Imaging Spectroscopy for Geo-Environmental Studies: Indian Experiences

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ABSTRACT

Imaging spectroscopy opens new vistas in understanding the interactions amongst various components and sub-ecosystems of the ecosystem that are hitherto unexplored using the conventional broad band remote sensing. This paper discusses the hyperspectral studies taken up in India from ground, air and space borne platforms for different themes viz., vegetation studies, Mineralogy, crops, soils, coastal zone management, etc. with the relevant case studies. In this regard, the general techniques employed by the analysts of the data are also discussed. Hyperspectral Imager, developed by India, operating in 64 contiguous bands in the VNIR region was also discussed. Hyperspectral data throws several challenges for processing and analyses to realize its potential for understanding the state and composition of the ecosystem. Extensive availability of real time spectral and ground information, coupled with algorithms and operational procedures and spectral libraries, through international cooperation, could make hyperspectral remote sensing a reality in due course of time. **(Key words:** Imaging spectroscopy, Hyper spectral Imager, HySI, Chandrayaan, Inadian Mini Satellite-1, IMS-1, Hyperion, Natural Resources Management)

INTRODUCTION

Imaging spectroscopy has become one of the most promising and challenging techniques in remote sensing. Hyperspectral remote sensing is a recent technology that has been growing fast and the volume of data provides incentive for developing methods and algorithms for analysis. Hyperspectral images possess large information that allows a wide variety of methods in order to improve the detection and quantification of the materials that constitute the scene. Thus, hyperspectral approach brings a new conception in remote sensing that enables the identification of the major scene components.

Imaging spectroscopy is the simultaneous acquisition of images in many contiguous bands. The resulting hyperspectral data offers a more detailed view of the spectral properties of a scene than the more conventional broad (spectral) band data, which is created in wide ans sometimes non-contiguous bands. Multispectral bands donot produce a 'spectrum' of an object, whereas hyperspectral data due to the narrow and contiguous bands produce a signature of all pixels of the scene in a spectral image.

Hyperspectral imaging expands and improves capability of multispectral image analysis. It takes advantage of hundreds of contiguous spectral channels to uncover materials that usually cannot be resolved by multispectral sensors. One of great challenges for hyperspectral imaging is subpixel detection, which is not treated in standard spatial-based image processing. After a target is detected, the next step is classification of the detected targets, manifested as mixed pixels due to high spectral resolution of a hyperspectral sensor and a large spatial coverage by GSD, is a still bigger challenge. A brief comparison of the spatial processing exploring the conventional multispectral data and spectral processing exploring the hyperspectral data is given below in table 1.

In India, studies using hyperspectral data have been carried out from ground, aerial and space platforms. The ground and airborne studies have immensely helped in understanding the intricacies of hyperspectral data

Table 1: Comparison of spatial processing with spectral processing (Mianji, et al., 2008)

Spatial processing	Spectral processing
Spatial arrangement of pixels is the information	Materials can be identified by the associated spectrum of pixels
Better shape recognition needs higher spatial resolution	High spatial resolution is not of crucial importance.
Data volume increases with the square of the spatial resolution	Data volume linearly increases with the number of spectral bands.
Main challenge is the pixel size.	Main challenge is to explore the spectral variability

collection and analysis for extraction of various kinds of thematic information. Modular Opto-electronic Scanner (MOS)-B on-board IRS-P3 was the first narrow waveband width sun-synchronous satellite of India with 13 bands in the 0.408-1.01um region. Oceanographic, atmospheric and land surface parameters were retrieved using this data. Subsequently, a hyper- spectral sensor called Hyper Spectral Imager (HySI) was launched on Indian Mini Satellite (IMS) -1 for observations over the Earth's surface and on Chandrayaan over Moon. India has further plans to design and launch a hyperspectral sensor operating upto 10 um. In addition, data from international hyperspectral sensors like Hyperion and CHRIS Proba, etc. are also explored for various studies on natural resources and environment. This paper deals with Hyperspectral camera developed by India, some of the salient studies conducted for different thematic applications such as vegetation studies, mineralogy, soils, coastal zone studies, etc and the way forward to make hyperspectral remote sensing as an operational tool.

