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Feasibility of a standard for full specification of spectral imager performance

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ABSTRACT

The current state of the art of specifying spectral imagers falls short of what is needed. Commercial datasheets do not adequately reflect the performance of hyperspectral imagers offered as standard products. In particular, imperfections such as coregistration error, noise performance and stray light are rarely well specified. A standardized way to specify spectral imagers would benefit both developers and users of such instruments. The paper reviews the many different characteristics that are needed to describe various aspects of imager performance, and discusses possible ways to form figures of merit relevant to application performance. In particular, the product of quantum efficiency, optics transmission and nominal throughput (étendue) is shown to be a good figure of merit for radiometric performance. A list of about 30 characteristics is suggested as a standard for a complete specification of spectral imagers. For some characteristics, notably coregistration, it is necessary to establish a standardized measurement methodology.

Keywords: Hyperspectral imaging, Multispectral imaging, Remote sensing, Optical design, Coregistration, Spectroscopy

1. INTRODUCTION

Hyperspectral imaging has become a widely used measurement technique in applications ranging from microscopy to planetary science. Many types of hyperspectral cameras are available commercially, and new sensor technologies are being developed. For developers, customers and users alike, it is important to have a clear and common understanding of the characteristics that describe the quality of a hyperspectral imager. In most hyperspectral imaging applications, the image data are first processed as individual spectra for each pixel, and it has been pointed out that a more appropriate term would be "imaging spectroscopy" [1]. Therefore, it is essential that hyperspectral imagers are well characterized in terms of their ability to generate spectra with good quality. This requirement gives rise to additional performance metrics compared to conventional cameras.

Here it will be argued that the current state of the art of specifying spectral imagers falls short of what is needed. Table 1 is an overview of characteristics given in online data sheets of spectral imagers from many commercial suppliers. It is evident that all the data sheets are missing numerous characteristics that are important for proper assessment of instrument performance. Commonly given figures such as peak signal to noise ratio or f-number are not really helpful for assessing actual imager performance in a given application. Compared to other types of instruments, there is clearly room for improvement in the specification of spectral imagers.

This paper reviews the various performance characteristics in some detail, highlighting areas where the current practice does not give a fully satisfactory specification of performance. Several papers have presented results from experimental characterization of hyperspectral cameras, such as [2] and [3]. A broad review of calibration of hyperspectral measurements is given in [4]. A full review of all relevant literature is not included here, but the papers cited can be consulted for further references to the field.

This paper discusses in particular how all relevant properties of a spectral imager can be condensed into a set of numbers that specify its performance in a compact form, apply to a wide range of spectral imager types, and adequately convey features and limitations. The treatment focuses on hyperspectral imagers, but is also mostly valid for multispectral imagers. This paper is inspired in part by experience from a recent tendering process for a hyperspectral camera procurement at FFI. The paper is not intended as a final word on the subject, but rather as a contribution towards establishing improved practices or standards in the hyperspectral community.

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Table 1. List of a selection of hyperspectral imager performance parameters and their appearance in published product datasheets. For 12 well-established commercial suppliers, the online datasheets of their high-end cameras have been reviewed. Eight of the 12 are imaging spectrometers (for which "keystone" and "smile" distortions are relevant), the others are FTIR, AOTF and filter-based imagers. The numbers on the right indicate how many of the suppliers report a given parameter.

Radiometric	
Peak signal to noise ratio	3
Peak noise equivalent signal radiance	2
Dynamic range	1
Radiometric accuracy	1
Polarization sensitivity	1
Noise floor, in photoelectrons	1
Digitization resolution, in bits	3
F-number	9
Pixel size	6
Optics transmission	0
Detector quantum efficiency	0
Uniformity of response across FOV	0
Recording speed, frames per second	8
Spatial	
Pixel count	12
FOV or pixel sampling interval	9
Spatial resolution FWHM	2

Spectral	
Spectral range	12
Sampling interval or no. of bands	9
Spectral resolution	8
Spectral stability	1
Wavelength accuracy	1
Coregistration	
Keystone and smile distortion (of 8)	5
PSF shape coregistration	0
Spectral-spatial interdependence	0
Temporal coregistration of bands	0
Burden	
Mass	11
Dimensions	10
Power	9
Cost	0

2. REVIEW OF SPECTRAL IMAGER CHARACTERISTICS

The basic function of a hyperspectral imager is to record the incoming angular distribution of spectral radiance, resolved in two spatial dimensions and the wavelength dimension. The results are represented as a cube of radiance samples from this three-dimensional space. (Strictly, in microscopy and close-range imaging, the measured quantity is instead spatial distribution of excitance, but otherwise the treatment remains the same.) The quality of the measurement thus depends on characteristics related to the radiance measurement, the spatial sampling and the spectral sampling, as well as the time needed for the measurement. The quality of the hyperspectral imager from the user point of view depends additionally on the burden it represents in terms of size, weight, power and cost, as well as operator effort and competence requirements.

