Professional Development Short Course On:

Hyperspectral and Multispectral Imaging

Instructor:

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Course Outline

• **Introduction to Imaging Spectrometry**
  – Spectral Sensing Concepts
  – Quantitative Remote Sensing Techniques
  – Literal and Non-Literal Information
  – Multi-Sensor Concepts
  – Hyperspectral/Multispectral Systems
  – Scientific Principles

• **Hyperspectral Concepts and Multi-System Tradeoffs**
  – Spectral/Spatial Resolution, Sampling, Range
  – Temporal Resolution
  – Signal-to-Noise Ratio (SNR)
  – Calibration Techniques
  – Spectral Smile and Keystone Effects
  – Dispersion Techniques
  – Infrared HSI Systems
  – Current HSI Active and Passive Systems
Course Outline (Cont.)

- **Hyperspectral Imaging Data Processing**
  - N-Dimensional Analysis and Visualization
  - Classification Techniques
  - Pattern Recognition Methods
  - Principal Component Analysis (PCA)
  - Spectral Matching
  - Spectral Angle Mapping
  - Pixel Purity Index (PPI)
  - Minimum Noise Fraction (MNF)
  - Mixture Tuned Matched Filtering (MTMF)
  - Spectral Libraries
  - Case Studies
  - U.S. National Policy Issues
What is Hyperspectral Sensing?

- Quantitative measurements of the spectral characteristics of materials using a remote sensing system having greater than 60 spectral bands with a spectral resolution less than 10 nm producing a contiguous portion of the light spectrum which defines the chemical composition of the material through its spectral signature.

- Hyperspectral sensing allows the analyst to perform reflectance or fluorescence spectroscopy on each spatial element (pixel) of the image scene.
What is a Photon?

- \( \Delta E = h\nu \)

- \( \Delta E = E_2 - E_1 = \) Energy of photon in joules (J).
  \( \nu = \) Frequency of the photon in hertz.
  \( h = \) Planck's constant = 6.625 \( \times \) 10\(^{-34}\) joule-seconds

- Wavelength \( \lambda = c/\nu = hc/\Delta E \)

- A light wave that is emitted with a single quantum of energy \( \Delta E = h\nu \) is called a “photon”
Electromagnetic Energy

- REFLECTED
- SCATTERED
- ABSORBED
- TRANSMITTED (AND REFRACTED)
- EMITTED
Hyperspectral Sensing Concept

Spatial Information

Imagers

Imaging Spectrometers

Spectrometers

Imaging Radiometers

Spectroradiometers

Radiometers

Spectral Information

Intensity Information

After Elachi, JPL
Hyperspectral Sensing Concept (Cont.)

Images acquired simultaneously in many narrow, registered spectral bands.
Hyperspectral Sensing

- Flight Line
- Single Pixel
- Spatial Pixels
- Spectral Bands
- Single Sensor Frame
- Series of Sensor Frames
- Pixel Spectrum
- Wavelength
- Intensity
Data Space Representations

- Image Space - Geographic Orientation
- Spectral Signatures - Physical Basis for Response
- N-Dimensional Space - For Use in Pattern Analysis
Multispectral Imaging

Alunite as seen by three systems:

- ~65-250 nm
- 10-50 nm
- 5-10 nm

Reflectance + Offset

Wavelength (μm)
Hyperspectral Imaging

![Graph showing the reflectance of alunite as seen by various imaging spectrometers.](image)
Classification of Sensors

• Image Acquisition Modes
  – Whiskbroom Imagers
  – Pushbroom Imagers
  – Staring Imagers

• Spectral Selection Modes
  – Dispersion Element (grating, prism)
  – Filter-Based Systems
    • Interference Filters
    • Acoustical-Optical Filters
    • Liquid Crystal Tunable Filters (LCTF)
  – Interferometer-Based Systems
    • Michelson Interferometer
    • Fourier Transform Interferometer System

• Other (e.g., Multi-order etalons)
Airborne Hyperspectral Systems

- 1983 AIS, 10m pixels, 128 bands (0.8-2.4um) - retired
- 1986 GER 63, 10m pixels, 63 bands (0.43-2.5um)
- 1987 AVIRIS, 3, 20m pixels, 224 bands (0.40-2.45um)
- 1989 CASI, 10m pixels, 288 bands (0.4-0.9um)
- 1993 AISA, 286 bands (0.43-0.9 um)
- 1994 TRWIS III, 242 bands (0.45-2.5 μm)
- 1995 HYDICE, 210 bands (0.4-2.5 um)
- 1996 HyperCam, 256 bands (0.45-1.05 μm)
- 1997 PROBE-1, 128 bands (0.43-2.5um)
- 1998 HyMap, 126 bands (0.4-2.5 um)
- 1999 AURORA, 512 bands (0.4-0.9 um)
Spaceborne Hyperspectral Systems