Hyperspectral Imager (HySI)

India, in its first spacecraft mission of ISRO beyond Earth orbit to moon, christened as Chandrayaan-1, envisaged the primary objectives to expand scientific knowledge about the moon, to upgrade India's technological capability and to provide challenging opportunities for planetary research to the younger generation of Indian scientists. India built a CCD camera called as Hyperspectral Imager (HySI) is one of the payloads, designed to obtain the spectroscopic data for mapping of minerals on the surface of the moon as well as for understanding the mineralogical composition of the moon's interior. Hyper-Spectral Imager (HySI) is conceived as a highly compact instrument keeping with the mission requirement of low weight, size and power for mapping the lunar surface along with other imaging payloads. HySI will help in improving the already available information on mineral composition of the lunar surface operating in the visible and near infrared region of the electromagnetic spectrum, it images a strip of lunar surface which is 20 km wide with a resolution of 80 m. The instrument splits the incident radiation into 64 contiguous bands, in 421-964 nm range, of 15 nm width. A similar HYSI was also flown on Indian Mini Satellite-1 (IMS-1) in the Low Earth Sun synchronous Orbit for taking observations over the Earth's surface. It has been providing hyperspectral data in 64 contiguous bands in the wavelength range of 400-950 nm at 506 m spatial resolution.

The instrument on-board Chandrayaan is mapping the lunar surface in push broom-mode from a polar orbit of 100 km altitude. HySI will collect the Sun's reflected light from the Moon's surface through a tele-centric refractive optics and focus on to an area detector. One frame will correspond to 40 km along-track by 20 km across-track area on ground. The 20 km across-track corresponds to the swath coverage. Rectangular frame size is to improve the spectral resolution. The pixel footprint is a uniform square. Wedge filter is planned for spectral dispersion. The advantage of wedge filter over prism/grating is the implementtation simplicity and the compactness.

Table 2: Features of HySI on-board Chandrayaan-1 (Kiran Kumar and Roy Chowdhury, 2008)

No	Parameter	Specification
1	Ground resolution (m) from 100 km altitude	80m
2	Swath (km)	~ 2
3	Spectral range (μm)	0.4–0.92
4	No. of spectral bands	64
5	Spectral resolution (nm)	< 15
6	No. of gains	2
7	Quantization (bits)	12
8	SNR	> 100
9	Estimated power (W)	16
10	Estimated weight (kg)	3

The radiometric resolution of the instrument will be 12 bits to cover the large signal variation of the Moon's surface with a single gain. This will facilitate imaging the high and low illumination scenes simultaneously. In addition, provision will be there to operate the instrument at a higher gain by ground command. High spatial and spectral resolution data of HySI along with NIR payloads onboard Chandrayaan-1 viz., SMART-1 Infra-red Imager (SIR-2) (Nathues *et al* 2000) and Moon Mineralogy Mapper will significantly improve upon the available mineral compositional information. Study of deep regions like South Pole–Aitken basin, which represents lower crust or upper mantle material, will also help in understanding the composition and mineralogy of the interior of the Moon and its formation and evolution.

Applications of Hyperspectral Data

Studies have been carried out in India using hyperspectral data towards mineral mapping, precision agriculture, discrimination of vegetation types, condition assessment, relating with biophysical and chemical constituents, urban studies, biogeochemical cycles and coastal studies, including water quality assessment, etc. However, most of these studies have yet to be operationalized for generation of information in a routine manner.

