

IEEE P4001: Progress Towards a Hyperspectral Standard

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ABSTRACT

Hyperspectral imaging is an innovative and exciting technology that holds incredible diagnostic, scientific and categorization power. Current industry innovation is a testament to the creative power and imagination of the diverse community seeking to optimize this technology. However, fundamental instrument performance is not consistently well characterized, well understood or well represented to suit distinct application endeavors or commercial market expectations. Establishing a common language, technical specification, testing criteria, task-specific recommendations and common data formats are essential to allowing this technology to achieve its true altruistic and economic market potential. In 2018 the IEEE P4001 was formed to facilitate consistent use of terminology, characterization methods and data structures. This talk is a progress report to inform the hyperspectral community of the status of the work to date, the interconnection with other standards and outline the roadmap.

Keywords: hyperspectral, imaging spectroscopy, spectral imaging, pushbroom, spectral scanning, spatio-scanning, snapshot, IEEE, P4001, terminology, data structures, characterization

1.0 INTRODUCTION

Hyperspectral imaging is an expanding technology that was first reported more than thirty years ago. It is finding utility in a wide range of applications from Earth remote sensing to food analysis and security. The applications seem endless simply because of the power of optical spectroscopy to identify the chemical and biological elements in a material and how they are distributed. In many applications, with the appropriate calibration, concentrations of materials can be determined.

The term, “hyperspectral” seems to be grounded in the incorporation of higher sensitivity focal plane technology that enabled contiguous spectral band sampling through adjacent sensors (aka, two-dimension CCDs, InGaAs, MCT and other focal planes). These technologies allow single frame capture of a spatial image with all the corresponding spectral bands on one chip. This new single frame contiguous band capture was nicknamed hyperspectral to differentiate from multispectral sampling. Technically, hyper and multi are still forms of imaging spectroscopy. However, this form-factor innovation also allowed for much more compact optical and instrument geometries which shrunk the size, improved the speed and lowered the cost of these products. This instrument and name change allowed the instruments to really develop into commercially viable technology. Therefore, the name hyperspectral is now synonymous with small, fast, lightweight camera like spectral imagers and it is the way the market has adopted this concept and terminology.

There are now many manufacturers of hyperspectral instruments each with its own terminology, manufacturer specifications and characterisation methods as well as propriety data structures for the resulting measurement data. Lacking a set of consensus standards to define “hyperspectral” and related parameters, it is not clear where the line should be drawn for what constitutes a hyperspectral imager.

There are four common types of hyperspectral imager available in the market place today: these comprise of:

Push-Broom (Line Scan) Spectral Imagers: The data is collected in a line imaging mode, like machine vision line scan cameras, but onto a two-dimensional detector that in the orthogonal axis to the spatial line an optical

spectrum is measured, i.e. for each spatial pixel there is an optical spectrum. Such push-broom images are ideal for remote sensing and on-line production applications

Spectral Scanning Imagers: Use tuneable filters to take application complete images at a range of wavelengths. These type of images commonly use Liquid Crystal Tuneable Filters (LCTF) or Acousto-Optic Tuneable Filters (AOTF). They ideal where the sample under study is static and can achieve high spatial resolutions

Spatio-Scanning imagers: Comprise of wedge type linear spectral filters in front of the sensor and require moving camera or moving samples rather like push-broom techniques. These instruments usually have reasonable spectral resolution and have the promise to be lower cost in the visible spectral range compared to push-broom imagers. The resulting data frames require recalculation to provide spectral and spatial information.

Snapshot Spectral Imagers: Simultaneously record both spatial and spectral information of a scene. There are many forms of these types of images, but one commonly referred to type is the "Computed Tomography Imaging Spectrometry, CTIS. This uses a two-dimensional kinoform dispersing element and reconstruction of image and spectral data by computation.

As these instruments develop and the applications they are used in develop there is an increasing need for standardisation in terminology, performance specifications, and data structures to allow comparison of devices and also transferability of results. The IEEE P4001 project has grown out of that need. Sponsored by IEEE Geological Remote Sensing Society (GRSS) the P4001 project formally was launched in June 2018. This report provides an update to the first 9 months of the program of developing a standard for hyperspectral imagers.

