Surveillance using Hyperspectral, LiDAR and Spectro-Polarimetric Data

Bob Plemmons

Wake Forest University

Challenges in Dynamic Imaging Data, Isaac Newton Institute, Cambridge, June 2015

Outline

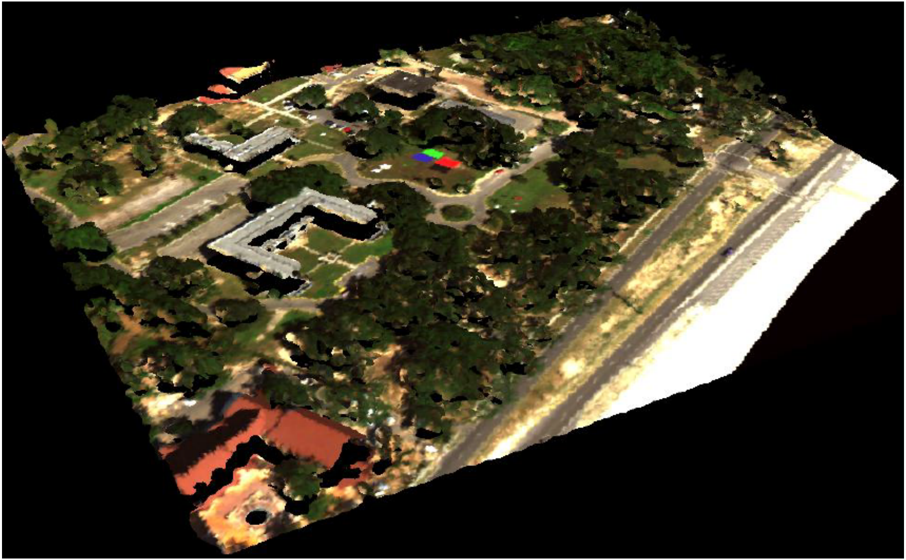
2015 - UNESCO's International Year of Light & Light Technologies

- Overview of **3D, 4D** Optical Imaging Data Modalities for Dynamic Surveillance
  1. Hyperspectral Imaging (HSI)
  2. Light Detection And Ranging (LiDAR), Fused HSI/LiDAR
  3. Snapshot HSI and Spectro-Polarimetric Imaging (SPI) - Dynamic HSI and SPI
- Overview of Projects for US **NGA** and **AFOSR**
- **Processing High Dimenssional Data taken through Atmospheric Turbulence** - Challenges

Optical Remote Sensing for Surveillance

- **Hyperspectral** (2D spatial & 1D wavelength) and **LiDAR** (2D spatial & 1D range) Imaging
  - Hyperspectral imaging (**HSI**) collects information across the visible and IR spectrum for interrogating scenes, wavelengths generally 400 to 2,500 nm. **HSI Video is 4D image tensor**.
  - **LiDAR** measures distance by illuminating targets with a scanning laser and analyzing the reflected light. Laser wavelengths vary to suit the target: 5 nm to UV. Very short.
  - **Fused** HSI and LiDAR for enhanced analysis. **Combined laser ranging & object material identification**.

Feature Level Fusion of HSI and LiDAR from NGA Project

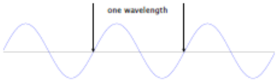


Targets placed in scene by sponsor

- **Spectro-Polarimetric Imaging (SPI)**
  - 3D hyperspectral & 1D polarization. Data is a **4D tensor**.
  - Spectral traces identify **materials**.
  - Polarizations identify **object shapes, metallic surfaces**.
  - **Object characterization using spectrally compressive polarimetric image data, funded by AFOSR grant** to UNM (Physics), Duke (ECE) and WFU (Math & CS). **Snapshot spectro-polarimetric cameras** developed at Duke.
  - **Snapshot SPI “video” creates a 5D image data tensor**.

HSI: Spectral (beyond RGB) Imaging at Wavelengths λ

Electromagnetic radiation: energy in the form of electromagnetic waves.



Electromagnetic spectrum: the entire family of electromagnetic radiation.