In this regard, analysis of spectroscopic data from the laboratory and *in situ,* from aircraft and from spacecraft requires a knowledge base and, thus, the spectral library forms a knowledge base for the spectroscopy of terrestrial and planetary objects / materials. Large wavelength range with very high precision, and sample analysis and documentation play important role in generation of spectra of high quality. Quality required in a spectral library to successfully perform an investigation depends on the scientific questions to be answered and the type of algorithms to be used, from simple diagnostic absorption band to completely uncontaminated spectra. Efforts and the outcome of these spectral libraries need to be shared across the research community. India has also initiated steps to develop spectral libraries of select minerals, crops and soils on a priority basis.

Technological innovations, right from data collection through processing to computation and product generation, have been immensely helpful towards better understanding of the hyperspectral responses of different features towards further upscaling the technology.

Analysis of Hyperspectral data

A direct extension of multispectral imaging techniques is not applicable in hyperspectral data analysis. In light of this, suites of algorithms and software are being developed. Hyperspectral cube, or hypercube, is a dynamic and powerful method to visualize data in terms of the spatial and spectral features that otherwise cannot be displayed in a single format. The spectral cube is a 3-d array containing spatial information on the x and y axes and spectral information on z-axis. Individual spectra, spectral maps and full spectral cubes can be created from a single spectral cube. A hyperspectral data cube is composed of pure and mixed pixels, where a pure pixel contains a single surface material and a mixed pixel contains multiple materials. Using the hypercube as an analytical tool is often the first step in data analysis and exploitation. Hypercubes are automatically generated through many commercially available hyperspectral analysis software packages. Amount of data required to generate hyperspectral data cubes increases as the spectral and spatial resolutions become finer. The broad steps used in the exploration and analysis are given hereunder:

Broadly, Hyperspectral data analysis comprises of 3 steps viz., a) pre processing (atmospheric correction and noise treatment); b) spatial analysis and c) spectral analysis for material identification. Atmospheric correction is performed using ATREM method (Atmosphere Removal Program), to calculate the scaled surface reflectance values from hyperspectral radiance data using an approximate atmospheric radiative transfer modeling technique (Gao et al., 1993). EFFORT (Empirical Flat Field Optical Reflectance Transformation) is used in a complementary manner to determine and apply mild adjustments to ATREM apparent reflectance data to make the spectra appear more like spectra of real materials. This is followed by the identification of the end members through: spectral reduction by the MNF (Minimum Noise Fraction), spatial reduction by the PPI (Purity Pixel Index), and n-D visualization and identification. A similar scheme was implemented by Caravalho et al., in 2003 for the Geo-botanical analysis in the Brazilian Savannah region.

MNF transformation is similar to principal components (PC) transformation. It was specifically designed as a linear transformation that maximizes the signal-to-noise ratio to order images in terms of decreasing image quality in lower order components (Green et al., 1988). Besides eliminating noise, the MNF method allows to compress data in axes described by materials or physical and environmental features that constitutes the scene. Pixel Purity Index is a way of finding the most spectrally pure pixels in images. This step stipulates how many times the pixel is extreme in the simplex. The most spectrally pure pixels typically correspond to spectrally unique materials. The PPI procedure generates an image where pixel values correspond to the number of times that this pixel was recorded as extreme. This way, threshold of the PPI image can stipulate the most extreme pixel results in further spatial reduction. The n-D Visualizer generates clouds of points related to the pixels in a n-dimensional space defined by the MNF components. This tool allows manipulating the clouds providing a better positioning to discriminate different spectral groups. This procedure promotes a better definition of the groups and the distinction can be manually made using an interactive drawing tool. Thus, this method consists in a classification process where the analyst defines the classes. The set of the selected points can be isolated in groups and analyzed by statistic processes. The employment of this technique allows selecting a spectral series related to vegetation.

Analysis of imaging spectrometer data allows extraction of a detailed spectrum for each pixel of the image. High spectral resolution spectra collected by the imaging spectrometers enable direct identification of individual materials based on their reflectance characteristics. Thus, these hyperspectral data finds applications in precision agriculture, camouflaged target identification, species discrimination, monitoring phytoplanktons and pollution in coastal management, characterization and mapping of soil types, mineralogical investigations, etc.