To a large extent, concepts from signal theory and conventional imaging can be applied to express performance of the radiance measurement and the resolution along any one of the three axes of the data cube. Still, it will be argued here that there is a need to improve the current state of the art of specifying spectral imagers, particularly with respect to those characteristics that involve a coupling between spectral and spatial behavior. The following is a review of the many characteristics that together describe spectral imager performance.

2.1 Spatial characteristics

Consider first characteristics related to image geometry and spatial resolution. These can for a large part be taken from the way conventional cameras are specified. This includes the pixel count, field of view and geometrical distortion (as opposed to misregistration, discussed below). Since spectrum integrity is more important than spatial contrast, it is basically the shape of the sampling point spread function (SPSF) [5] which is relevant. A more appropriate measure of resolution would then be the average ensquared energy [6], the mean fraction of energy from a randomly placed point source which is received by the pixel that nominally covers the source position. This quantity is directly related to the ability to form a valid spectrum from the pixel footprint in the scene. An alternative and more conventional measure of spatial resolution could be MTF at the Nyquist frequency.

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2.2 Spectral characteristics

For the spectral dimension, a hyperspectral imager is primarily characterized by its spectral range and spectral resolution. Also important is the accuracy and stability of the wavelength calibration. Imagers with a large number of bands will often oversample the actual signal spectra. In such cases, resolution may be sufficiently specified by the bandwidth, for example as a full width at half maximum (FWHM) value. When bands are broad compared to relevant spectral features, such as for multispectral imagers, it may be necessary to specify the shape of the spectral response function (SRF) in more detail, for example by the band edges. In both cases, a preferable way to quantify resolution could be to adopt an analogy of the average ensquared energy. On the spectral axis, this would be the relative amount of signal energy from a broadband source that originates from within the nominal bandwidth.

2.3 Coregistration

Different bands may collect light from slightly different areas in the scene due to spatial misregistration between bands, caused by for example optical distortion in imaging spectrometers or chromatic aberration in lens foreoptics. Such imperfections can be seen as leading to a band-dependent crosstalk from neighboring pixels. Similarly, the spectral response of a given band may vary somewhat across the field of view. In Ref. [7] and several other early works from NASA, it was pointed out that spectral and spatial coregistration is essential for signal integrity in a spectral imager.

Coregistration can be quantified in many ways. For imaging spectrometers, coregistration errors are customarily specified in terms of "smile" and "keystone" distortions, which only depend on the PSF centroid positions on the image sensor in the spectral and spatial directions. Ref. [7] outlines a design procedure which also takes into account the shape of the response functions in a combined merit function for optical design. Ref. [5] proposes a general coregistration metric, which in its basic form quantifies spatial coregistration error ε_s between two bands in a single pixel, or spectral coregistration error ε_λ between two pixels in a single band. The metric is simply the integrated difference between two SPSFs or SRFs respectively. In the paper, it is shown that such a metric has reasonable mathematical properties and contains the conventional smile and keystone measures as special cases. Furthermore, the proposed metrics give an upper bound on the absolute radiometric signal error for extended sources, and can be used to estimate effects of misregistration on the signal. Ref. [8] demonstrates experimental measurement of these metrics. Ref. [9] points out that the method in [5] does not account for worst-case misregistration when imaging a point source. The work in [9] proposes and demonstrates a different method for quantifying coregistration based on scanning of a point source. The method in [9] is implemented for one-dimensional scanning to characterize an imaging spectrometer, but appears to be well generalizable to the two-dimensional case. However with the method in [9], the coregistration measure depends on the integral of each PSF within its nominal pixel, and therefore may not capture all types of PSF shape differences within the pixel. Such effects are captured by the method in [5], which should be sound for extended sources such as reflective scenes, but may need to be supplemented with a different metric for point sources such as stars. A coregistration metric for point sources may be akin to the one proposed in [9], or simply based on the maximum difference between PSFs. In the following, coregistration error will be discussed in terms of the metrics in [5] since the mathematical foundation is developed for the general 2D case and since most applications of spectral imaging involve extended sources such as reflective scenes.

The works just mentioned deal with spectral and spatial coregistration. It is well known from conventional imaging that non-synchronous readout of image data may cause undesirable effects such as "rolling shutter" artifacts, or distortions in line-scanned images due to imperfect scan movement. In spectral imaging, if different spectral components are sampled at different times, the spatial coregistration of bands may be severely distorted by relative movement of scene and imager, or by temporal variation in the scene. As mentioned above, it is therefore desirable to specify such "temporal misregistration" of different bands in a pixel. Typically, the recording is either simultaneous, such as for an imaging spectrometer, or sequential, such as for an FTIR imager. Then a reasonable specification of simultaneity would be to give the ratio (integration time for one band) / (total time for recording of a pixel spectrum). It can be observed that a more general metric for temporal coregistration error can be defined in analogy with the spatial and spectral coregistration metrics in [5] as a time integral over the difference in responsivity between two bands.

2.4 Stray light

Apart from misregistration, the optical signal can be affected by stray light from spatially distant parts of the scene. This contribution can be quantified by measures like the Veiling glare index, *VGI* [10], which is the relative signal from a pixel viewing a very dark part of an otherwise brightly illuminated scene. For a scene with mean radiance $\bar{L}$, the stray

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light contribution will be on the order of $\overline{L}\,VGI$. It may be possible to correct for stray light by using image data combined with detailed instrument characterization [11], but only for stray light originating from within the field of view.

