The Multivariate Optical Element: A Promising Technology for Next Generation Hyperspectral Imaging Systems

Prepared for IDRC 2018
August 2, 2018

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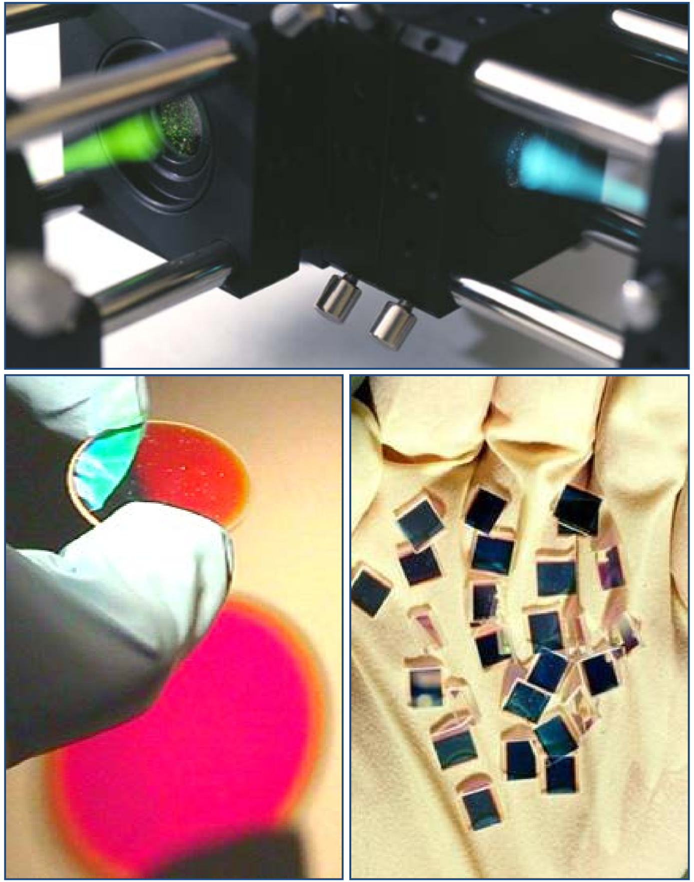
Overview

- CIRTEMO™
- Multivariate Calibration
- The Multivariate Optical Element Platform
- MOE Hyperspectral Imaging Example
- Conclusions



What Does CIRTEMO Do?

CIRTEMO™ designs and manufacturers optical filters called Multivariate Optical Elements (MOE)

- for point detection or hyperspectral imaging
- operating in real-time
- exhibiting low SWAPc

CIRTEMO provides real-time chemical information for real-time decision making.

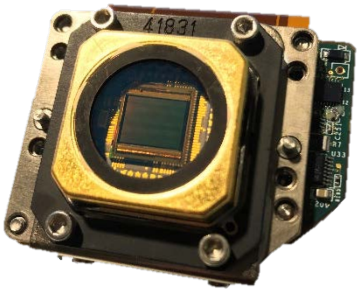
MOE Commercialization History

Year	Milestone
1998	Myrick Group (USC) publishes 1st Multivariate Optical Computing paper
2001	Myrick Group (USC) demonstrates 1st Multivariate Optical Element
2004	OMETRIC is founded to commercialize MOE technology
2012	Halliburton Energy Services purchases OMETRIC
2013	CIRTEMO is founded to commercialize MOE technology

1st Multivariate Optical Element
(University of South Carolina)

Inline Process Control
(OMETRIC)

MOE Filter Wheel
(Halliburton)

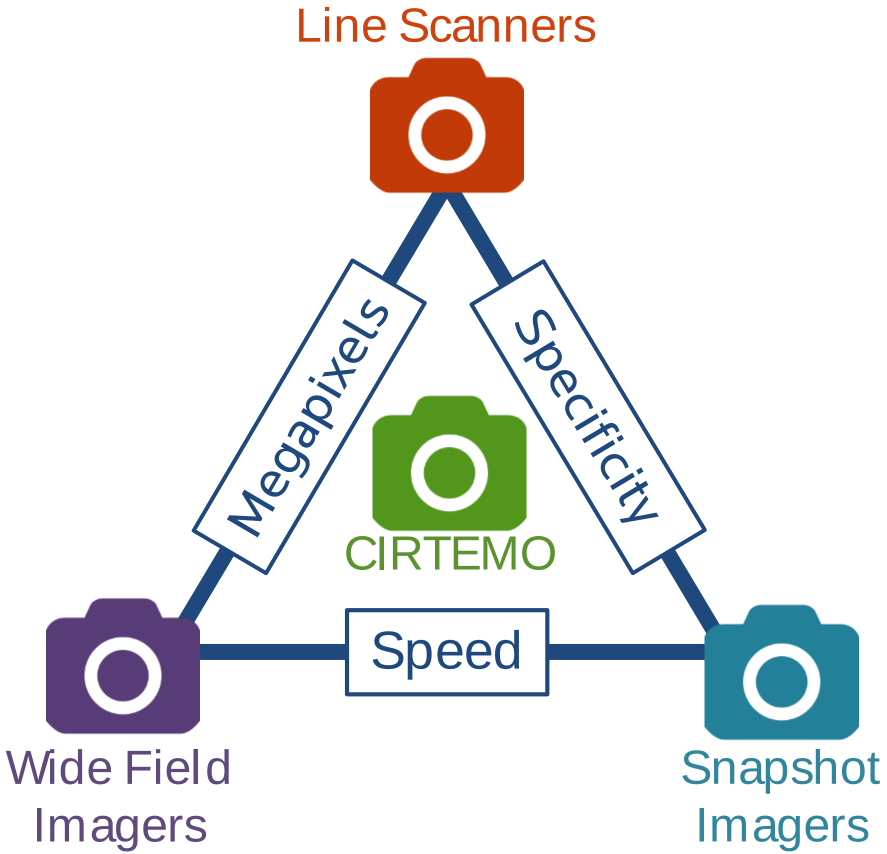


MOE Mosaic Imager
(CIRTEMO)

THE MOE PLATFORM

Problem & Current Solutions (Hyperspectral Imaging)

- Hyperspectral Imagers produce vast amounts of data- *not real-time info*
- Significant backend post processing is required
- To achieve a near real-time operation, *data quality is sacrificed*



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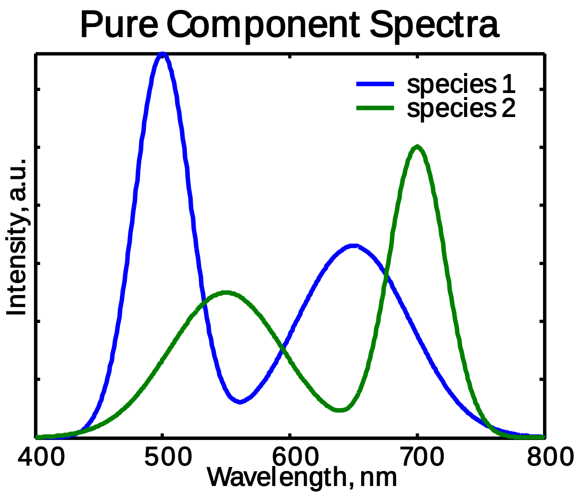
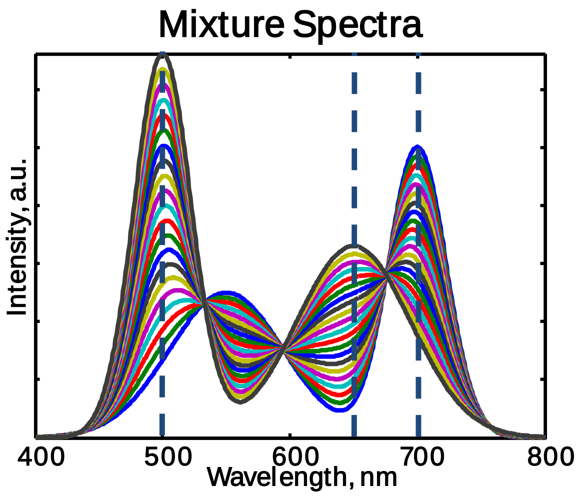
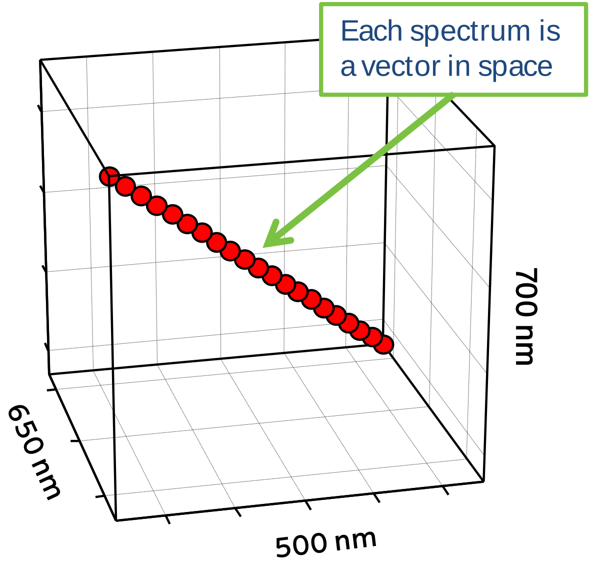
Optical Spectroscopy: Univariate Calibration







- Optical spectra contain chemical-specific information
- For simple mixtures, nearly any two variables (wavelength channels or colors) is sufficient for a calibration.

