Best Practices in Passive Remote Sensing VNIR Hyperspectral System Hardware Calibrations

Joseph Jablonski[1], Christopher Durell[1], Terrence Slonecker[2], Kwok Wong[3]
Blair Simon[3], Andrew Eichelberger[4], Jacob Osterberg[4]
[1]Labsphere, Inc., North Sutton, NH USA
[2]USGS, Reston, VA, USA
[3]Headwall Photonics, Fitchburg, MA USA
[4]Aeroptic, North Andover, MA USA

ABSTRACT:

Hyperspectral imaging (HSI) is an exciting and rapidly expanding area of instruments and technology in passive remote sensing. Due to quickly changing applications, the instruments are evolving to suit new uses and there is a need for consistent definition, testing, characterization and calibration. This paper seeks to outline a broad prescription and recommendations for basic specification, testing and characterization that must be done on Visible Near Infra-Red grating-based sensors in order to provide calibrated absolute output and performance or at least relative performance that will suit the user's task. The primary goal of this paper is to provide awareness of the issues with performance of this technology and make recommendations towards standards and protocols that could be used for further efforts in emerging procedures for national laboratory and standards groups.

KEY WORDS:

Hyperspectral, passive remote sensing, remote sensing, spectrometer, Lambertian target, integrating sphere, uniform source, hyper cube, data cube, absolute calibration, sensor characterization, ground truth, vicarious calibration, imaging spectroscopy.

1.0 INTRODUCTION:

Hyperspectral imaging (HSI) is commonly understood to be defined as a form of imaging where each spatial pixel in a scene is represented by many contiguous narrow spectral bands. HSI is a rapidly evolving technology that holds great promise for scientific analysis and enhancement of human understanding of multiple fields of study. Last year at the SPIE Defense & Security Conference in Baltimore, a forum was held regarding creation of a new working group to study standards and governance of HSI technology. This paper is an initial response to that call to action. While the breadth and depth (and potential use) of all HSI technology is far beyond the capacity of a single paper to contain all aspects of use, there is value in trying to contain a guide for people entering the field and to provide a current "short cut" summary resource to some of the best practices that are employed in HSI today. The focus of this paper will be primarily on silicon range grating based spectrometers. There are six major themes which can be generalized discussion sections:

1) Absolute versus relative calibrations
2) Specification of HSI instruments
3) Characterization of diffraction-based VNIR HSI instruments
4) Calibration of HSI instruments
5) Validation of HSI in the field
6) HSI specific glossary of terms (Appendix I).

It is the sincere hope of the authors of this paper that this initial treatment of HSI will provide a starting point for the discussion and expansion of proposed future HSI standards groups.

2.0 ABSOLUTE VS. RELATIVE CALIBRATION:

The discussion begins first with helping the reader to understand the frame of reference of this paper with regards to absolute or relative calibration. These two terms often infer two very different perspectives on the performance of an instrument see figure 1. Absolute calibration generally conforms to normalized or standardized practices that have a calculated uncertainty distribution associated with traceability in the measurement values in an unbroken chain back to a national measurement institute (NMI) such as the National Institute of Standards and Technology (NIST)[1]. In most cases, the absolute value is related to a sampling interval (SI)-based unit and derived from an equation of state. NMIs generally also relate to each other through inter-comparisons and International Laboratory Accreditation Cooperation (ILAC) affiliation activity that ensure a NMI in one country has understood and similar uncertainty values and processes to that of any other NMI.[2] Statements of absolute traceability generally conform to **G**uide the expression of **U**ncertainty in **M**easurement (GUM) or other NMI process that governs how the data and related uncertainties are to be represented, quantized and verified.[3] Embedded in absolute statements are many aspects of repeated measurements with statistical variation and analysis.

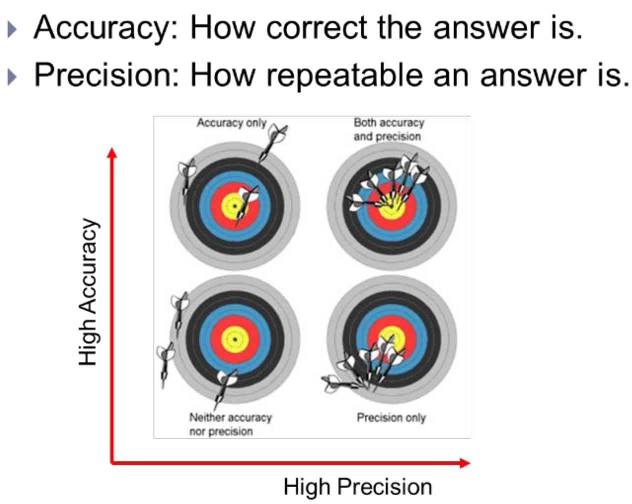

Figure 1: Accuracy vs. Precision Concept

In effect, if a vendor provides an absolutely traceable statement of performance, then *any* laboratory in the world should be able to, using the same processes and equipment, repeat that measurement within the given uncertainty. In this sense, this data, within its given *k=2* statistical bounds as shown in figure 2, can be used with high confidence.

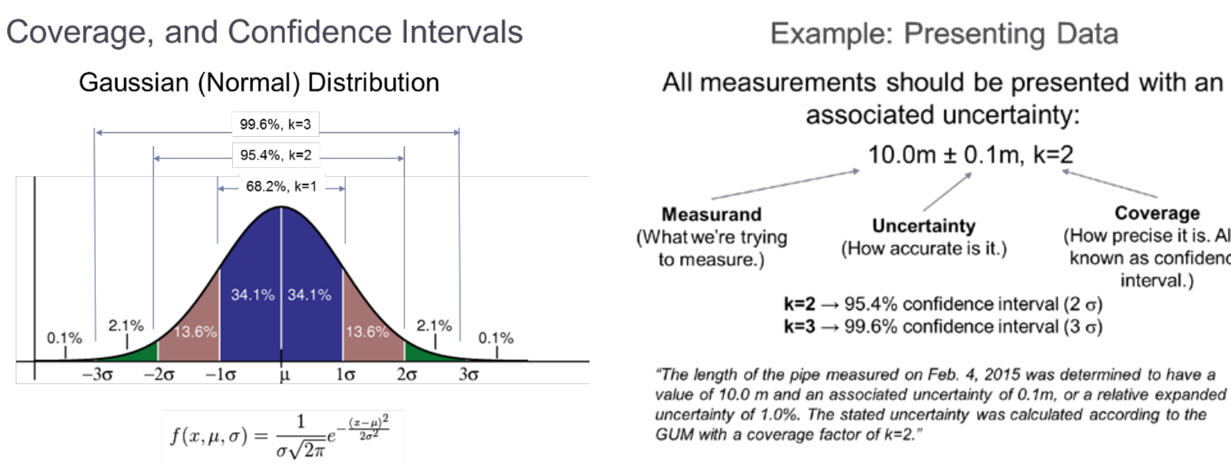

Figure 2: General Uncertainty Method (GUM) and Example of Data Expression[3]

For more information, a full treatment of absolute measurements can be found in the reference section of this paper to suit the appropriate application.[4],[5],[6] Relative characterization, while certainly part of aspects of absolute calibration, is more concerned with the ability to reproduce a measurement in a specific situation or with a specific target in mind. The results of the measurement may have no connection to absolute scale, but within the defined task still represent a valid and valuable result. In most cases, the ability to generate and verify repeatability is much less difficult than the data effort required to provide absolute characterization. Very good relative data are easier to achieve and less costly in time and money to attain than absolute because they do not need uncertainties (a Coefficient of Variance (COV) may be sufficient)[7]. Great repeatability may be easily achievable even with instruments that have poor absolute calibration. It is up to the user and their application to decide if they are looking for relative or absolute values.