In analogy with spatial stray light, the reading in a given band may be affected by distant parts of the spectrum through stray light. This can be a significant effect in hyperspectral imagers [11]. Spectral stray light can be characterized in an analogous way to the VGI, by testing with broadband illumination and band stop filters at different wavelengths. For instrument specification, such testing should be carried out at the wavelengths that are subject to the strongest stray light effects. Notably, shorter wavelengths will tend to scatter more strongly, and wavelengths where detector quantum efficiency is low may be more subject to stray light from other wavelengths. There appears to be no established definition of a figure of merit for spectral stray light. It would be quite reasonable to define a spectral stray light index (SSI) analogous to the VGI, by integrating the relative contribution from all out-of-band light. Then spectral stray light will be on the order of $\overline{L}\,SSI$. The SSI could be defined more precisely in a specification standard, probably analogously to the VGI.

The VGI will vary with position across the field of view and, in particular, the SSI will be a function of the wavelength taken to define in-band light. Characterizing this wavelength-dependence in detail may be useful for correction of stray light effects. For the purpose of instrument specification, however, it could be sufficient to give the maximum values for the VGI and SSI. If the instrument incorporates a stray light correction of the raw data then the appropriate measure may be a residual VGI and SSI after correction, but including stray light contributions from outside the field of view.

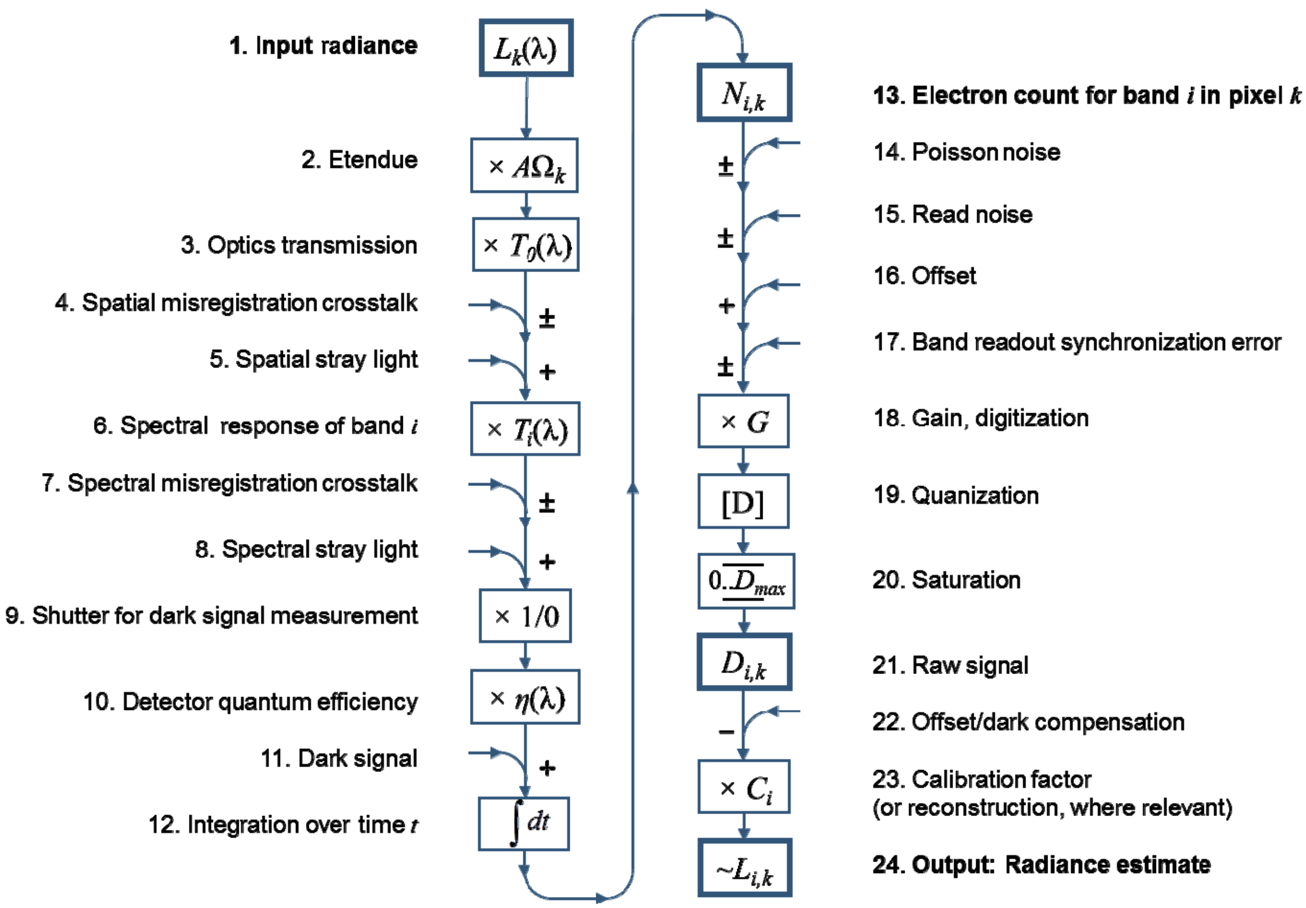

Figure 1. Conceptual illustration of the signal path of a hyperspectral imager. Many factors and signal contributions affect the measured radiance value, as discussed in the text. Thick boxes indicate several signal representations relevant to the analysis, marking the transitions from the optical to the electronic to the digital domains. Noise contributions are indicated by "±", offset contributions are indicated by "+" and offset compensation is indicated by "-".