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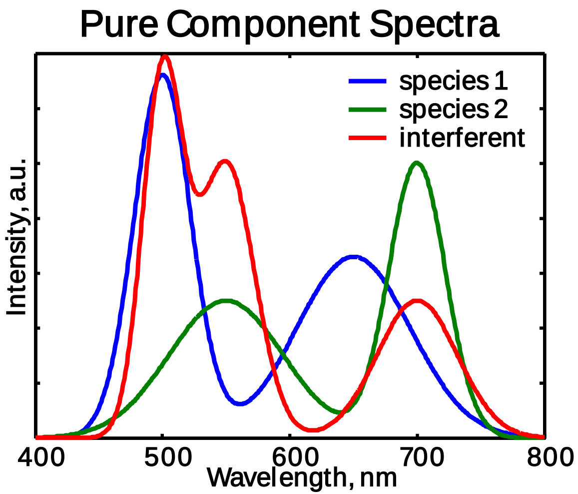
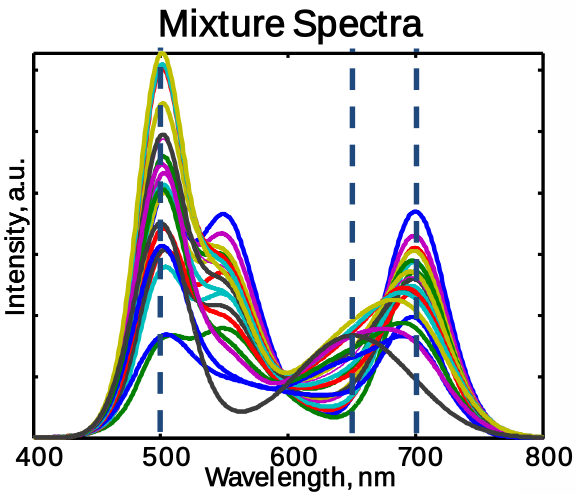
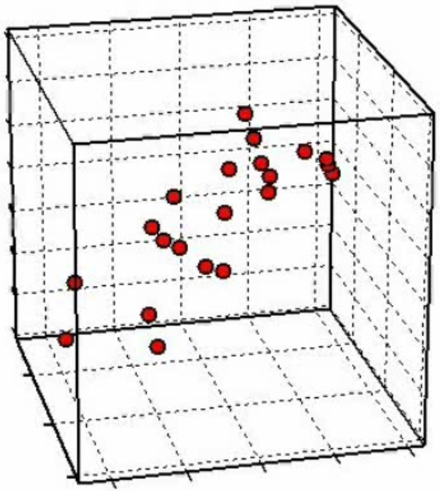
Optical Spectroscopy: Multivariate Calibration

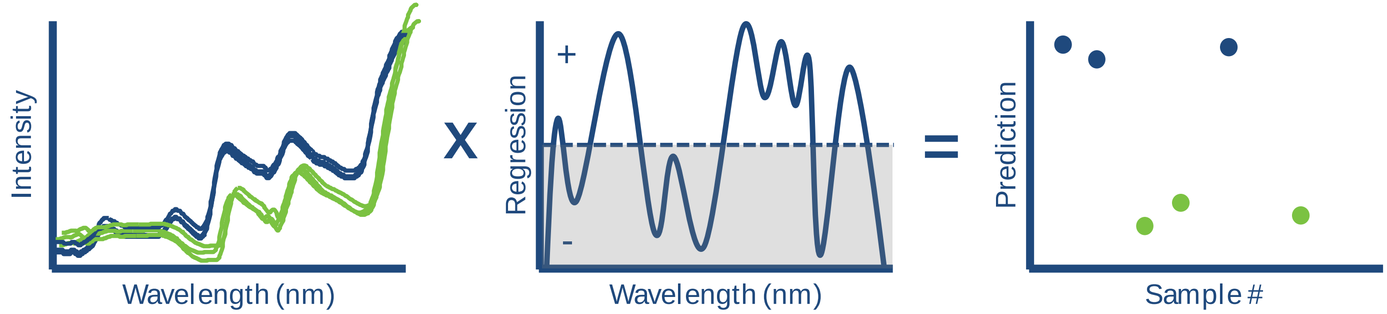






- For complex chemical systems, more variables or dimensions are required for a calibration
- A pattern exists inside the data set that is related to the chemical measurements of interest but orthogonal to any interferences.

Multivariate Analysis & Pattern Recognition



- Multivariate analysis / regression translates spectral data into information for decision making
  - Model parameters may be applied to data from a spectrometer (or series of band pass measurements) to estimate the composition of unknowns
  - Multivariate data sets (especially image sets) can be very large (MB to GB).
  - Real-time chemical detection/ imaging is hindered by the dependency of post processing.

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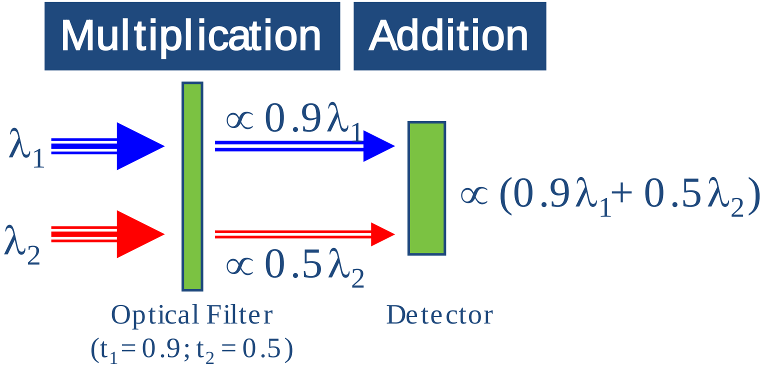
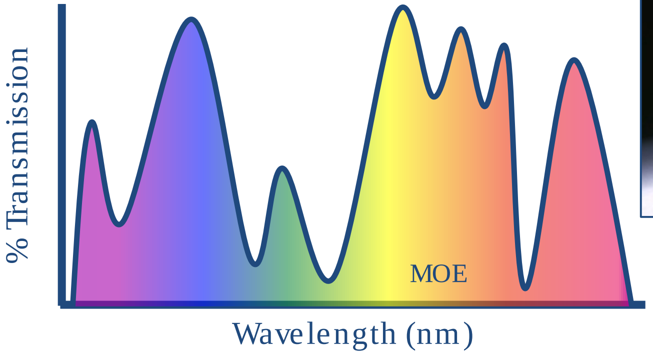
The Multivariate Optical Element (MOE) Platform

- Multivariate Optical Computing is the optical equivalent of a dot product
  - ŷ - estimated analytical property (eg. concentration)
  - t - scaled regression vector
  - λ - analytical spectroscopic response (eg. SWIR spectrum)

$$\hat{y} = \boldsymbol{t} \cdot \lambda = \sum_{i}^{N} t_i \cdot \lambda_i$$



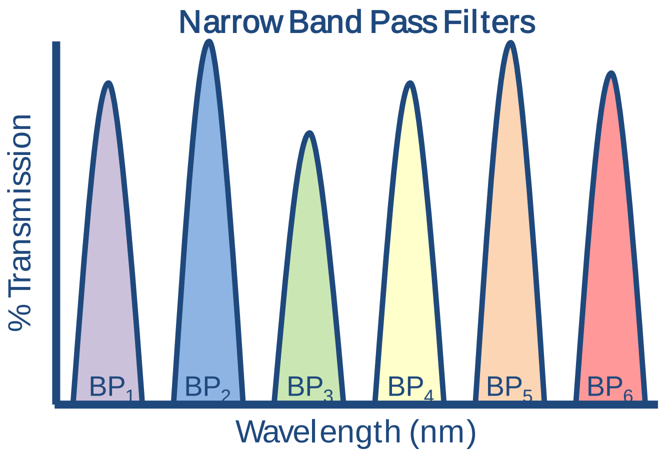
- Multivariate Optical Elements (MOEs)
  - are patented, wide-band, optical interference filters encoded with an application-specific regression (or pattern) to detect/measure complex chemical signatures.
  - realize the measurement advantages of Multivariate Optical Computing (MOC)
  - enable a filter based instrument to achieve the sensitivity/specificity of a laboratory spectrometer as well as convert a focal plane array into a real-time hyperspectral imager.

