Hyperspectral Imaging: A Paradigm in Remote Sensing

Introduction
Science and technology of remote sensing has grown immensely in recent times, thanks to the improvement in sensor technology. Powerful sensors, now available, have opened up new application vistas using remotely sensed images. Remote sensing of the earth using imaging spectroscopy has enabled quantitative analysis of an area within an instantaneous field of view (IFOV) of the sensor. Spectral imaging allows extraction of the information, which cannot be done by human eyes. Hyperspectral (HyS) imager collects two-dimensional (2D) spatial images over the numerous contiguous wavelengths. Each image captures information in the part of the electromagnetic spectrum known as spectral band. Width of each band in the spectrum is known as spectral resolution. Hyperspectral imager measures the reflected radiance over very narrow and contiguous wavelength bands. This results in an extremely high spectral resolution when collected over many bands. Band wise images are then fused to produce the hyperspectral image cube. The three dimensional (3D) cube is a combination of the spatial (X and Y axis) and spectral information (Z axis) of the ground surface as shown in Fig. 1. The image shown in Fig. 1 is one of the bands captured by AVIRIS. This phenomenon of capturing enormously high spectral resolution images is responsible for the nomenclature "Hyper spectral" for the given cube.

Table 1 Imaging sensors and their characteristics

<table>
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<th>Characteristics of Hyperspectral Imaging (HySI)</th>
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The spectral resolutions in HySI spans across visible, infrared and short wave infrared spectral band. The examples of hyper spectral imaging sensors with their characteristics is shown in Table 1 which is available in the J. Nascimento Ph.D thesis.

The pixel value at the ground which determines the spatial resolution varies widely from few meters to tens of meters depending on the altitude of the sensor. Spatial resolution discriminates actual objects of interest on the ground. Higher the spatial resolution, smaller is the size of object on the ground which can be uniquely captured by the sensor.

Multispectral and Hyperspectral Imaging
Notion of capturing ground information across various spectral bands is not new for geospatial applications. In fact since 1970’s satellite images have been captured across multiple bands using multispectral sensors. Some important examples of the multispectral sensors are LANDSAT, SPOT, AVHRR. They measure the earth surface with a small number of wavelengths bands. Also a large gap exists between each of these bands. For example, advanced very high-resolution radio meter (AVHRR) has following channel characteristics shown in Table 2.

Multispectral images thus deals with multiple “isolated” spectral bands spread over a range (0.58 - 12.50 μm). They cannot take measurements across all parts of the electromagnetic spectrum as certain bands are left out. Thus, multispectral sensor fails to capture the complete signature range of the object due to these isolated patches of the spectrum, which do not contribute in the spectral measurements. Hyperspectral imagers on the other hand capture same information over the contiguous wavelength bands and thus they produce the “continuous” spectra for all the pixels in IFOV. The spectrum of the single pixel across the spectra appears like the one measured by spectrometer in the lab. Therefore, HySI is also known as the image spectroscopy. This detail is responsible for providing colossal quantity of information, which is not possible with multispectral imaging sensors. Typical spectral signatures are shown in Fig. 2.

Table 2: AVHRR Channel characteristics

<table>
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<tr>
<th>Channel Number</th>
<th>Wavelength (μm)</th>
<th>Application</th>
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<tbody>
<tr>
<td>1</td>
<td>0.58 - 0.68</td>
<td>Daytime cloud and surface mapping</td>
</tr>
<tr>
<td>2</td>
<td>0.725 - 1.00</td>
<td>Land-water boundaries</td>
</tr>
<tr>
<td>3A</td>
<td>1.58 - 1.64</td>
<td>Snow and ice detection</td>
</tr>
<tr>
<td>3B</td>
<td>3.55 - 3.93</td>
<td>Night cloud mapping, sea surface temperature</td>
</tr>
<tr>
<td>4</td>
<td>10.30 - 11.30</td>
<td>Night cloud mapping, sea surface temperature</td>
</tr>
<tr>
<td>5</td>
<td>11.50 - 12.50</td>
<td>Sea surface temperature</td>
</tr>
</tbody>
</table>
Mathematically hyperspectral image is an over determined system due to excessive information availability over the numerous contiguous wavelength bands (0.4 to 2.5 μm cf. Table 1). This provide immense amount of information and allows greater discrimination between the spectrally similar ground information. Thus, due to data abundance hyperspectral imaging provide more detailed and accurate information about the ground content within IFOV, which has similar spectral signature. However, one must note that narrow and contiguous bands are more important in hyperspectral imaging rather than the number of bands, which it can measure. As seen from the Table 1 typical spectral width is in between 10 - 20 nm. This phenomenon of narrow and contiguous bands also yields a great advantage to the hyperspectral imaging as it can clearly distinguish between the spectrally similar signatures. This means it can be successfully deployed to distinguish between the vegetation, construction material, camouflage identification for the defense forces and many other applications.

