Recent developments in imaging spectroscopy have seen a dramatic improvement in the characterisation of terrestrial features due to the high spectral resolution of the sensors used. For example, vegetation species discrimination, stress detection and foliar chemistry mapping can now be achieved using these high spectral resolution sensors, a task that was almost impossible with coarse resolution satellite sensors. In spite of its capabilities, imaging spectroscopy is still in its early stages of development and application in southern Africa. This overview will attempt to briefly describe the science and analysis techniques, as well as review trends and challenges in the South African imaging spectroscopy landscape. It therefore is not intended as a pure research paper, but merely to illustrate the potential of and developments in imaging spectroscopy. This is pertinent to the South African scientific community where the technology is still in its infancy, especially given that the first-ever spaceborne South African imaging spectrometer, the Multi-Sensor Micro-Satellite Imager Satellite (MSMISat) is being developed for launch in the near future.

Key words: hyperspectral sensors, vegetation analysis, sensor characteristics, trends, spectral resolution

Introduction

Assessment and monitoring of the environment have become increasingly reliant on remote-sensing technologies, especially given the availability of historical data as well as the ability to provide data covering large spatial extents. These remote-sensing sensors typically are defined in terms of their specifications related to resolution. Spectral resolution has recently received immense attention as research has proven the capability of sensors with narrow channels (bandwidths of less than 2 nm) to detect subtle variations in surface features that might otherwise be masked by broader bands of multi-spectral scanner systems. Research has shown that subtle variations in features such as vegetation species, foliar chemistry and stress can be detected and mapped using high spectral resolution sensors. In this regard, a review and illustration of the developments of sensors with narrow channels (bandwidths of less than 2 nm) provide data covering large spatial extents. These remote-sensing sensors typically are defined in terms of their specifica-

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apply to a specific question be identified from the hyperspectral curve. The goal in this case is to identify, from this oversampled imaging spectroscopy data source, exactly which spectral features are required to address an application of interest. The research question thus becomes an issue of moving from a situation of ‘more data than we need’, to ‘exactly the data we need’. This effectively allows the development of operational sensors that are multi-spectral in design, cheaper and tailor-made for a specific set of applications. Research by Curran and Yoder and Pettigrew-Crosby, for instance, serve as examples where specific features were identified to describe chlorophyll and other leaf components. Such research allows design and development of operational multi-spectral sensors that incorporate application-specific wavelengths.

The main objective of this paper is to describe the science, analysis techniques and broad South African imaging spectroscopy landscape. The paper briefly reviews the imaging spectrometers available, the utility of imaging spectroscopy in vegetation analysis and its potential in southern Africa, with reference to the scheduled MSMIsat imaging spectrometer in South Africa.

**Selected imaging spectrometers**

This section provides an overview of a selection of available high-profile imaging spectrometers and their characteristics. The utility of the various sensors in remote sensing vegetation characteristics within the South African context are discussed. Table 1 highlights the main sensors available and their potential applications.

Airborne imaging spectrometers include HyMap and AVIRIS, both of which measure electromagnetic radiation from 400–2 500 nm. The AVIRIS, developed by the Jet Propulsion Laboratory in 1983, arguably is the benchmark for airborne imaging spectroscopy. AVIRIS first started operating in 1987 and has the distinction of being the first imaging spectrometer to measure the electromagnetic spectrum from 400–2 500 nm. This range of the electromagnetic spectrum has seen a wide application of AVIRIS in surface features characterisation (Table 1). The HyMap sensor includes two thermal bands (3–5 µm and 8–10 µm) in addition to the 400–2 500 nm spectral range. These types of spectral characteristics have expanded the utility of HyMap to applications such as pollution monitoring and soil mapping.

Spaceborne sensors with a synoptic view, such as Hyperion, allow coverage, and therefore monitoring, of large areas. However, the use of Hyperion is limited to large spatial objects due to its relatively coarse spatial resolution.

