

IMAGING SPECTROMETRY

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Summary

Imaging spectrometers are sensors that acquire imaging data in many narrow and spectrally contiguous bands with the aim of reproducing the spectral response of targets on the earth's surface. Many airborne systems are operational and a series of spaceborne imaging spectrometer experiments will be set up and conducted in the future. Electronic processes and changes in vibrational energy levels largely determine the spectral response of materials resulting in absorption bands of <100 nanometres (nm) in width in the visible part of the spectrum and between 10 and 30 nm in width in the shortwave infrared. Variations in thermal emission can also be measured with some imaging spectrometer systems. Pre-processing of imaging spectrometer data includes sensor calibration, atmospheric correction, geocoding, and noise adjustment. The resulting calibrated reflectance data sets are well suited for environmental studies. In mineral and petroleum exploration, such data are used for mineral mapping, providing insight into alternative schemes that may lead to new discoveries of ore deposits and allow prosperous zones for oil and gas reservoirs to be located. In soil science, much emphasis has been placed on the use of spectroscopy for soil surface properties and soil compositional analysis. Biophysical models for leaf constituents are now available as well as soil-vegetation models. Estimates of plant material and structure and biophysical variables include carbon balance, yield/volume, nitrogen, cellulose, and chlorophyll. The leaf area index and vegetation indices have been extended to the hyperspectral domain and remain important physical variables characterizing vegetation. Very important in imaging spectrometry of water bodies are the atmospheric correction and air–water interface corrections. Water quality of freshwater aquatic environments, estuarine environments, and coastal zones are important to national water bodies. The detection and the identification of phytoplankton-biomass, suspended sediments and other matter, coloured dissolved organic matter, and aquatic vegetation (i.e. macrophytes) are crucial variables in optical models of water quality. Much emphasis has been put on the mapping and monitoring of the state and the growth or breakdown of coral reefs, as these are important in the carbon dioxide cycle. Atmosphere studies are important in global change models and aid in the correction of optical data for scattering and absorption due to atmospheric trace gases.

1. Introduction and Historical Perspective

Remote sensing is concerned with devices that measure and quantify physical properties of objects without making contact with these objects. In the optical window, we typically are concerned with the measurement of radiance or photon flux densities from objects. Often this is translated as reflectance: the dimensionless ratio of incident and outgoing radiance from an object. Most currently operational satellite Earth-observation systems and sensors acquire data in a number of broad wavelength bands. Typical diagnostic absorption features characterizing materials of interest in reflectance spectra are in the order of 20 to 30 nanometres (nm) in width. Hence, the broadband sensors

undersample this information. Imaging spectrometers typically acquire images in a large number (>40) of narrow (<0.01 to 0.02 micrometres (μm) in width) contiguous (i.e. adjacent and not overlapping) spectral bands to enable the extraction of reflectance spectra at a pixel scale that can be directly compared with similar spectra measured either in the field or in a laboratory. The objective of imaging spectrometry is to measure quantitatively the components of the earth's system, radiance, upwelling radiance, emissivity, temperature, and reflectance from calibrated spectra acquired as images for scientific research and applications. Different names, although similar in use, have been coined for this field of remote sensing, including “imaging spectrometry” (i.e. measuring spectra), “imaging spectroscopy” (i.e. seeing spectra), and “hyperspectral remote sensing.” The latter term literally means “too many bands available.”

Imaging spectrometers have been used for many years in military applications such as differentiating camouflage from real vegetation. Due to the classified nature of the data and sensors, not much can be said about the origin and applications being served. The first scanning imaging spectrometer was the scanning imaging spectroradiometer (SIS) constructed in the early 1970s for the U.S. National Aeronautics and Space Administration (NASA) Johnson Space Center. Civilian airborne spectrometer data were measured in 1981 using a one-dimensional profile spectrometer developed by the Geophysical Environmental Research Company, which acquired data in 576 channels covering the 0.4 – 2.5 μm wavelength range, followed by the shuttle multispectral infrared radiometer (SMIRR) in 1981.