Commercial industry and even some scientific applications find that for a given target application or a known target, that relative values may constitute "good enough" measurements to validate, identify or give a "go or no-go" result. This is true in HSI and many other forms of spectroscopy as well – where shape and identification of waveform may be much more important than absolute value of the measurement of that shape.[8] For some specific applications where the type of targets are known and well defined, an absolute calibration or characterization may be overkill for producing good results. However, when talking about instrument-to-instrument comparison of performance or suitability to task, one would be at a disadvantage to compare without absolute scale of performance.[9] Additionally, if results are intended to be used to compare with results from other instruments, other locations, or other times, then absolute calibration is necessary. For discussion in this paper, values attained using standard methods with absolute traceable results are assumed. This paper does not prescribe absolute or relative modalities to specific practices, but merely makes the user aware that absolute methodologies are preferred when talking about instrument performance or comparison.

3.0 SPECIFICATION OF HSI INSTRUMENTS:

The rapid growth in the development and application of hyperspectral imagers has led to a variety of instrument designs and packages. The large range of application of hyperspectral imagers makes it difficult to prescribe one set of performance parameters that will satisfy the range of potential uses. While mass produced consumer electronics (with international standards), such as a digital single lens reflex (DSLR) camera, can be expected to meet basic expectations, hyperspectral imager performance can vary widely. In order to facilitate a common understanding between the producer and consumer, a set of "standard" specifications could be developed. Performance specification is defined as "A specification that states requirements in terms of the required results with criteria for verifying compliance, but without stating the methods for achieving the required results."[10] We use the term "specification" to include both design and performance related requirements.

The following are specifications that may be key to determining the suitability to an application:

1) Instrument Architecture
2) Spectral range (example, 400 nm to 1100 nm)
3) Signal-to-noise over sensor's spectral range -
   Expected linear response range (based on SNR).
4) Spectral sampling interval (SI) which defines the number of channels (or bands) within the sensor range (5 nm SI over 400-1100 nm yields 140 channels)
5) Spectral bandpass for channels
6) Spectral resolution – minimum resolvable spectral feature which is a function of both the sampling interval and the channel bandpass
7) Wavelength accuracy
8) Radiometric uncertainty (*k = 2*)
9) Radiance responsivity ($W \cdot sr^{-1} \cdot m^{-2} \cdot nm^{-1}$ /(counts$\cdot sec^{-1}$))
10) Spectral stray light
11) Number of pixels vs. potential spatial resolution for the given instantaneous field of view (iFOV).

First, the fundamental instrument architecture (Offner-Dyson, Cerzy-Turner, etc.) can play a great role (or limit) in the capability of the instrument in specific applications. The spectral range is the second parameter to be considered by the consumer to determine if the imager will cover the spectral range of the object or substance of interest. The spectral range may further be defined by the signal-to-noise over the spectral range. The signal-to-noise in each spectral band must be sufficiently larger than the difference between two spectra that are intended to be separated. In addition to the spectral range and signal-to-noise, the spectral sampling, spectral resolution, and spectral bandpass must be sufficiently small to resolve spectral features of interest. Spectral stray light is light that contributes to a signal from a spectral band where it should not be present. Stray light reduces the ability to discriminate spectral features even if the spectral resolution is sufficient.

For applications that may require comparisons to measurements by other sensors or at different points in time, an absolute radiometric calibration is necessary to compare results to a physics-based scale. A physics-based scale of radiance response and wavelength accuracy allows the realization, dissemination, and validation by independent organizations. Beyond the spectral parameters, there is a need to describe the spatial characteristics of the imager. The number of pixels is fundamental to the ability to differentiate spatial information in a scene. For airborne uses, there is an important negotiation of iFOV, spectral, spatial, and signal-to-noise characteristics in order to achieve a useful image cube. In a push-broom imager configuration, the number of spatial pixels is limited to one spatial dimension. The relationship between the spectral and spatial performance characteristics of a push-broom imager is describe by keystone and smile, discussed later in this paper.

We present these characteristics as key parameters; however, there is an ongoing need to better describe how these values are determined and reported.

4.0 CHARACTERIZATION OF DIFFRACTION-BASED VNIR HSI INSTRUMENTS:

The following sections talk about the characterization of the specification terms in section 3, which is common to most types of HSI devices, and their influence on the measurement quality. Each section will discuss a critical parameter of the instrument, why it is important and how it is generally measured. The intent is to give the HSI user a better chance to understand and compare performance of different instruments and to test the manufacturer's ability to validate market specifications.

There are many types of HSI instrument architectures; however, this discussion is limited to Visible, Near-Infra-Red (VNIR) silicon instruments based on diffraction gratings. The discussion and techniques do apply generally to most types of instruments, but it is beyond the scope of this paper to discuss the nuances of those characterizations for different architectures.[11]

4.1 Sensor Type Choice – CMOS vs. CCD:

The most common type of commercial VNIR HSI instrument uses either a Charge Coupled Device (CCD) or Complementary Metal Oxide Semiconductor (CMOS) Focal Plane Array (FPA). It is beyond the scope of this paper to get into specific individual technology performance, however, it is worthwhile to comment on the general features of both types of sensors.[12],[13],[14] Because of the proliferation of smart phones and advances in semiconductor technology, CMOS FPAs have surpassed CCD FPAs in certain applications in terms of number of units in service. The fabrication of CMOS image sensors is more widespread and economical than CCD sensors, but that does not always make it the right choice for an application.

Both CCD and CMOS image sensors convert incident light into electrical charge. The charge is converted into a voltage before being amplified and finally converted to a digital signal via an analog to digital (A/D) converter. With CCDs the charge for each pixel is transferred to one (sometimes more) output node(s) where the charge is converted into a voltage, amplified and then sent off-chip usually as an analog signal requiring an external analog-to-voltage (A/D) converter. In the CMOS design each pixel has its own charge to voltage converter allowing for fast and flexible (selectable area of interest) signal transfer to usually an array of amplifiers (1 for each column) and then to either one or an array of A/D converters, all on a chip. This results in very fast digital output directly from the CMOS focal plane chip. However, the extra charge to voltage converter circuitry per pixel on CMOS sensors uses up silicon real estate resulting in lower fill factors for CMOS sensors compared to that for CCD sensors. Because CCD sensors use a single charge to voltage converter, linearity is consistent and image uniformity is generally better than CMOS sensors.

Newer CMOS technologies are cheaper and provide better uniformity and response across the visible spectrum (up to 1,000nm) than earlier versions. A variant of CMOS technology called Scientific CMOS (targeted for scientific applications, abbreviated sCMOS) offers very low noise, fast frame rates, large dynamic range and high sensitivity. While the sCMOS does not have the dynamic range of a CCD, the sCMOS chip is often the focal plane of choice for the most demanding (low light sensitivity and high speed) hyperspectral imaging applications due to its SNR vs. speed vs. relative cost benefit.

Understanding the tradeoffs of the focal plane technologies is important for making the right sensor choice that will best serve the application.

