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James B. Breckinridge

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## Invited Paper

Evolution of imaging spectrometry:  
past, present and future

James B. Breckinridge  
Observational Systems Division  
Jet Propulsion Laboratory, California Institute of Technology  
Pasadena, California 91109

### ABSTRACT

An overview of the physical principals of imaging spectrometry for detailed characterization of remote objects and of gas vapors is given. The terms Multi-spectral, Hyperspectral, and Ultra-spectral are defined within the framework of applications and instrument system design approaches. History of the development of imaging spectrometers is reviewed. We are at the threshold of major commercial efforts for these instrument systems.

### 1. INTRODUCTION

Man views his surroundings in color and draws conclusion about the character of the environment that effects his well being. For example, red and yellow leaves on trees indicates the season is fall and perhaps an overcoat is required. A 2-inch spherical object is observed to have a rough texture and be yellow, a clue this might be a lemon. Man fuses his senses of color, shape, size and weight to characterize his surroundings. The visual colors provide clues about the maturity and health of plants and help us to identify rock, soil and mineral types. Man's vision is limited to less than 10% of the spectral region available to imaging spectrometers. These new instruments which cover over 10 times the spectral region covered by the eye are a powerful tool that is providing new understanding of the world around us.

Economic security of the US depends our ability to manage our resources of land, water, forestry, crops, coastal zone, and atmosphere. The NASA mission to planet earth (MTPE) science objectives address the fundamental physical, chemical, and biological phenomena that govern and integrate the Earth system. Imaging spectrometers will provide much of the scientific data required. MTPE observations will permit assessment of various Earth system processes, including the following: 1. Hydrologic processes, which govern the interactions of land and ocean surfaces with the atmosphere through the transport of heat, moisture, and momentum. 2. Biogeochemical processes, which contribute to the formation, dissipation, and transport of trace gases and aerosols, and their global distributions. 3. Atmospheric processes, which control the formation, dissipation, and distribution of clouds and aerosols and their interactions with solar radiation. 4. Ecological processes, which are affected by and/or will affect global change, and their response to such changes through adaptation. 5. Geophysical processes, which have shaped or continue to modify the surface of the Earth through tectonics, volcanism, and the melting of glaciers and sea ice.

### 2. FUNDAMENTAL PRINCIPALS

Each solid, liquid and gas has its own unique spectral fingerprint characteristic of its chemical composition. These unique spectral finger prints are seen using infrared spectrometers. Imaging spectrometers are used to obtain information about both the spectral and the spatial distribution of solids, liquids and gases. Solids are typically observed in reflected sunlight in the visible and in the near infrared wavelength regions. Imaging spectrometry from surfaces (liquids or solids) reveals information about the chemical composition of that surface. For example, soil types, minerals, and agriculture crops (oats, grasses, barley, etc.) are identified and characterized by interpreting data recorded by imaging spectrometers in aircraft or spacecraft. The molecular structure of gases or vapors are observed in either emission or absorption and typically in the 2 to 16 micrometer wavelength region.

#### 2.1 System categories:

Three categories of instrument systems are identified based on a pre-defined measurement objective. These are: Multi-spectral, Hyperspectral and Ultra-spectral.

### 2.1.1 Multi-spectral:

Instruments that record multi-spectral data are broad band spectral instruments that provide images in broad select color bands not unlike the response of the eye to a color photograph. The colors that are used in the image are selected to maximize the contrast of those aspects of the object space irradiance distribution that are desired. Ten to twenty spectral bands spread between 0.4 and 14 microns might be used. Most instruments, however, cover a much smaller wavelength interval. For example, LANDSAT uses ten bands across ten wavelengths. This spectral resolution of  $\frac{\Delta\lambda}{\lambda} \approx 0.1$ , is used for terrain classification and land use assessment.

### 2.1.2 Hyperspectral:

Instruments that record hyper-spectral data are narrower band spectral instruments that provide images in a large (100–200) number of select color bands. At this spectral resolution, the surface reflectance of solids and liquids, reveal details of the chemical composition of solids. The AVIRIS and the HYDICE instruments are examples of operational reflectance hyperspectral imaging spectrometers. This spectral resolution of  $\frac{\Delta\lambda}{\lambda} \approx 0.01$ , is used for agriculture, forestry, mineral exploration, soils, watershed management, and analysis of the coastal zone. Information processing has been a limitation to the real-time applications of hyperspectral instruments. However new commercial off the shelf technology being used by the entertainment industry will quickly revolutionize the processing and data visualization from these instruments.