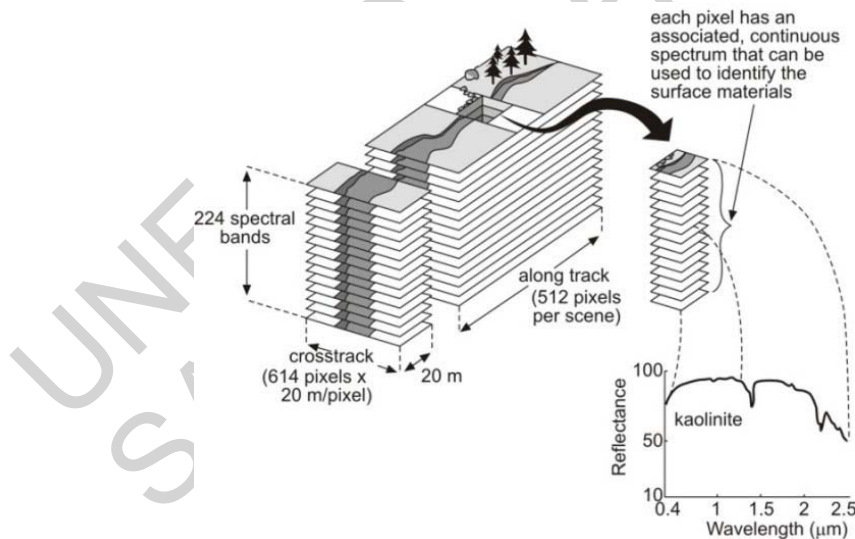


Figure 1. Concept of imaging spectrometry

The first imaging device was the fluorescence line imager (FLI; also known as the programmable line imager, PMI) developed by Canada's Department of Fisheries and Oceans (in 1981) followed by the airborne imaging spectrometer (AIS) developed at the NASA Jet Propulsion Laboratory, which was operational from 1983 onwards, acquiring 128 spectral bands in the range 1.2 – 2.4 μm . The field of view of 3.7° resulted in 32

pixels across-track. A later version of the instrument, AIS-2, covered the 0.8–2.4 μm region, acquiring images 64 pixels wide. Since 1987, NASA has been operating the successor of the AIS systems, the airborne visible/infrared imaging spectrometer (AVIRIS). Since then, many private companies have also taken part in the rapid development of imaging spectrometry. Initiatives are described in a later paragraph on airborne systems.

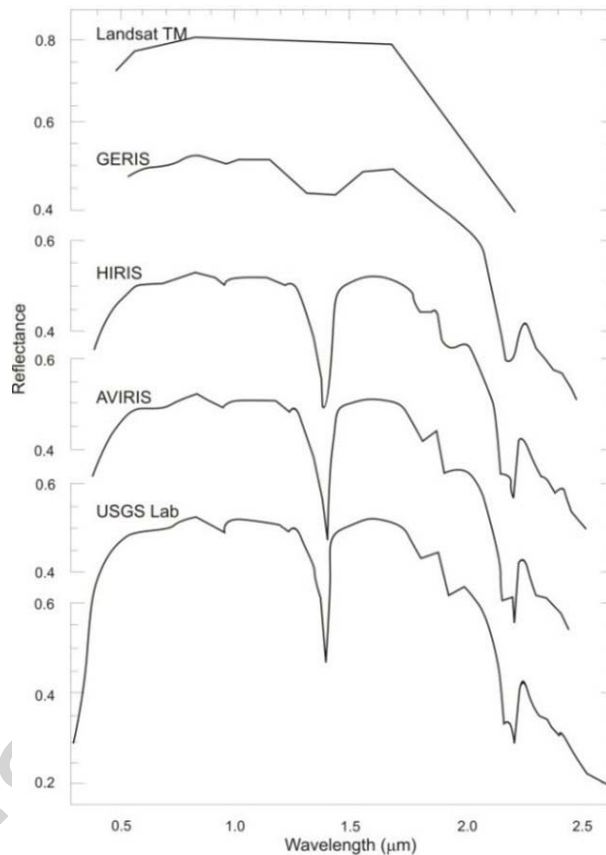


Figure 2. Example of a kaolinite spectrum at the original (USGS Laboratory) spectral resolution and at the spectral resolutions of various imaging devices

Through measurement of the solar reflected spectrum, a wide range of scientific research and application is being pursued using signatures of energy, molecules, and scatterers in the spectra measured by imaging spectrometers. These fields include:

- Atmosphere: water vapour, cloud properties, aerosols, absorbing gases
- Plant ecology: chlorophyll, leaf water, lignin, cellulose, pigments, structure, vegetation species and community maps, nonphotosynthetic constituents, etc.
- Geology and soils: mineralogy, soil type, etc.
- Coastal and inland waters: chlorophyll, plankton, dissolved organics, sediments, bottom composition, bathymetry, etc.
- Snow and ice hydrology: snow cover fraction, grainsize, impurities, melting, etc.
- Biomass burning: subpixel temperatures and extent, smoke, combustion products, etc.

- Environmental hazards: contaminants direct and indirect, geological substrate, etc.
- Calibration: aircraft and satellite sensors, sensor simulation, standard validation, etc.
- Modelling: radiative transfer model validation and constraint, etc.
- Commercial: mineral exploration, agriculture and forest status, etc.
- Algorithms: autonomous atmospheric correction, advanced spectra derivation, etc.
- Other: human infrastructure, mine detection, etc.

