

Development of a web-enabled spectral data archival, visualisation and analysis architecture for tropical phytodiversity inventory

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Abstract: The tropical ecosystems constitute a rich array of plant species. The identification and discrimination of varieties of plant species using remote sensing techniques, particularly imaging spectroscopy demands conceptualization and development of a web-enabled spectral library architecture. In this study, a web-accessible spectral data archival, visualisation and analysis architecture has been developed using open-source software. It is a 3-tier architecture consisting of the client interface, the application server and the database server. Spectral signatures have been archived in a relational database management system which can be viewed and shared along with the related metadata descriptions such as sensor specifications, target details, observation geometry, field photograph, geolocation in ‘Bhuvan’ geoportal, collector details, etc. The online spectral data analysis such as averaging, resampling, continuum removal, spectral matching, derivative spectra and spectral indices have been demonstrated with appropriate examples for vegetation studies. The web-enabled feature may encourage researchers, academicians and operational users of Earth observation data to use it for the archival, organisation, analysis, long-term use and exchange of their field spectra.

Key words: Hyperspectral remote sensing, open-source, plant diversity, spectral analysis, spectral library.

Handling Editor: Sunil Kumar

Introduction

The tropical ecosystems encompass a rich array of plant species. Conventionally, species discrimination for floristic mapping involved exhaustive field work and is time-consuming and expensive (Kent & Coker 1992). Remote sensing is advantageously used in such a situation to discriminate different species based on their unique spectral properties that are attributed to species’ biochemical and biophysical characteristics (Clark *et al.* 2005; Gajendra *et al.* 2015). The narrow bands of imaging spectroscopy data (350 nm to 2500 nm) can resolve subtle differences

in the spectral signatures of plant species and help in their identification and mapping (Féret & Asner 2013; George *et al.* 2015; Krishnayya *et al.* 2015).

Spectral signatures make a useful source of information to understand reflective properties of plant species along with the underlying physical and biological phenomena. Spectral signatures are used for calibration, validation and simulation of imaging spectroscopy data, predicting the pigment concentrations in foliage, as a reference signature for spectral matching, and choice of wave bands for sensors (Joseph 2005). A large number of spectral signatures are collected using spectro radiometers in various remote sensing field campaigns;

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however, the methods of data archival and sharing information are limited.

An organised, accessible and non-redundant means of storing spectral signatures and their associated metadata is an important step toward better data quality management for long-term usability and information exchange among researchers (Huni & Kneubuhler 2007). Spectral data library mainly deals with collection of spectral reflectances of targets using spectro radiometer and is applicable to a range of land cover classes (e.g., plants, minerals, and man-made objects). Developing spectral library is the key to improve the ability to utilise the full potential of data available from advanced hyperspectral images (Zomer *et al.* 2008).

Most of the existing spectral libraries have been developed by the premier space agencies / universities. The ASTER spectral library has a compilation of over 2,400 spectra of natural and artificial materials, which includes data from three other spectral libraries such as Johns Hopkins University (JHU) Spectral Library, Jet Propulsion Laboratory (JPL) Spectral Library and United State Geological Survey (USGS) Spectral Library (<http://speclib.jpl.nasa.gov/>). The spectrum database SPECCHIO offers ready access to spectral data, modelled data and existing spectral libraries (<http://www.specchio.ch>) (Bojinski *et al.* 2003). Thermal infrared spectra of minerals, rocks, and soils have been developed by Mars Space Flight Facility at Arizona State University (<http://speclib.asu.edu/>). DLR Spectral Archive is a web-enabled spectral library developed using MySQL database (<http://cococon.caf.dlr.de>). PRISM software developed by USGS is the most complete solution for spectral signature storing, processing and analyzing available till date (<http://pubs.usgs.gov/of/2011/1155/>). However, it lacks a web interface and requires local installation, which somehow limits its use for 'data' sharing.

Since long the need for development of a unified repository of spectral signatures and their metadata is being felt in India. A desktop-based stand-alone system to access and perform analysis on spectral library for major plant species of western Himalaya has been developed in Java platform (Sanghavi *et al.* 2008). Several major research and academic organisations in the country have procured hand-held spectro radiometers, and have started collection and archival of *in-situ* spectra of diverse material types. Over 90 spectroradiometers were purchased from Analytical Spectral Device (ASD) ([http:// www.asdi.com](http://www.asdi.com)) and Spectral Vista Corporation (SVC) (<http://www.spectravista.com>) in the country in past decade. Spectroradiometer is a costly instrument (~US\$70,000), not affordable for many researchers / organisations interested in its use. Spectra not archived at a web-accessible platform results in unavailability of data to other interested groups. Sharing of field spectra through a web-enabled library would allow optimal use of available instruments.