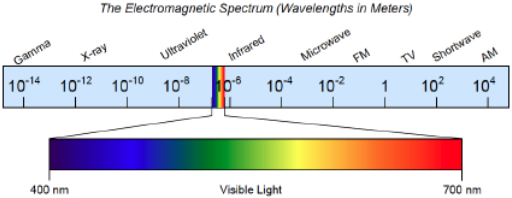
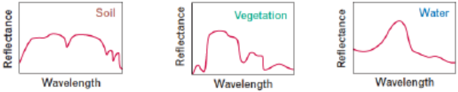


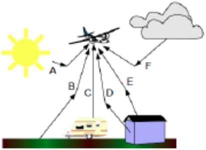
Figure 1: λ **generally ranges between 400 and 2500 nanometers.**

Using the Spectra λ

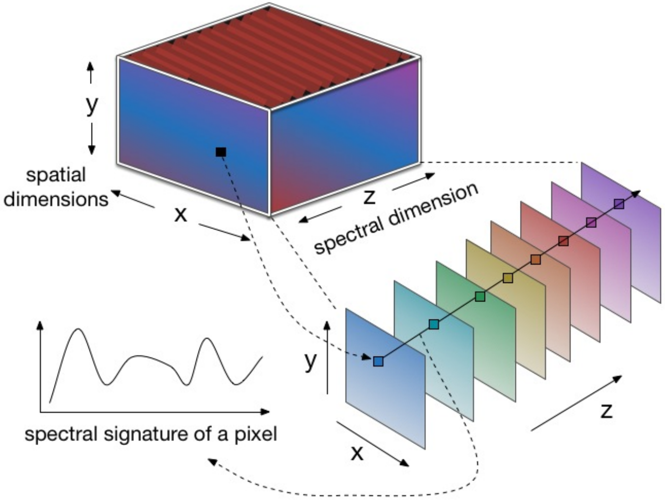
Different materials produce different electromagnetic radiation spectra.



After adjusting for sensor, atmospheric, and terrain effects



Structure of HSI Data



Extract Spectral Signatures (Traces) from HSI to Identify Materials

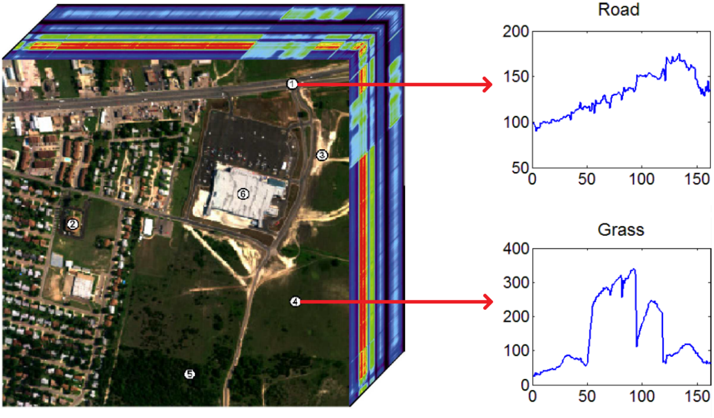


Figure 2: **Illustration High Resolution - Each pixel represents a vector**

Some Applications of Hyperspectral Imaging (HSI)

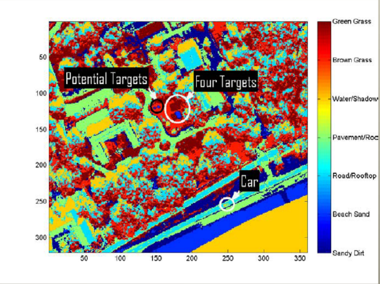
- Environmental remote sensing, e.g., monitoring chemical/oil spills and gas plumes (HSI video)
- Military target discrimination
- Astrophysics
- Sensing for agriculture & food quality and safety
- Biomedical optics, medical microscopy, etc.
- Disaster relief, land/water management
- Tracking and identifying people (HSI video)
- Remote surveillance for defense & security, e.g., imaging a compound in western Pakistan

Recent Remote Sensing Work

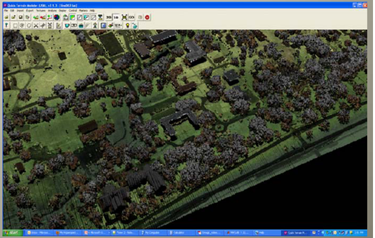
NGA Project

- National Geospatial-Intelligence Agency (NGA) Funded Project "Compressive Sensing and Fusion of LiDAR and Hyperspectral Data using Tensor Factorizations". Boeing and Wake Forest 2011-2013

Hyperspectral



LiDAR



NGA - USA's "Eye in the Sky"