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2.5 Radiometric measurement

Now consider the measurement of a radiance value. The output radiance samples are the result of a long measurement chain with many possible influences, as illustrated in Figure 1. This somewhat unconventional representation of the typical signal chain is discussed in the following list, which also indicates how each item may be quantified. Numbers refer to the stages in Figure 1.

1. The input signal is the radiance spectrum $L(\lambda)$ arriving at the camera entrance aperture.
2. Imaging optics collects light through an entrance pupil area A over the nominal field of view Ω_k for pixel *k*, defining the nominal optical throughput, or étendue, $A\Omega_k$.
3. There will be some light loss in the optics, for example due to diffraction grating efficiency or optical coatings. Such losses can be represented by a transmission coefficient $T_0(\lambda)$ for the optics.
4. Spatial coregistration errors will lead to wavelength-dependent crosstalk with neighboring pixels. Using the coregistration error metric $\bar{\varepsilon}_s$ from [5], a scene where the mean nearest-neighbor pixel spatial contrast is σ_s will tend to give a relative signal error on the order of $\sigma_s\bar{\varepsilon}_s$.
5. For a scene with mean radiance $\bar{L}$, the stray light contribution will be on the order of $\bar{L}\,VGI$.
6. Some form of spectrally selective optics will define each band, represented in Figure 1 as a wavelength-dependent transmission $T_i(\lambda)$ for band index *i*. For hyperspectral imagers based on Fourier transform spectroscopy, or other forms of spectral reconstruction, $T_i(\lambda)$ can represent any spectral component, such as a point in the interferogram, for the sake of the analysis here.
7. Spectral coregistration errors will tend to give some degree of crosstalk from parts of the spectrum adjacent to the nominal band. Using the coregistration metric $\bar{\varepsilon}_\lambda$ from [5], a scene with mean relative neighboring-band spectral contrast is σ_λ, will tend to give a relative error due to spectral misregistration on the order of $\sigma_\lambda\bar{\varepsilon}_\lambda$.
8. Stray light in the spectral direction will give a signal contribution on the order of $\bar{L}\,SSI$ where *SSI* is a spectral stray light index as discussed above.
9. The optics signal path may incorporate a shutter which can block out all external light for direct measurement of signal contributions from the instrument itself.
10. The photodetector, usually a pixel element of an image sensor, transforms the optical signal into the electronic domain. All detectors exhibit some degree of signal loss represented by a quantum efficiency $\eta(\lambda)$, often with relatively strong wavelength dependence. In most cases the electronic signal arises in the form of electrons excited by photons. If the fill factor of the detector array is less than unity, it can be incorporated in $\eta(\lambda)$.
11. Various mechanisms will contribute to a "dark signal" independent of the incoming light. Such mechanisms include thermal emission from within the optics and leakage current in the photodetector. These are combined into one contribution in the model in Figure 1. The dark signal can be represented as a dark current i_{dark}, measured in electrons per second.
12. An important function of the photodetector and electronics is to form a time average of the signal by integrating it over a defined integration time, or "exposure time". The integral includes the electrons from the dark signal.
13. After the integration, the radiance signal is now represented as a number of electrons, $N_{i,k}$ for band *i* in pixel *k*.
14. The arrival of photons and excitation of electrons is a random process that follows (or approximates) Poisson statistics: For a mean signal $\bar{N}_{i,k}$, both the standard deviation and the signal to noise ratio will be $\sqrt{\bar{N}_{i,k}}$. This is a fundamental, unavoidable source of noise ("photon noise") whose influence can be reduced by collecting more light or by reducing light loss in the imager, as well as by reducing the dark signal. (Some detector types, notably uncooled bolometers, will have a different noise model, less dependent on the signal.)