4.2 Signal to Noise Ratio (SNR):

The signal-to-noise ratio (SNR) is the ratio between the signal produced by the scanned object and the total noise signal inherent in the sensor. This ratio of the object signal to noise is calculated as the mean of the signal originating from the object divided by the standard deviation in the total input, which includes both the signals from the object and the noise. Noise comes from many sources within the within the hyperspectral imaging system. A major source of noise is the electronic noise, specifically read-out and thermal noise. Another contributing element of noise in a hyperspectral imaging system is its optical path. Two ways to improve the SNR are incorporating aberration corrected optical systems and using a camera with the fewest optical components. Aberration correction increases the signal in the SNR by preventing improper detection of incoming signals. Each optical component the signal passes through increases noise because the physical aberrations within the optical component scatter the signal. Limiting the number of optical components lowers the noise. Using high quality optical and electronic components will help preserve the input signal because it limits noise introduced by and to the system.

It is important to consider the source of the signal when calculating the SNR. Sources can be natural, such as the sun, or artificial, such as a quartz tungsten halogen bulb. The energy distribution of a broad band or blackbody-based source is generally based on temperature. The distribution of signal wavelengths originating from the source decreases with increasing source temperature. This signal part of the SNR is determined solely by the illumination source in the scene versus the source in the calibration lab. How the signal source differences influence the SNR (as much as the physical instrument noise sources) will be discussed later in section 5.

Modeling a system includes SNR calculations which take into account the various origins of noise. This includes the electronic and thermal noise inherent in a sensor's electronics and noise introduced by transmission losses along the optical path.

4.3 Smile & Keystone:

The ideal diffracted slit image that is projected onto the focal plane in a push-broom hyperspectral imager is a rectangle with the spatial direction parallel to the slit direction and the spectral direction perpendicular to that. Smile and keystone describe how the ideal rectangular image is distorted due to design and assembly deficiencies. Figure 3 shows exaggerated smile and keystone distortion. Since the distorted diffracted slit image is still being sensed by a rectangular focal plane array, the effects of smile and keystone distortions require further explanation. For high end hyperspectral imagers, these distortions are in the order of a few micrometers or a small fraction of a focal plane pixel.

SMILE: Smile is spectral mis-registration (wavelength shift error) between data from different points along the slit. It is characteristic of the inherent instrument design but can be exaggerated by improper alignment or focus. If the diffracted slit image for a single optical wavelength is a curved line (because of optical aberrations), the optical wavelength of light landing on each pixel in a row of pixels on the FPA varies along the slit. This distortion is called "smile" distortion. Serious smile distortions can result in misclassifications of materials being measured.

KEYSTONE: Keystone is spatial mis-registration (enlargement/reduction in the slit direction) between images from different wave bands. It is characteristic of the inherent instrument design but can be exaggerated by improper alignment or focus. If the diffracted slit image is distorted such that it becomes a trapezoid, wider near the top of the trapezoid than at the bottom, the distortion is called "keystone" distortion. Since this is imaged onto the rectangular pixel grid of the FPA, keystone distortion can result in different wavelengths from a single scene position (a leaf on a tree, for example) showing up on different pixel positions on the FPA.

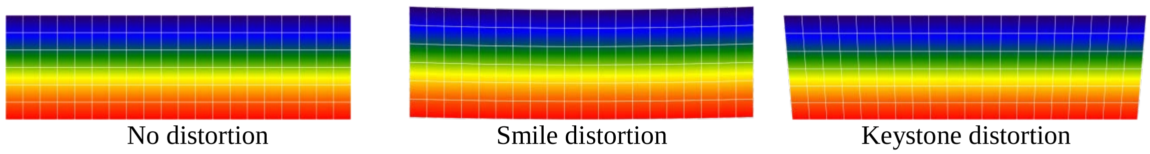

Figure 3: Examples of Ideal diffracted slit image and exaggerated smile and keystone distortion

CHARACTERIZATION OF SMILE AND KEYSTONE: Smile distortion can be measured by illuminating the input slit with various laser wavelengths or using an atomic line source and analyzing which pixels on the FPA are illuminated. The FPA image should be horizontal lines representing the emission wavelengths of the light source. To measure to sub-pixel accuracy, the light source should have peaks or valleys that spread across 5-6 spectral pixels to allow for curve fitting analysis (discussed in Section 5). A mercury (Hg) or argon (Ar) line source or a quartz tungsten halogen source through an absorption filter with narrow absorption bands can be such a source.

Keystone distortion can be measured by using a broad band source such as a quartz tungsten halogen lamp to image a sequence of narrow spots across the length of the input slit of the spectrograph. The diffracted image should ideally be a sequence of vertical lines as seen by the FPA. By analyzing the fractional pixel position of these lines, again, using curve fitting, for each row of the focal plane, slight deviations from vertical can be measured especially for the lines toward the ends of the slit. This deviation is the effect of keystone distortion.

If the manufacturer has provided an appropriate level of characterization of smile and keystone the user should not have any issues with internal optical alignment. These issues may re-appear as a result of instrument change, physical shock or aggressive use that disrupts the optical alignment; the user should be aware to look for these effects.

4.4 Spectrometer Optical Aberrations:

In high end optical systems design, such as for a hyperspectral imaging system, managing optical aberrations such as field curvature is critical in system performance. These aberrations will distort the diffracted slit image from the ideal rectangular focused flat field to a curved distorted surface resulting in performance degradations on the hyperspectral output data. Figure 4 shows a perspective view of such distortion:

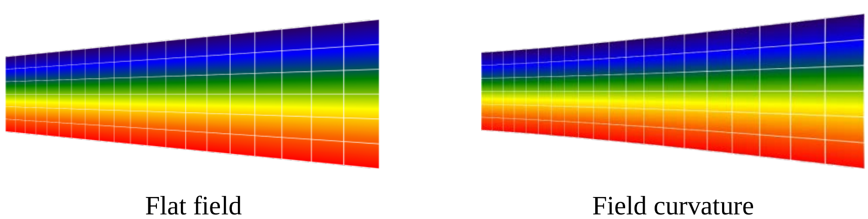

Figure 4: Perspective view of flat field vs. field curvature

Field curvature will produce poor focus in part of the image, especially towards the edges. Since the FPA is flat, any curvature in the surface of focus of the diffracted slit image will mean a defocused image on part of the FPA, which results in poorer image quality and spectral resolution in those regions.

Some HSI instrument manufacturers use proprietary aberration corrected optics in their hyperspectral imagers to reduce smile and keystone distortion to a small fraction of a pixel, and flatten the surface of focus of the diffracted slit image to enable the use of long slits while maintaining sharp image quality across the full length of the slit.

4.5 Fore-Optic Aberrations:

The fore-optic of the system (lens or lens system) projects the slit image into space ideally well focused on the intended target. Most manufactures characterize/calibrate their instruments with a specific fore-optic in place and changing the fore-optics may result in significant changes to instrument performance/calibration. The user should be aware that simply changing a lens on an HSI instrument may result in calibration errors. The instrument manufacturer should be consulted prior to changing the fore-optic and/or a new characterization should be obtained for each desired fore-optic.

4.6 Polarization Effects:

Real images in the world, such as bodies of water, can introduce significant polarization to observed signals. The simplest characterization would be to introduce polarized filters in front of a non-polarized source (such as an integrating sphere) and develop a response profile of the HSI instrument to these specific effects.[9] Full analysis of polarization effects are difficult to measure accurately on production instruments without investing in specialized test equipment .

5.0 CALIBRATION OF HSI INSTRUMENTS:

In this section the paper outlines common calibration techniques for HSI instruments. In spectral instrument calibration it is typically best to start with spectral calibration before proceeding to radiometric and flat fielding activities, and the discussion will progress in a recommended “procedure” or process of steps.