The proposed launch of the MSMIsat, developed by Sunspace in Stellenbosch, South Africa, has substantial advantages over the existing sensors since it has both multi-spectral and hyperspectral sensors that could be used to capture variations in surface features at different scales. The pointing ability of the platform allows sensors to acquire imagery of the same target area at different viewing angles which, in turn, allow for the assessment of bidirectional reflectance distribution (BRDF) effects. The BRDF describes the hemispherical angular distribution of outgoing radiation relative to incoming radiation (irradiance).

This measurement is important especially in mountainous areas such as the Drakensberg of South Africa where variations in the anisotropic reflectance signature of vegetation are controlled by topographic elements such as slope and aspect, thus rendering nadir sensing less efficient in capturing vegetation structure. The multi-angular viewing capabilities of the MSMIsat enable capturing of such off-nadir variations. In addition, the high temporal resolution of the microsatellites as
compared to the current spaceborne sensors provides high multi-temporal data that can facilitate constant monitoring of dynamic variables, such as crop growth and climate change effects on vegetation.

However, the traditional trade-offs of the proposed MSMIsat in terms of spectral, spatial and temporal resolutions will apply, given the 14.9-km swath width at an altitude of 660 km. While a revisit time of less than four days is foreseen when using off-nadir data acquisition, this mode of data collection has implications for data use in terms of BRDF effects and atmospheric correction. The nominal revisit time of more than 100 days at nadir, in turn, has implications for applications that require monitoring capabilities, e.g. crop yield estimation and stress detection. These types of applications demand higher temporal resolution, often greater than two days. However, MSMIsat should reasonably be regarded as an experimental platform that can address most of these issues when used in conjunction with three similar satellites, as is envisaged with the African Resource Management constellation. Other opportunities for MSMIsat research and use include food security applications, invasive species mapping, and mineral mapping, while geometric and atmospheric corrections, tasking, and sensor calibration are challenges that face operators and users of MSMIsat data.

In summary the sensors described in this section are capable of imaging at least 100 bands ranging from 350 nm to 2,500 nm. This region of the electromagnetic spectrum is critical for vegetation assessment and monitoring, with certain wavelengths sensitive to biochemical absorption while others, such as the near infrared region, reflect radiation. Data users should be guided by image resolution (spectral, spatial, temporal) and availability, as well as the cost involved. Although the spectral resolution is generally similar in the sensors highlighted above, cost and revisit time play a crucial role. Airborne sensors, such as HyMap, can be made available at any time; however, they are quite expensive compared to satellite-borne sensors such as Hyperion. Nevertheless, the spatial resolution of Hyperion is coarser (30 m) than that of HyMap (between 1–4 m). If one is therefore assessing objects with a relatively coarse spatial resolution of about 30 m (e.g. agricultural land classifications), then Hyperion should suffice. Landcover studies in mountainous regions would require multi-angular image sensors, such as the Compact High Resolution Imaging Spectrometer (CHRIS) Proba or the proposed MSMI sensor for South Africa that can cater for the effects of aspect and slope.

It is imperative to note that the success of hyperspectral data for characterising vegetation biophysical parameters is also dependent on the analytical techniques followed. These analytical techniques can be broadly divided into physically-based models and empirical methods. While most physically-based radiative transfer models, such as the PROSPECT and SAIL, have been developed and widely applied in homogenous vegetation, their application in southern Africa is not common. This is partly because of difficulties related to model parameterisation and also because of the heterogeneous nature of vegetation. Owing to the heterogeneous nature of vegetation in South Africa, which is rather site specific, most studies have followed the empirical approach using statistical tools, such as multiple regression, discriminant analysis, transforms (e.g. principal component analysis) and support vector machines. Research in the physical modelling approach is moving towards the 3D radiative transfer models that can cater for the heterogeneous nature of the vegetation in southern Africa.