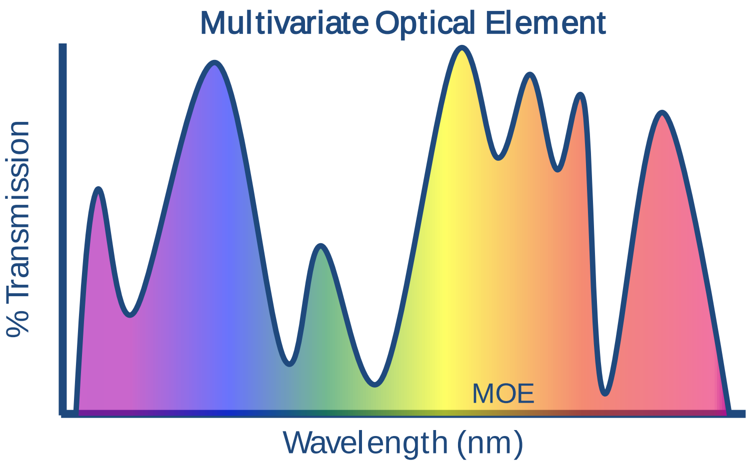


M.P. Nelson, J.F. Aust, J.A. Dobrowolski, P.G. Verly and M.L. Myrick "**Multivariate Optical Computation for Predictive Spectroscopy**" Anal. Chem. **70**, 73-82 (1998).

MOEs Versus Narrow Band Pass Filters

- Multivariate Optical Elements (MOE) are not narrow band pass (BP) filters
  - MOEs possess a higher overall throughput than individual BP filters yielding a higher analyte sensitivity based on superior SNR
  - MOEs sample more spectral wavelengths than discrete BP filters yielding a higher analyte specificity
  - MOEs are physically less complex than BP filters
- MOEs tend to exhibit fewer layers and overall filter thicknesses less than traditional band pass filters.
  - Unlike well defined quarter wave optical thickness (QWOT) deposition recipes used for BP filter fabrication, there are multiple MOE solutions possible for any application
  - Optimal MOE designs are selected based on a set of performance criteria inclusive of overall physical thickness and number of layers
- MOEs are fabricated via the same methods as traditional BP filters





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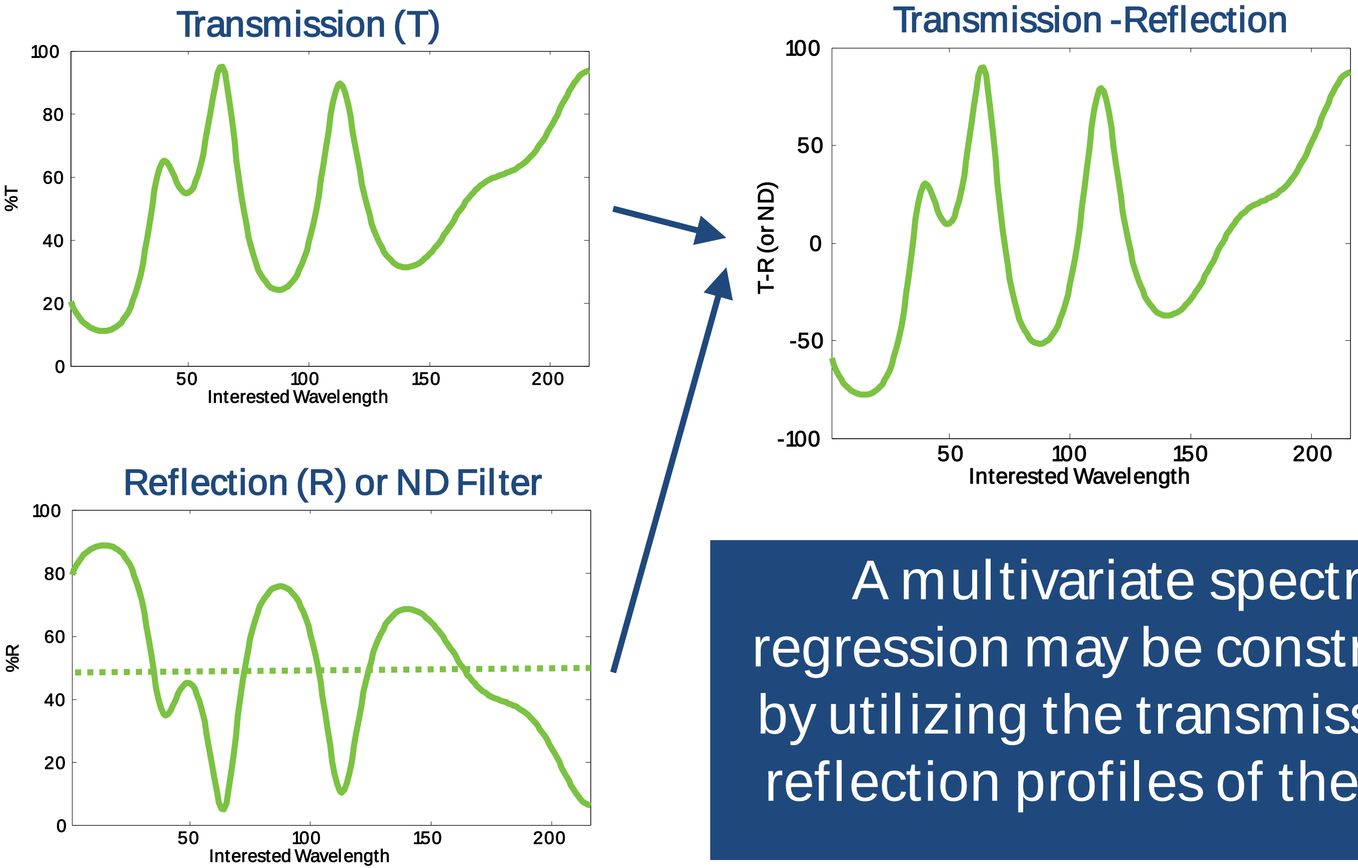
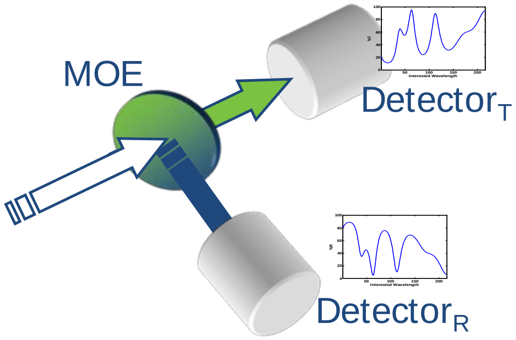
Example Spectral Regression Encoding with an MOE

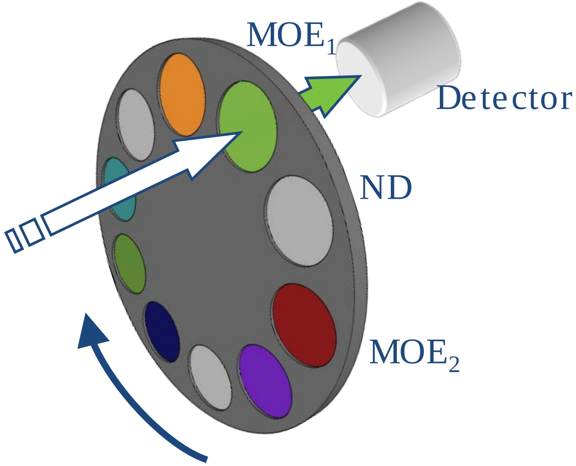


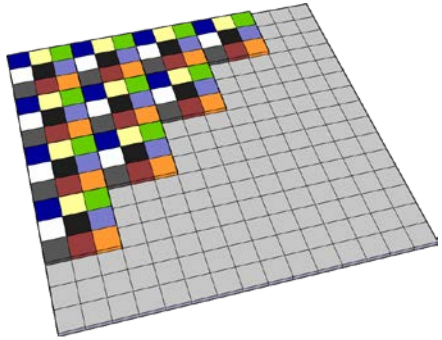
A multivariate spectral regression may be constructed by utilizing the transmission & reflection profiles of the MOE

The Multivariate Optical Element (MOE) Platform

Beam-splitter Configuration	Filter Photometer Configuration	Snapshot Array Configuration







- MOEs may be incorporated into optical systems in a variety of ways:
  - Beam-splitter configuration (single MOE; multiple detectors)
  - Filter photometer configuration (multiple MOEs; single detector)
  - Snapshot array configuration (multiple MOEs; multiple detectors)

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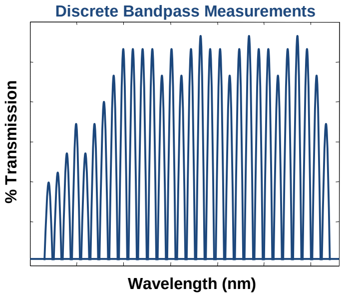
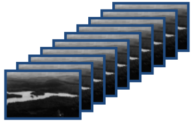
Hyperspectral Imaging with Multivariate Optical Elements