2. Physics of Spectroscopy

This section deals with the physical basis of imaging spectrometry (for more details, see *Physical Basis of Remote Sensing*). When light interacts with a mineral or rock, light of certain wavelengths is preferentially absorbed while at other wavelengths is transmitted in the substance. Reflectance, defined as the ratio of the intensity of light reflected from a sample to the intensity of the light incident on it, is measured by reflection spectrophotometers, which are composed of a light source and a prism to separate light into different wavelengths. This light beam interacts with the sample and the intensity of reflected light at various wavelengths is measured by a detector relative to a reference standard of known reflectance. Thus, a continuous reflectance spectrum of the sample is obtained in the wavelength region measured. Reflectance spectra have been used for many years to obtain compositional information on the earth's surface. Electronic transition and charge transfer processes (e.g. changes in energy states of electrons bound to atoms or molecules) associated with transition metal ions such as iron (Fe), titanium (Ti), and chromium (Cr) largely determine the position of diagnostic absorption features in the visible and near-infrared (NIR) wavelength region of the spectra of minerals. In addition, vibrational processes in water vapour (H₂O) and hydroxide ions (OH⁻) (e.g. small displacements of the atoms about their resting positions) produce fundamental overtone absorptions. The total energy of a molecule W_t is the sum of the electronic energy W_e , the vibrational energy W_v , and the rotational energy W_r , as

$$W_t = W_e + W_v + W_r. \quad (1)$$

Changes in energy states of molecules due to changes in rotational energy levels do not occur in solids and will not be treated here. Thermal radiation is emitted by all objects at temperatures above absolute zero. Consider an area dA and radiation arriving at a direction θ to the normal of dA , but in the range of directions forming a solid angle of $d\Omega$ steradians. Radiance, L , in $\text{Wm}^{-2}\text{sr}^{-1}$, is defined as

$$d\Phi = LdAd\Omega \cos\theta. \quad (2)$$

The total power falling on dA from all directions is given by the integration over 2π steradians in case of no absorption nor scattering by

$$\Phi = dA \int_{2\pi} L \cos\theta d\Omega = EdA, \quad (3)$$

where E is called irradiance measured in Wm^{-2} . In the reverse case, when E measures the total radiance leaving dA , we refer to exitance, M , and the total power emitted by the source is radiant intensity, I , defined as

$$\Phi_{total} = Id\Omega. \quad (4)$$

These quantities can be expressed spectrally by introducing an interval of wavelength λ and integrating over $d\lambda$. Spectral radiance according to Planck's relationship (see *Physical Basis of Remote Sensing*) is given by

$$L_{\lambda} = \frac{2hc^2}{\lambda^5} (e^{hc/\lambda kT} - 1)^{-1}, \quad (5)$$

where h is Planck's constant, k is Boltzmann's constant ($1.38 \times 10^{-23} \text{JK}^{-1}$), c is the speed of light (in a vacuum), and T is the temperature. The total outgoing radiance of a black body of temperature T is given by

$$L = \int_0^{\infty} L_{\lambda} d\lambda = \frac{2\pi^4 k^4}{15c^2 h^3} T^4, \quad (6)$$

where $\sigma = \frac{2\pi^4 k^4}{15c^2 h^3}$ is known as Stefan-Boltzmann's constant ($5.67 \times 10^{-8} \text{Wm}^{-2} \text{K}^{-4}$).

Wien's displacement law gives the relation between the wavelength at which the maximum radiation is reached, λ_{\max} , and the temperature of the black body as

$$\lambda_{\max} = c_w / T, \quad (7)$$

where c_w is a constant (Wien's constant) of $2.898 \times 10^{-3} \text{Km}$ (see *Physical Basis of Remote Sensing*). When radiation interacts with a surface, it is partly absorbed into the substance, and partly scattered or reflected by the object. Consider a collimated beam of radiation incident on a surface at an incidence angle θ_0 . The irradiance E is given by $F \cos \theta_0$ and scattered into a solid angle $d\Omega$ in a direction θ_1 . The outgoing radiance of the surface as a result of this illumination is L_1 in the direction (θ_1, ϕ_1) where ϕ_1 is the azimuthal angle. The bidirectional reflectance distribution function (BRDF) (see also *Field Spectrometry*) R (in sr^{-1}) is defined as

$$R = L_1 / E. \quad (8)$$

R is a function of the incident and scattered directions and can thus be noted as $R(\theta_0, \phi_0, \theta_1, \phi_1)$. The reflectivity of the surface, r , (also known as albedo) is the ratio of the total power scattered to the total power incident as

$$r(\Theta_o, \Phi_o) = \int_{\Theta=0}^{\pi/2} \int_{\phi=0}^{2\pi} R \cos \Theta_1 \sin \Theta_1 d\Theta_1 d\phi_1. \quad (9)$$

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Bibliography

Baumgardner M.F., Stoner E.R., Silva L.F., and Biehl L.L. (1985). Reflectance properties of soils. *Advances of Agronomy* (ed. N. Brady), pp. 1–44. New York: Academic Press. [This chapter provides a review of the reflectance properties of soils.]