2.0 IEEE P4001 Overview

The P4001 project is sponsored project by the IEEE to develop a comprehensive and clear standard for push-broom hyperspectral imagers across the spectral range from 250 to 2500nm.

It is timely to consider such standards not only because of the increased number of suppliers of compact and innovative designs but importantly because of the greatly expanding applications areas such devices are used in. Push-broom imagers were initially targeted because they form one of the largest classes of spectral imagers and when stabilised can achieve excellent radiometric repeatability. Therefore, they can be considered one of the fundamental measurement technologies in hyperspectral imaging to which other methods can later be compared. Modern computing power allows the data acquisition to be readily available for the large amounts of data collected as well as processing these measurements into useful information.

Today there are few standards in hyperspectral imagers that are commonly applied. Notable exceptions are the standards for the characterisation of remote sensing instruments that are flown such as: ISO 19130 - Imagery sensor models for geo-positioning and ISO 19159-1:2014 - Calibration and validation of remote sensing imagery sensors and data -- Part 1: Optical sensors

The P4001 project has been operating since June 2018 and today has over 250 members worldwide. Out of this group approximately 60 are active voting members and a further 35 are core members attending all meetings. Membership encompasses all of the well-known manufactures as well as national standards bodies and importantly application users. What has become clear is three key points:

- That the group consists of some of the best technical people in the area,
- Manufacturers have been very open and willing to embrace the project and share information that might even be considered propriety to them
- All members have been willing to devote their time to the standard free-of-charge.

The task of the P4001 project is therefore to bring together the basic tools to define, characterise and be able to use the resulting data from push-broom hyperspectral imagers, such that users can ensure proper performance can be achieved. The standard will encompass visible, near-IR and short-wave IR sensors (300 to 2500nm) using sensor technologies such as Silicon, InGaAS, MCT and T2SL sensors, with imaging spectrographs comprising of grating based systems for use in application areas using passive remote sensing from benchtop to airborne.

During the last nine months there have been six working group meetings both face-to-face and virtual. These meetings have outlined the requirements for the standards and have branched the work load to three sub-groups: Terminology, Characterisation, and Data Structures. Each group has about 20 members and many work in all three groups allowing both correlation and cooperation between sub-groups. This has allowed much of the work to be done in parallel. Items ready for evaluation can be submitted from the subgroup to the main P40011 working group for review and voting.

3.0 TERMINOLOGY SUB-GROUP

The goal of the terminology subgroup is to collate and define fundamental underpinning of establishing methods, means for testing, and for accurately and unambiguously conveying product specifications. Having written definitions, and well-defined equations (where possible) that objectively and unambiguously define these terms is critical for success.

Initial work in this subgroup has been on the collation of terms for review. In order to be consistent with the characterization sub-group then the terms have been separated into four groups for example:

- Spectral Terminology
- Spatial Terminology
- Signal/Radiometric Terminology
- System and Operational Terminology

Spectral Terminology	Spatial Terminology	Signal/Radiometric Terminology	System and Operational Terminology
Bandpass	Angular resolution	Bit Depth	Absolute Calibration
Diffraction Grating	Angular Response Function (ARF)	Dark Current	Achromatic Lens
Full Width Half Maximum	Distortion	Dynamic Range	Bad Pixels
Higher-Order Diffraction	Field of View (FOV)	Flat Field	Binning (Spectral and Spatial)
Order Blocking Filter	Ground Sampling Distance (GSD)	Gain	Charge-Coupled Device (CCD)
Spectral Band	Input slit	Ghosts	Complementary Metal-Oxide Semiconductor (CMOS)
Spectral Bandwidth	Instantaneous Field of View (IFOV)	Linearity	Dead Time
Spectral Radiance	Keystone	Noise	F-Number
Spectral Range	Nonuniformity Correction (NUC)	Offset	Focal Plane Array
Spectral Resolution	Point Spread Function (PSF)	Polarization Sensitivity	Frame
Spectral Response	RMS Spot Size	Quantum Efficiency (QE)	Framerate
Spectral Response Curve	Slit width	Radiometric Correction	Global Shutter (FPA)
Spectral Sampling Interval	Smile	Radiometric Resolution	Integration Time
Spectral Sampling Ratio	Spatial Fill Factor	Read Noise	Interlaced Scan Readout (CCD)
Transmission Grating	Spatial Nonuniformity	Responsivity	Pixel Pitch
Wavelength Calibration	Swath	Saturation	Progressive Scan Readout (CCD)
		Stray Light	Readout Smear
		Signal-to-Noise Ratio (SNR)	Relative Calibration
		Well Depth	Rolling Shutter (FPA)
		Vignetting	Scan Line
		Temporal Fill Factor	Slit Width
			Telecentric Lens
			Vicarious Calibration