### 2.1.3 Ultra-spectral:

Instruments that record ultra-spectral data are the narrowest band spectral instruments that provide images in a large (1000–10000) number of select color bands. At this spectral resolution, the chemical composition of gases is revealed. The ATMOS, the AES and the TES instruments are examples of ultra-spectral. This spectral resolution of  $\frac{\Delta\lambda}{\lambda} \leq 0.001$ , is used to determine the chemical composition of gases. Information processing has been a limitation to the real-time applications of ultra-spectral instruments. Instruments which image at a resolution of 128×128 pixels have yet to be built. Giga bit processors are required.

## 3. HISTORICAL PERSPECTIVE

The Astronomer George Ellery Hale (1892), founder of Mt. Wilson Observatory, is credited with being the inventor and the first person to make practical scientific operational use of an imaging spectrometer, although he did not call it that. At the turn of this century, Hale recognized the importance of using both spectral (color) and spatial information for scientific research on the sun. He designed and built a spectrograph with a long entrance slit that could be moved at a constant velocity across the disk of the solar image at the focal plane of a solar telescope. At the output of the spectrograph was a fixed, non moving photographic plateholder. Uniform translation at a constant velocity caused an image of the sun at the single wavelength (tuned at the spectrograph) to be “painted” out across the photographic plate.

From that very humble beginning, today we see the Imaging Spectrometry has developed into a major tool (Norton, et al. 1995) for scientists, engineers, and military tacticians. Hundreds of scientific papers have used data recorded by the JPL *Airborne Visible and Infrared Imaging Spectrometer* (AVIRIS) instrument (Green, 1996).

## 4. RESOLUTION AND INFORMATION

Often the question is asked for what application which resolution (multi, ultra, hyper) be used. An answer to this question is obtained either experimentally or by analysis. Experiment requires recording large amounts of data, developing training algorithms and changing the resolution and noise in models until threshold detection is found. An intuitive understanding of the importance of spectral resolution is obtained by analysis. Too much spectral resolution and you are placing a more than necessary burden on your communications and signal processing channels. Too little resolution and you may not recognize what you want to see reliably.

The reflectance spectra of solids and liquids are different from those for gases. This difference is caused by the fact that solids and liquids are a different form of matter than is a gas. The spectrum of light reflected or emitted from solids and liquids is characteristically broader in color than light from gases, in some cases by a factor as high as 10000.

Following the earlier work of Breckinridge and Schindler (1981) we develop resolution trade-offs for hyperspectral instruments, and then apply our analysis to hyperspectral scenarios. Fourier transform spectrometers are used for most ultra-spectral instruments because of the required very high spectral resolution, the infrared spectral region (2 to 16 micrometers) and the typically very low energy from the source. Here we calculate the Fourier Transform Spectrometer optical path difference or spectral resolution required enable the accurate recording of spectral features. The optical path difference required to resolve spectral features in emission or absorption for a feature broadened only by Doppler effects and not by collisional, electromagnetic, or nearest neighbor phenomena is calculated to illustrate a baseline design approach.

The shape (intensity as a function of frequency) of a Doppler broadened spectral line is given by:

$$I = b^{-1} \ln(2/\pi)^{1/2} \exp\left\{-\left[(\nu - \nu_0)/b\right]^2 \ln 2\right\} \quad (1)$$

where,

$$b = \left(\frac{mc^2}{2\pi kT}\right)^{-1/2} (\ln 2/\pi)^{1/2} \nu_0, \quad (2)$$

and the Doppler half width (full width at half maximum) in units of centimeters<sup>-1</sup> is given by Es. 3-30 in Penner (1959) to be

$$\Delta\nu = \nu_0 [2kT(\ln 2)/m]^{1/2}, \quad (3)$$

where k is the Boltzmann constant, c is the speed of light, and the spectrum line is from a gas whose molecular weight is m and which is at thermodynamic equilibrium at temperature T.