5.1 Wavelength Calibration:

Wavelength Accuracy: Shown below (figure 5) is a representation of the spectrometer section of an HSI instrument. To calibrate the system to covert pixel number to wavelength, and later determine wavelength accuracy it is necessary to perform the following steps.

A spectral line source such as mercury (Hg) or argon (Ar) is used to illuminate the entrance slit of the spectrometer. The image of the slit is projected onto the 2-D FPA. The imaging grating projects a series of lines on the FPA.

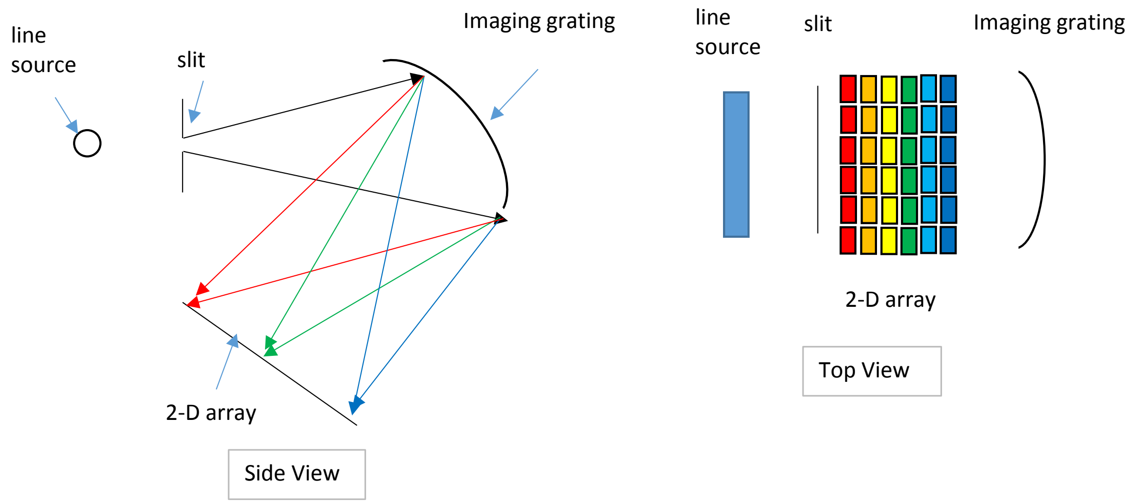

Figure 5: A representation of an HSI spectrometer where a slit is imaged on to a 2-D FPA where the spatial data are projected onto the rows of the array and spectral data from each element in the row is recorded in the corresponding column x

For each column the count value for each pixel is recorded, and at the location of each spectral line produced by the line source, a double Gaussian (or equivalent) curve is used to fit the individual pixel data (figure 6). The mathematical peak is calculated. The position of this peak is used as the inter-pixel value at the particular line wavelength.

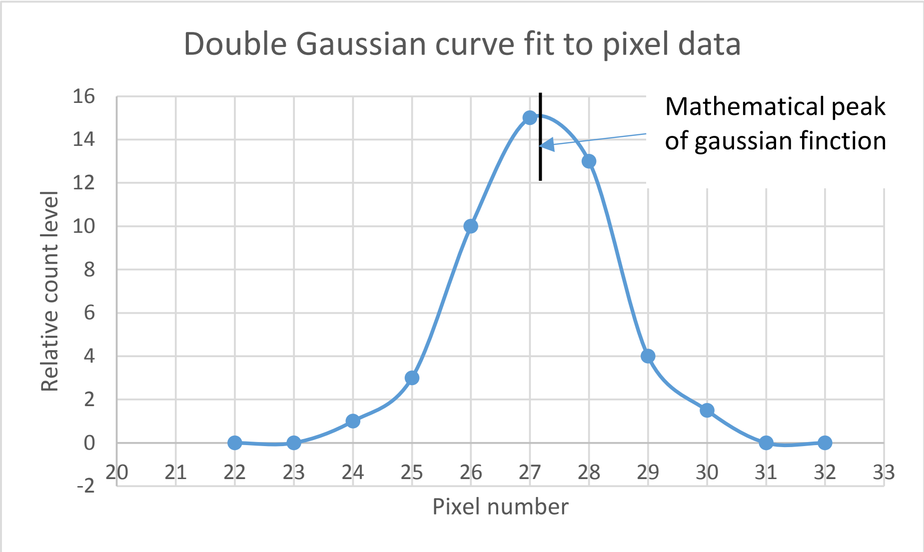

Figure 6: A double Gaussian (or equivalent) is used to fit the individual pixel data around each spectral line emitted by the line source

Once a series of wavelengths and corresponding pixel locations are determined, a 3rd or 4th order polynomial is used to fit the wavelength versus pixel location curve. The 3 or 4 coefficients are recorded and are used to convert pixel number to wavelength (figure 7).

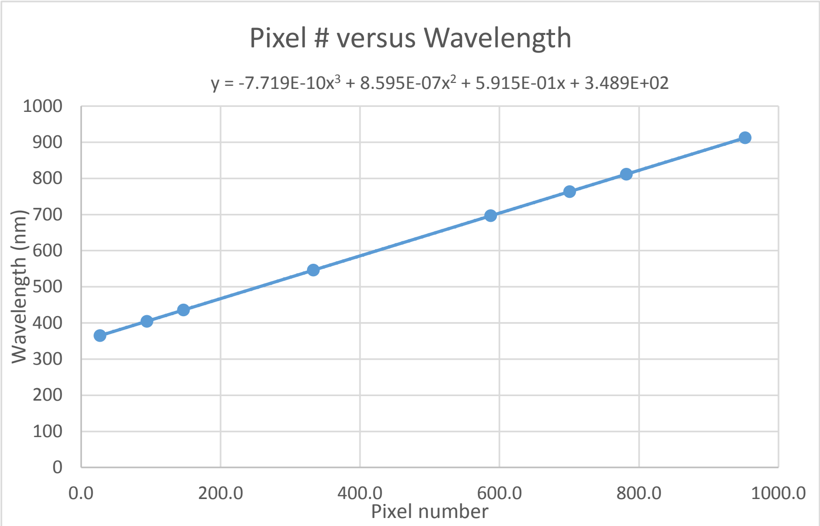

Figure 7: A 3rd or 4th order polynomial is used to fit a curve to the Wavelength versus pixel number data

Once the pixel to wavelength conversion is complete for single line, the additional spectral lines can be recorded. A similar curve fit can be applied, but this time the calculated peak wavelength of the new spectral line can also be recorded.

Comparing the calculated peak wavelength with the actual known wavelength for each of the lines measured will determine the wavelength accuracy over the spectral range of the spectrometer.

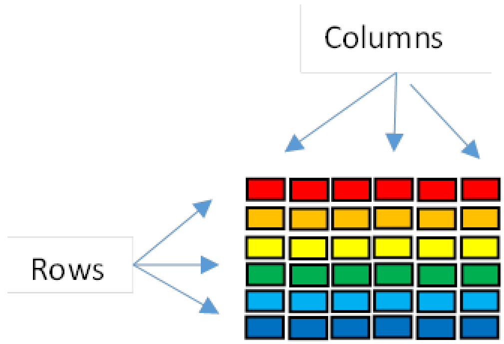

Figure 8: In the 2-D FPA the spatial data is represented in the rows, where the spectral data for each pixel in the row is represented in the corresponding column

Wavelength accuracy cannot be assumed to be constant for each of the columns in the array due to keystone effects; therefore, the wavelength calibration and associated wavelength accuracy must be determined for several columns within the array (figure 8). If the slit were replaced by a series of monochromatic point sources, or apertures with a broad band source, along the slit length, then the characterization of the image quality along the spatial axis could also be observed.