Figure 1: This list is provided as an initial starting point for topics under discussion related to terminology

Importantly one of the key definitions required is “what is hyperspectral?” this is an ongoing work to provide an unambiguous definition of hyperspectral rather than anecdotal.

4.0 CHARACTERIZATION SUB-GROUP

The characterisation subgroup consists primarily of instrument designers and those involved in instrument qualification and testing. This group has had an initial focus on understanding the requirements of a spectral imager and determining a physical process model as well as image and spectral sharpness and co-registration issues in push-broom spectral imagers.

For example, the physical performance roadmap could be considered as follows (courtesy of Torbjorn Skauli [2]):

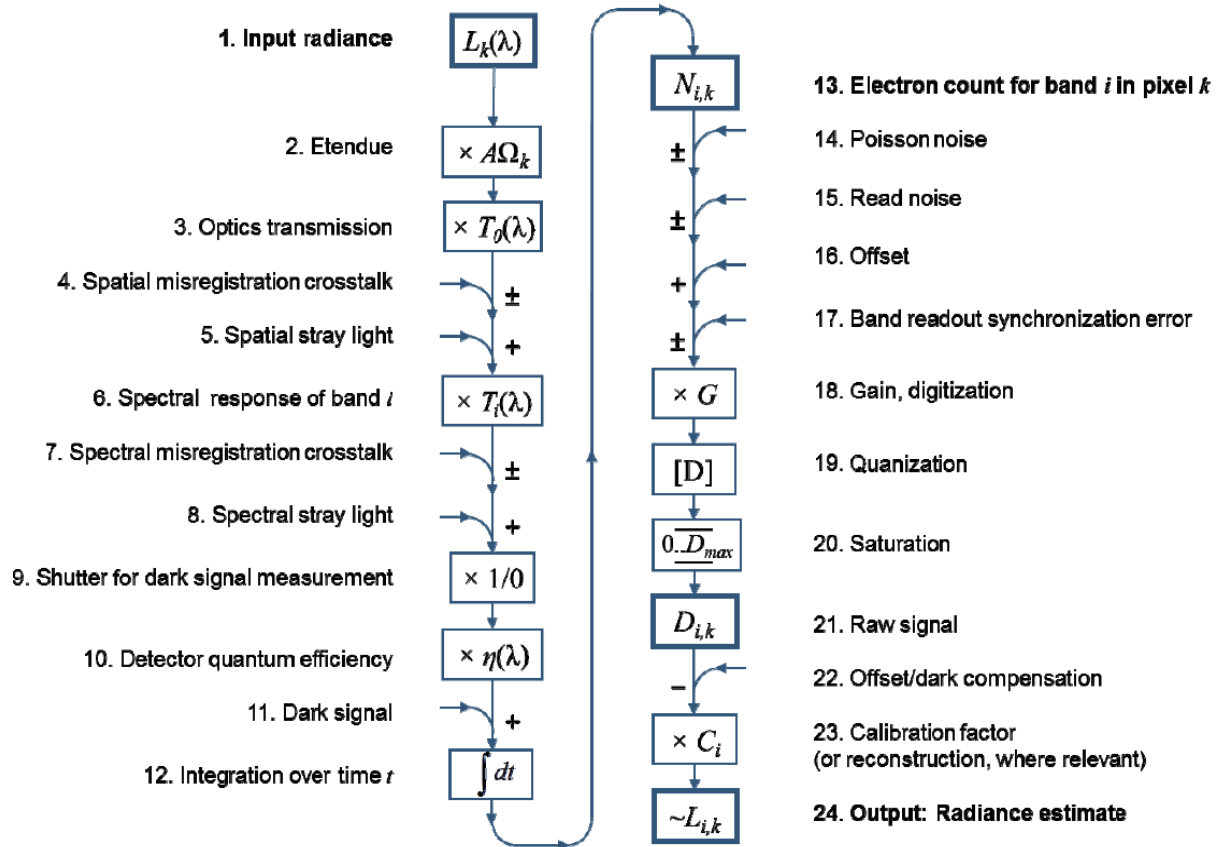


Figure 2: This diagram is provided as an initial starting point for topics under discussion related to calibration and characterization.