Narrow Band pass or Tunable Filters

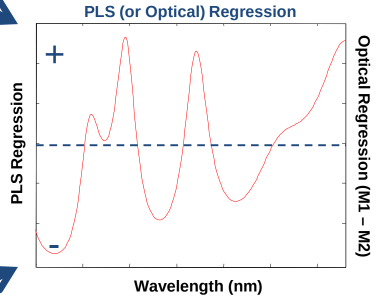
Scene

Radiation from Scene

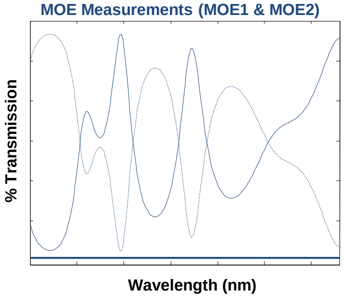




1. Narrow band images are measured (HSI data cube) or line scan spectrometer
2. Regression is applied to each pixel (or spectrum) to yield analyte score image



Multivariate Optical Element(s)



1. MOE intensity images are measured
2. Simple image math is performed to yield analyte score image

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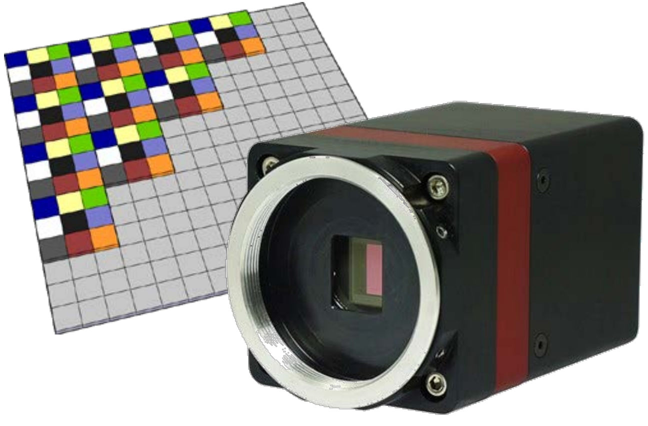
MOE Hyperspectral Configurations

Filter Wheel

Partner Filter Wheel Camera
w/ MOE Cartridge

Pixelated

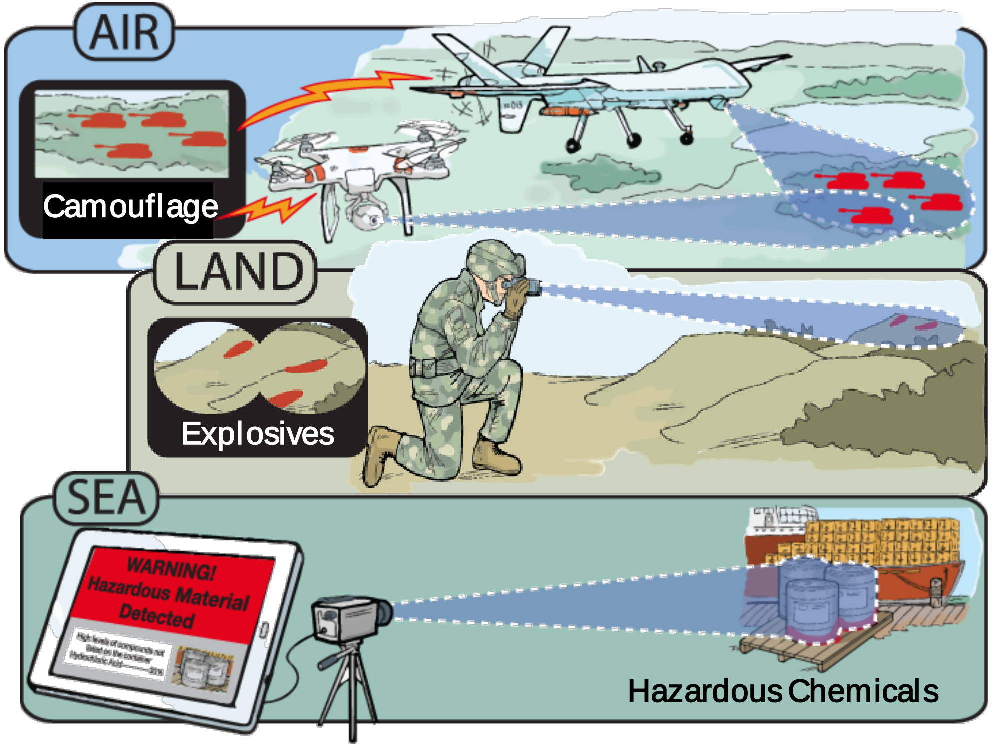


Partner Camera
w/ MOE Pixelated Mask

Explosive Precursor Detection

MOE HYPERSPECTRAL IMAGING EXAMPLE

HSI MOE Defense & Security Example



- Urea and ammonium nitrate are fertilizer-based explosives
  - are commonly used in both improvised explosive devices (IEDs) and homemade explosives (HMEs)
  - can have highly destructive effects
- Real-time chemical detection and identification of explosives is desired by the both the Department of Defense and first responder community

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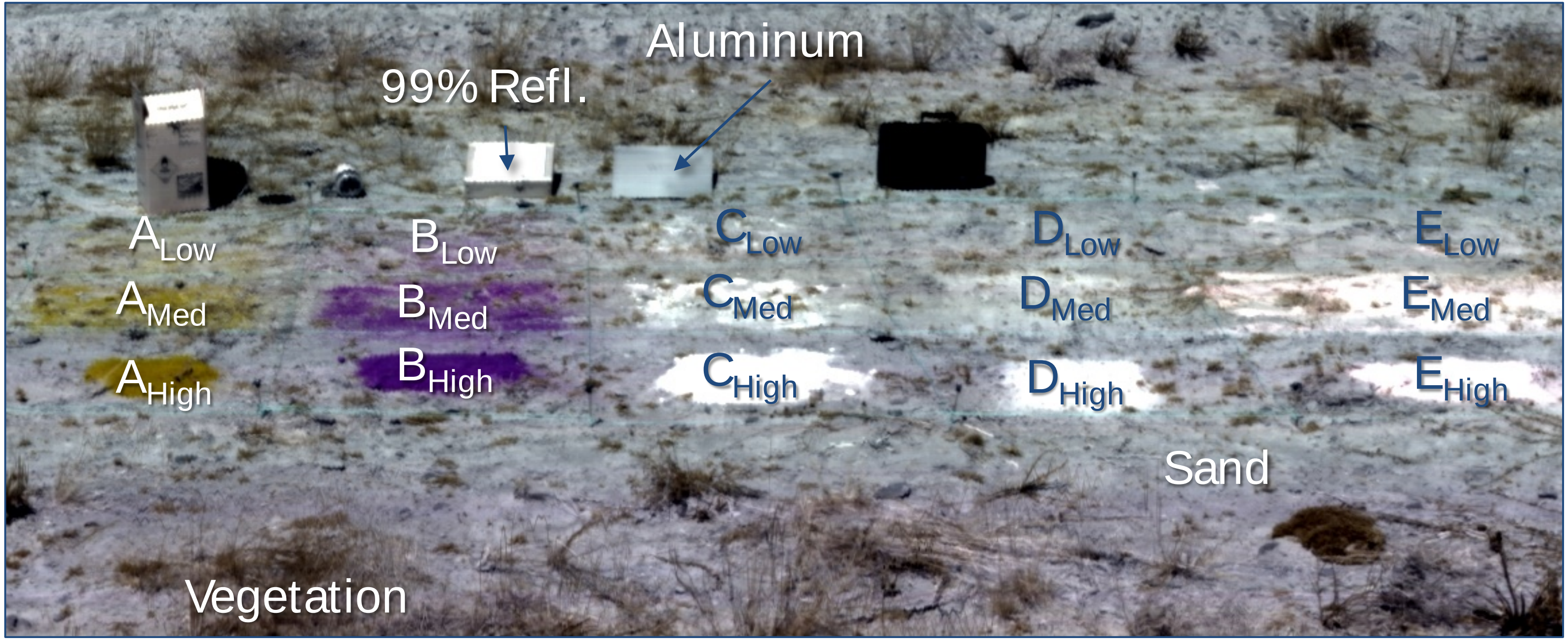
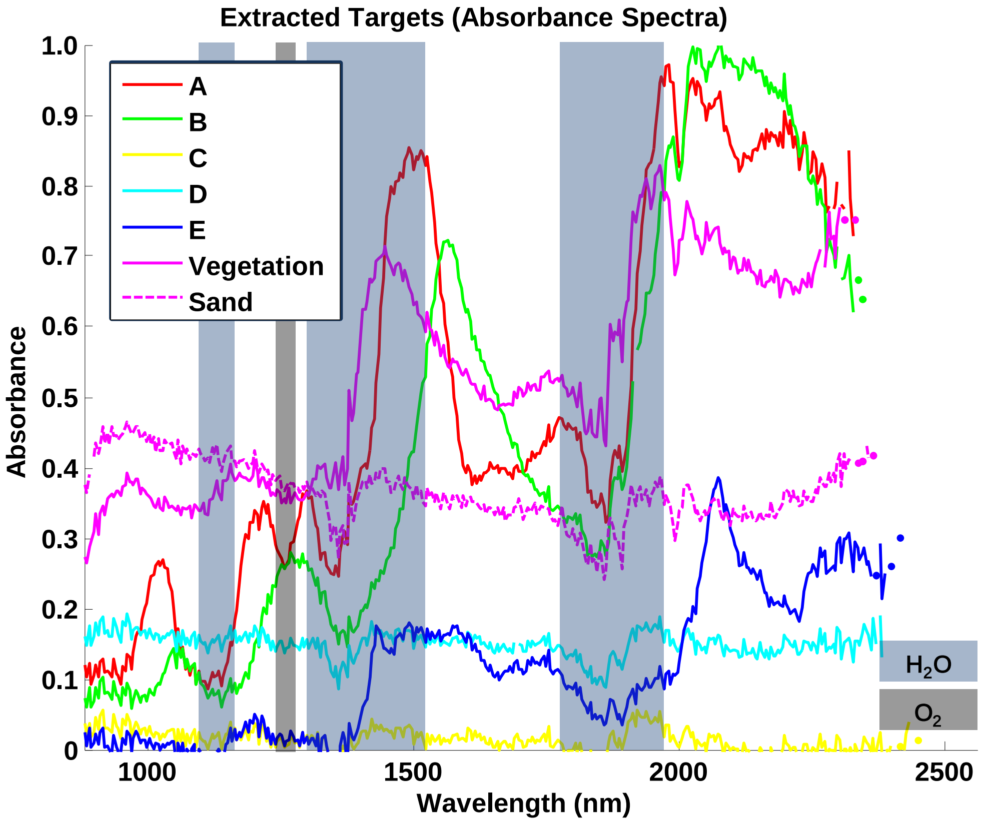
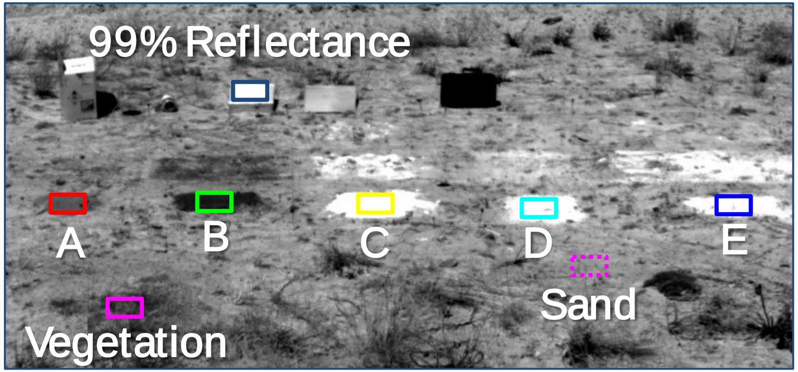
HSI Stand Off Detection of Explosive Powders