So far, most of the spectral libraries have been developed using proprietary solutions and tools for both desktop and web applications which limits the participation of multiple stakeholders. Commercial solution for maintaining spectral database is expensive and difficult to update, instead a spectral library stored, edited and archived using open-source technologies is economical and flexible for customisation. Current trend is towards developing spectral libraries using open-source technology in order to demonstrate archival and visualization spectroscopy data to the remote sensing community. Spectral Workbench (<https://spectralworkbench.org/>) is a web-based open-source application developed to collect, archive, share, and analyze spectral data. Cornell Spectrum Imager (CSI) (<http://code.google.com/p/cornell-spectrum-imager>) is another open-source platform developed for analysis and processing of hyperspectral data. Open-source software are freely available for the public to view, modify, and redistribute and also huge repository of codes are available online to use for developing any new application, instead of reinventing the whole from scratch. At national level, due to the absence of a web-enabled spectral database, there is a lack of efforts to capture, analyse and disseminate location specific *in-situ* spectra and metadata information. Often libraries are developed for specific applications which necessarily restrict the participation of other stakeholders. Using web-enabled applications, it is easy to share the data among wider user groups.

The foregoing discussion motivated us to design and build a web-enabled spectral library architecture using open source software, with additional tools to perform online analysis and visualisation of archived spectra. In this study, spectral data storage, analysis, dissemination and visualization in web environment along with metadata standards for spectra cataloguing were implemented using open source software. Eventually, the aim is to develop a simple user oriented online spectral library to handle, store and

interpret the data and connect hyperspectral experts to facilitate exchange of data among them and enhance their research activities. Development of web-enabled spectral library would be especially useful for spectral discrimination of tropical plant canopies, exotic invasive species, and economically and medicinally important species.

Materials and methods

Field spectra archive

The prototype version of spectral library presented in this article is named as *SpecVizPro* (Spectral data Visualization Program). The spectral database can be made free for browsing to all web users and the usage of the data can be restricted to registered and authorised users only. Users interested in uploading spectra in *SpecVizPro* have to follow standard field spectra collection protocols and provide relevant metadata information to moderator who check quality of spectra before spectra become part of *SpecVizPro*'s archive. Currently, the library archives over 75 spectra of different species (tree, shrub, herb and grass) and over 200 associated samples of soils, rock and minerals, snow and ice and urban and other man-made features. The period of field campaign for collection of spectra was from 2008 to 2014. Spectra have been collected in different seasons but not during rainy season (from July to October) months. Two instruments *viz.*, SVC HR 1024 and ASD hand-held field spec pro (spectral coverage: 350 nm to 2500 nm) were used to record the field spectra at different view angles (4°, 18° and 25°) with spectral resolution of (1, 2 and 2.5 nm) respectively. *SpecVizPro* spectral archive mainly represents spectra from western Himalaya and Indo-Gangetic plains in North India. *SpecVizPro* was developed using Java platform, and thereby independent of operating systems. *SpecVizPro* has been designed as a 3-tier architecture comprising client interface, application server and database server (Fig. 1).

The client interface has been developed using HTML (Hypertext Markup Language), JQuery, JavaScript and CSS (Cascading Style Sheet). JSP (Java Server Pages) has been used as a server side scripting language to interface with the database server. The data are archived in a database and retrieved and processed using JSP. JFree Chart has been used for rendering of various spectral graphs. All the data/spectra have been archived in an open-

source database; PostgreSQL-a relational database management system (RDBMS), which acts as a backend database server to store the data in a consistent and non-redundant manner. PostgreSQL has a very rich data type system and allows user-defined data types and composite data types. Postgres is "better SQL" -- more standardized, with better query planning so you can follow the relational model more closely if it suits, since all the analysis modules are complex in nature and have been implemented using SQL and it was easier to implement them in Postgres. Moreover the spatial extension to Postgres (i.e. PostGIS) is an easy and popular option for the integration of spatial data in database. In future, there is a plan for the upgradation of the existing library with spatial components. SQL (Structured Query Language) is used in analysis part for performing various spectral queries. Apache tomcat has been used as the web server, which is a container for java-based applications.

