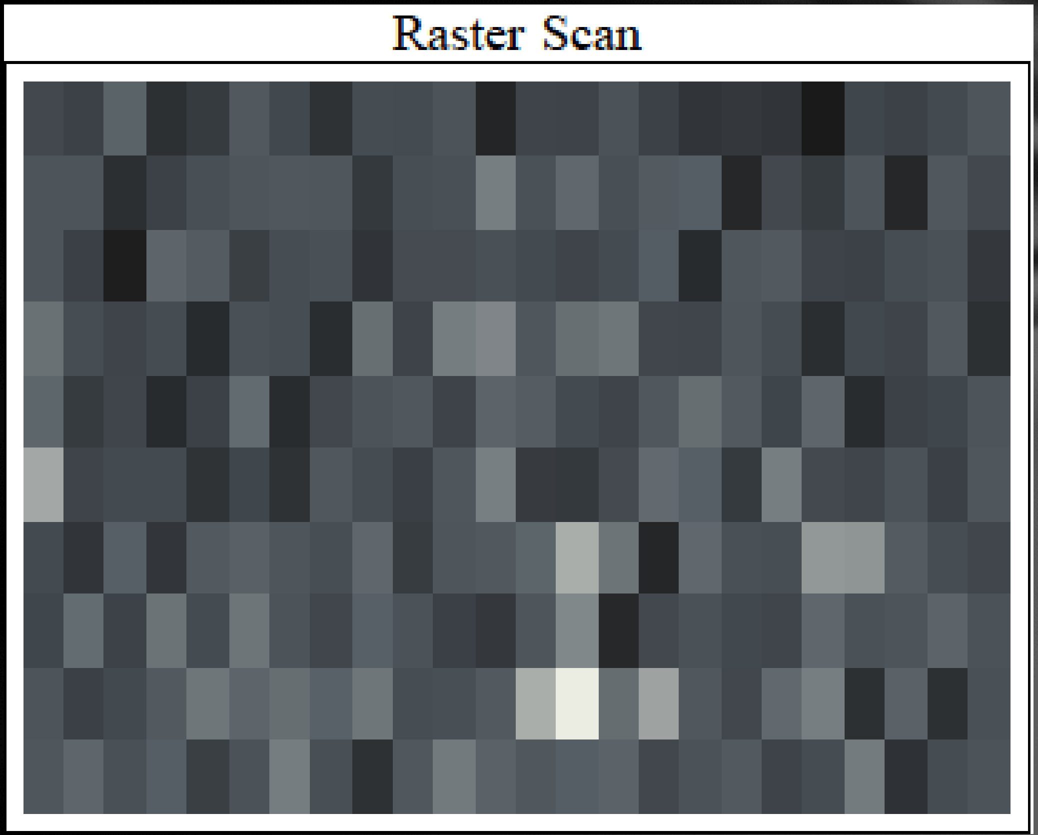
Raster Scan

Image is full of "snow".

No image visible.

This tells us that the signal to noise ratio was too low.

The flame was too dim to use this imaging technique.



The raster scan turns on one pixel at a time and only records light from the CH* radical.