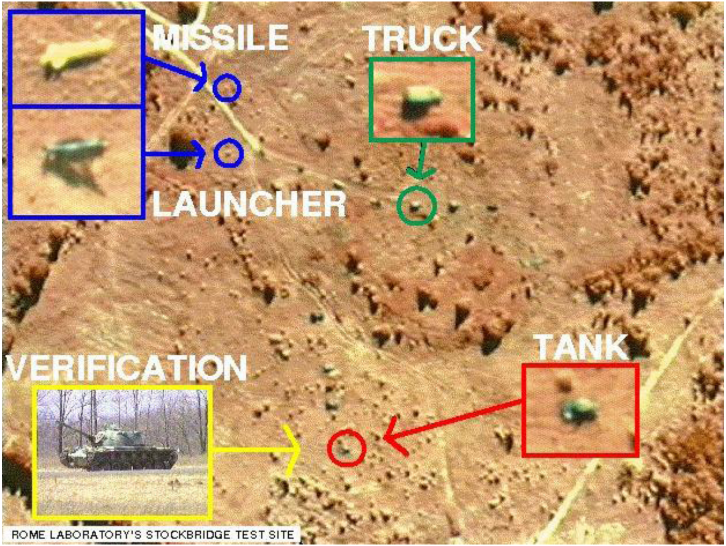
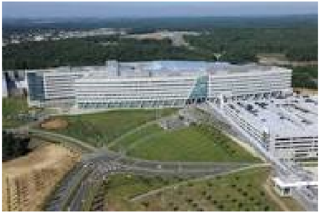


Figure 3: **Warfighter NGA application**

NGA HSI/LiDAR Project

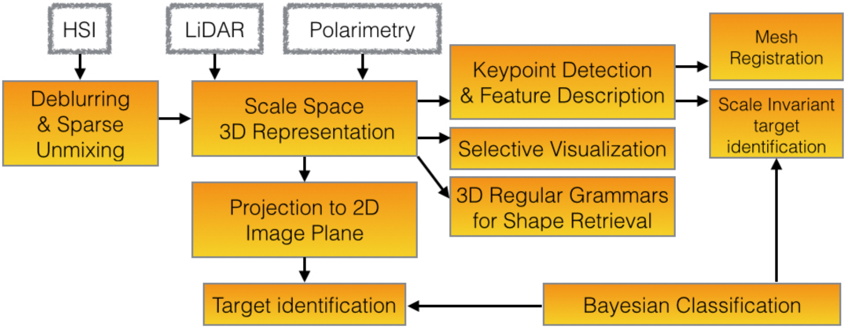
- Implicit Geometry Framework (IGF) using **level set methods**, Osher, et al., for LiDAR data representation and compression. "Reconstructing Compressive LiDAR and HSI Datasets."
- Clustering and classification of fused data, and information-theoretic results, detecting objects in shadows, etc.
- 3D object shape recognition for identification and tracking, differentiate <u>people</u> from background.



NGA Campus, near DC

Proposed WFU Project for NGA - Academic Research Program

"Geometric Representation, Processing and Information Optimized Fusion of LiDAR, HSI and Polarimetric Data"

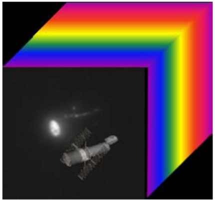


AFOSR Project

- <u>Air Force (AFOSR) Funded Project</u>

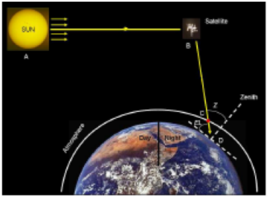
  "Space-Object Characterization using Spectrally Compressive Polarimetric Image Data," Duke, New Mexico and Wake Forest 2011 - 2015

Space Object Identification with Spectral Imagers



Hubble Space Telescope

Analysis of reflectance.



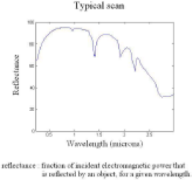


Figure: Reflectance of an object pixel results from additive reflectance of its constitutive elements.

Space Situational Awareness, Military and Commercial

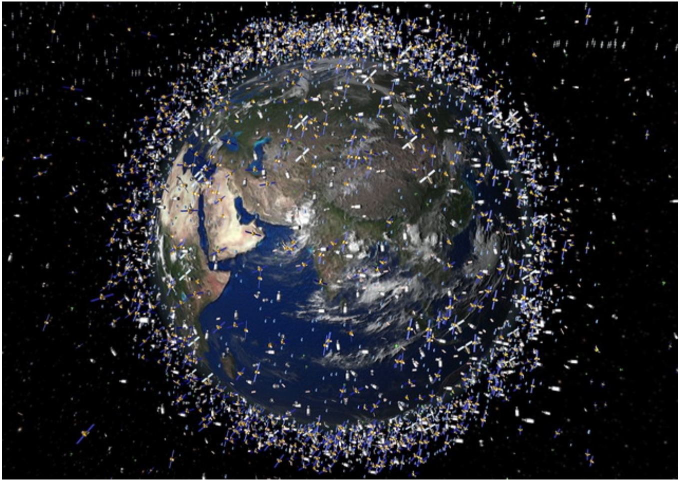
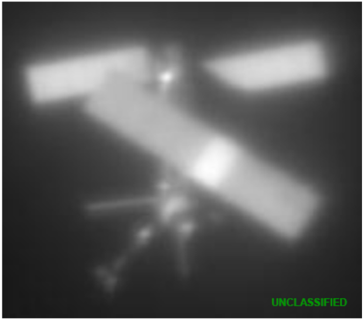