- Australian Resource Information and Environment Satellite (ARIES)

- NASA’s Aqua satellite carries the Atmospheric Infrared Sounder (AIRS) an advanced sounder containing 2378 infrared channels and four visible/near-infrared channels was launched 4 May 2002

- Orbview 4 (Warfighter 1)  
  Launched: 21 September 2001  (Failed to Orbit)

- NASA EO-1 Hyperion (Built by TRW)  
  Launched: 21 November 2000

- AFRL MightySat II.1 (Sindri) - FTHSI  
  Launched: 19 July 2000

- Compact High Resolution Imaging Spectrometer (CHRIS)  
  Launched aboard ESA’s Proba satellite on 22 October 2001
Spectral Database Issues

• Existing spectral libraries are in a wide variety of formats and need to be consolidated

• A spectral database is an essential tool on which to base future research

• A spectral database will be absolutely necessary to handle flood of future data

• A spectral database could be federated with other applicable databases (e.g., Imagery, DEMs, IFSAR, etc.)
Atmospheric Effects (Richards Fig. 2.1)
Atmospheric Compensation Models

• Physics – based Models
  – ATmospheric REMoval (ATREM)
  – Atmospheric CORrection Now (ACORN)
  – Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH)
    • FLAASH utilizes the Full MODTRAN-4
  – High-Accuracy Atmospheric Correction for Hyperspectral (HATCH) Data

• Semi-Empirical Models

• Empirical Models
Hyperspectral Data Processing

After Sam Barr, TEC
Spectral Sensing Processing Systems

- Spectral Analysis Manager (SPAM) – JPL
- Integrated Software for Imaging Spectrometers (ISIS) – USGS Flagstaff
- Hyperspectral Image Processing System (HIPS) – U.S. Army TEC
- Spectral Image Processing System (SIPS) – University of Colorado, Boulder
- SPECtrum Processing Routines (SPECPR) – USGS Denver
- Optical Real-time Adaptive Spectral Identification System (ORASIS) – NRL
- DIMPLE – RockWare, Inc.
- Imaging Spectrometer Data Analysis System (ISDAS) – CCRS in Canada
- PCI – PCI Remote Sensing Corporation
- Environment for Visualizing Images (ENVI) – Research Systems, Inc.
- Multispectral Image Data Analysis System (MultiSpec) – Purdue University
- HyperCube – U. S. Army TEC
- ProVIEW – Applied Coherent Technology, Inc.
- ERDAS IMAGINE – Commercial package
- Others
Refraction bends the light downward upon entrance into the glass and again upon exit from a double convex lens.

Snell's Law governs the directions taken.

The image distance can be determined by using the lens equation and the linear magnification is determined from the ratio of image and object distances.

Parallel rays pass through principal focus point.

OBJECT

IMAGE (inverted, real image)

Real Images

Virtual Images
Index of Refraction and Snell’s Law

Snell's Law

\[ \frac{n_1}{n_2} = \frac{\sin \theta_2}{\sin \theta_1} \]

\( n = \frac{c}{v} \) (refractive index)

\( c = \text{speed of light in vacuum} \quad v = \text{speed of light in medium} \)
Prism

\[ n = \frac{\sin \xi_0}{\sin \xi} = \frac{\sin \zeta}{\sin \zeta_0} \]

\[ n = \sin \left( \frac{\alpha}{2} + \frac{\varphi}{2} \right) / \sin \left( \frac{\alpha}{2} \right) \]

\[ D = \frac{d\varphi}{d\lambda} = \left( \frac{d\varphi}{dn} \right) \left( \frac{dn}{d\lambda} \right) \]

\[ \frac{dn}{d\varphi} = \frac{\cos \left( \frac{\alpha}{2} + \frac{\varphi}{2} \right)}{2\sin \left( \frac{\alpha}{2} \right)} \]

\[ D = \frac{2\sin(\alpha/2)}{\cos(\alpha/2 + \varphi/2)} \cdot \frac{dn}{d\lambda} = \frac{2\sin(\alpha/2)}{\sqrt{1 - n^2 \sin^2(\alpha/2)}} \cdot \frac{dn}{d\lambda} \]
Double Slit Diffraction

Assumption of infinite source distance gives plane wave at slit so that all amplitude elements are in phase.

\[ \tan \theta = \frac{y}{D} \]

For distant screen assumption

\[ \tan \theta \approx \sin \theta \approx \theta \approx \frac{y}{D} \]