Ground based studies

Field spectro-radiometers are used towards understanding and characterization of the reflectance / absorption spectra of soils, crops, forest vegetation and minerals. A brief description of the studies carried out on soils, crops and minerals is given hereunder:

Soil Studies:

Spectral reflectance of soils is largely influenced by soil colour, texture, organic matter, minerals, soluble salts and moisture content. Efforts were put towards preparing a compendium of soil reflectance data in narrow spectral bands (between 350 to 2500 nm) of soils occurring in different physiographic / climatic regions of the country together with their laboratory measured soil parameters to identify suitable bands for prediction of soil properties. All major soil orders of India viz., Entisols, Inceptisols, Vertisols, Mollisols, Alfisols, Aridisols and Ultisols are covered. Wide variations in soil properties viz., soil colour, texture, organic carbon content, pH, electrical conductivity, calcium carbonate content, cation exchange capacity, base saturation, iron content (Fe^{2+}, Fe^{3+} and free Fe_2O_3) and clay mineralogy; were observed in soils occurring on different physiographic regions.

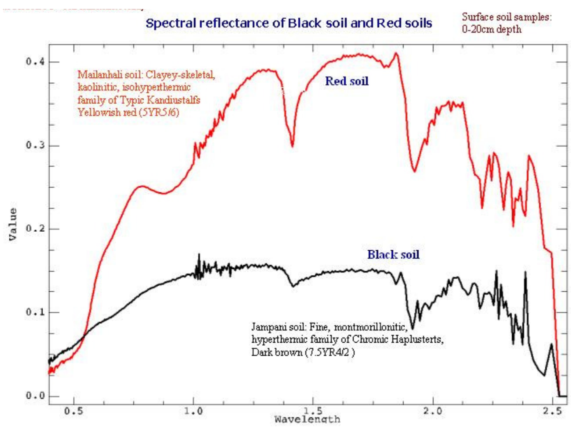

Fig. 1: Spectral reflectance patterns of black and red soils

The soil reflectance characteristics were studied both under filed and laboratory conditions. Spectral reflectance of all soils showed prominent absorption features at 1400, 1900 and 2200 nm. These features are mainly associated with free and lattice OH feature of the clay minerals. Soils dominant in kaolinitic clay minerals showed strong absorption features at around 2200 nm than the soils with smectitic clay mineralogy. Braod absorption feature around 950 nm was observed in the red and ferraltic (dominant in Fe content) soils. Salt affected soils rich in Na / Mg chloride salts showed a characteristic U-shaped absorption feature at 1900 nm. Soils high in iron, organic carbon and moisture showed reduced reflectance in all the wavebands, thus reducing the albedo.

With the, thus, developed database a digital spectral reflectance library of soils was developed. The soil spectral reflectance library is a systematic collection of spectral reflectance data of soils whose basic properties (morphological, physical and mineralogical) are known and these could be used as reference to predict the properties of unknown soils based on the reflectance data. Biggest challenge lies in inverting these soil spectral reflectance information towards retrieval of the soil properties. The spectral library will be a very useful tool in the interpretation of hyperspectral remote sensing data. Studies are in progress to populate the spectral database of soils and correlating them with the soil properties.

Vegetation Studies: Hyperspectral remote sensing increases our ability to accurately map vegetation attributes. Images acquired simultaneously in narrow spectral bands may allow the capture of specific plant attributes, previously not viable with the broadband sensors. Hyperspectral data produced better classification accuracy of different vegetation types than multispectral data. In order to realize better discrimination of crop and forest tree species, appropriate waveband candidates are to be identified.