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15. The photodetector and electronics will generate an additional "read noise" associated with reading out the signal. This noise is often taken to be constant, and its relative effect will be larger for weaker signals. The read noise can be represented as a variance in the number of electrons, σ_{read}^2 .
16. The electronics may also add some offset to the electrical signal, often by design.
17. For some spectral imaging technologies, measurement of the different bands is not synchronous. If the input signal varies in time, nonsynchronous measurement of bands may lead to errors in the sampling of the spectrum, in analogy with spatial misregistration, as discussed above. The effect on the signal will depend on whether the scene is stationary or dynamic, therefore a specific error estimate cannot be made here.
18. At the end of each integration interval, the integrated signal is sampled and converted to a digital value which varies linearly with the electron count, with some scaling factor G representing the overall analog gain.
19. The signal is digitized to an integer value, leading to a quantization error. The error can be modelled as a noise contribution, but is negligible in most cases.
20. The electronic signal and digitization only operates over a limited range of values. Signals above this range will result in an end-of-scale reading $D_{\max}$, and are said to be in saturation. Normally the saturation corresponds to the "well capacity" of the image sensor, the maximum number of electrons that can be collected.
21. The resulting digital value $D_{i,k}$ is the raw image data, which now needs to be processed into an estimate of the incoming radiance.
22. The total offset due to dark signal and electronics offset can be measured and represented as a value D_0 on the digitized signal scale, which is subtracted as part of the data preprocessing.
23. The resulting digital value is finally scaled by a calibration coefficient $C_{i,k}$ into an estimate of the incoming radiance for band i in pixel k. This coefficient must be determined from calibration against an absolute radiometric reference and is critical for the radiometric accuracy of the camera. Some hyperspectral camera types, notably those based on resampling or FTIR, require a more complex reconstruction step, which in some cases may add uncertainty or noise. In those cases the analysis will need an appropriate adaptation, see the discussion below.
24. The final output is an estimate $L_{i,k}$ of the incoming radiance in band i and pixel k.

In addition to this list of contributions in the model of Figure 1, there are several other factors that can affect the radiometric measurement, but which in some cases may have only a small or moderate influence:

- Polarization sensitivity may be introduced by various optical effects in the camera, such as metallic diffraction gratings, but will only affect the result if the incoming light exhibits a significant degree of polarization. Polarization sensitivity may be specified as the relative amplitude of the polarization dependence [11] at the wavelength where the dependence is largest.
- Linearity of response is normally very good in relevant types of photodetectors. It can be noted that linearity is particularly critical in Fourier transform-based systems, to avoid spectral artifacts. The relevant quantity for spectroscopic measurement is the maximum integrated linearity error, *i.e.* the largest deviation from the ideal linear response, which can be expressed as a percentage of the reading.
- The fill factor of sensitive area on the photodetector array, if significantly less than unity, can lead to a point source responsivity that varies across each pixel. Of course, it is not of interest to the user to specify the fill factor of the image sensor if its effects are completely blurred by the point spread function of the optics. However some spectral imaging technologies have potential for undersampling the scene, such as the one presented in Ref. [12]. If a point source is scanned across the field of view then the integrated response from all pixels surrounding the source may depend on the position of the source relative to the pixel centers. Such effects can be specified by the ratio of lowest to highest integrated point source responsivity within a pixel, which can be considered an effective fill factor for the imager.

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- In analogy with the spatial fill factor, it is possible to envisage cases where the responsivity for a monochromatic source depends on how the wavelength is placed relative to the band limits. This can be quantified in an analogous way as the ratio of lowest to highest photon responsivity across a band, using the binned response from all bands containing signal from the source. This may be termed a "spectral fill factor".
- It may also be relevant to specify the duty cycle for photon collection, or "temporal fill factor", as the fraction of time where a given band is collecting signal, relative to the total time the pixel is within the field of view. For example, if a pushbroom imager operates in "integrate, then read" mode with a frame time down to 10 ms and a readout time of 5 ms then it would be relevant to specify a minimum duty cycle of 50%, or to give the readout time as part of the specification.
- The spatial and spectral response functions for a single radiance sample may be interdependent. This is discussed in [5], where a metric for this effect is proposed. The effect is likely to be small in most cases, since the interdependence will tend to be blurred out by the PSF and SRF.

From this treatment, it is clear that the radiance measurement is subject to several types of error and noise, some of which are specific to spectral imaging. It is also clear that any reasonably complete specification of a hyperspectral imager needs to contain data for many different properties. In a sense, the list of specifications needs to be longer than the combined specifications for a camera and a spectrometer.

3. FIGURES OF MERIT FOR SPECTRAL IMAGER PERFORMANCE

The preceding treatment outlines a way to specify a hyperspectral camera, and leads to a complex set of characteristics. It is obviously desirable to simplify the quantification of performance as much as possible by defining suitable figures of merit that combine several of the basic characteristics. This section discusses some possible ways to form relevant figures of merit. Only the first of these is proposed as part of a possible standard specification below, however.