Spectral data recorded by various instruments or generated through image processing packages are stored in different formats. The developed software changes the input formats in a common compatible format. *SpecVizPro* supports GER (Geophysical and Environmental Research Corporation) formats (ASCII tab separated and SIG formats), ASD binary, ENVI spectral library, and comma separated value (CSV) files as data input formats. The outputs/download formats are CSV files that can be read by statistical and spreadsheet applications.

The database of *SpecVizPro* has a provision for metadata storage and a unique identifier has been marked for each spectral data entry. Besides storing the basic set of metadata about the target, geographic coordinates of the place, field photograph, and date of collection are also stored. More detailed metadata descriptions such as circumstances of capture, illumination and sensor geometries, environmental factors and object characteristics can also be incorporated. There is a provision to geo-locate spectra collection sites over ISRO's *Bhuvan* geo portal (http://bhuvan.nrsc.gov.in/bhuvan_links.php) and this allows browsing the globe while viewing the reflectance signatures of library.

The data smoothening is carried out by recalculating reflectance in a particular band using the previous and next reflectance values of the neighboring bands through weighted average method. Spectral resampling transform the dataset by inter-

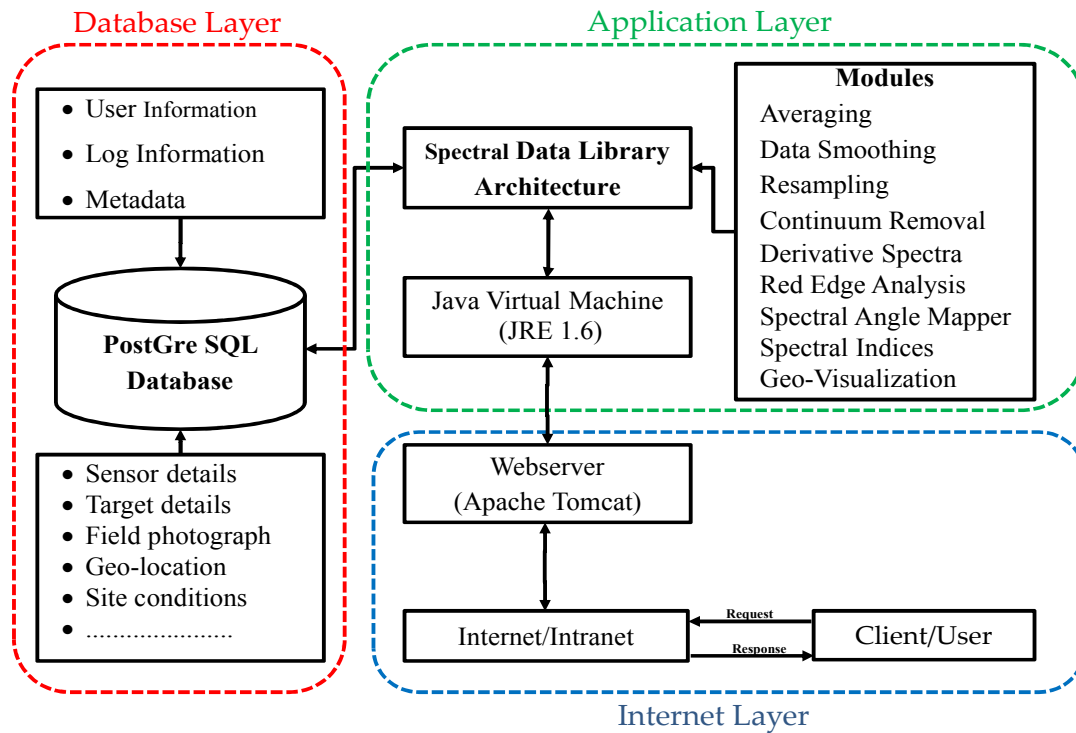


Fig. 1. Schematic representation of *SpecVizPro* architecture.