5.2 Calibrated Source Practices:

It is common practice to use a uniform source or uniform field of light in order to fill the Field of View (FOV) and to look at pixel-to-pixel non-uniformity and set baseline responsivity. It is also a good plan to understand the source uniformity levels through a good calibration or characterization as uniform sources do have some real variation (the real variance can be applied as a map for flat-fielding). We will start the discussion with the simplest (and cheapest) means of testing and progress to the most accurate (and costly/complex) solutions.

5.2.1 Radiometric Calibration Options

LAMP & TARGET: The most basic form of calibration is most commonly used for relativistic testing. This test is to make sure the camera is operational by simply placing a light source on one side of a room and a designated target (white, bar target, Air Force resolution bar targets, spectral) at the other. The principle of this test is simple and effective in terms of using a point source at distance to provide a relatively uniform distribution, but it can have problems with repeatability, uniformity and radiometric accuracy. The questions the user is typically trying to answer are:

- Is my camera working?
- Can I see a pre-set target (focus, resolution, spectral)?
- What level of response can I expect from a real scene, and how might I have to set up pre-set conditions to view those properly?
- Can I repeat evaluation for different optics?
- Can I flat-field my image? (that is, obtain a uniform response across the pixels).

While these can sometimes be the “go” or “no go” conditions of the camera, they are not very helpful in establishing radiometrically calibrated response or performance of the system. The next level is to attempt to get some valid, traceable baseline for the observed uniform source.

UNIFORM SOURCE - LAMP: 0/45 Calibrated FEL (FEL is an ANSI Standard Code) Lamp and Lambertian Target: One of the fundamental ways that radiometric instruments are tested is through use of a 1000 W FEL Quartz Tungsten Halogen lamp and a diffuse reflectance (Lambertian) target.[11], [16], [18] The FEL is calibrated by a NMI or secondary lab for spectral irradiance at a specified distance from the lamp. The target is calibrated for total hemispherical reflectance or reflectance factor (at specified geometries) by a NMI or a secondary lab. The target is placed at 50cm (typical) from the lamp source, which creates a uniform irradiance area of about 5 cm.[15] The spectral irradiance is known and the reflectance of the target has a known uncertainty, and therefore the radiance of the target at this area is also a traceable value. This process is described below:

- A spectral radiance calibration transfer device is placed at 45 degrees (typically) from the lamp-target optical axis so as not to interfere with the radiance of the lamp. The radiance transfer device might be items such as a monochromator (with optics), spectral radiometer, spectrometer with optics, or a detector and optics with filter wheel for different bands. The transfer device is imaged onto that calibrated radiance area, and the device response is measured against this traceable radiance field.
- Typical geometry of the 0/45 is used with a Lambertian target (pressed Poly Tetra Fluoro-ethylene (PTFE) or sintered PTFE plaque), but at the highest levels of uncertainty it is better to have a target with known Bi-directional Reflectance Distribution Function (BRDF) at the 0/45 geometry to ensure the target's radiance is compensated for any angular reflectance deviation from the Lambertian assumption.[15],[16]
- The customer's HSI instrument can be used in place of the spectral radiance transfer device as long as the Field of View (FOV), working distance and spot size instantaneous Field of View (iFOV) will accommodate the central area on the target.
- A multi-step target with different calibrated reflectance values (2 %, 25 %, 50 % and 99 %) could also be used for linearity checking of the instrument in a single image or series of images.

One clarification on the term "target" in reference to calibration is needed. Target is often used by imaging people as to mean "a viewed or acquired object in the scene". Metrologists often refer to the same "target" as a calibrated reflectance plaque (classical metrology reference) or calibrated target to differentiate the absolute nature of that device versus any other target in the scene. The two terms are often interchanged and can lead to confusion. For the intent of this paper, a calibrated reference plaque and a calibrated target or target generally refers to a Lambertian calibrated reference plaque.

UNIFORM SOURCE SPHERE: (Integrating Sphere versus a Lambertian Target) – Rather than using a target and lamp to calibrate the HSI device, an integrating sphere can also be used as a field of Lambertian spatial and angular spectral radiance.[11],[16],[17],[18] Integrating spheres are a first choice for many calibration efforts for their following advantages:

UNIFORMITY: Integrating sphere ports are extremely uniform. The size of the uniform area of the spot on the target from the lamp irradiance is governed by a $\cos^4$ angular variation.[15],[16] While the uniform spot size on the Lambertian target is somewhat controllable by distance of the lamp from the target (and using a larger target), changing distance will also change the radiance of the target dramatically. Over smaller area of the sphere port diameter (especially the center of the port) it is possible to achieve >99 % uniformity.

APERTURE/SPOT SIZE: In contrast to the target the uniform aperture of a sphere is usually >98 % uniformity over any given port size (+/-1 %). Large ports (>200cm) are easily achieved for larger optical system apertures or fast F-number systems. Down-selecting a port size is easy to do by mechanical reducers at the sphere port plane. The radiometry of the port also may only change slightly for these changes, but any change will be registered by sphere internal monitor detectors.

ANGULAR FIELD: A sphere also provides for a significantly larger angular field of view than a target, in most cases. In a target the angular extent is limited by the aperture size of the device under test (DUT), its working distance and the ~5cm uniform spot size on the target. In a sphere, the uniformity can often still be 98 over a >60 degree full angle FOV, or, in some special cases of sphere design >180 degree FOV for "fish-eye" lenses.

LEVEL ADJUSTMENT: Level adjustment with a target is typically done through distance variation between the target and lamp, or worse, through changing the current of the lamp which changes spectral output dramatically. In a sphere level can be set via numbers of lamps or via altering the input from a lamp into the sphere via filters or mechanical attenuators. Spheres can achieve large calibrated and uniform dynamic ranges and with commercial systems are typically at least 12-14 bit or in extreme cases >32bits (60 to 160dB - lowest to highest value).

SPECTRAL SOURCE SELECTION OR BLENDING OF SOURCES: Quartz Tungsten Halogen (QTH) has been used for over a century as a stable, spectral calibration source. QTH lamps are also commonly used with sphere sources or FEL targets (as described above). However, in most passive remote sensing applications the source will not be a convenient lamp, but the sun at different albedos. In comparison with sunlight, QTH is a red and IR-rich spectrum and is “blue –poor”. Figure 9 displays a classic problem of spectral mismatch between test conditions and actual observed spectrum.[11],[19],[20] This problem also leads to SNR issues with testing in the blue and saturation in the red bands.[22],[26],[27]

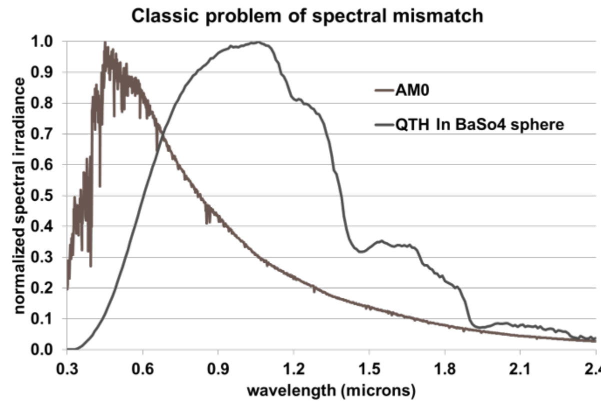

Figure 9: Normalized representation of QTH Spectrum in a Sphere versus desired Solar Spectrum (AM0)

If these conditions are not corrected for in the calibration, then the user may see out of band leakage or stray light occurring in the HSI system. The idea of the **S**pectral **I**rradiance and **R**adiance responsivity **C**alibration using **U**niform **S**ources (SIRCUS) type calibration, conducted by NIST,[9] and the Zong[21],[22] or Jablonski Method[23],[24] will alleviate this problem, but most people simply do not have access to that level of characterization. Thus, most users will be seeing artifacts of cross calibration between a bluer source (the sun) and a redder source (QTH). The advantage of a sphere in this case is that it is possible to combine or blend blue-rich light sources in the sphere with QTH and get a spectrally uniform output at the port that more effectively matches the target spectrum. These specialized systems concepts are discussed later in the paper.