Crop Species Discrimination: Naresh Kumar et al., 2008 generated Hyperspectral reflectance data in 400-2500 nm spectral region over different species of *Vigna* and observed that the hybrid approach of spectral angle mapper (SAM) and spectral information divergence (SID)was found to be better discriminator than spectral angle mapper or spectral information divergence alone. They proposed a hybrid technique based on the spectral correlation angle (SCA) and spectral information divergence (SID), termed as SIDSCA(TAN), which has produced higher similarity values than SIDSAM(TAN) in 400-700nm spectral range. The proposed hybrid measure SIDSCA(TAN) has also produced a highest discriminatory power between horsegram and cowpea with greengram as reference when compared to SIDSAM(TAN) measure in 400-700nm spectral range

Spectral vegetation indices

One of the approaches used for extracting and mapping vegetation biophysical variables from remotely sensed data is based on spectral vegetation indices (SVIs). SVIs are dimensionless, radiometric measures that function as indicators of relative abundance and activity of green vegetation. There are now more than 20 indices in vogue developed from broadband multispectral imagery. As the availability and use of hyperspectral data is growing, the development and application of vegetation indices is expected to increase further.

The selection of the optimum SVIs for a particular purpose is not straightforward, due to the wide choice of band combinations and transformations, combined with specific application purposes and conditions. The empirical-statistical approach we used in this study allowed us to systematically formulate and assess new and existing vegetation indices for sugarcane disease detection. Interactive visual interpretation of spectral plots, focusing on the magnitude of difference and the direction of relationship of sample pixel values, allowed the identification of candidate bands for index formulation. (Apan et al., 2004)

Crop Phenology &Condition Assessment:

The symptoms of plant diseases like rust and wilt can be related to changes in leaf pigments, internal leaf structure, and moisture. Chlorophyll degradation and alterations in the vascular system of the crop plants pronouncedly influence the reflectance patterns. Thus, spectral vegetation indices (SVIs) that focus on one or more attributes associated with these symptoms could be useful for identification of the diseased plants. Basic statistics (minimum, maximum, mean, and standard deviation) in different responsive bands, red edge dynamics enable identification of candidates responsive to the disease detection and monitoring.

Observations made on the rust affected plants of *Vigna spp* revelaed increased reflectance in red region due to the degradation of chlorophyll to brown coloured pustules on the leaf surface. This was also accompanied by a significant reduction in the reflectance in the near infrared bands and increase in the water absorption regions due to disruption of vascular tissues. This information is useful towards developing spectral indices that would be highly associated with the incidence and severity of the plant diseases. Similar observations were made by Apan et al., 2004 also in response to the incidence of orange rust of sugarcane.

Species level classification of vegetation

Though many problems are posed for the discrimination of different species using remotely sensed data, potential for separation of different species based on foliar reflectance needs to be analysed in greater detail using hyperspectral data metrics employing both parametric and non-parametric approaches. Investigations need to be further carried out in greater details to explore the relations of foliar chemistry and spectral reflectance. Preliminary studies reported by Curran (1989) are encouraging.

Air-borne Imaging Spectrometer Studies on Crops

Patel et al., (2001) collected spectral reflectance measurements from ground as well as aerial platforms over wheat plots at different growth stages along with bare soil.

Fig.2: Spectral reflectance of healthy and rust affected cow pea (*Vigna spp.*)

Table 3: Spectral indices of healthy and diseased crop plants of *Vigna spp.*

	Central wavelength /index	Healthy	Diseased	Percent change
1	550/680	2.8	1.4	48.7
2	(800-550/ 1660+680)	1.7	1.1	37.9
3	800/1660	2.2	1.4	36.6
4	1660/680	0.1	0.1	-36.7
5	1660/550	3.5	5.5	-58.0

Position and shape characteristics of the red edge in the VNIR range are good indicators of plant parameters. Hence, the red edge position was determined by the inflection wavelength, which is defined as the wavelength at which the rate of increase of reflectance is the maximum. A shift of 10 nm, from 713 to 723 was observed at different growth stages of the crop. A linear relation was obtained between LAI and chlorophyll with the red edge indicated he potential of Hyperspectral data for assessing crop growth conditions.