Compressive Sensing

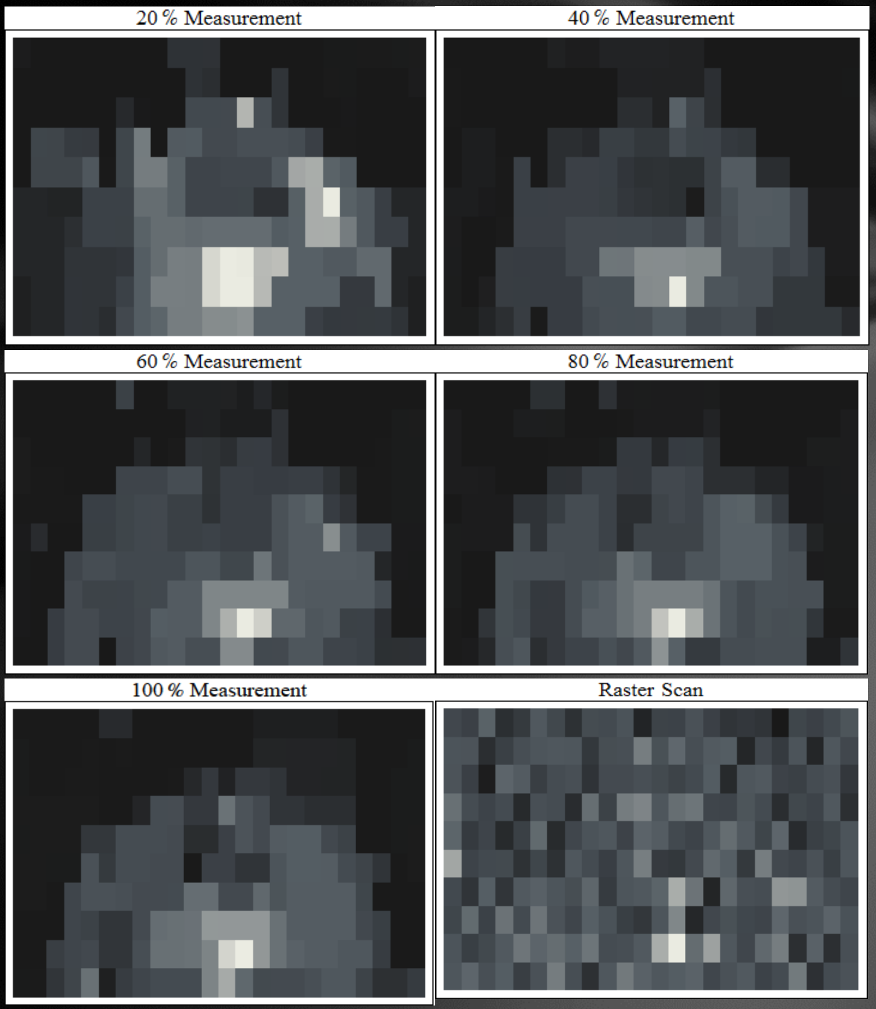
Clear, discernible image

Low resolution, but good enough to gather valuable information on flame emission, spatial shape, etc.

The raster scan failed because it only turns on single mirrors as a time, rejecting most light.

Compressive Sensing gathers on average half the light hitting the DMD, resulting in a better signal to noise ratio.

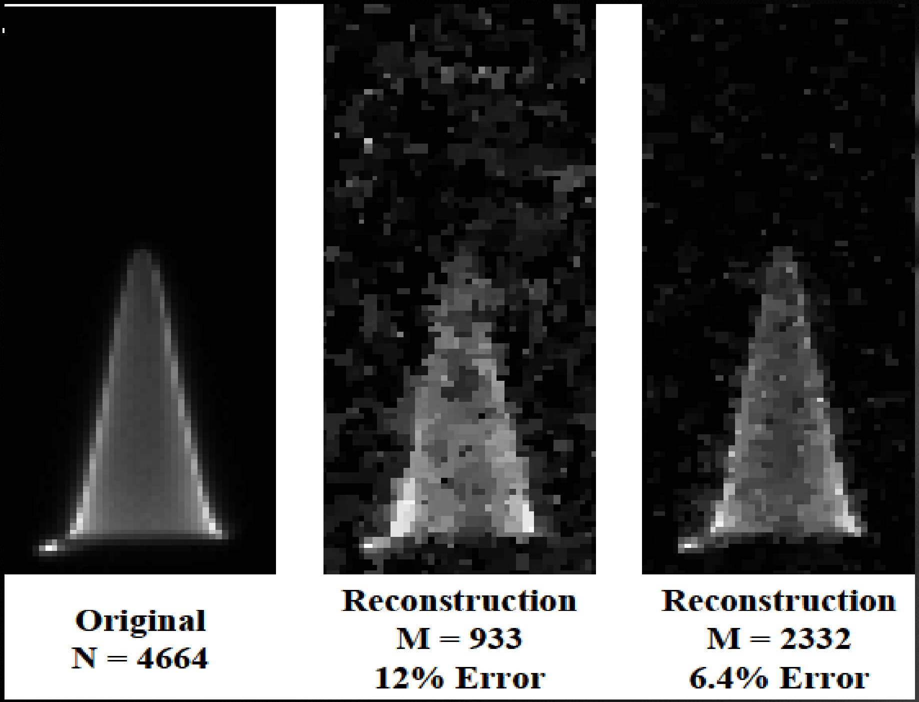
Shown on the right is a raster scan compared against compressive scans of 20%, 40%, 60%, 80% and 100% sampling proportions.



Conclusion

ICCDs are too expensive for smaller research labs.

Compressive sensing can be used to undersample significantly and still retain image integrity.



Compressive sensing was shown to be a viable alternative for applications that do not require the resolution of ICCDs.