Analysis of imaging spectroscopy data furthermore presents various challenges, especially in terms of ensuring statistical validity of an approach, given on the large number of potential independent variables in a modelling scenario. This is referred to as ‘reduction of data dimensionality’ and hints at the types of applications that imaging spectroscopy data and analysis are suited for. Many applications, e.g. mineral mapping, require a contiguous set of wavelengths to define a spectral feature that differentiates between minerals, while other applications, e.g. foliar chemistry assessment, require a defined selection or combination of wavelengths. In the first instance, the hyperspectral data curve can be subset to include only that spectral range of interest. However, in the second case, robust methods for sub-selecting only those wavelengths that are pertinent to the application need to be developed. A review of hyperspectral vegetation studies in southern Africa follows.

### The South African vegetation and imaging spectroscopy

The nature of heterogeneity that exists in southern Africa poses many challenges to the remote-sensing techniques that are applied in characterising vegetation variables, e.g. species identification, biochemical concentration, stress and biomass, in this region. The South African vegetation distribution closely correlates with the level of annual precipitation. Where rainfall is high and frequent all year round (above 400 mm per year), moist and tropical rain forests are common. Forests are also widespread across the tropical dry regions where miombo mopane and *Acacia* woodlands are dominant. Along the eastern coast down to the Cape of Good Hope, woody vegetation is characterised by coastal forests with different floristic, struc-

### Table 1. Hyperspectral sensors and their characteristics.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Spatial resolution</th>
<th>Spectral resolution</th>
<th>Altitude/platform</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSMI76</td>
<td>14.5 m hyperspectral 4.6 m multi-spectral</td>
<td>200 bands (400–2 350 nm) 4 bands (visible region)</td>
<td>Spaceborne (660 km) Spaceborne (660 km)</td>
<td>Plant production modelling, leaf biomass, fruit production, fruit quality, species discrimination</td>
</tr>
<tr>
<td>HyMap</td>
<td>2–10 m</td>
<td>128 bands (440 nm–2 500 nm)</td>
<td>Airborne (2 000–5 000 m)</td>
<td>Pollution monitoring, agriculture and forestry production systems, soil mapping, invasive species assessment, vegetation quality</td>
</tr>
<tr>
<td>Hyperion</td>
<td>30 m</td>
<td>220 bands (356–2 577 nm)</td>
<td>Spaceborne (705 km)</td>
<td>Foliar canopy nitrogen, biomass, LAI species mapping, agriculture land classifications, surface mineralogy</td>
</tr>
<tr>
<td>AVIRIS</td>
<td>20 m</td>
<td>224 bands (400–2 500 nm)</td>
<td>Airborne (20 km)</td>
<td>Vegetation leaf water, canopy chemistry studies, mineral mapping, coastal/water monitoring, atmospheric modelling, snow/ice studies, biomass assessment, environmental hazard detection</td>
</tr>
</tbody>
</table>
tural, and physiognomic properties from the woodland types.25

Dry montane forest occurs in small patches at higher elevations and mangroves are very common along the coast of the tropical regions.

Plants and/or animals occurring together with some degree of permanence have been classified into biomes in South Africa. These biomes broadly correspond to climatic regions, although other environmental controls are sometimes important. Each biome has a characteristic set of plant and animal species, as well as an overall physiognomy. Rutherford and Westfall26 mapped seven biomes in South Africa: Grassland, Savanna, Succulent Karoo, Nama Karoo, Forest, Fynbos and Desert, while Low and Rebelo27 included a Thicket biome. Acock28 described vegetation patterns at a scale that is still smaller than the biome and provided descriptions of 70 veld types in South Africa, Lesotho, and Swaziland. Cowling et al.29 give an updated description of vegetation in southern Africa.