As can be seen from the spectrums in figure 10, adding blue spectrum source often adds spectral features, which could be either a boon (with stable peaks) or a serious problem if the structures happens to fall within bands that are critical to the hyperspectral instrument performance or a critical feature in the target’s spectral signature.

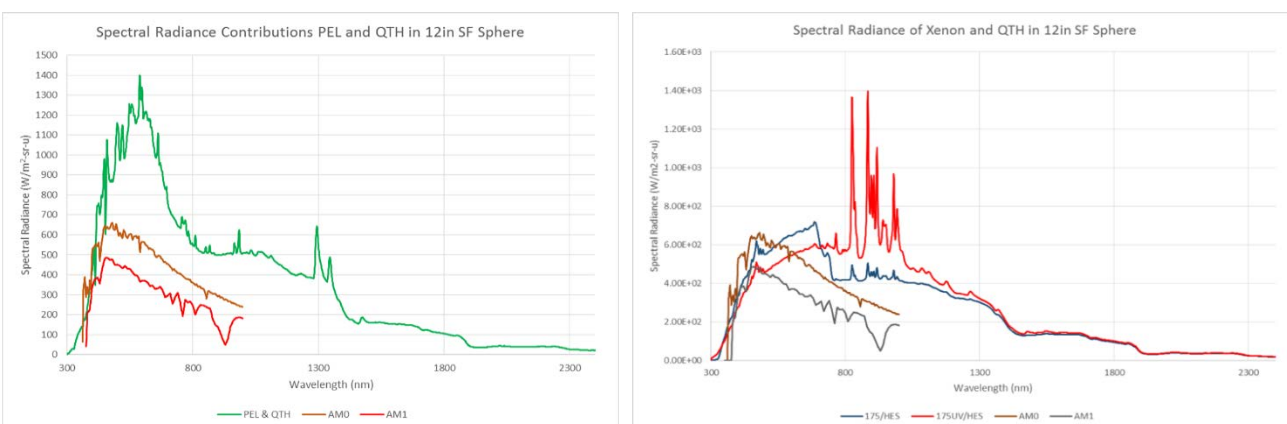

Figure 10: Example Combinations of Xenon and Plasma (PEL) sources in a Sphere with QTH Lamps and solar spectrum levels

COST & COMPLEXITY: A target and lamp, in concept, is a relatively simple arrangement to accomplish, requiring only physical space, an alignment rail (or system) and some degree of ambient light control (dark room). Absolute solutions for targets and lamps can be several thousands of dollars ($5,000 to $25,000) due to the calibration files, accurate power supplies and associated electrical optical equipment and a degree of experience in using such equipment. An integrating sphere system generally requires specialized coatings, support electronics, possible software, control hardware and calibrations. A sphere system is generally a turnkey solution that does not require special alignment or set up, but it is usually a minimum entry investment of $10,000 to more than $100,000 in complicated, high performance systems.

STABILITY: A lamp and target is a relatively simple system that relies on the FEL lamp stability and first surface reflection and physical alignment. Most people would be capable of keeping the lamp and targets clean and performing the physical alignment. Once the system is set up, if physically unperturbed, the primary degradation mechanism in the uncertainty of this type of calibration is decay of the lamp output as a function of burn time (hours that the lamp is on). On the other hand, a sphere is also physically robust and self-contained and generally considered by most to be quite stable. Like the lamp, the primary degradation of the sphere radiance will be the lamp burn time; however, a sphere chamber has a multiple reflection effect (versus single reflectance surface of the target) and therefore will be exponentially more sensitive to contamination or degradation of its coatings. Keeping the sphere sealed when not in use will minimize contamination, and the optical coatings should have a useful life of many years if kept free of contamination in normal use conditions.

5.2.2 Noise, Dynamic Range & Stray Light

BASELINE NOISE VALUE: A spectrum from a 3000K QTH source in an integrating sphere (figure 11) is measured 10 times and the standard deviation/average is recorded over the instrument spectral range and is used to calculate percent baseline noise versus wavelength.[14]

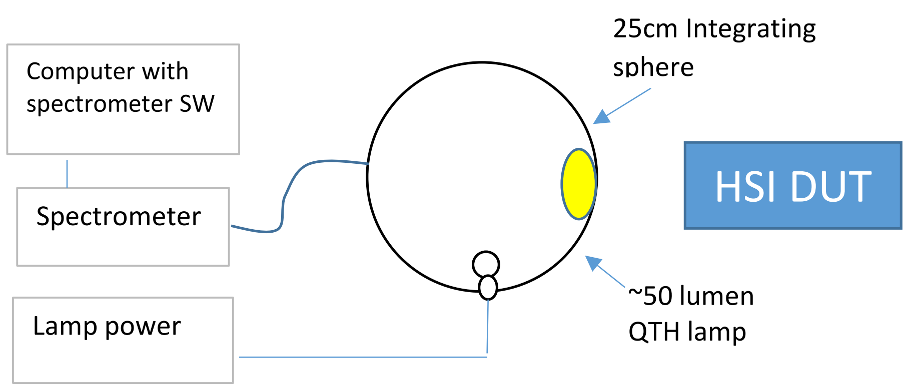

Figure 11: System used to determine baseline noise.

MAXIMUM USEABLE INTEGRATION TIME: The maximum integration time cited by a spectrometer manufacturer is dictated by the electronics which controls the time that the FPA accumulates charge. However, especially for non-cooled Si arrays, the maximum integration time may not be usable due to the fact that the dark signal may exceed the saturation level of the array. The maximum usable integration time can be defined as the integration time necessary for the dark signal to reach 50% of the saturation

SINGLE SCAN DYNAMIC RANGE: Single scan dynamic range is the inverse of the baseline noise (SNR) found in section 4.2.

LINEARITY: By setting light levels with the sphere and referring to the sphere absolute monitor detector, the linearity of the camera image can also be obtained. A multistep reflectance target with calibrated values between 2% to 99% could also be used for the same purposes, but with less dynamic range in most cases.

TOTAL DYNAMIC RANGE: The total dynamic range is calculated by multiplying the single scan dynamic range by the ratio of the maximum usable integration time to the system's shortest integration time.