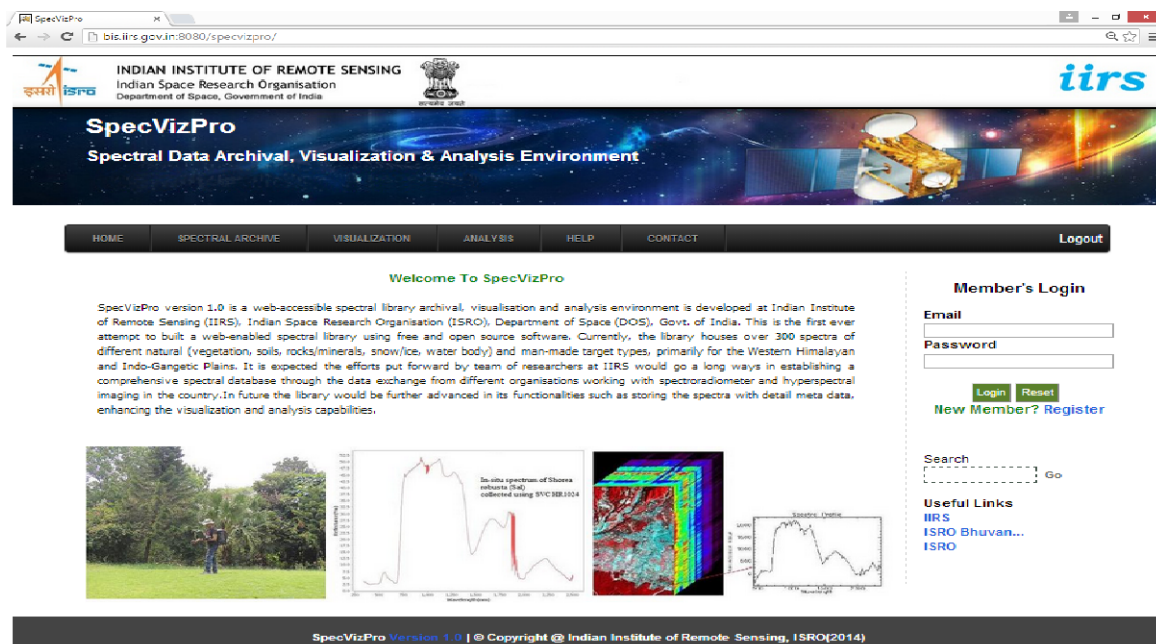


Fig. 2. *SpecVizPro* portal Graphic User Interface.

polating the spectrally provided data and line up the exact changes in shifted data (eq. 1):

$$\text{Reflectance} = \frac{\sum_{i=240}^{i=2500} \lambda_i}{\lambda_n} \dots \dots \dots (1)$$

Where, λ_i = the current wavelength band i ; λ_n

= the total number of wavelength bands

The continuum (eq. 2 and eq. 3) is the background absorption onto which other absorption features are superimposed which may be the wing of a large absorption feature:

$$\rho_D = 1 - \rho_{CR} \dots \dots \dots (2)$$

$$\rho_{DN} = \rho_D / \rho_{DC} \dots \dots \dots (3)$$

Whereas, ρ_D = Band depth, ρ_{CR} = Continuum - removed reflectance, ρ_{DN} = Normalized band depth, ρ_{DC} = Band depth at the center (Kokaly & Clark 1999).

Derivative spectroscopy uses first or higher derivatives of absorbance with respect to wave length for qualitative and quantitative analysis. Derivatives were shown to be less sensitive to variations of soil background, illumination, and surface albedo (Demetriades- Shah *et al.* 1990). The First Derivative Reflectance (FDR) and Second Derivative Reflectance (SDR) were calculated according to the eq. (4) and eq. (5):

$$FDR_{\lambda_i} = \frac{dR}{d\lambda} = \frac{R_{\lambda_{j+1}} - R_{\lambda_j}}{\Delta\lambda} \dots \dots \dots (4)$$

$$SDR_{\lambda_i} = \frac{d^2R}{d\lambda^2} = \frac{R_{\lambda_{j+2}} - 2R_{\lambda_{j+1}} + R_{\lambda_j}}{(\Delta\lambda^2)} \dots \dots \dots (5)$$

Where, FDR_{λ_i} = The FDR between band j and band j+1, where wave length equals to i; SDR_{λ_i} = The SDR between band j and band j+2, where wavelength equals to i; R_{λ_j} , $R_{\lambda_{j+1}}$, $R_{\lambda_{j+2}}$ = Reflectance of band j, j+1, j+2; $\Delta\lambda$ = Difference of wavelength between band j and band j+1.

Red-edge represents the region of abrupt change in leaf reflectance between 680-780 nm caused by the strong chlorophyll absorption in the red wavelength and high reflectance in the near infrared wave lengths due to intermediate scattering (Horler *et al.* 1983). The linear four-point interpolation method assumes that the reflectance curve at the red-edge can be simplified to a straight line centered near the mid-point between the reflectance in the NIR at about 780 nm and the reflectance minimum of the chlorophyll absorption feature at about 670 nm (Guyot & Baret 1988). Red-edge position is a two-step process. In the first step, reflectance at the infection point (R_{re}) is calculated (eq. 5):

$$R_{re} = (R_{670} + R_{780})/2 \dots \dots \dots (6)$$

Where, R is the reflectance.