Although these vegetation types have been described and mapped, detailed features such as species distribution and finer physiognomic and biochemical characteristics are still outstanding. Variations in leaf structure and orientation due to the different vegetation types,30 plant composition and phenology,31 different soil background effects,32 as well as the highly variable effects of standing litter, which often dominates the total fraction of aboveground biomass,33 complicate the remote sensing of vegetation variables such as biochemicals and species distribution in such heterogeneous environments. Imaging spectroscopy of vegetation is a relatively new field of study in southern Africa, yet research has revealed that the approach is critical in characterising various properties of southern African vegetation.12 A brief overview of the application of imaging spectroscopy for vegetation analysis is presented with particular reference to southern Africa.

Foliar chemistry

Laboratory near-infrared spectroscopy methods34,35 triggered the remote sensing of foliar chemistry, mainly predicting protein, amino acids, lignin and cellulose concentrations contained in dried, ground forage.34 This technique has replaced wet chemistry as the standard analytical procedure for assessing plant biochemicals in many laboratories.34 The premise behind the detection and mapping of foliar biochemicals is that plants absorb electromagnetic radiation through the molecular vibration (rotation, bending and stretching) of bonds (C-H, N-H, O-H, C-N and C-C) which form the primary constituents of organic compounds.34 Therefore, the amount and composition of biochemicals in plants determine the amount of energy reflected per wavelength.17-20 Curran17 produced a list of absorption features that are related to particular plant compounds. The list was modified by Kumar et al.7 to comprise 45 absorption features that are related to particular biochemical compounds between 400 nm and 2,500 nm.

Techniques to estimate foliar biochemicals using imaging spectroscopy have gradually developed over the years.17,38-45 Attempts were made during the late 1980s to estimate forest biochemical composition using first difference-at-sensor radiance measured by the Airborne Imaging Spectrometer (AIS).42 Strong correlations were found between AIS data and total canopy lignin and nitrogen content in deciduous and coniferous forests. Biochemical concentrations have also been estimated using AVIRIS spectra in mixed species forest canopies using first derivative reflectance and stepwise linear regression.46-48 Attempts to estimate foliar chemistry in sparsely vegetated canopies have been made using wavelengths related to known biochemical absorption features,49 a data reduction technique that minimises over-fitting and the effect of spectral variability that is independent of the biochemical concentration.50-53,54,55

With reference to southern Africa, research carried out in the Kruger National Park was aimed at predicting the quality of grass for herbivores as determined by the concentration of biochemicals (N, P, Na, K, Ca, Mg) using field spectroscopy56 and airborne imaging spectroscopy data.12 Owing to the heterogeneous nature of the environment in southern Africa, techniques that minimise the effect of spectral variability that is independent of the biochemical concentration were developed and applied as an alternative to the traditional laboratory near-infrared spectroscopy methods.7

Continuum-removed band depths of selected absorption features57-59 were correlated via stepwise regression to the biochemical concentration of sampled grass, as measured in a laboratory. Results indicated that the continuum-removed absorption features could explain up to 80% of the variation of biochemicals in grass.59 In a related study, researchers established a relationship between reflectance and nitrogen content as well as condensed tannin concentration in mopane (Colophospermum mopane) trees.59 The study confirmed that key wavelengths located in the shortwave infrared region as well as the red edge position, are linked to the concentration of foliar nitrogen and tannins.59 The technique was successfully scaled to canopy level for the estimation of foliar biochemicals using airborne HyMap imagery with an artificial neural network.59-64 Studies such as these have proven the potential of imaging spectroscopy in mapping detailed vegetation characteristics in the Savanna biomes of southern Africa at both field and airborne levels. The challenge is to upscale the techniques to spaceborne imaging spectrometers, such as Hyperion. To date, only a few studies have tested the potential of Hyperion data in estimating vegetation parameters.55,65