3.1 Net throughput as a key parameter for signal to noise ratio, dynamic range, compactness and more

Consider first the photoelectron signal in absence of misregistration, stray light and dark signal, which can be written as

$$N_{i,k,phot} = A\Omega_k t \int L(\lambda)T_0(\lambda)T_i(\lambda)\eta(\lambda)d\lambda \approx A\Omega_{pix}\eta_{eff}(\lambda_i)tL(\lambda_i)\Delta\lambda_i \equiv A_{eff}(\lambda_i)tL(\lambda_i)\Delta\lambda_i \quad (1)$$

Here the integration of signal contribution over wavelength has been approximated by multiplication with an equivalent bandwidth $\Delta\lambda_i$ and likewise the integration over time by multiplication by t. Ω_{pix} is the average pixel field of view and $\eta_{eff}(\lambda)$ is an overall quantum efficiency that incorporates losses in the optics. The product

$$A_{eff}(\lambda) \equiv A\Omega_{pix}\eta_{eff}(\lambda) \quad (2)$$

then determines the net optical throughput. (A refractive index factor n^2 must be included for instruments with optical immersion of the detectors.) Together with the bandwidth, and the exposure time chosen by the user, it determines the photoelectron signal for a given radiance. Note that $A_{eff}(\lambda)$ has the unit of area, with a useful interpretation: The amount of light collected by the imager is equal to the flux of light within the band crossing an area $A_{eff}(\lambda)$ when the signal radiance arrives from a solid angle of 1 steradian. In other words, $A_{eff}(\lambda)$ is the pixel area of an equivalent ideal camera with aperture setting F/1.4 (which gives Ω=1 sr at the detector). The throughput $A_{eff}(\lambda)$ is an interesting figure of merit for several reasons:

- For sufficiently strong signals, noise is dominated by Poisson noise from photoelectrons. Then the signal to noise ratio will be proportional to $\sqrt{A_{eff}(\lambda)}$ and can be estimated for a given application using (1) for a typical input radiance $L(\lambda)$ and integration time t.
- In the low-signal limit, the signal to noise ratio is

$$SNR_{low} = \frac{A_{eff}(\lambda)tL(\lambda_i)\Delta\lambda_i}{\sqrt{i_{dark}t + N_{dark}^2}} \quad (3)$$

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where N_{dark} is the number of electrons in the integrated dark signal. The corresponding noise equivalent signal radiance is

$$NESR = \frac{\sqrt{i_{dark}t + N_{dark}^2}}{A_{eff}(\lambda)t\Delta\lambda_i} \tag{4}$$

which is inversely proportional to $A_{eff}(\lambda)$.

- The saturation level corresponds to $N_{\max} = D_{\max} / G$ photoelectrons, neglecting dark current. This in turn corresponds to a saturation radiance

$$L_{\max}(\lambda_i) = \frac{N_{\max}}{A_{eff}(\lambda)t\Delta\lambda_i} \tag{5}$$

which is again inversely proportional to $A_{eff}(\lambda)$.

- The area $A_{eff}(\lambda)$ can be compared to the size of the camera to judge whether it makes efficient use of space, for example by the dimensionless ratio $\overline{A}_{eff} / V^{2/3}$ where $\overline{A}_{eff}$ is a mean over the wavelength range of the imager and V is the volume of the camera.

Thus based on $A_{eff}(\lambda)$, a user can estimate the expected SNR from the typical radiance levels in the application, using a value for the exposure time determined from application requirements or from the saturation level (5). As pointed out in [13], $A_{eff}(\lambda)$ can also be used to define an image data format that enables the user to estimate noise levels in each image. Because of the strong variation of quantum efficiency with wavelength, it will be necessary to specify $A_{eff}(\lambda)$ as a graph, or as several values for different spectral intervals.

At this point, it can be commented that a more customary measure related to optical throughput is the responsivity. Neglecting offset and dark current, the responsivity can be defined as

$$R = \frac{D_{i,k}}{L_k(\lambda)\Delta\lambda_i t} = \frac{GN_{i,k}}{L_k(\lambda)\Delta\lambda_i t} = GA_{eff}(\lambda_i) \tag{6}$$

Note that the gain factor G can be chosen quite arbitrarily in the design of the readout electronics. Therefore the responsivity is not suitable as a figure of merit for specifying and comparing cameras. The A_{eff} product in (2) on the other hand is a well-defined quantity in any optical system and does not contain any arbitrary factors.

3.2 "Spectral vignetting"

It is interesting to note that the wavelength dependence of $A_{eff}(\lambda)$ is analogous to light loss at the edges of the field of view due to vignetting and projection falloff ("cos^4") effects. The "spectral vignetting" is at least as important for signal quality as spatial vignetting. Thus one way to specify optical throughput would be to give its value at the wavelength of best throughput, $A_{eff,\max}$, and then specify the ratio

$$\frac{A_{eff,min}}{A_{eff,max}} \equiv \text{"spectral vignetting"} \tag{7}$$

This would be a way to quantify the wavelength dependence of $A_{eff}(\lambda)$ in terms of numbers instead of a graph. This characteristic would emphasize the importance of spectral responsivity variation, but is much less informative than giving the graph of $A_{eff}(\lambda)$.

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3.3 Combined figure of merit for resolution and coregistration

Ref. [5] discusses how the proposed coregistration metrics can be used to express overall coregistration performance, and proposes to specify imagers in terms of the mean ($\bar{\varepsilon}_s$, $\bar{\varepsilon}_\lambda$) and max ($\varepsilon_{s,max}$, $\varepsilon_{\lambda,max}$) values over all bands and pixels. The mean value can be used for signal error estimation, as mentioned above, and the maximum value gives a bound on the signal error.