STRAY LIGHT: Spectral stray light is caused by light scattering within the spectrometer and essentially evenly illuminating the array with light that is not directly in the designed optical train. One way to measure stray light is to introduce a QTH lamp to a sphere with a cut-on filter such that any signal seen below the cut-on wavelength is stray light (figure 12). A system proposed by Jablonski and others to measure stray is shown below.[23],[24]

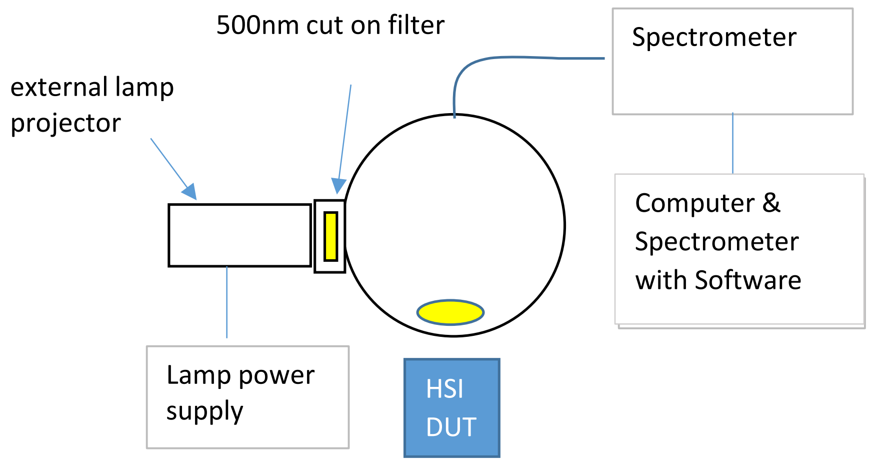

Figure 12: System used to quantify stray light in a spectrometer

The results of stray light can be seen from the transmission curve of a 500nm cut-on filter shown below in figure 13.

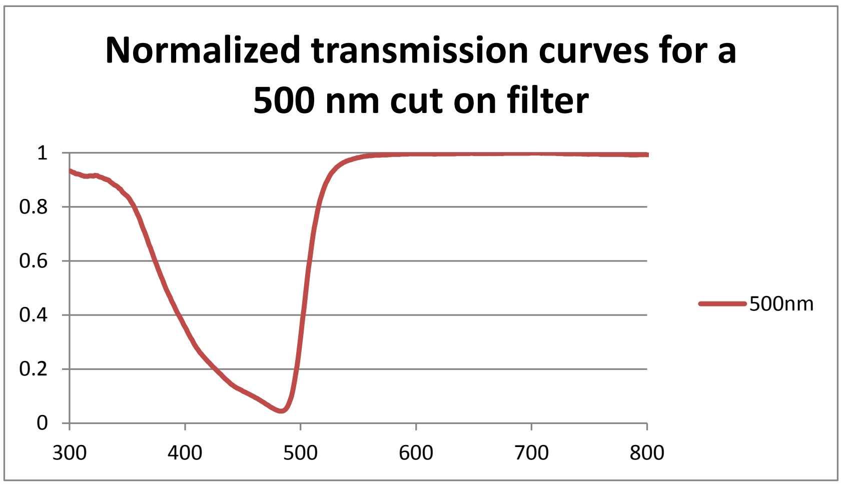

Figure 13: Measured transmission of a 500 nm long-pass filter with spectrometer exhibiting stray light

It should be noted that the measured transmission approaches 1 as it approaches deeper and deeper UV wavelengths; this can be explained by the graph below in figure 14.

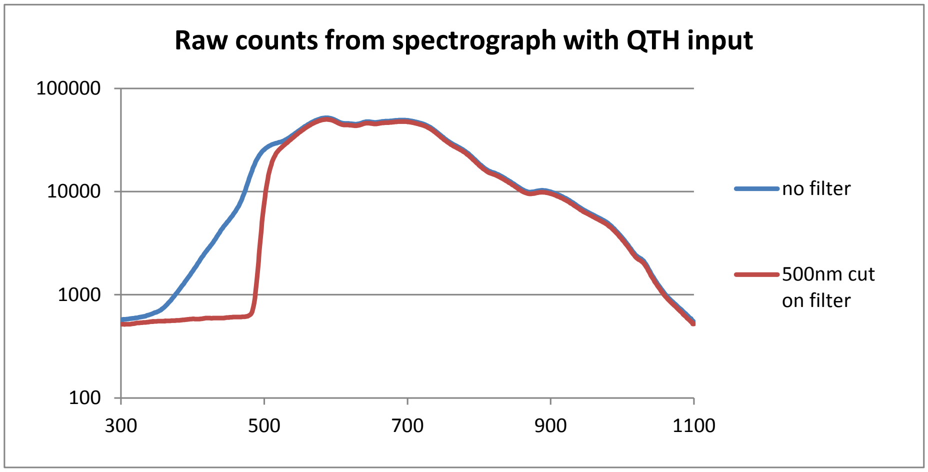

Figure 14: Raw counts from spectrometer looking at a QTH lamp with no filter and 500nm cut-on filter

A direct measure of the stray light can be seen in the 500nm cut-on filter curve at wavelengths below 500nm. The energy from the QTH lamp decreases with lower wavelengths to the point that the actual signal is much smaller than the stray light, and it is not difficult to imagine it you take the ratio of the 500nm cut-on filter signal to the no filter signal you would approach 1 at lower wavelengths.

The average percent transmission of a long-pass filter is measured in a short wavelength band and is used to baseline the broadband stray light of the unit. In a VIS/NIR unit the long-pass would be 500nm and the measured energy in 360 to 470nm (should be zero) is used to characterize the instrument. The average percent transmission from 360 to 470nm is used by one of the authors as a figure of merit of quantifying stray light for all spectrometers.

Alternately, in-band and out-of-band response (stray light) could be tested by using monochromatic inputs to the unit and looking at response over all spectral channels.

Spatially and angularly, this test could also be accomplished using the ISO 9358 methodologies for veiling glare (sphere, point source or goniometer). [25]

5.3 Alternate Source Calibration Techniques

SIRCUS [9] – Spectral Irradiance and Radiance Calibration using Uniform Sources (SIRCUS) is a facility developed by NIST (figure 15). It uses a series (hundreds) of laser lines and an integrating sphere in an extremely precise (0.5 %, *k=2* uncertainty), but difficult means of calibration with discrete laser sources over a large spectral range. The SIRCUS facility is one method of transferring the radiometric scale for the Primary Optical Watt Radiometer (POWR) to instruments under test by use of transfer standards such as trap detector-based radiometers.[27] In addition to providing the absolute radiance response, the SIRCUS facility can characterize spectrometers for stray light. With a sufficiently dense spectral sampling, a stray light correction can be applied channel by wavelength channel, and also out-of-band radiance can be captured and minimized through correction.[23],[24] This process is probably only practical at the national laboratory level and for the highest level of performance needed in an application. While very effective, the process is expensive may not be accessible to most end users. This technology and methodology is expected to become more routinely utilized as narrow band spectrally tunable sources become more prevalent. Once and instrument has been characterized using this method, there can be some transfer of knowledge regarding performance of other instruments with the same design.