Plant stress and damage

Pests and diseases cause mortality in plantation forests and natural vegetation. Advances in imaging spectroscopy have offered opportunities to timely assess and delineate a range of forest health conditions.20 Leaf reflectance and shifts in the red edge position have been associated with insect infestation through damage of the waxy cuticle, destruction of cell walls and reduction in plant moisture.57-61 Zhang et al.62 investigated the utility of imaging spectroscopy for crop disease detection using tomatoes infected by P. infestans (late blight) as an example. A minimum noise fraction (MNF) transformation was applied to AVIRIS imaging spectroscopy data (224 bands; 400-2,500 nm), which reduced the dimensions to 28 MNF components. The MNF components were subjected to end-member spectra selection and spectral angle mapper classification. Results indicated that the blight-diseased tomatoes could be effectively separated from the healthy plants.62

A series of spectral indices were computed from airborne CASI imaging spectroscopy data to detect the severity of plantation damage caused by Dothistroma needle blight in the New South Wales region of Australia.63 Results from independent validation data showed that hyperspectral data could discriminate between three levels of blight infection with accuracies above 70%. In South Africa, on the other hand, plantation forests are under threat from the wood-boring pest Sirex noctilio Fabricius (Hymenoptera: Siricidae; Sirex wood wasp). Sirex noctilio affects all commercial pine species in South Africa with none of the species showing a high resistance to attack.64 Recent reports have indicated that mortality might be as high as 30% in some forestry
compartments in KwaZulu-Natal. A recent study was aimed at identifying diagnostic spectral features of *Pinus patula* needles under varying degrees of attack by *S. noctilio*. The authors used data collected from a field spectrometer in the plantation forests of KwaZulu-Natal. Results of the Jeffries Matuzita distance analysis indicated that an acceptable separability of 99.2% for all the classes of different levels of *Sirex* infestation was reached when using a four-band combination comprising bands located in the visible and red edge portions of the electromagnetic spectrum.86

Other applications
Species discrimination, biomass assessment, leaf area index (LAI) estimation, foliar water content measurement, crop growth modelling and net primary productivity estimation are other areas where imaging spectroscopy has been applied effectively.79–82 Serrano et al.84 used AVIRIS data to estimate water content in Chaparral vegetation. A substantial review of imaging spectroscopy as applied to water content estimation is provided by Govender.77 In South Africa, Hyperion imagery was used to estimate LAI of *Eucalyptus* in the coastal Zululand of KwaZulu-Natal Province.78 A LI-COR 2000 was used to measure LAI on seven plots in the study area. Reflectance measurements and indices from Hyperion Level 1R data were regressed against LAI measurements. Results indicated that all relationships between LAI and the computed vegetation indices were significant *(P < 0.05)* with relatively high *R*² values *(R² > 0.80).* Another study assessed the utility of hyperspectral remote sensing to discriminate between site qualities in *E. grandis* plantation in KwaZulu-Natal, South Africa. The relationships between physiology-based hyperspectral indicators and site quality, as defined by total available water (TAW), were assessed for *E. grandis* using one-way analysis of variance (ANOVA). These results show that differences in site quality based on total available water, can be detected using imaging spectroscopy of canopy water or chlorophyll content.88

Conclusions
This review paper has highlighted the development of imaging spectroscopy (hyperspectral) applications in southern Africa, with particular reference to vegetation analysis and monitoring. A number of airborne imaging spectrometers, with largely similar characteristics are now operational. The paper has shown that there is a wide range of techniques, ranging from empirical to physically-based modelling approaches that have proven useful for analysing imaging spectroscopy data for vegetation analysis and monitoring. The development of a South African spaceborne imaging spectrometer presents new opportunities for detailed environmental assessment and monitoring. However, since imaging spectroscopy research is still in its infancy in South Africa, these new developments come with their own challenges in terms of human, financial and physical resources. Preprocessing and analysis of imaging spectroscopy data from the proposed MSMISat satellite, in particular, can only be achieved through collaboration between research institutions and application specialists before developed applications can be viewed as truly operational in the context of a constellation of satellites.

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