Figure 4: **Application: Satellites & Large Debris Objects Around Earth. (About 1000 active satellites to maintain, 5% of space objects to monitor - international cooperation, huge expenditures)**

Current DOD/NASA Imaging of Space Objects

- Current "operational" capability for spectral imaging of space objects – imaging and non-imaging

- Panchromatic images



- Non-imaging spectra

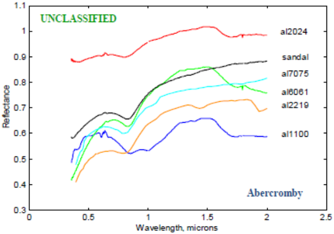


Figure 5: **Space object identification.**

Space Situational Awareness (SSA) by Monitoring Space Objects

- ‘Listen’ (laser enabled vibrometry)
- ‘Smell’ (chemical sensing with spectral imaging)
- ‘Touch’ (scatterometry/polarimetry for surface texture information)
- ‘See’ (by sequential speckle <video> imaging)
- ‘Object Laser Ranging’ (Ground based LiDAR)
- ‘Characterize Materials’ for SOI (hyperspectral imaging) (polarimetric imaging)

Figure 6: **Methods for monitoring space objects (satellites).**

Beginning Another AFOSR Project

- "Statistical Image Analysis and Applications to High Dimensional Imaging for Improved SSA," 2015 - 2018.

- To develop algorithms and statistical performance metrics as design tools for range-integrated high dimensional object tracking systems.

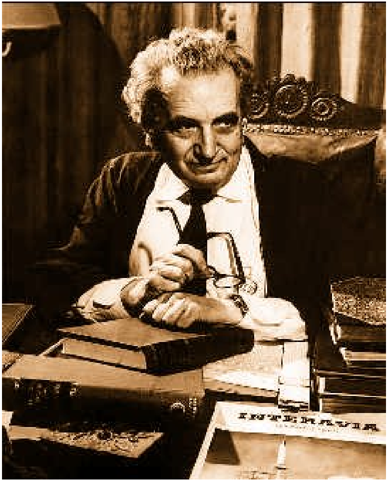
A US Air Force Observatory on Haleakala in Maui

Turbulence

Image contains sketch by Leonardo da Vinci, along with a remarkably modern description: “ the smallest eddies are almost numberless, and large things are rotated only by large eddies and not by small ones.” Called phenomena “**turbolenza**”, leading to modern word **turbulence**.

Leonardo da Vinci (1452-1519) : old man and vortices

Later, Galileo, 1564-1642, knew effects of atmospheric turbulence on telescopes. Modern mathematical models developed by:



(a) Th. von Karman, 1881-1963 (b) Andrey Kolmogorov, 1903-1987

Tracking Objects Using "Snapshot" Spectro-Polarimetric Imaging (Snapshot SPI)

- **Compressive Sensing from Snapshot HSI-Polarization Imaging**

- Prototype polarimetric coded aperture snapshot spectral camera designed at Duke in AFOSR project joint with: D. Brady (ECE, Duke), S. Prasad (Physics, UNM).

- Prototype polarimetric spatial light modulator (SLM) snapshot spectro-polarimetric camera.

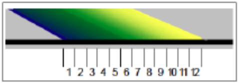
HSI and 4 polarization channels. All the PSFs are wavelength and diffraction blur dependent.

- **Data reconstruction and joint deblurring for removing atmospheric turbulence, as well as feature extraction.**

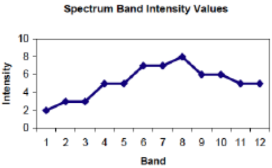
How HSI works

Dispersion of light through a prism

Spectrum divided into discrete bands



Record the intensity values for each band



Spectrometers

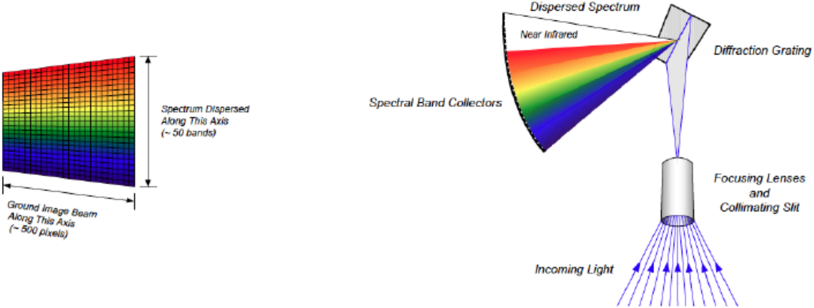
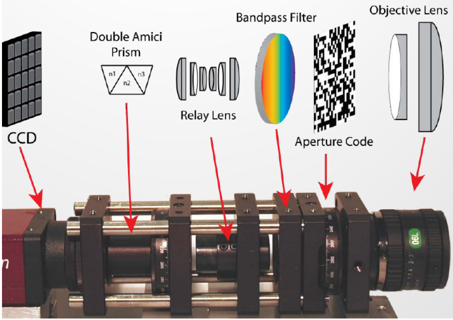


Figure 8: There are numerous ways to capture HSI, almost all of which are temporal. **However**, **new snapshot imagers provide method of capturing hyperspectral images during a single integration time of a detector array**.