From this a considerable amount of work is still needed to ensure that all definitions of parameters and robust, yet as easy as possible, characterisation methods are defined for spectral geometric (spatial) and radiometric performances, for example:

Spectral Performance

- spectral range (usable)
- spectral resolution (acceptance angle of a pixel; not FOV divided by number of pixels)
- spectral sampling interval (SSI) (distance of center wavelengths)
- spectral sampling ratio (resolution divided by SSI)
- spectral misregistration (Smile, in pixel and spectral units)
- SRF uniformity (How stable is a SRF within a band)
- spectral calibration accuracy and stability

Geometric Performance

- field of view (along- and cross-track)
- angular resolution (along- and cross-track; acceptance angle of a pixel; Not FOV divided by number of pixels)
- angular sampling interval (ASI) (distance of center angles)
- angular sampling ratio (resolution divided by ASI; measure for sharpness)
- geometric misregistration (Keystone, in pixel and angle units)
- angular response function (ARF) uniformity (How stable is a SRF within a geometric pixel)
- focus range / working distance
- geometric calibration accuracy and stability
- location of each pixel on the scene (precision, stability)

Radiometric Performance

- noise / SNR / NESR (signal dependent)
- read noise
- SNR vs. spectral radiance at specified operating conditions, unbinned (not binned peak SNR!)
- Well depth
- dynamic range / resolution
- ADC characteristics (bit depth, gain (DN/e-))
- sensitivity
- wavelength and angle dependent (vignetting)
- F/#
- polarization sensitivity
- non-linearity
- Detector QE/spectral response
- pixel pitch
- dark current
- operability?
- uniformity (DSNU?, PRNU)
- radiometric calibration accuracy and stability
- dynamic range and noise performance on a standard light source

Stray light

From our experience, stray light is usually not separable in spectral and geometric components.

However, we distinguish between two kinds of stray light:

- diffuse stray light

In general, the far tail, low frequency component of pixel response functions or PSFs which can distinguished in

- in-band diffuse stray light (correctable to a certain extent)

- out-of-band diffuse stray light (not correctable)

- ghosts

In general, high frequency component in the tails of a pixel response functions or PSFs.

- in-band ghosts (correctable)

- out-of-band ghosts (not correctable)

Other

- min / max frame rate / readout rate / data rate

- min / max integrating time

- dead time?

- instrument stability

- focal length

- number of pixels (spectral and spatial) (usable)

- detector stabilized (yes / no, temperature, stability)

- number of bad pixels

- Fill-factor (spatial and temporal)

Physical Specs

- instrument dimensions, instrument mass, power consumption (V, A or W, peak, nominal) of system (including computer and cables if separate)

- valid range of temperature, humidity, (pressure?) (storage and operation)

- instrument stability (maybe hardest to measure and specify)

- computer interface (USB, CameraLink, GigE, standalone; remote control?)

- MTBF

- lens mount (if appropriate)

- mechanical interface (mounting)

Figure 3: this list is provided as an initial starting point for additional details under discussion related to calibration and characterization.

5.0 DATA STRUCTURES SUB-GROUP

The data resulting from hyperspectral images is the product that ultimately all users wish to have and use to solve their application specific issues. Having said this there are a number of proprietary manufacturer standards for such data sets and not a consensus on how a data structure standard should be created, structured or co-ordinated. The data structures subgroup is tasked with laying out the means and methods to provide basic, generic structures for header files, data files, encoding and inter-format transfers. This can then be used to underlay instrument information, data collection, storage and interpretation that ensures at least a common starting point for data organization.