In second step, red edge wavelength or red-edge position (REP) is calculated (eq. 6):

$$REP = 700 + 40 \left(\frac{R_{re} - R_{700}}{R_{740} - R_{700}} \right) \dots \dots \dots (7)$$

Where 700 and 40 are constants resulting from interpolation in the 700-740 nm interval.

The Spectral Angle Mapper (SAM) algorithm generalizes geometric interpretation to n-dimensional space. It determines the similarity of an unknown spectrum to a reference spectrum r,

by applying the following equation (CSES 1992) (eq. 8):

$$a = cos^{-1} \left(\frac{\sum_{i=1}^n t_i r_i}{(\sum_{i=1}^n t_i^2)^{0.5} (\sum_{i=1}^n r_i^2)^{0.5}} \right) \dots \dots \dots (8)$$

User can upload their spectra into *SpecVizPro* and can calculate spectral similarity with reference spectra in the library.

Vegetation Indices (VIs) are combinations of surface reflectance at two or more wavelengths designed to highlight a particular property of vegetation. Table 1 has a list vegetation indices currently implemented in the library.

It also allows user to define custom made spectral indices. *SpecVizPro* also contains online help and user manual which describe step by step procedures for the execution of various operations.

Results and Discussion

The application server of *SpecVizPro* consists of three modules viz., visualization, analysis and spectral archive. Visualization deals with display of spectra in the form of graphs. This module provides option to the user to select individual or multiple target spectra, the selected spectra are fetched from the relational database and displayed as graph for visual inspection (Fig. 2). The second module, i.e. Analysis provides tools to perform various spectral operations like data smoothing for noise removal, data averaging, resampling for narrowband to broadband conversion, continuum removal, generation of derivative spectra, red-edge analysis and computation of spectral indices, etc. using SQL. The third module, i.e. Spectral Archive handles repository of available spectra in the library and allows authorized user to upload spectra into the database along with metadata and also downloading of desired reference spectra and derived information products.

The graphic user interface of *SpecVizPro* provides upload and download facility besides performing other operations including help through menus and sub-menus (Fig. 3). The database can incorporate all sources of signature data, including spectra collected in laboratory, field radiometers and imaging spectrometers.

User can access all the archived spectra and view single or multiple spectra (Fig. 4a). Data resampling includes averaging narrow bands spectra as per specified waveband intervals (Fig. 4b). Fig. 4b shows how *in-situ* spectrum of *Quercusleucotricophora* (banj oak) at 1-nm was averaged to 10-nm and compared with Hyperion

Table 1. Vegetation indices categories, indices with formulas and range values.

Indices Category	Index	Formula	Range Value
Narrowband Greenness	Red Edge Normalized Difference Vegetation Index	$NDVI_{705} = \frac{(R_{750} - R_{705})}{(R_{750} + R_{705})}$	-1 to 1
	Vogelmann Red Edge Index	$VOG1 = \frac{R_{750}}{R_{720}}$	0 to 20
	Photochemical Reflectance Index	$PRI = \frac{(R_{531} - R_{570})}{(R_{531} + R_{570})}$	-1 to 1
Light Use Efficiency	Structure Insensitive Pigment Index	$SIP1 = \frac{(R_{900} - R_{445})}{(R_{900} + R_{680})}$	0 to 2
	Normalized Difference Nitrogen Index	$NDNI = \frac{\log_1 R_{1510} - \log_1 R_{1680}}{\log_1 R_{1510} + \log_1 R_{1680}}$	0 to 1
Canopy Nitrogen	Normalized Difference Lignin Index	$NDLI = \frac{\log_1 R_{1754} - \log_1 R_{1680}}{\log_1 R_{1754} + \log_1 R_{1680}}$	0 to 1
	Cellulose Absorption Index	$CAI = 0.5 \times R_{2000} + R_{2200} - R_{2100}$	-3 to < 4
	Plant Senescence Reflectance Index	$PSRI = \frac{R_{680} - R_{500}}{R_{750}}$	-1 to 1
Leaf Pigments	Carotenoid Reflectance Index	$CRI1 = \frac{1}{R_{510}} - \frac{1}{R_{550}}$	0.8 to 1.2
	Anthocyanin Reflectance Index	$ARI1 = \frac{1}{R_{550}} - \frac{1}{R_{700}}$	0 to < 3
Water Content	Normalized Difference Water Index	$NDWI = \frac{(R_{857} - R_{1241})}{(R_{857} + R_{1241})}$	0 to < 15
	Moisture Stress Index	$MSI = \frac{R_{1570}}{R_{812}}$	0 to < 0.2