Table 4. Salient features of the Air borne Imaging Spectrometer (AIS) (Patel et al., 2001)

Parameter	Specifications		
Instantaneous geometric field of view (urad)	660, 2m×2m from altitude of 3 km		
Swath width (degrees); No. of pixels	14.5, 770m from 3 km 384		
Spectral range (nm)	450–880 nm		
Encoding bits/pixel	10		
Formatted bits/pixel	12		
Band to band registration	Inherent		
	Raw	Spectral	Spatial
No. of spectral bands	143	143	17*
Spectral bandwidth(nm)	3	3	3 to 24
Spatial Resolution			
Across track	0.66	5.28	0.66
Along track	0.66	0.66	0.66
FOV (degrees)	14.5	14.5	14.5

* within the specified interval

Space based Studies

Space based hyperspectral studies have been carried out in India mainly using the internationally available Hyperion data on EO-1 covering themes such as vegetation studies, Geology, Snow cover, Mineralogy in relation to urban sprawl and coastal zone management, etc. Though these studies are limited in number, these have been prioritized based on the limitations of the conventional broad bands. Some of the salient studies are narrated below:

Forestry:

Christian and Krishnayya (2008) compared the vegetation indices derived from Advanced Land Imager (ALI) and Hyperion datasets over Shoolpaneshwar Wild life sanctuary of Gujarat, India and concluded the indices derived from Hyperion had better dynamic range and sensitivity than those from ALI. They also studied the phenology of several forest species of the forest area and sensitivity of the spectra to the girth at breast height.

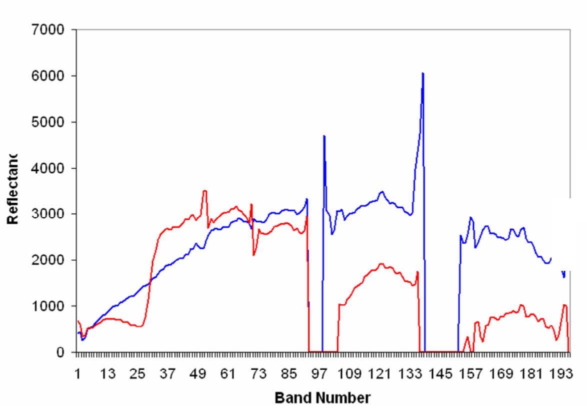

Fig.3: Reflectance spectra of *Tectona grandis on* two different dates (April in blue and red in October) [Courtesy: Christian, B. Ph. D. thesis, 2008]

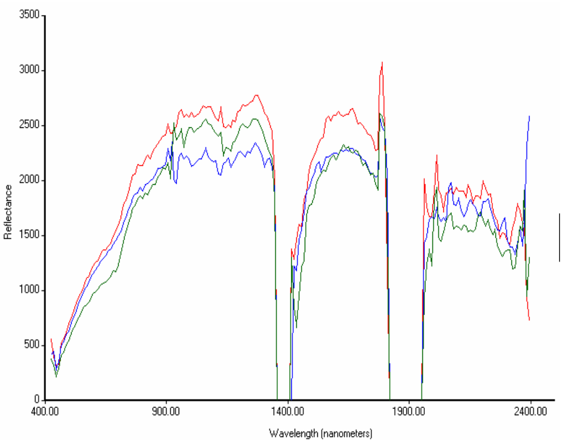

Fig.4: Spectral variability as influenced by the girth of *Tectona grandis* (red: 50-90, blue:35-50, green:30-50 cm dbh) [Courtesy: Christian, B. Ph. D. thesis, 2008]

Geology:

Rajendran et al.(2008) studies the impact of low SNR (<40:1) of Hyperion data in the wavelength region of 2000-2400 nm to resolve the spectral details over a study area in India, comprising of a diverse range of minerals with narrow diagnostic absorption bands in SWIR region. Processing of 40 SWIR bands in 2000-2400 nm region yielded only 3 MNF bands without apparent noise and extraction of spectral end members from these data was difficult. *A priori* knowledge enabled the identification of most of the other minerals like dolomite, talc, chlorite and various white micas expected in the study area. Further, Hyperion data was also found to be useful for measuring and mapping spectral reflectance shifts <10 nm in SWIR related to white mica chemical variations.