There are already some standards for meta data such as ISO 19115 – Metadata, which comprises of

- ▶ 19115:2003 Widely used in the science and applications community
- ▶ 19115-1:2014 Major revision and update (not fully backwards compatible)
- ▶ 19115-2:2009 remote sensing specific, revised (2018) to “Extensions for acquisition and processing”

In addition:

- ▶ ISO 19139:2007 defines an XML implementation of 19115
- ▶ ISO 19139-2:2012 defines an XML implementation of ISO 19115-2
- ▶ ISO 19115-3 (under development) XML implementation of 19115-1
- ▶ ISO 19130-3 XML implementation of 19130-1 and -2
- ▶ ISO 19139-1 (under development) XML implementation -- Encoding rules

They apply to all types of imaging system data but as of yet do not fully encompass the requirements of hyperspectral imagers.

The data structures group is actively surveying the requirements for metadata and has proposed initially to review image data types and data processing levels. At the same time, they have been considering possible meta-data arrangements and have proposed the following for discussion.

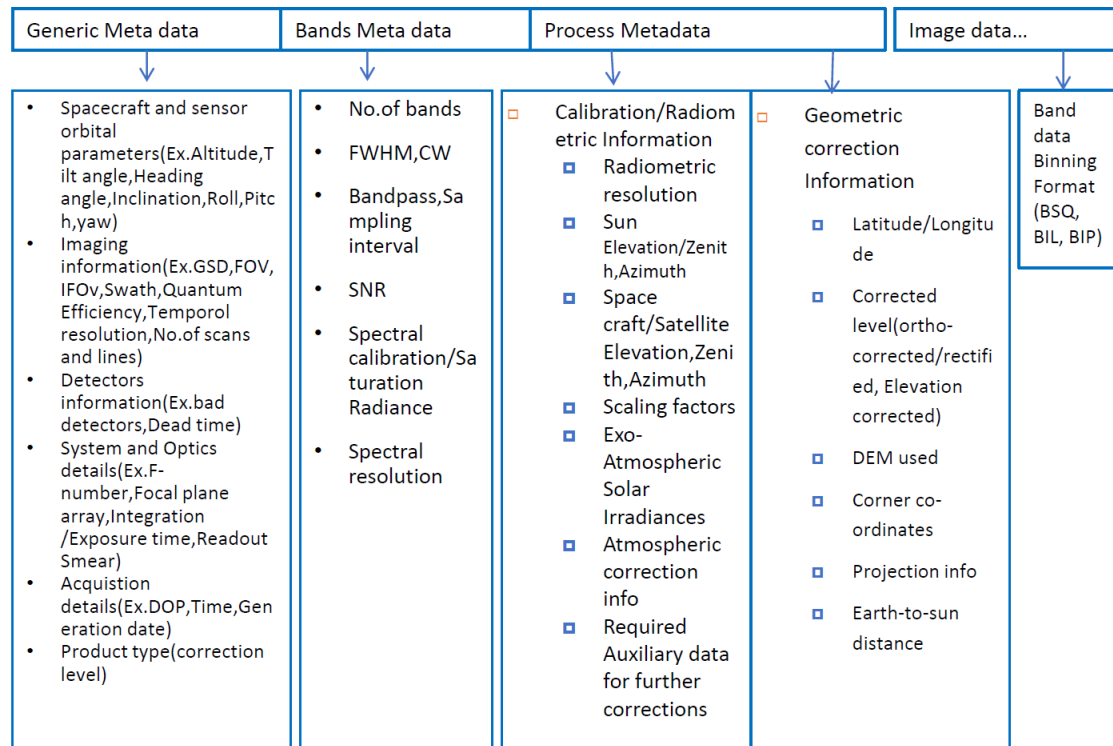


Figure 4: This list is provided as an initial starting point for topics under discussion related to data structures.

6.0 HOW TO BECOME INVOLVED

The IEEE P4001 project is an open and free forum for the hyperspectral (and multispectral) community, regardless of application. The success of the project depends upon you the community to actively support it and to consistently participate in the working groups.

Participation requires membership of the working group. To have voting rights one needs to attend on a rolling basis the last two meetings.

Contact for membership can be obtained through any of the officers:

- ▶ Chris Durell: cdurell@labsphere.com, Cell +1-858-414-1885
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8.0 REFERENCES

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