The screenshot displays the SpecVizPro web application interface. At the top, there is a header with the IIRS logo and navigation tabs: HOME, SPECTRAL ARCHIVE, VISUALIZATION, ANALYSIS, HELP, CONTACT, and a Logout button. Below the header, the main content area is titled "SpecVizPro Spectral Data Archival, Visualization & Analysis Environment".

The "Target information" section is active, showing a field photograph of a plant, a graph of collected spectra, and a map of the collection location in India. To the right of the map is a search bar and a list of useful links (IIRS, ISRO Bhuvan, ISRO).

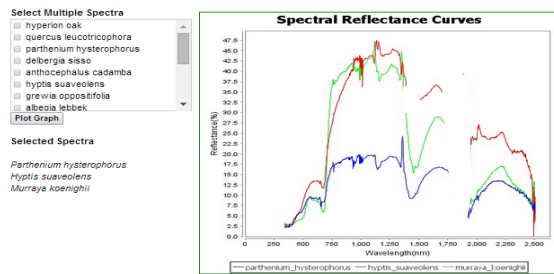
The metadata form contains the following fields:

- Botanical Name*: Sensor Owner:
- Vernacular Name*: FOV(degree):
- Phenology*: Date of collection*:
- Leaf/Foliage*: Time of collection*:
- Sensor Name*: Cloud cover:
- Number of Spectral Bands*: Ambient Temperature:
- Ambient Pressure:
- Land cover/Land use:
- Instrument Data*: No file chosen
- Target Photograph*: No file chosen
- Name of Collector:
- Address*:

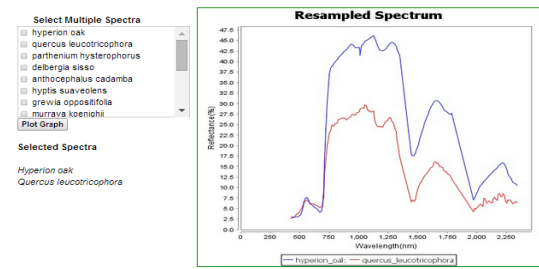
At the bottom, there is a comments section with a text area containing the following text: "Euphorbia suberosa is an alien invasive species from tropical America. The species is potential threat to the native biodiversity and ecosystems." Below the comments section are "Upload File" and "Reset" buttons.

The footer of the page reads: "SpecVizPro Version 3.0 | © Copyright © Indian Institute of Remote Sensing, ISRO(2014)"

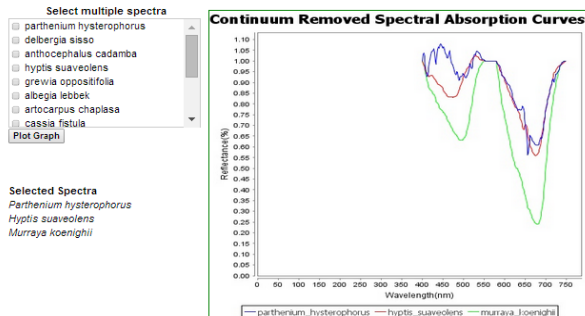
Fig. 3. Spectral data and metadata upload page.



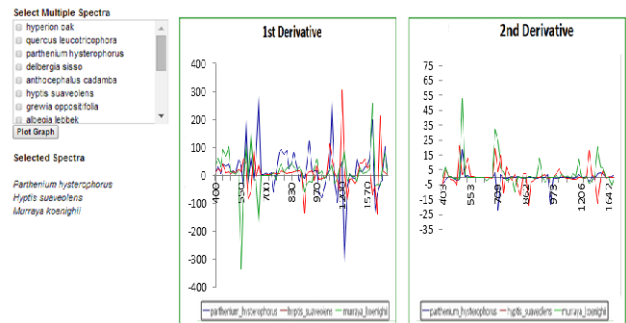
(a) Visualisation of spectral reflectance curves of multiple species (*Murraya koenighii*, *Hyptis suaveolens* and *Parthenium hysterophorus*)



(b) *In-situ* collected *Quercus leucotricophora* spectrum (1 nm) resampled to Hyperion image derived canopy spectra (10 nm) of *Quercus leucotricophora*



(c) Continuum removed absorption spectra of *Murraya koenighii*, *Hyptis suaveolens* and *Parthenium hysterophorus*.