Spectral features are examined by recording the spectrum at regular intervals or spacings across the spectra. A spectral feature in absorption is multiplied by a periodic comb function. The separation of samples in spectrum space is  $\Delta S$ . If this spectrum were recorded by a Fourier Transform Spectrometer, the maximum optical path difference, or retardation,  $X_0$  is given by

$$X_0 = \frac{1}{\Delta S} \quad (4)$$

To characterize and distinguish one spectral line from another with high certainty requires that the spectral lines be "resolved." A spectral line is resolved if it has two samples per full width at half maximum, or

$$2\Delta S = \Delta\nu \quad (5)$$

Combining Eqs. 3, 2, 5, we find:

$$X_0 = \left(\frac{c}{\sigma_0}\right) \cdot \left[\frac{m}{2} \ln 2kT\right]^{1/2}. \quad (6)$$

where  $\sigma_0$  is the frequency in wavenumber units cm<sup>-1</sup>. If mass M is expressed in atomic mass units (amu), and  $X_0$  is in meters, then

$$X_0 = 2.8 \times 10^4 \left(\frac{1}{\sigma_0}\right) \cdot \left(\frac{M}{T}\right)^{1/2}, \quad (7)$$

Equation 7 gives the optical path difference required to resolve a Doppler broadened absorption or emission feature from a gas. An example is the application of Eqs. 7 to features in the Earth's upper atmosphere, where the temperature is 240 degrees kelvin. Figure 1 gives a plot of the optical path difference (spectral resolution) required to resolve a Doppler broadened spectral feature at 240 degrees K shown on a graph of molecular weight as a function of wavenumbers ( $\text{cm}^{-1}$ ) for path differences 0.04 to 10 Meters. Also shown are the locations of absorption features for  $\text{N}_2\text{O}$ ,  $\text{CO}_2$  and  $\text{CH}_4$ . This figure shows that lines that form the  $\text{CO}_2$  band near  $3000 \text{ cm}^{-1}$  are resolved with a 4-meter optical path difference, whereas those in the adjacent  $\text{N}_2\text{O}$  band are not resolved.

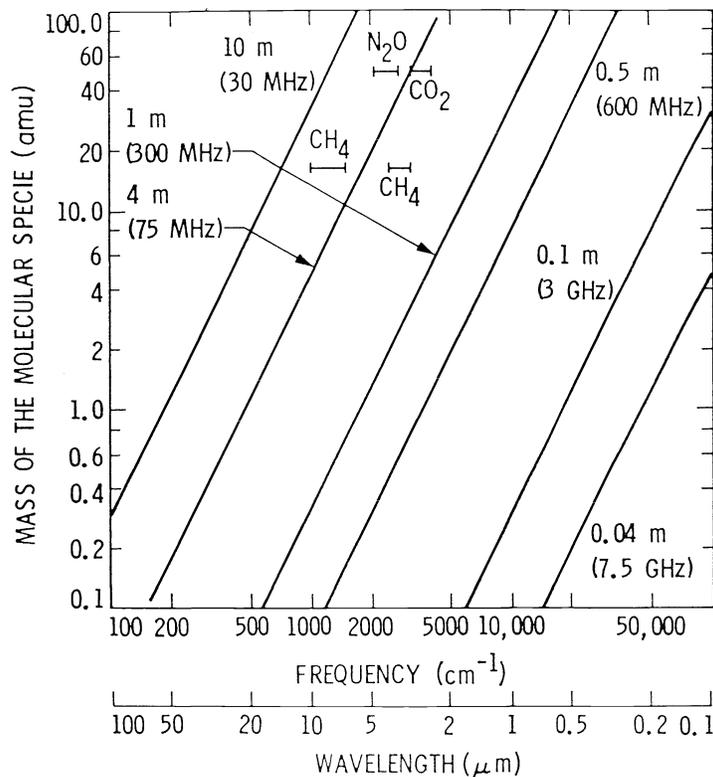


Fig. 1. Spectral resolution required to resolve typical atmospheric spectra shown on a plot of mass of the molecular specie (amu) as a function of frequency, for FTS optical path lengths between 0.1 and 10 meters.

The optimum resolution for solids is derived in a similar manner. Lower resolution is needed for solids than for gases because the atoms and their electronic transitions which form the lines are more tightly bound in the solid lattice and thus give much broader spectral features than those spectral features produced by gases. A calculation similar to that above shows that a spectral resolution of 10 nanometers across the spectral range 0.4 to 2.5 microns approaches the optimum for solids.

## 5. SUMMARY

Imaging spectrometers were invented over 100 years ago and have been successfully applied to solar physics for the past 100 years. Similar instruments are now being applied to earth and atmosphere remote sensing in support of the NASA mission to planet earth and other government programs. We have provided a calculation of spectral resolution required to resolve atmospheric spectral features and have applied similar calculations to solid earth and liquid remote imaging spectrometer sensing.

## 6. ACKNOWLEDGMENTS

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