**Processing the Hypercube**

As seen from Table 1 the pixel size in HyS image covers roughly 100 m² on a ground for a typical hyperspectral sensor. It is very likely that several substances are present in this coverage area. As a result signal captured by the sensor in a specific band and at a specific spatial resolution is the mix up of the substances present in the area. Therefore, a single pixel in an image is formed due to combination of these substances. The constituent substances in the pixels are termed as end members in the hyperspectral terminology. Each of these end members has a unique signature in the electromagnetic spectrum and therefore a single pixel in the hyperspectral image is formed due to mixing of these end member spectrum. It is very likely that this mixing phenomenon is applicable to every pixel in the given hypercube. Therefore one of the problem formulations using the hyperspectral imaging is as follows:

*Given the hyperspectral cube, decompose each pixel into its basic spectral signature(s) (end member(s)) and find their corresponding fractions known as abundances which are contributing to a pixel formation.*

Abundance indicates the fractions or proportion of each end member present into the given pixel. The problem of decomposing given pixel into its end members and finding proportion for each one of them is known as hyperspectral unmixing. This is a very tough problem to solve if only the hypercube is given and both; end members and their abundances are to be identified from it. This problem is known as blind hyperspectral unmixing.

Depending on the mixing proportions, problem is modeled using the linear mixing model (LMM) or non-linear mixing model. Linear mixing model is easy to solve and is applicable if the mixing proportions are very large and substances do not significantly overlap in the pixel. The linear mixing model assumes minimal interactions among the end members constituting the pixel.

The LMM can be written as

\[ r = Mα + n, \]

where \( n \) indicates additive white Gaussian noise (AWGN), \( r \) is the spectral measurement (reflectance), \( M \) is the mixing matrix containing end member signature present in the scene and \( α \) are the fractional abundances.

In the nonlinear mixing scenario end members significantly overlap and the light is scattered heavily before it is captured by the sensor. In case, the light scattering is not very heavy than linear model is applicable with a good accuracy.

Typical steps involved in the hyperspectral unmixing are as follows and can be further referred from the J. Nascimento work:

**Input:** Radiance data cube

**Output:** End members and/or fraction (abundances).

**Step I: Atmospheric correction** is applied to radiance data cube which results in the reflectance values. This correction takes care of illumination, atmospheric effects, shadow effects, sensor and sun directionality effects.

**Step II: Data reduction** is required due to mammoth dimensionality of the hypercube. Reasons for data reduction are also aided by the fact that number of end members is significantly smaller than number of wavelength bands in the hyperspectral cube. Further, certain noisy bands with minimal information are removed from the cube. The wavelengths in these bands are more susceptible to a specific form of distortions. This step reduce the data size, improves computational efficiency, and signal to noise ratio (SNR).

**Step III: Spectral unmixing** yields the end members and their abundances at each pixel in the hypercube. Abundances at each spatial locations are combined to yield the abundance maps.

Typical abundance maps are shown Fig. 3. The fractional abundances are non-negative and they sum up to one. Thus, non-negativity and sum to one constraint are imposed on the abundances during spectral unmixing. The problem can be simplified by assuming that either of the \( M \) or \( α \) is known and then unravel problem to find the other unknown entity. This solution is known as supervised hyperspectral unmixing.

**Application of Hyperspectral Imaging**

U.S. geological survey (USGS) has used tetracorder to identify and map minerals present on surface of the earth, vegetation, snow, water, and pollution. It has created the enormous bank of spectral signatures for various materials and is made available to the researchers. Hyperspectral imaging can be used for many applications like...
target detection, mineral mapping, earth and sea surface properties, material identification and many more. Some application may require identifying targets from a very similar background e.g. detecting military vehicles or installation under the canopy. Similarly, agricultural scientist use hyperspectral imaging to identify the diseased plants among the non-diseased ones. Another interesting application of hyperspectral imaging is in the area of oil exploration. Hydrocarbons leave a specific signature, which can be captured very efficiently by the hyperspectral sensors. Normally hydrocarbons mix with the other substances on the surface and they are very difficult to track using the multispectral sensor. Hyperspectral imaging can be used to identify the material in a terrain, which is inaccessible to humans. Such a finding can have a huge impact on economy of the country. HySI can also be used to map the soil properties like moisture, salinity and helps in improving the agriculture yield.

**Summary**

Hyperspectral imaging opens up tremendous opportunity in many application domains simply due to the richness of available data. Even though blind hyperspectral unmixing is a relatively difficult and an ill posed problem, researchers are striving to develop rich mathematical models and efficient software and hardware solution for the hypercube. These efforts are making HySI a very promising technology for the geo spatial technologies of the future.

**References**


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