(d) 1st and 2nd order derivative spectra calculation of selected species

Calculation of Red Edge Position using Linear Interpolation Method

Reference Spectra	REIP(reflectance(%))	REP(wavelength(nm))
<i>Albegia lebbek</i>	45.6200	727.3680
<i>Anthocephalus cadamba</i>	34.9950	722.7830
<i>Artocarpus chaplase</i>	34.6750	726.1170
<i>Cassia fistula</i>	43.0500	730.4443
<i>Delbergia sisso</i>	25.0700	746.8966
<i>Eugenia jambolana</i>	18.8500	723.1429
<i>Grewia oppositifolia</i>	25.6300	718.0719
<i>Hyperion oak</i>	27.0920	727.9020
<i>Hyptis suaveolens</i>	23.7100	729.3868
<i>Melia azadirach</i>	25.6300	718.0719
<i>Murraya koenighii</i>	27.7875	727.3340
<i>Parthenium hysterophorus</i>	15.3600	732.7481
<i>Quercus leucotricophora</i>	19.2550	732.6453
<i>Shorea robusta</i>	29.6300	729.7489
<i>Tectona grandis</i>	34.6850	730.1981
<i>Toona cedrela</i>	31.0550	726.1945

(e) Calculation of red edge infection point (REIP) (% reflectance) and red-edge wavelength (nm) using linear interpolation method for selected species.

Spectral Angle Matching

Selected Spectrum :	Target Spectrum	Spectral Angle(Degrees)
<i>Murraya koenighii</i>	<i>Murraya koenighii</i>	0.0800687025266789
<i>Albegia lebbek</i>	<i>Murraya koenighii</i>	0.149801116504481
<i>Anthocephalus cadamba</i>	<i>Murraya koenighii</i>	0.150453390935527
<i>Artocarpus chaplase</i>	<i>Murraya koenighii</i>	0.142793159594941
<i>Cassia fistula</i>	<i>Murraya koenighii</i>	0.139574183356755
<i>Delbergia sisso</i>	<i>Murraya koenighii</i>	0.125144185800355
<i>Eugenia jambolana</i>	<i>Murraya koenighii</i>	0.192684731607938
<i>Grewia oppositifolia</i>	<i>Murraya koenighii</i>	0.230950443390782
<i>Hyptis suaveolens</i>	<i>Murraya koenighii</i>	0.192684731607938
<i>Melia azadirach</i>	<i>Murraya koenighii</i>	0.00
<i>Murraya koenighii</i>	<i>Murraya koenighii</i>	0.00
<i>Parthenium hysterophorus</i>	<i>Murraya koenighii</i>	0.249048804801824
<i>Shorea robusta</i>	<i>Murraya koenighii</i>	0.146681577152879
<i>Tectona grandis</i>	<i>Murraya koenighii</i>	0.0994694940058581
<i>Toona cedrela</i>	<i>Murraya koenighii</i>	0.0781479839616034

(f) Comparison of selected spectra with all the spectra in database and calculating spectral angle values for all the species

Fig. 4. Spectral analysis tools provided in *SpecVizPro*.

image derived spectrum at 10-nm. Fig. 4c shows how the use of continuum removal can differentiate spectrally similar species, i.e. *Murraya koenighii* (karipatta) (a native shrub in sal forests in Doon valley) and *Hyptis suaveolens* (vilayati tulsi) and *Parthenium hysterophorus* (congress grass) (alien invasive herb) in post-monsoon season. Fig. 4d shows 1st and 2nd derivative spectra of selected species and their spectral separability in distinctive absorption regions. Fig. 4e shows differences in red-edge position for

different plant species. Fig. 4f depicts computation of spectral similarity values between user uploaded spectra into *SpecVizPro* and reference spectra in the library using SAM (Spectral Angle Mapper). User can compute a range of spectral indices related to various physio-chemical properties of feature types, and can compare and evaluate the sensitivity of different spectral indices.

The use of *SpecVizPro* as a distance learning tool could help in dissemination of knowledge on

processing, analysis and interpretation of *in-situ* spectral data. The future work would involve inclusion of calibration data to provide error estimates of spectral signatures, defining generic data exchange formats and expanding database through crowd sourcing tools. We plan to develop a computer application with all *SpecVizPro* functionality which could be made available in smart-phones.