- Target and background signatures were extracted from a HSI data set acquired from Night Vision Electronic Sensors Directorate (NVESD)
- Ground truth regions of interest (ROIs) were defined by NVESD for targets, vegetation, sand, and a 99% reflector
- A 99% reflector was be used to normalize the ROI intensities to yield reflectance values

HSI Target/ Background Feature Extraction

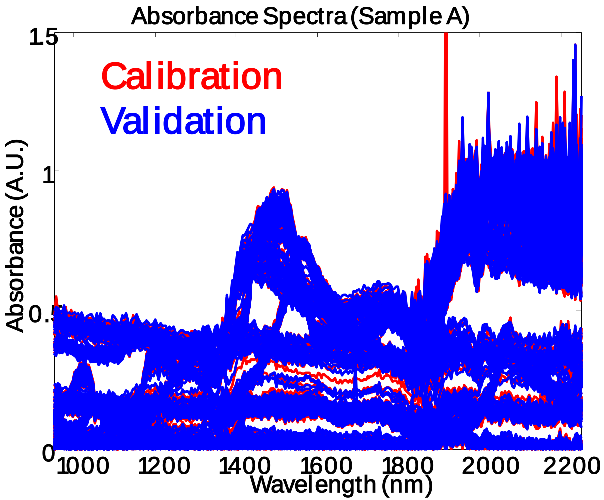


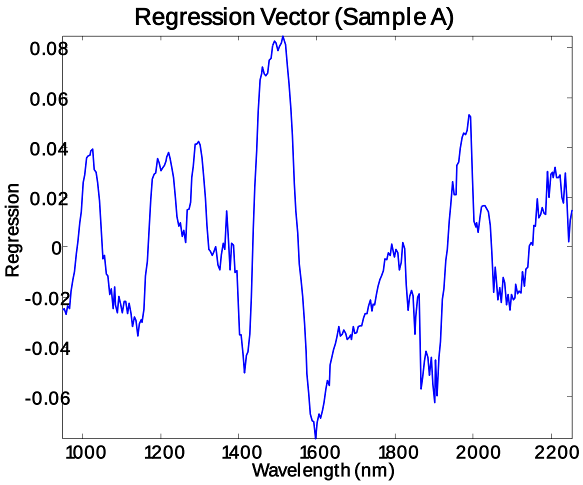


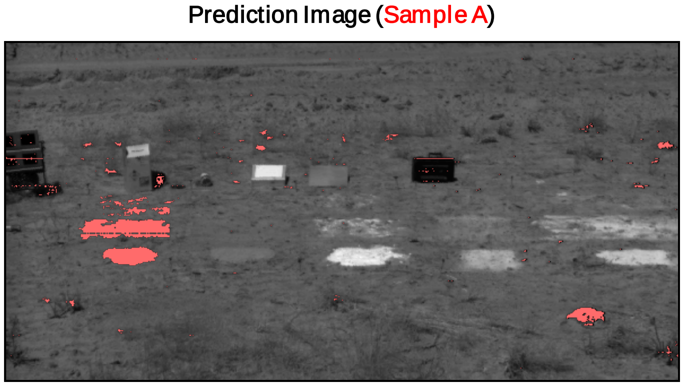
- The absence of data points near 2400 nm is due to absorbances of infinity because of a decreasing detector sensitivity and SNR
- Atmospheric absorptions have been overlaid with the extracted target/ background spectra

PLS-DA Overview

- PLS-DA (Eigenvector Research PLS_Toolbox) was employed as a multivariate classification tool and to determine whether a MOE would be viable for this application
- Only samples A, B and E were evaluated based upon a unique absorbance signature as samples C and D appear to be featureless in the 950 – 2450 nm range
- The data was split into a calibration and validation (challenge) set for each target analyte analysis yielding a total of ~900 spectra

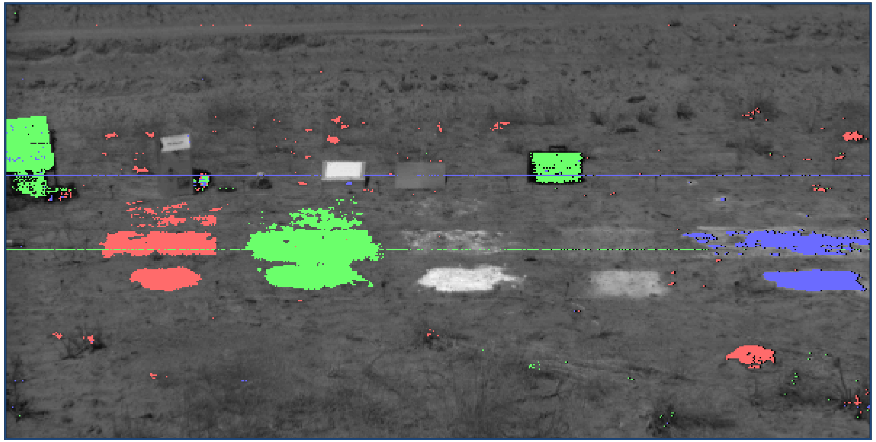




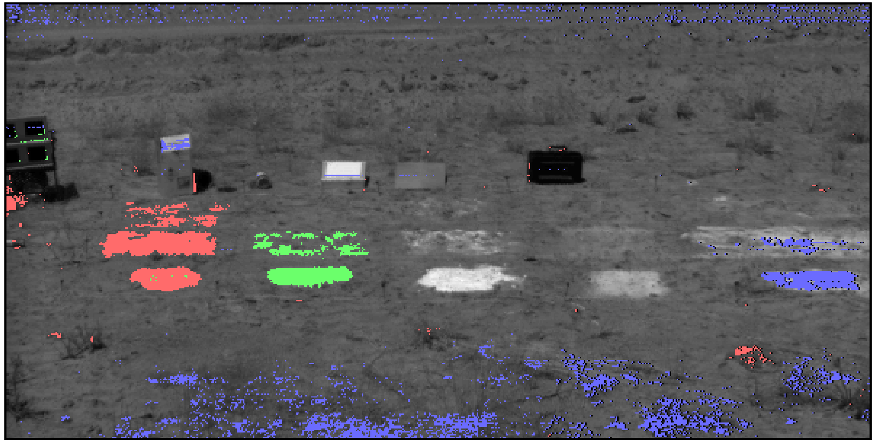


False Colored Detection Image Comparison (Simulation)

PLS-DA



MOE



- MOE imager has the potential to yield comparable detection performance as a high resolution NIR HSI system
- The MOE imager can operate at a higher framerate, smaller overall footprint, and at a cost orders of magnitude cheaper than incumbent technologies.