Coded Aperture Snapshot Spectral Compressive Sensor



- Dave Brady et al., Duke U., part of AFOSR SOI project.

$$g(x,y) = \int_{\lambda} C_{\lambda}(x,y) f(x,y,\lambda) d\lambda + \epsilon_{\lambda}(x,y).$$

Spectro-Polarimetric Compressive Sensing - Enables HSI Video Imaging

- Spatial Light Modulator (SLM)-based - snapshot spectro-polarimetric imager forward model.

$$g(x,y) = \int_\lambda C_\mu(x,y,\lambda)[h(x,y,\lambda) * f_\mu(x,y,\lambda)]d\lambda + \epsilon_{\lambda,\mu}(x,y).$$

$C =$ system function, $\mu =$ linear polarization variable, $\lambda =$ wavelength, $h =$ PSF system function, solve inverse problem for f.

- Applied to surveillance through atmospheric turbulence, as part of UNM, Duke, WFU project.

Zhang, Plemmons, Kittle, Brady, Prasad. "**Joint segmentation and reconstruction of hyperspectral data with compressed measurements**". Applied Optics, 2011.

Tsai, Yuan, Carin, and Brady, "**Spatial light modulator based spectral polarization imaging**", OSA COSI Proc., 2014.

Plemmons, Prasad, Pauca, "**Spectro-polarimetric images taken through atmospheric turbulence**". OSA SRS Proc., 2014.

Spatial Light Modulator (SLM)-Based Imaging

Segmentation model:

$$f(x, y, \lambda) = \sum_{i=1}^{m} s_i(\lambda) u_i(x, y).$$

Resulting system forward model:

$$g(x, y) = \int_{\lambda} C_{\lambda}(x, y)[h_{\lambda}^{\phi}(x, y) * \sum_{i=1}^{m} s_i(\lambda) u_i(x, y)] d\lambda + \epsilon_{\lambda}(x, y).$$

Knowns: coded, blurred image g, and imaging system operator C.
Unknowns: phase function ϕ (in terms of the OPD), spectral signatures s_i, and support functions, u_i.
Approach: estimate the optical path difference function (OPD) first using a HSI of a laser guide star, then classify features of object.

Feature Classification of Hyperspectral Objects

- Assume the OPD is known as the estimated $\hat{\phi}$ from Berisha, Nagy, Ple. 2015 so each PSF h_λ is available. We estimate support functions u_i and spectral signatures s_i.

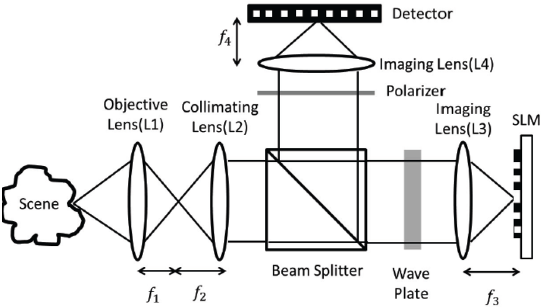
$$J(u,s) = \frac{1}{2}\left\|\int_\lambda C_\lambda(x,y)\left[h_\lambda(x,y) * \sum_{i=1}^{m} s_i(\lambda)u_i(x,y)\right] - g(x,y)\right\|_2^2 + \alpha \sum_{i=1}^{m}\int_{\mathbb{R}^2}\sqrt{\nabla_x^2 x_i + \nabla_y^2 y_i} + \frac{\beta}{2}\sum_{i=1}^{m}\int_\lambda \|s_i(\lambda)\|_2,$$

where we use total variation regularization for u_i and Tikhonov for spectral signatures s_i.

- Solve inverse problem for u_i, s_i using ADMM.