Condition for maximum

\[ d \sin \theta = m \lambda \]

\[ y \approx \frac{m \lambda D}{d} \]
The Pixel Mixing Problem
Hyperspectral Sensing Applications

- Material Identification
- Homeland Security
- Environmental (wetlands, land cover, hydrology, etc.)
- Health Care (food safety, medical diagnoses, etc.)
- Littoral Studies (bathymetry, water clarity, etc.)
- Trafficability Analysis
- Land Mine Detection
- Plume Analysis
- Camouflage, Concealment, Detection
- Biological and Chemical Detection
- Precision Agriculture/Farming
- Disaster Mitigation
- City Planning and Real Estate
- Law Enforcement
- Many Others
Classification (Cont)
Problem: Find the value of vector $\mathbf{x}$ from measurement of a different vector $\mathbf{y}$, where they are related by the matrix equation given by:

$$\mathbf{y} = \mathbf{A}\mathbf{x}$$

or

$$y_i = \sum a_{ij}x_j \quad \text{sum over } j$$

Note 1: If both $\mathbf{A}$ and $\mathbf{x}$ are known, it is trivial to find $\mathbf{y}$

Note 2: In our problem, $\mathbf{y}$ is the measurement, and $\mathbf{A}$ is determined from the physics of the problem, and we want to retrieve the value of $\mathbf{x}$ from $\mathbf{y}$
Mean and Variance

- Mean:

\[
<x> = \frac{1}{N} \sum x_k
\]

- Variance:

\[
\text{var}(x) = (1/N) \sum (x_k - <x>)^2 = \sigma_x^2
\]

where \( k = 1,2,\ldots,N \)
Covariance

\[ \text{cov}(x,y) = \frac{1}{N} \sum (x_k - \langle x \rangle)(y_k - \langle y \rangle) \]

\[ = \frac{1}{N} \sum x_k y_k - \langle x \rangle \langle y \rangle \]

Note1: \( \text{cov}(x,x) = \text{var}(x) \)

Note2: If the mean values of \( x \) and \( y \) are zero, then

\[ \text{cov}(x,y) = \frac{1}{N} \sum x_k y_k \]

Note3: Sums are over \( k = 1,2, \ldots, N \)
Covariance Matrix

• Let $\mathbf{x} = (x_1, x_2, \ldots, x_n)$ be a random vector with $n$ components.

• The covariance matrix of $\mathbf{x}$ is defined to be:

$$
C = \langle (\mathbf{x} - \mu)(\mathbf{x} - \mu)^T \rangle
$$

where

$$
\mu = (\mu_1, \mu_2, \ldots, \mu_k)^T
$$

and

$$
\mu_k = \frac{1}{N} \sum x_{mk}
$$

Summation is over $m = 1,2,\ldots, N$.
The SAM algorithm uses a reference spectra, \( r \), and the spectra found at each pixel, \( t \). The basic comparison algorithm to find the angle \( \alpha \) is: (where \( nb = \) number of bands in the image)

\[
\arccos \left[ \frac{\vec{t} \cdot \vec{r}}{\|\vec{t}\| \|\vec{r}\|} \right]
\]

OR

\[
\arccos \left[ \frac{\sum_{i=1}^{nb} t_i r_i}{\sqrt{\sum_{i=1}^{nb} t_i^2} \sqrt{\sum_{i=1}^{nb} r_i^2}} \right]
\]
Monitoring Tissue Physiology

Reflectance and fluorescence could be used with a hyperspectral sensor to determine tissue characteristics.
Clinical Chemistry Hyperspectral Sensing

The quantitative reagentless determination of analytes in such common fluids as blood/serum or urine.
Automated Chicken Inspection

Use of spectral imaging technology for on-line detection of wholesome poultry during slaughter. (Agriculture Research Magazine)
NASA AVIRIS flights over Cuprite, Nevada. The JPL and the Spectroscopy Group at the U.S. Geological Survey in Denver reduced and manipulated the data.
The fusion of higher spatial resolution panchromatic imagery with high spectral, low spatial resolution MSI or HSI resulting in a spectrally accurate, high spatial resolution image.
Summary

• Hyperspectral Imaging (HSI) is a Mature Technology

• Sensor and Data Fusion is the way to go

• Data Collection, Storage, and Usage Methods are Currently Inefficient
  – Crucial Data are Costly and Hard to Find
  – Need for Accessible, Up-to-Date, Relevant, Accurate, Timely, and User- Friendly Digital Spectral Information Library (Spectral Data Bank)

• Need Standards, Definitions, Policies, and Collaborations

• Emphasis Needs to be Placed in Training the Workforce
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