Specification	NVESD Linescan HSI	MOE Widefield HSI
Spectral Range (nm)	950 - 2450 nm	950 – 1650 nm
Spectroscopic Encoding	Grating Spectrometer	Optical Filter (MOE)
Raw File size (MB)	1,280 (400 frames)	12.8 (4 frames)
Collection Speed (HSI/ s)	---	15
Cost	$$$	$

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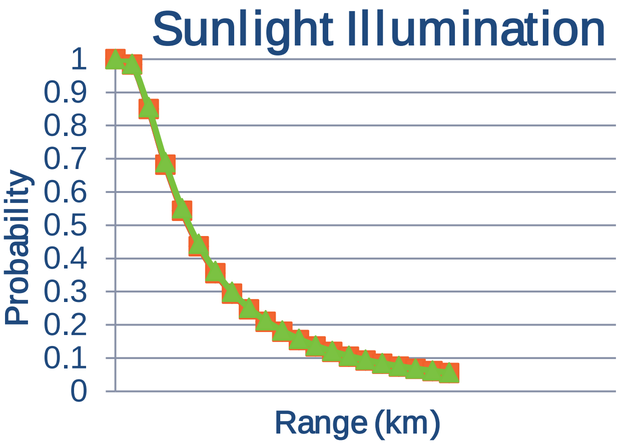
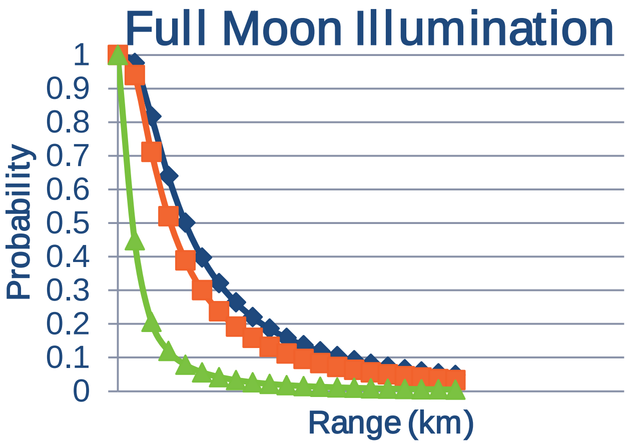
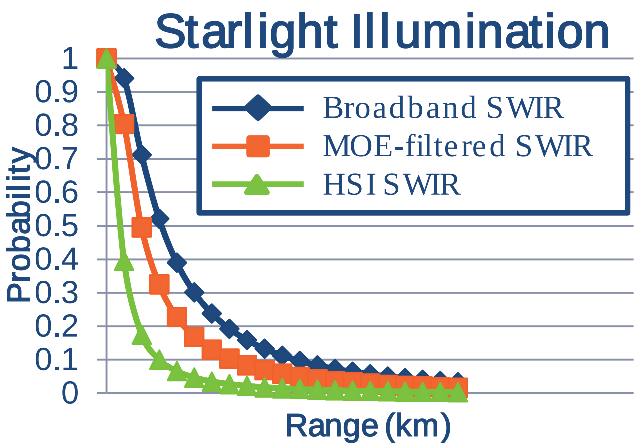
Detection Range Simulation







- A standoff range model was created under Sunlight through Starlight illumination using SSCam-IP Software.
- Three different SWIR product concepts operating under similar conditions have been modeled.
  - **Broadband Sensor**:- Unfiltered SWIR imaging sensor
  - **MOE-filtered sensor:** MOE in front of SWIR imaging sensor with average 50% transmission
  - **HIS Sensor -** Selective Narrow band pass filter(s) in front of detector. Each scan increment set to 50nm bandwidth @85% throughput
- The following configuration / operating conditions were defined for the above product concepts:
  - 640x512, 15um pitch InGaAs detector – SCD Cardinal Detector
  - 100mm F/1.5 Lens
  - 60 Hz Frame rate
  - 0.95/km atmosphere transmission
  - Man Target

MOE filters can achieve up to 2.5x range improvement compared to HSI systems, especially under Low Light Level conditions.

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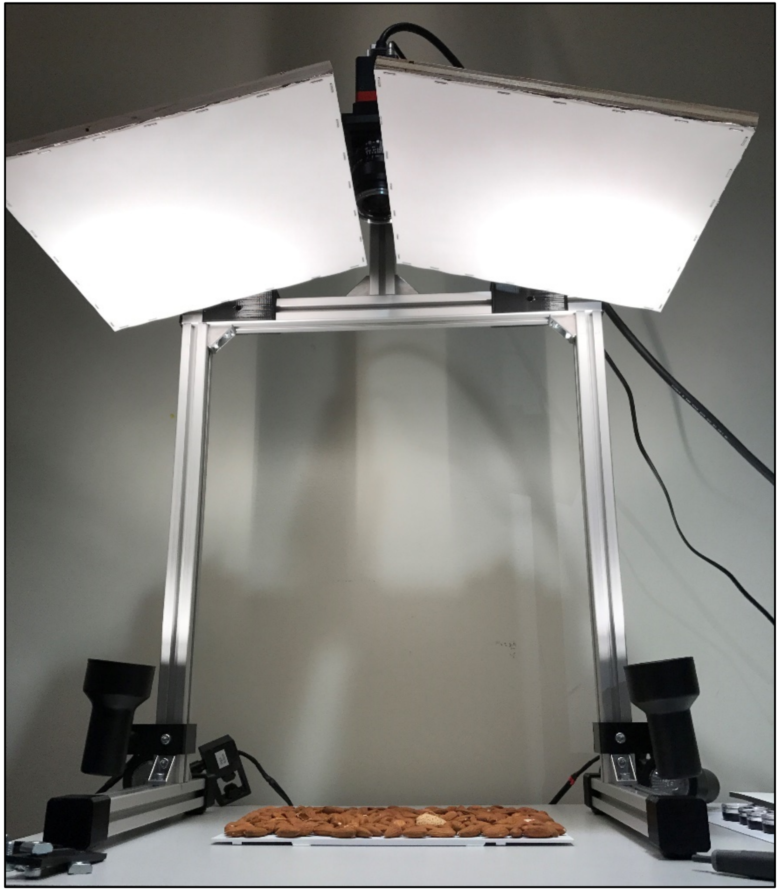
Measurement System Configuration



- A pair of diffuse reflectance panels were employed to evenly illuminate the sample field of view
- A small gap was left for the fore optic to image the field of view without obstruction
- Pixelteq's Spectrocam was employed for cycling the MOEs and ND reference filter in/out of the optical path

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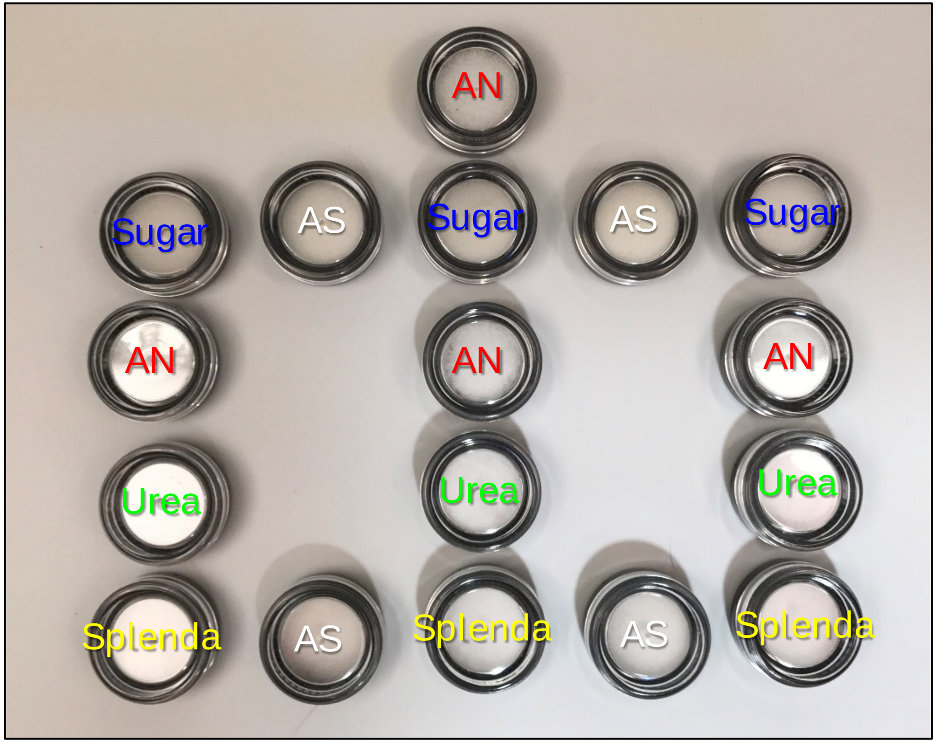
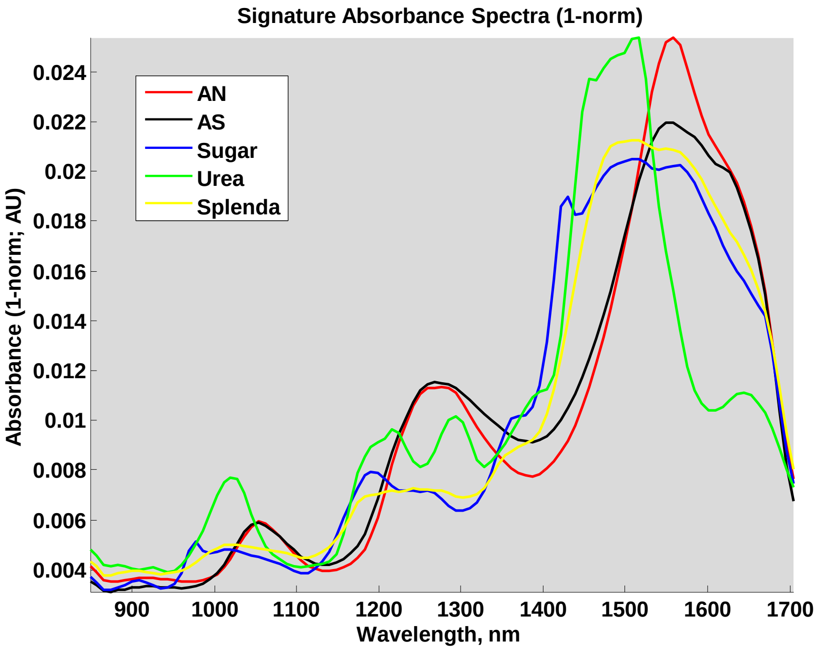
Sample Arrangement (Explosive Powders)