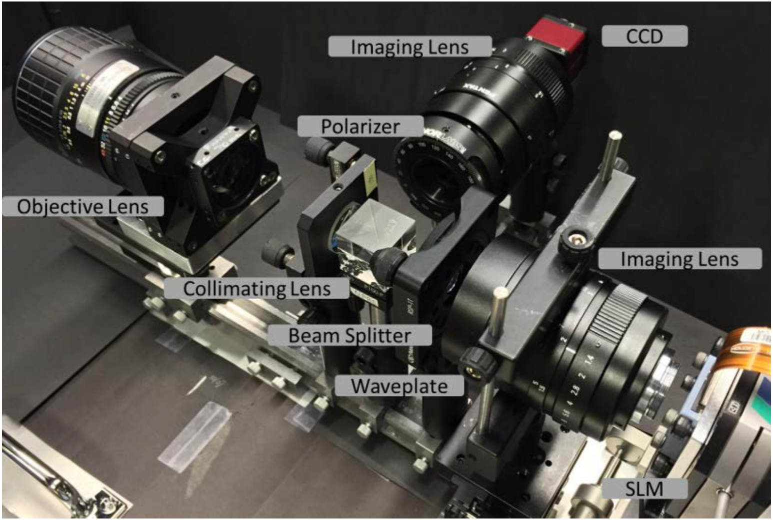
Sample Test Results by Duke graduate student TH Tsai

Schematic of compressive snapshot SPI



- Spatial light modulator (SLM) is from Holoeye Photonics and uses a liquid-crystal-on-silicon modulator.

Spectro-Polarimetric Camera - Duke, UNM, WFU AF Project



System modulates 4D tensor array images onto a 2D detector (matrix). Reconstruct 4 linearly polarized images.

Sample Test Results by Tsai at Duke - Cars

- (a) Unpolarized reference in RGB.
- (b) Compressed spectro-polarimetric measurement.
- (c) - (f) Reference polarized image channels in RGB.
- (g) - (j) Reconstructions from (b), pseudo color.

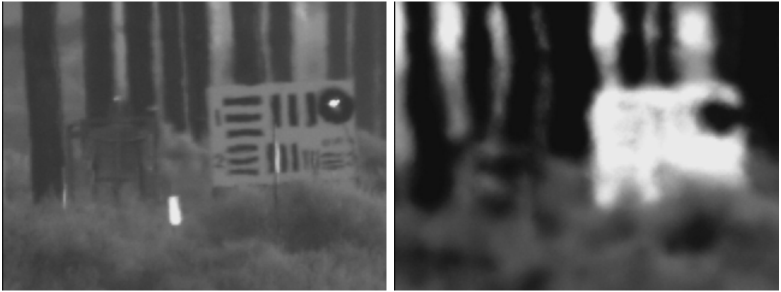
Atmospheric Turbulence Effect on Optical Images

Recent video: The Unexpected Math behind Van Gogh's "Starry Night" by Natalya St. Clair: http://youtu.be/PMerSm2ToFY

- **Variations in the index of refraction cause the plane optical wavefront from objects to be distorted**. Caused by variation of air temperature in eddies and air currents.
- In surveillance for **space situational awareness**, resolution of all ground-based telescopes is severely limited by turbulence.
- Can also cause extreme blurring in **ground-level (horizontal) imaging**.

Imaging Through Atmospheric Turbulence - Estimating a PSF for Deconvolution

- Ground-level turbulance - video imaging illustration 1km distance.



(a) Image taken in early morning (b) Afternoon inage through turbulence.

Active research topic: e.g., Zhu and Milanfar, 2012-13. Lou, Kang, Soatto, Bertozzi, 2013. Others ...
Methods generally based on selecting “lucky frames”, patches, image registration, fusion, segmentation etc.

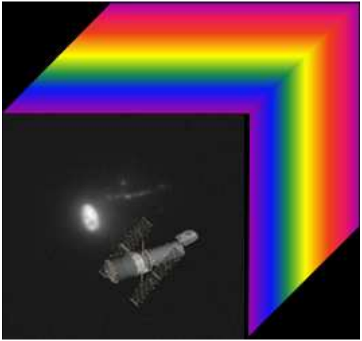
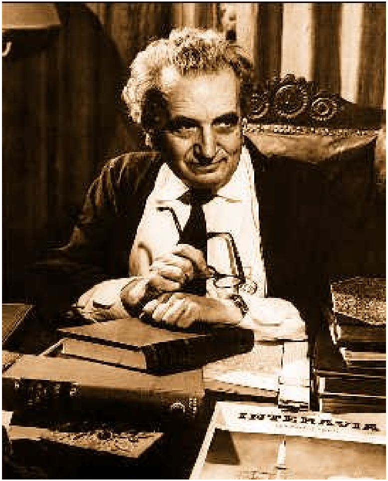


Figure 9: **Space object imaging from AFOSR Project**

Atmospheric Turbulence

Galileo, 1564-1642, knew effects of atmospheric turbulence on telescopes. Modern mathematical models developed by:



(a) Th. von Karman, 1881-1963

(b) Andrey Kolmogorov, 1903-1987

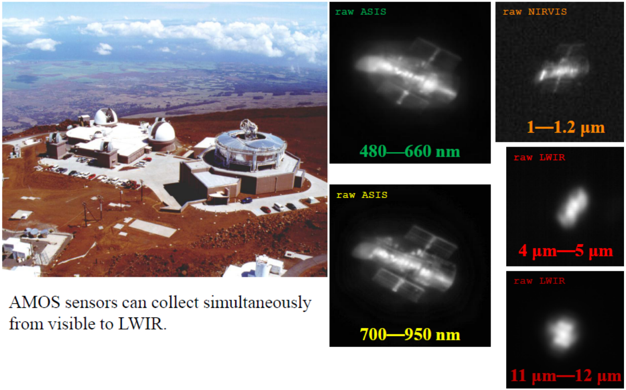
Elementary Optics - HSI Resolution Revolution (Physics Today, Dec. 2014)

Ernst Abbe
(1840-1905)

- German physicist Ernst Abbe realized the resolution of an imaging instrument is constrained by the wavelength of light used, and the aperture of its optics.
- Resolution (detail an image holds) is **proportional to the size of its aperture, and inversely proportional to the wavelength of the light** being observed: $Res \approx d/\lambda$. - opposite to the effect of atmospheric turbulence. Resolution also affected by blur & noise.
- We **estimate wavelength dependent PSFs for HSI**.

Imaging Through Atmospheric Turbulence - Estimating a PSF, or PSFs, for Deconvolution

- Satellite Surveillance. CBS 60 Minutes TV Documentary “The Battle Above,” May 2015.



AMOS sensors can collect simultaneously from visible to LWIR.

Berisha, Nagy, Plemmons 2015. Others ... Methods based on gradient & phase estimation leading to a PSF, turbulence modeling.

Hyperspectral Imaging (HSI) - Atmospheric PSFs

The image acquired at wavelength λ can be represented as

$$g_\lambda(x,y) = h_\lambda(x,y;\phi) * f(x,y,\lambda) + \epsilon_\lambda(x,y),$$

where the blurring kernel, with diffractive scaling included, is

$$h_\lambda(x,y;\phi) = \left(\frac{\lambda_0}{\lambda}\right)^2 h_0\left(\frac{\lambda_0}{\lambda}x, \frac{\lambda_0}{\lambda}y;\phi\right),$$

with $\lambda_0 =$ reference baseline wavelength, and

$$h_0(x,y;\phi) = \left|\mathcal{F}^{-1}\left(pe^{i\phi}\right)\right|^2,$$

and where the wavefront phase $\phi = \frac{2\pi}{\lambda} \times OPD$.

- **OPD** is the optical path difference function, i.e. the optical phase shift in passage through turbulent atmosphere.

HSI Unmixing/Deblurring: Wavelength Dependent PSFs

Solve the deblurring and sparse hyperspectral unmixing inverse problem of the form

$$\min_{\boldsymbol{X}\geq 0} \frac{1}{2}||\boldsymbol{HXM} - \boldsymbol{G}||_F^2 + \mu_1||\boldsymbol{X}||_1 + \mu_2 TV(\boldsymbol{X})$$

- $\boldsymbol{H} \in \Re^{N_p \times N_p}$ is a block diagonal PSF system matrix, with blocks h_λ constructed using HSI image of laser guide star.
- μ_1, μ_2 are two regularization terms used to control the importance of the sparsity and total variation. **ADMM** applied to compute $\boldsymbol{X}$.

Zhao, Wang, Huang, Ng, and Plemmons "Deblurring and Sparse Unmixing for Hyperspectral Images." IEEE Transactions on Geoscience and Remote Sensing, 2013.

Berisha, Nagy and Plemmons "Deblurring and Sparse Unmixing of Hyperspectral Images using Multiple (wavelength-dependent) PSFs." SIAM J. Sci. Comp., 2015.

Observed Hubble on Maui using HSI, 100 Channels

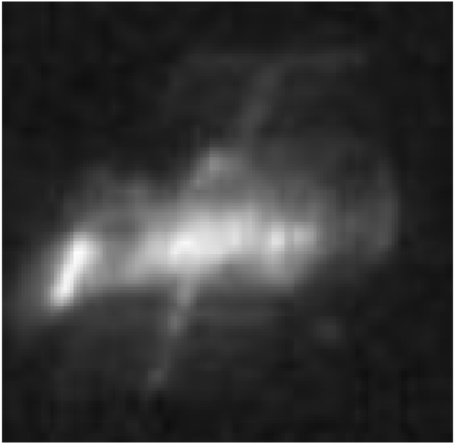
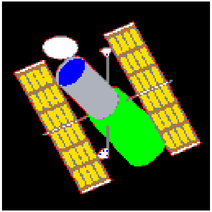