As discussed in [5] and [14], the coregistration error can be made smaller if the pixel size is made larger, either by binning or by changing to an image sensor with larger elements. If, for example, an imager has a mean coregistration error of $\bar{\varepsilon}_s = 20\%$, a 2x2 spatial binning of the imagery will tend to reduce the coregistration error by a factor 4, to 5%. If the application calls for a coregistration error of 1%, which may still be large compared to the relative photon noise, then it would be necessary to do spatial binning of groups of 20 pixels. Thus an illustrative way of representing coregistration error would be to give the effective number of pixels P_{eff} that can be resolved for a given upper limit requirement $\bar{\varepsilon}_{s,lim}$ on the mean coregistration error when the total pixel count is P:

$$P_{eff} = P \frac{\bar{\varepsilon}_{s,lim}}{\bar{\varepsilon}_s} . \qquad (8)$$

By standardizing on a reasonable limit, for example $\bar{\varepsilon}_{s,lim} = 1\%$, a specification of P_{eff} would give users a sensible way to compare the resolution of different spectral imagers. Thus a 1-megapixel frame-imaging spectral camera with $\bar{\varepsilon}_s = 20\%$ could be specified to have $P_{eff,1\%} = 50\,\text{k pixels}$. In the particular case of a pushbroom-scanning spectral imager, it may not be reasonable to reduce its pixel count by the same factor, since binning should be applied equally in the along-track and across-track directions (assuming that there is no predominant directionality of the coregistration error). Instead, the effective pixel count of a pushbroom hyperspectral imager with P across-track pixels could be given as $P\sqrt{\bar{\varepsilon}_{s,lim} / \bar{\varepsilon}_s}$, assuming that the same binning factor is applied in the along- and across-track directions.

In the spectral dimension, it would be possible to define similarly an "effective number of bands". This may be a less meaningful measure, however. It is quite clear that the utility of a spectral imager tends to be proportional to the number of spatial pixels, but in the spectral dimension the utility of a given band configuration depends strongly on the application. Therefore it may be better to specify spectral coregistration in terms of the metric values $\bar{\varepsilon}_\lambda$ and $\varepsilon_{\lambda,max}$.

3.4 Information capacity as an overall figure of merit

The basic task of a hyperspectral imager is to collect information. As discussed in [14], the performance of an imager can be quantified as an information capacity in the information-theoretic sense, by considering misregistration-induced signal errors as a form of noise. In principle, it is then possible to combine all performance characteristics and use the information capacity as a single figure of merit. However it may be difficult to create a standardized definition of such a global figure of merit. Also, the information capacity cannot be directly related to application requirements. This concept for imager specification is therefore not discussed further here, but it could be a topic for consideration in the future.

4. A POSSIBLE STANDARD SET OF SPECIFICATIONS

Table 2 presents a suggested minimum set of characteristics that need to be specified in order to give a first-order description of the performance of a hyperspectral imager. The table has two parts: The "nominal performance characteristics" describe the main features of the imager, including the spectral, spatial, radiometric and temporal resolutions and ranges. These characteristics should give a lower bound on the imager performance. "Imperfections" are the deviations from ideality that normally occur, to a larger or smaller extent, in all spectral imagers. These characteristics should give an upper bound on the imperfections.

This set of characteristics could be a starting point for a future standard way of specifying spectral imagers.

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Table 2. A set of specifications that give a reasonably complete picture of the performance of a spectral imager. This can be considered as a suggestion for a standard set of specifications. See discussion in the text.

Nominal performance characteristics	**Unit**	**Comment**
Wavelength range	µm	
Band format		No. of bands, or band limits, as appropriate
Spectral resolution relative to spectral sampling interval	%	Average "band ensquared energy", a mean value over all pixels* and minimum over all bands
Pixel count		No. of spatial pixels in each dimension
Field of view	deg.	(Or lateral dimension, for finite range imaging)
Spatial resolution relative to pixel sampling interval	%	Average ensquared energy, given as mean value over all bands* and minimum over all pixels
Frame rate range	Hz	(Or line rate, for pushbroom imagers)
Integration time range	ms	
Graph of $A_{eff}(\lambda)$	μm^2	Can alternatively give minimum value
Saturation level	e^-	Full well electron count
Dimensions	cm	
Mass	kg	
Power consumption	W	
List price	currency	
Imperfections	**Unit**	**Comment**
Wavelength accuracy and stability	µm	
Radiometric calibration accuracy	%	
Spatial coregistration $\bar{\varepsilon}_s$ and $\varepsilon_{s,max}$	%	May need another metric for point source imaging
Spectral coregistration $\bar{\varepsilon}_\lambda$ and $\varepsilon_{\lambda,max}$	%	
Read noise	e^- rms	Can alternatively give a combined value for these at the longest exposure time
Dark signal	e^-/s	
Dead pixels	%	
Throughput falloff at edges of FOV	%	Relative to peak value.
Spatial stray light	%	VGI according to [10]
Spectral stray light	%	Analogous to VGI, see text
Time difference between spectral components	%	Integration time relative to pixel time, see text
Polarization sensitivity	%	
Nonlinearity	%	Max. integrated linearity error
Spatial distortion	%	Relative to ideal projection imaging
Effective fill factor	%	Variation of total response across a pixel
Spectral fill factor	%	Photon response variation across a band, see text
Duty cycle or readout dead time	% or ms	
Spectral-spatial response interdependence	%	See discussion in [5]

*Mean values can be used here because deviations from ideality are quantified by the coregistration specifications.