Conclusions

In this study, development of a web-enabled spectral library architecture has been demonstrated to archive and visualize spectroscopy data using open-source software. Developed in an open-source environment, *SpecVizPro* allows customization and integration of newer spectral tools as per requirement and application, and making them available to other user groups through its online interface. Being a distributed and dynamic database, library is concurrently accessible to a large numbers of web users. The web-enabled feature may encourage researchers, academicians and operational users of earth observation data to use it for the archival, organisation, analysis, long-term use and exchange of their field spectra, and contribute towards synergizing the development of a comprehensive spectral database covering a variety of earth surface feature types of different geographic regions.

Acknowledgements

Authors are grateful to Dr. Y. V. N. Krishna Murthy, Director, Indian Institute of Remote Sensing (IIRS), and Dr. S. P. S. Kushwaha, Head, Forestry and Ecology Department, IIRS (ISRO) for encouragement and support.

References

- Bojinski, S., M. Schaepman, D. Schlapfer & K. Itten. 2003. SPECCHIO: a spectrum database for remote sensing applications. *Computer & Geosciences* **29**: 27-38.
- Center for the Study of Earth from Space (CSES). 1992. *SIPS User's Guide, The Spectral Image Processing System*. ver. 1.1, University of Colorado, Boulder.
- Clark, M. L., D. A. Roberts & D. B. Clark. 2005. Hyperspectral discrimination of tropical rain forest tree species at leaf to crown scales. *Remote Sensing of Environment* **96**: 375-398.
- Demetriades-Shah, T. H., M. D. Steven & J. A. Clark. 1990. High resolution derivative spectra in remote sensing. *Remote Sensing of Environment* **33**: 55-64.
- Féret, J. & G. P. Asner. 2013. Tree species discrimination in tropical forests using airborne imaging spectroscopy. *IEEE Transactions of Geosciences & Remote Sensing* **51**: 73-84.
- George, R., Hitendra, P. & S. P. S. Kushwaha. 2014. Forest tree species discrimination in western Himalaya using EO-1 Hyperion. *International Journal of Applied Earth Observation and Geo-information* **28**: 140-149.
- Guyot, G. & F. Baret. 1988. *Utilisation de la Haute Resolution Spectrale Pour Suivre l'état des Couverts Végétaux*. pp. 279-286. Proceedings of the 4th International colloquium on spectral signatures of objects in remote sensing. ESA SP-287, Assois, France.
- Horler, D. N. H., M. Dockray & J. Barber. 1983. The red edge of plant reflectance. *International Journal of Remote Sensing* **4**: 273-288.
- Huni, A. & M. Kneubuhler. 2007. SPECCHIO: a system for storing and sharing spectroradiometer data. *SPIE Newsroom*, DOI 10.1117/2.1200711.0956.
- Joseph, G. 2005. *Fundamentals of Remote Sensing*. Universities Press.
- Kokaly, R. F. & R. N. Clark. 1999. Spectroscopic determination of leaf biochemistry using band-depth analysis of absorption features and stepwise multiple linear regression. *Remote Sensing of Environment* **67**: 267-287.
- Kent, M. & P. Coker. 1992. *Vegetation Description and Analysis: A Practical Approach*. Wiley, Chichester, UK.
- Krishnayya, H. S. R., B. Christian, D. Vyas, M. Saini, M. Joshi, K. R. Manjunath, T. Kumar, H. Padalia, R. George & S. P. S. Kushwaha. 2015 Monitoring of forest cover in India : imaging spectroscopy. *Current Science* **108**: 869-878.
- Sanghavi, C., S. S. Ray & R. B. Singh. 2008. A software tool for reflectance spectra analysis. *Journal of Indian Society of Remote Sensing* **11**: 129-137.
- Singh, I. D., G., H. Padalia, R. R. Bharti & G. S. Rawat. 2016. Spatial extent and conservation status of Banj oak (*Quereus leucotrichophora* A. Camus) Forests in Uttarakhand, Western Himalaya. *Tropical Ecology* **57**: 255-262.
- Zomer, R. J., A. Trabucco & S. L. Ustin. 2008. Building spectral libraries for wetlands land cover classification and hyperspectral remote sensing. *Journal of Environment Management* **90**: 2170-2177.

(Received on 11.05.2015 and accepted after revisions, on 02.08.2016)