Clark R.N., King T.V.V., Kleijwa M., Swayze G.A., and Vergo N. (1990). High spectral resolution reflectance spectroscopy of minerals. *Journal of Geophysical Research* **95**, 12653–12680. [Example of a study of the spectroscopic behaviour of minerals and rocks.]

Curran P.J. (1994). Imaging spectrometry. *Progress in Physical Geography* **18**, 247–266. [This provides an interesting review of imaging spectrometry for soil and vegetation sciences.]

Elvidge C.D. (1990). Visible and near infrared reflectance characteristics of dry plant material. *International Journal of Remote Sensing* **11**, 1775–1795. [This work provides an extensive review of the spectral properties of vegetation and plant materials.]

Gao B.C. and Goetz A.F.H. (1995). Retrieval of equivalent water thickness and information related to biochemical components of vegetation canopies from AVIRIS data. *Remote Sensing of Environment* **52**, 55–162. [Good text on the use of imaging spectrometry for atmospheric sciences.]

Goetz A.F.H., Vane G., Solomon J.E., and Rock B.N. (1985). Imaging spectrometry for Earth remote sensing *Science* **228**, 1147–1153. [Classic paper that marked the start of the era of imaging spectrometry; good geologic examples.]

Hunt G.R. (1980). Electromagnetic radiation: the communication link in remote sensing. *Remote Sensing in Geology* (ed. B. Siegal and A. Gillespie), pp. 5–44. New York: John Wiley. [In my opinion, still the best text to understand the interaction between electromagnetic radiation and matter.]

Ichoku C. and Karnieli A. (1996). A review of mixture modelling techniques for sub-pixel land cover estimation. *Remote Sensing Reviews* **13**, 161–186. [This paper reviews the mixture modelling and fuzzy techniques for classifying imaging spectrometer data.]

Kähle A.B., Palluconi F.D., Hook S.J., Realmuto V.J., and Bothwell G. (1991). The advanced spaceborne thermal emission and reflectance radiometer (ASTER). *International Journal of Imaging Systems Technology* **3**, 144–156. [This first paper on the ASTER sensor was followed by a special issue of the IEEE journal in 1999.]

Kruse F.A. (1988). Use of airborne imaging spectrometer data to map minerals associated with hydrothermally altered rocks in the Northern Grapevine Mountains, Nevada, and California. *Remote Sensing of Environment* **24**, 31–51. [Typical paper demonstrating the use of imaging spectrometry for geologic prospecting.]

Rast M., Bézy J.L., and Bruzzi S. (1999). The ESA medium resolution imaging spectrometer MERIS: a review of the instrument and its mission. *International Journal of Remote Sensing* **20**, 1681–1702. [A paper providing details of the MERIS instrument; part of a special issue on MERIS.]

Salisbury J.W. (1993). Mid-infrared spectroscopy: laboratory data. *Remote Geochemical Analysis: Elemental and Mineralogical Composition* (ed. C.M. Pieters and P.A.J. Englert), pp. 79–98. Cambridge, U.K.: Cambridge University Press. [The best text on mid-infrared spectroscopy.]

Van der Meer F. and De Jong S. (2001). *Imaging Spectrometry: Basic Principles and Prospective Applications*. Dordrecht: Kluwer Academic, 425 pp. [Recent edited volume of imaging spectrometry containing three chapters dealing with fundamental principles and 10 chapters dealing with various thematic applications.]

Biographical Sketch

Professor Dr. Freek D. van der Meer (1966) received his B.Sc. in geology (1984) from the Free University of Amsterdam and his M.Sc. in structural geology and tectonics from that same university in 1989 after completing major topics on geophysics at the University of Utrecht. He worked for Delft Geotechnics on the processing of groundradar data and was appointed lecturer in geology at the International Institute for Aerospace Survey and Earth Sciences ITC in 1989. To date, he has worked in various positions at ITC, being involved in education, research, and consulting activities, mostly abroad. His research interests lie in the field of geologic imaging spectrometry and spatial statistics. In 1999, he was appointed part-time full professor in imaging spectrometry in the Faculty of Civil Engineering and Geosciences of the Delft University of Technology, a position he combines with his work at ITC. Dr. van der Meer has published over 70 papers in international journals and has authored more than 100 other publications. He is chairman of the Netherlands Society for Earth Observation and Geoinformatics, associate editor for *Terra Nova*, editor of the Remote Sensing and Digital Image Processing Series of Kluwer and editor of the books *Spatial Statistics for Remote Sensing* and *Imaging Spectrometry: Basic Principles and Prospective Applications* published by Kluwer Academic.