Mineralogy & Urban Sprawl:

Using SWIR bands in the ASTER data for detecting the clay minerals in the western part of India in the state of Gujarat, India, clay minerals viz., montmorillonite, illite and mica having absorption at 2.2 μm and kaolinite at 2.17 and 2.2μm were detected using linear spectral unmixing technique. These are confirmed with field spectrometer observations and X-ray diffraction (XRD) outputs (Vinod Kumar, Personal Communication, 2008).

Ramakrishnan and Kusuma(2008) have evaluated the swelling potential of tidal flats and estuarine regions of Mumbai using geotechnical and mineralogical inputs. In metro cities like Mumbai and Kolkata reclaimed area is the major source of additional land. Expansive soils cause serious damages to shallow footed residential and commercial establishments and transport causeways. Developmental activities in the reclaimed areas are often hampered due to swelling potential of marine clay. Reflectance spectra of representative samples collected from the field were used to map the spatial distribution of these maruine clays using

Spectral Angle Mapper (SAM) technique. The derived expansive clay abundance mapping is of importance in planning appropriate remedial measures and for future development.

Snow Studies:

Negi et al., 2008 reported spectral reflectance measurements in snow bound areas of Indian Himalayas using spectro-radiometer in 350-2500 nm. Detailed analysis of the field collected reflectance spectra suggested that due to ageing and grain size variation in snow, maximum variations in reflectance were observed in near infrared region around 1040 and 1050 nm, while for contamination and snow depth, maximum variations in reflectance were observed in the visible regions around 470 and 590 nm, respectively and for moisture changes, these variations were maximum around 980 and 1100 nm. Normalized Difference Snow Index was also found to increase with ageing, grain size and moisture content. This study was helpful in identification of suitable spectral bands and for developing algorithms for snow cover applications.

Coastal Zone Management:

James and Rajendran (2008) used hyperspectral data to deduce surface characteristics and extracted information related to the features of the coastal ecosystem using spectral reflectance and a variety of hyperspectral data metrics and employed neural network analysis for studying the physical and biological interactions of the system.

CONCLUSIONS

- Non-availability of real time space borne hyperspectral data for active research, operationalization and upscaling has been an impediment. This needs to be overcome with the easy accessibility of data and software for taking hyperspectral data forward. Synchronous SAR and thermal observations alongwith the hyperspectral observations in VNIR-SWIR region would further enhance the scope of investigations.

- Inherent variability in target and background spectra are major constraints in development of effective detection algorithms for hyperspectral imagery. The use of adaptive algorithms deals quite effectively with the problem of unknown backgrounds; the lack of sufficient target data, however, makes the development and estimation of target variability models challenging.

- Potential that the hyperspectral data has shown needs to be translated to address the real time issues in an operational manner. Broad band data could be used complementarily towards achieving synergy.

- Algorithms integrating data from different sources need to be developed for application to the real data. E.g., Incorporation of information on variations in leaf angle, crown structure, non-photosynthetic vegeta-tion and other factors will make datasets more complex should cu,minate in better separation of species.

- Finally, hyperspectral data acquisition, processing and analysis pose both challenges and opportunities for the whole remote sensing community. In conjunction with the broad band data, hyperspectral data in optical, thermal and microwave regions facilitates characterization of objects in a more comprehensive manner for natural resources management in a substan-tive manner, thereby operational hyperspectral remote sensing to become a reality in due course of time.

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