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5. DISCUSSION

In total, Table 2 contains some 30 different elements that are needed to specify a spectral imager reasonably completely. This large number reflects the complexity of the task. Obviously some of these characteristics, such as spectral-spatial response interdependence, may have a totally negligible effect in many cases. Also some characteristics, such as spatial distortion, may be of little importance in a given application. On the other hand, the majority of the listed parameters have the property that for a commercial instrument, reduced performance could save cost on the part of the manufacturer and lead to disappointment on the part of the user. Considering Table 1, there is thus a strong motivation for buyers to demand better data about spectral imaging products than what is provided today.

Some of the characteristics may not be straightforward to measure in detail. For example, Ref. [11] reports that a high-quality laser-based spectral-spatial stray light measurement has taken several person-years to set up. In that case, however, the aim was to collect high accuracy measurements suitable for correcting the output image data. It is important to realize that in contrast to a full characterization, specifications need only be a bound on a given property, and not a precisely measured value. For stray light measurement, for example, simpler methods based on band-stop filters can provide sufficient data for specification of performance. For some elements of the specification, it may also be possible to derive meaningful results from the raytracing simulations that are performed as part of optics design anyway.

The discussion here has mostly considered sensors where each radiance sample in the output spectral image corresponds to a single raw data sample. Many spectral imaging technologies employ a significant amount of software preprocessing (reconstruction, transformation, resampling, correction or calibration) to generate the output image. To be relevant to the user, specifications must reflect the properties of the output image after preprocessing. In such cases, specifications will then take into account the effect of preprocessing. For example, averaging or binning of raw data may tend to increase signal to noise ratio or reduce coregistration errors. Resampling or similar processing of the raw data will produce output data with irregular noise and coregistration properties, but estimates of noise and coregistration can still be propagated though the preprocessing to obtain specifications for these properties. Generally, software preprocessing tends to consist of linear operations, which simplifies this propagation of imperfections to the output. In cases where preprocessing introduces variability in data quality, the camera specifications should primarily report the worst-case performance, possibly supplemented by an average value.

It must be noted that some spectral sensing concepts rely on application-specific prior knowledge, or assumptions about the scene. Even a noisy, sparse and non-coregistered subsampling of the spectral cube can be used to derive useful knowledge about the scene if the range of scene variability is bounded and known. Then paradigms such as compressive sensing or deep learning can be applied, and can lead to very efficient sensing systems. In such cases, however, the performance of the imager becomes deeply intertwined with the scene properties and application requirements. Then the kind of specifications discussed here become less relevant, and it is instead necessary to judge the system by its overall application performance, which may be good even if the imager by itself scores poorly in terms of some key specifications in Table 2. In general, any comparison of application-dependent and generic spectral imagers must be done very prudently in order to make sense, if possible at all.

The majority of the characteristics in Table 2 are already widely used and well known from conventional imaging. However, as noted initially, hyperspectral imagery is primarily being exploited by processing the spectral dimension first. This focus on spectroscopy, rather than imaging, leads to some less conventional ways of specifying performance in the suggested standard set in Table 2:

- Spectral processing relies, implicitly or explicitly, on the assumptions that in a given pixel, all bands record light from the same spatial region in the scene, with the same point spread function, and that all pixels see the same bands. Therefore coregistration is an important part of the specification for a spectral imager.
- Hyperspectral imagers normally exhibit very large variations of responsivity across the spectral range. Therefore, $A_{eff}(\lambda)$ is a better overall figure of merit for light collection than for example the f-number.
- The quality of the pixel spectrum has priority over preservation of spatial contrast. Therefore, resolution should be specified in terms of the average ensquared energy, rather than in terms of MTF.
- Absolute radiometric accuracy is often important in applications, therefore characteristics such as polarization sensitivity, nonlinearity, stray light and fill factor are of more concern in hyperspectral imaging than in conventional imaging.

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6. CONCLUSION

This paper has pointed out significant shortcomings of current practices in specifying hyperspectral imagers. It has been argued that it is possible to specify hyperspectral imagers in a way that adequately represents their capabilities, limitations and imperfections. A suggestion is given for a list of about 30 characteristics that could be used as a standard for specification of spectral imagers. Most of the entries on the list are such that if the parameter is unreported, reduced performance in that parameter could save cost on the part of the manufacturer and lead to disappointment on the part of the user. Having a standardized and adequate set of performance metrics would be a benefit to spectral imager users, buyers and developers. It has been argued that it is entirely feasible to do the measurements needed to provide such a full specification. This paper is by no means intended as the last word on hyperspectral imager specification, but rather as a contribution towards establishing improved practices or standards in the hyperspectral community. A revised version may appear as a journal paper at a later date.

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