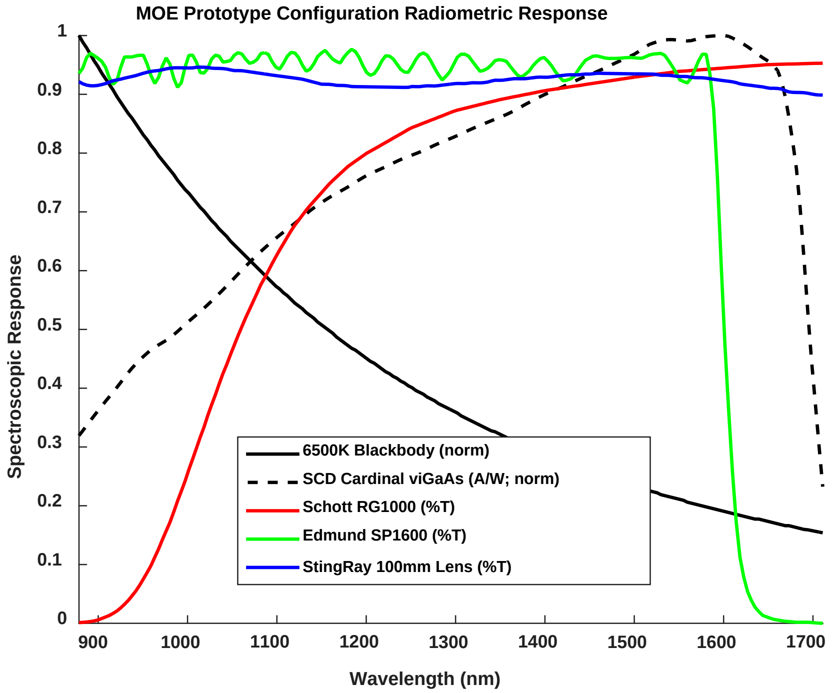


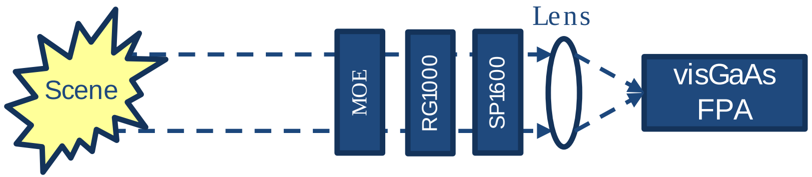


- Five discrete white powder samples were arranged across the field of view
- Ammonium Nitrate (AN) is considered the target while the interferants include: sugar, ammonium sulfate, Splenda and urea.

Radiometric Calibration – Discrete Components

- The key optical subcomponents of the imaging prototype were measured/ simulated for designing the MOEs
  - Transmission spectra were measured for the long pass (RG1000) and short pass (SP1600) filters
  - The light source was simulated as a 6500K blackbody emitter to represent passive solar illumination
  - The SCD Cardinal visGaAs FPA radiometric response was calibrated via Optronic Laboratories NIST traceable instrumentation
  - The transmission throughput of the StingRay 100mm lens was extracted from the component specification sheet





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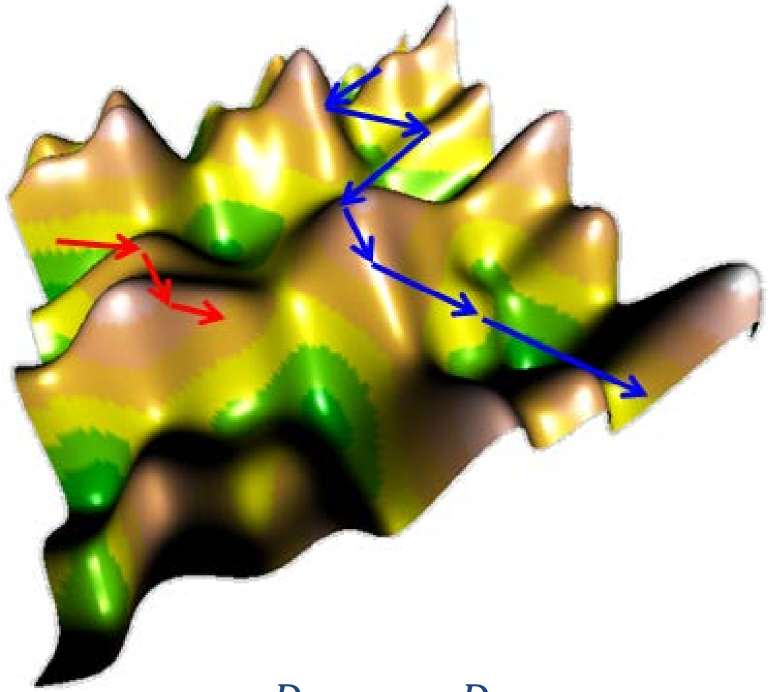
CIRTEMO's Secret Sauce: The MOE Design Process

Parameter	Value
Target Analyte	Ammonium Nitrate
Classification Value	Target (1); Other (0)
Pre-processing	None
MOE Field of View	15° (+/ - 7.5°)
# Designs	5000
Figure of Merit	Area Under the ROC (AUROC)

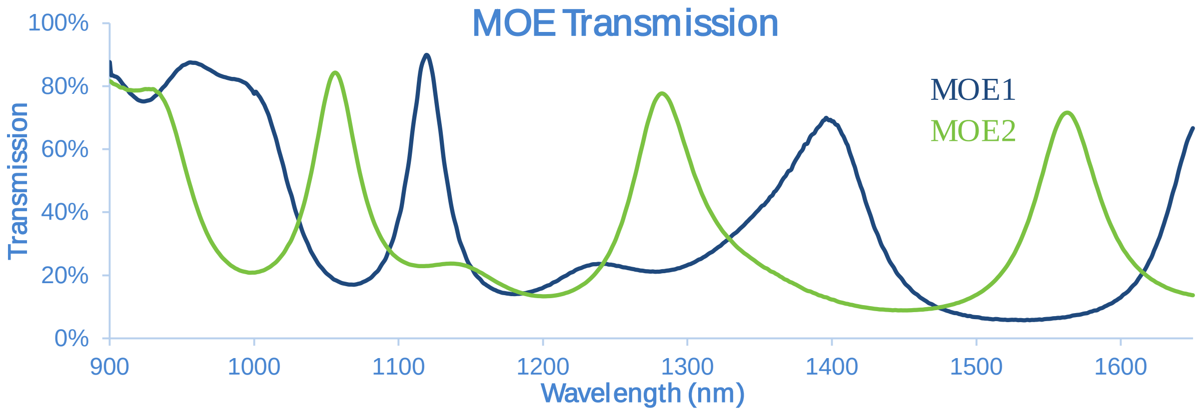
The optical computation (c_{MOE}) or class member prediction is comprised of:

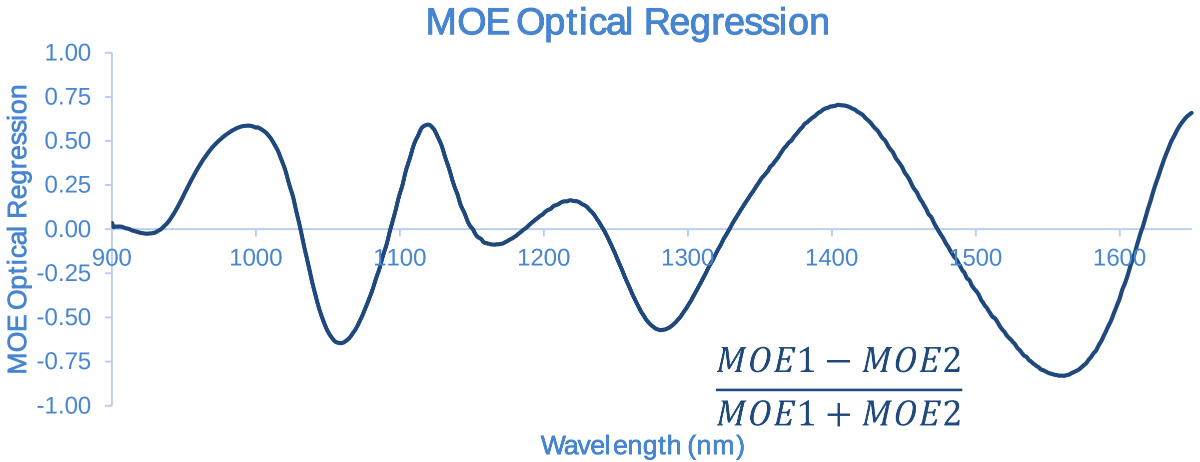
- MOE1 detection image (D_{MOE1})
- MOE2 detection image (D_{MOE1})
- Gain (G) determined via least squares regression
- Offset (off) determined via least squares regression



$$c_{MOE} = G \cdot \frac{D_{MOE1} - D_{MOE2}}{D_{MOE1} + D_{MOE2}} + off$$

Multivariate Optical Element Fabrication

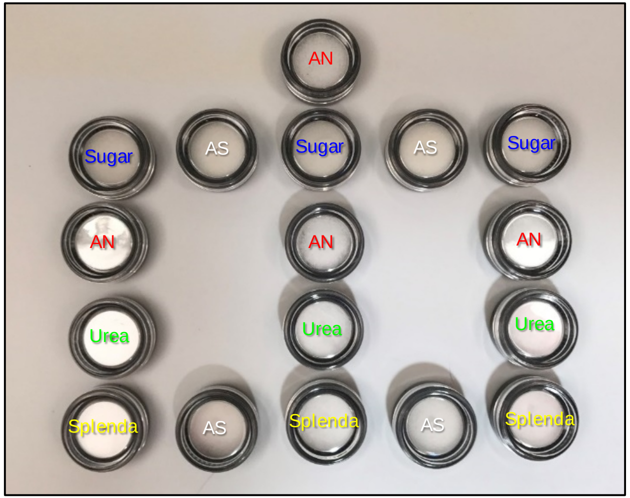




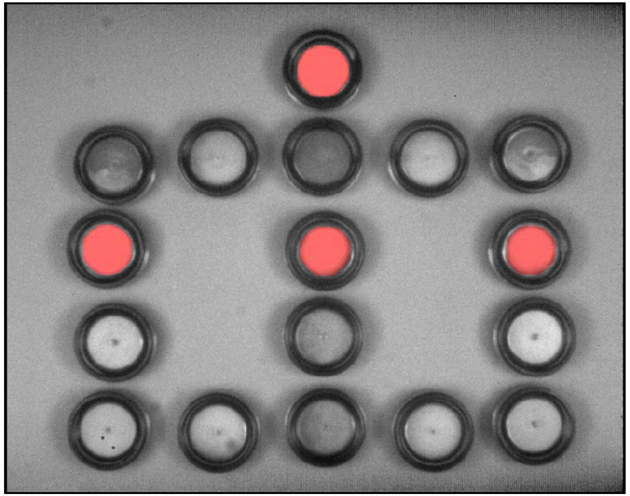
- MOEs were successfully fabricated by one of CIRTEMO's optical filter partners
- The resulting MOE optical regression spans from -1 to 1 across the instrument spectral band pass
- This optical computation also offers an intrinsic intensity normalization

Sample Measurement (AN Detection)

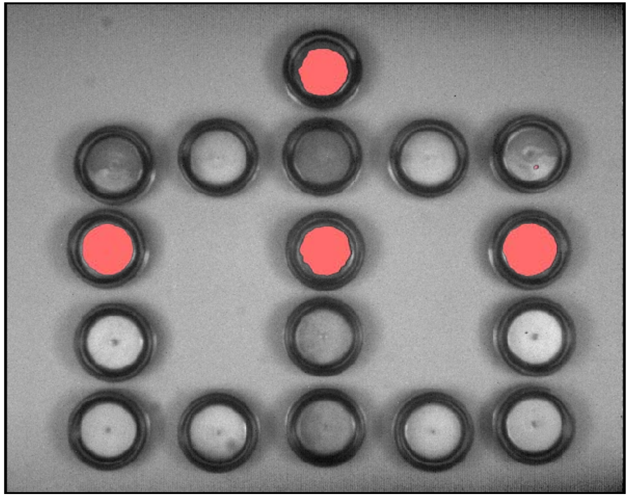
Brightfield Reference Image



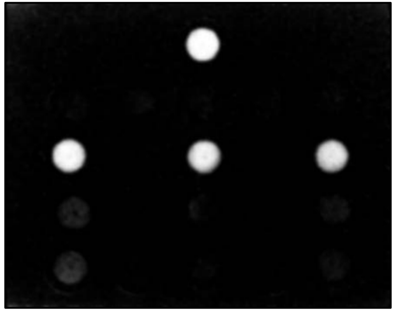
AN Detection Overlay (BP Filters)



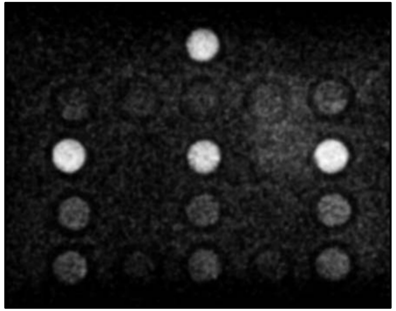
AN Detection Overlay (MOEs)



- 5 Narrow bandpass filter measurements were employed (and required at a minimum) to generate a prediction model.
- 2 MOE measurements were employed for computing the final detection image
- The overall light levels were approximately 3-4 orders of magnitude higher for the MOE measurements as compared to the narrow bandpass filters



Score Images



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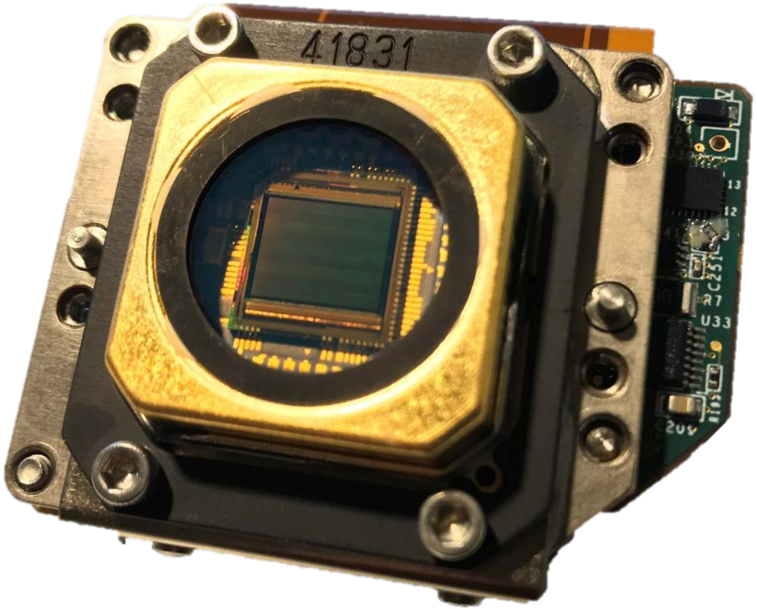
Next Steps: Pixelated Imaging

- Pixelated MOE sensors offer
  - a significant reduction in SWaPc
  - a rugged (no moving parts) configuration
  - measurements on the order of sensor readout
- Traditional narrow band pass optical filters are physically thick – thicker than the pixel pitch of infrared FPAs
- MOEs are ideally suited for mating to infrared FPAs due to their inherently thin physical thickness
- CIRTEMO has successfully manufactured an infrared FPA with a pixelated MOE array (3 MOEs + reference) and is currently in field testing



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Conclusions

- Multivariate Optical Elements (MOEs)
  - are patented, wide-band, optical interference filters encoded with an application-specific regression (or pattern) to detect/ measure complex chemical signatures.
  - enable a filter based instrument to achieve the sensitivity/ specificity of a laboratory spectrometer as well as convert a focal plane array into a real-time hyperspectral imager.
  - Are manufactured using the same deposition equipment as traditional narrow band pass filters
- MOE HSI imagers offer:
  - Low SWaPc
  - Minimal data post-processing (and bandwidth) as compared to traditional hyperspectral and multispectral sensors
- CIRTEMO is developing a new class of pixelated MOE sensors for addressing applications simply not accessible today using traditional HSI systems

Questions?

Thank you for your attention

CIRTEMO™