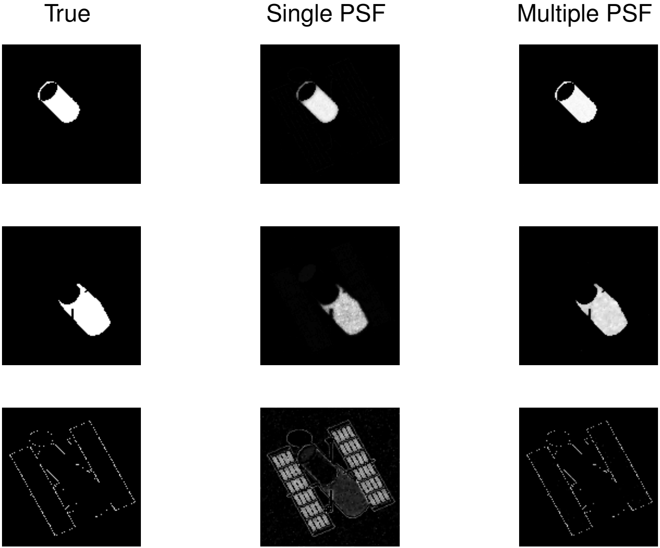
Figure 11: **Space object imaging - HST image wavelength 575 nm.**

Test Results: Simulated Data for HST Satellite - Materials from NASA Database



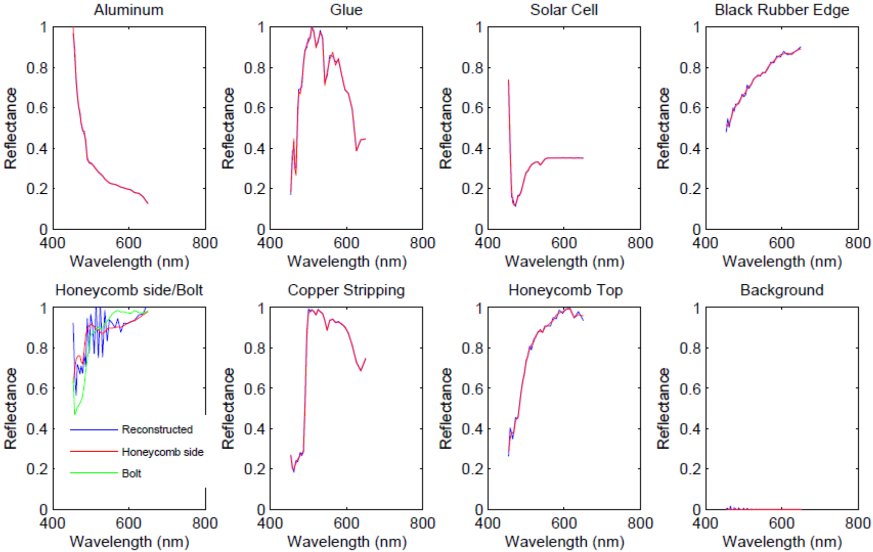
Material	Color	Constituent Endmembers	Frac. Abun. (%)
Material 1	green	Aluminum	37
Material 2	light grey	black rubber edge	4
Material 3	red	copper stripping	8
Material 4	dark gray	honeycomb side	4
Material 5	brown	bolts	3
Material 6	gold	solar cell	28
Material 7	blue	glue	9
Material 8	white	Hubble honeycomb top	7

Blurred - von Karman Model for At. Turb., SNR 20
Some Reconstructed Fractional Abundance Maps



Some Reconstructed Material Spectral Signatures

True material spectral signatures: — Computed spectral signatures: —.



Comments

- Overview of optical imaging data modalities for dynamic surveillance.
- Overview of our projects - NGA & AFOSR, recent and new.
- Compressive snapshot HSI - enables HSI video for object tracking and identification.
- SLM-based spectro-polarimetric imaging - Adds polarization channels useful in identifying object shape and surface properties.
- Prototype camera systems and test results.
- Estimating wavelength-dependent HSI PSFs for atmospheric turbulence. Joint deblurring and feature identification.

Topics in Current Work

- Mathematical design tools for range-integrated high-dim. object tracking systems, including 3D, 4D imaging using rotating HSI PSFs, dynamic surveillance for current Air Force (AFOSR) project.
- LiDAR, HSI and polarimetric imaging surveillance technologies, with video. Proposed National Geospatial-Intelligence Agency (NGA) Project.

Final thoughts, inspired by Sigfried Russwurm at Siemens. “We might keep in mind that it’s not always data volume but the content and algorithms for processing data that are crucial.”

Thank You!

Papers available at: http://users.wfu.edu/plemmons/