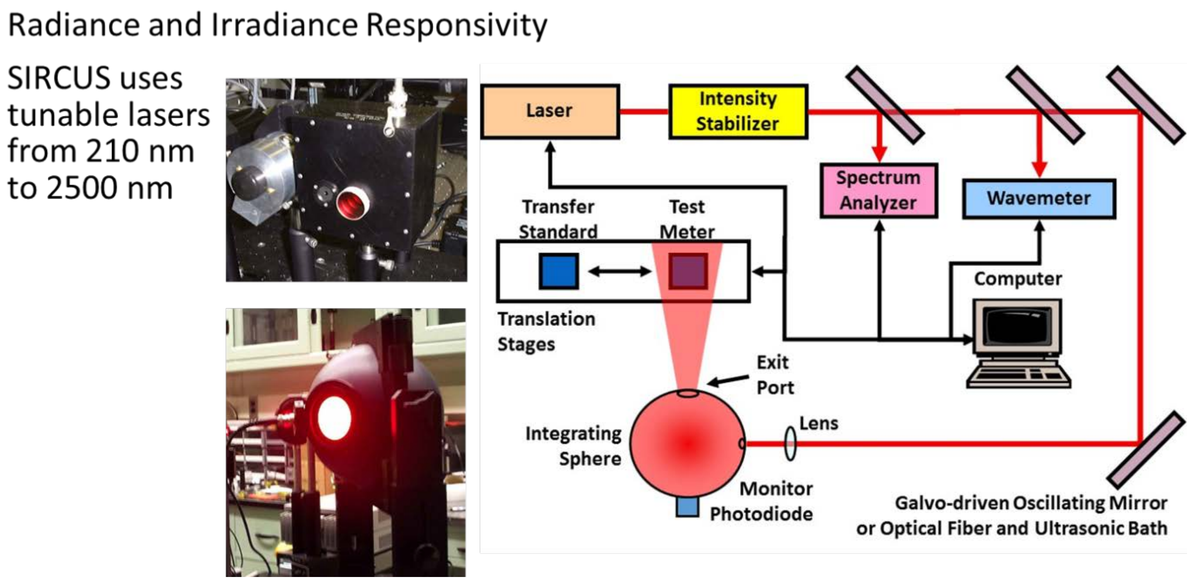

Figure 15: NIST SIRCUS System[24] - http://www.nist.gov/pml/div685/grp06/sircus_facility.cfm

The NIST Hyperspectral Image Projector (HIP) System shown in figure 16 provides a full spectrally and spatially tunable calibration source.[26],[28] Based on the use of spatial light modulators, in this case digital micro-mirror devices (DMDs), it can project either synthetic scenes or reality based scenes from remote sensing instruments. This allows characterization of spectral imagers with content that is of relevance to the user. Examples include water quality monitoring, biomass estimation, precision agriculture and medical imaging.

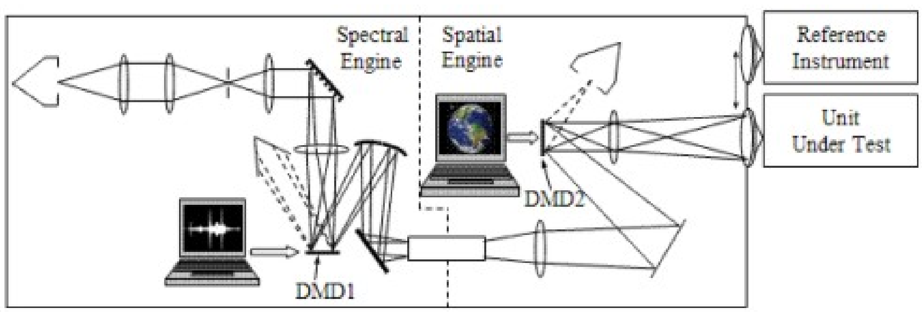

Figure 16: NIST HIP System[26] - http://www.nist.gov/pml/div685/grp04/hip.cfm

Both of the above mentioned methods (SIRCUS and HIP) described for calibration and characterization of hyperspectral imagers are available as calibration services by NIST.

6.0 VALIDATION OF HSI IN THE FIELD:

Validation of real-time and field hyperspectral instruments is still an evolving field. The best opportunity to frame the problem is from what is already known about validation of measurements in passive remote sensing from the aerospace and reconnaissance communities.[11],[18],[32] Active remote sensing is not part of this discussion as it usually involves specific light sources and tasks. What is under discussion is the ability to relate laboratory traceable values to real situations in sunlight (passive) situations.

In remote sensing the exercise of collecting absolute information about a target on the ground is called "ground truth" and refers to information collected on location. Ground truth allows the remote sensing image data to be related to real features and materials on the ground. The collection of ground truth data enables calibration of remote sensing data, and aids in the interpretation and analysis of what is being sensed. Examples include cartography, meteorology, analysis of aerial photographs, satellite imagery and other techniques in which data are gathered at a distance. These concepts should be applied to HSI.

More specifically, ground truth may refer to a process in which a pixel on a hyperspectral image is compared to what is there in reality (at the present time) in order to verify the contents of the pixel and spectrum on the image. In the case of a classified (known) image, it allows supervised classification to help determine the accuracy of the classification performed by the remote sensing software and therefore minimize errors in the classification such as errors of commission and errors of omission. Classification, beyond simple targets, however, is beyond the scope of this discussion – procedures and techniques in getting the data right from set calibration scenarios is the intent.

Ground truth is best done on site, performing surface observations and measurements of various properties of the features of the ground resolution cells that are being studied on the remotely sensed digital image at nearly the same time that the site is being observed from the air. Ground truth relies on the following basic concepts:[30],[31],[32],[33],[34],[35],[36]

- The user has a stable transfer instrument (spectral or filter band) to hold the transfer of a calibration from a calibration plaque to an intended target in the scene.
- The imager is looking at an illuminated target on the Earth.
- Relative reflectance is computed as the ratio between two radiance spectra with the transfer instrument,
    - The Radiance Spectrum of a (Lambertian) Target with known reflectance and
    - The Radiance Spectrum of the intended object to be measured.
- Implicit in this calculation is the assumption that the source illuminating both objects is constant.
- Relative reflectance can be converted to absolute values by using a target with traceable calibration.

Ground truth also involves taking geographic coordinates of the ground resolution cell with GPS technology and comparing those coordinates with those of the pixel being studied by the remote sensing software to understand and analyze the location errors and how they may affect a particular study. Ground truth also helps with atmospheric correction. Because reflected energy from a target is distorted by the atmosphere, ground truth can help fully identify objects in satellite photos.

We used the concept of “Test as You Fly” as an example of how to set up calibration. Conversely, we now need to keep “Fly as you Test” in mind while setting up the validation, to get the conditions of ground as close to the calibration scenario as possible.[37],[38],[39],[40],[41] This concept is a noble goal and virtually proves impossible to do in most cases of field measurement due to the complexity of influences on most real remote sensing and HSI scenes as shown in figure 17.

Using solar illumination or a different illumination spectrum than the calibration source from the laboratory is a possible source of noise in system level real-world observations. It is important when trying to observe a given scene to perform relative or absolute testing with a source that has magnitude and spectral shape similar to the observed scene. Section 5.2.1 discussed spectral blending and spectral distributions with an integrating sphere, which would provide a spectrum similar to sunlight. Ideal calibration in the lab will take account of spectral difference by using a similar source or characterizing the full response of the array with monochromatic lines such as the method mentioned under SIRCUS or HIP.

6.1 Calibration Targets:

The easiest way to get the native source spectrum and magnitude for relative testing is to use a Lambertian calibration target as part of the actual test scene. A target's reflectance and spectrum is known, so a of bit of post-processing on its image can help contain the scale of the scene or even absolutely quantify specific situations.[35],[36] While it may be possible to use natural targets or simpler targets like paint on surfaces, it may not yield good results and the BRDF of these targets are not known, therefore, there will be some error in observation and illumination angle. In the case of specular coatings or surfaces, the errors could be quite large. For best results the targets to should be as Lambertian as possible (therefore scene, source and observation independent) or have a well understood BRDF for the reflectance geometry the experimenter is establishing.

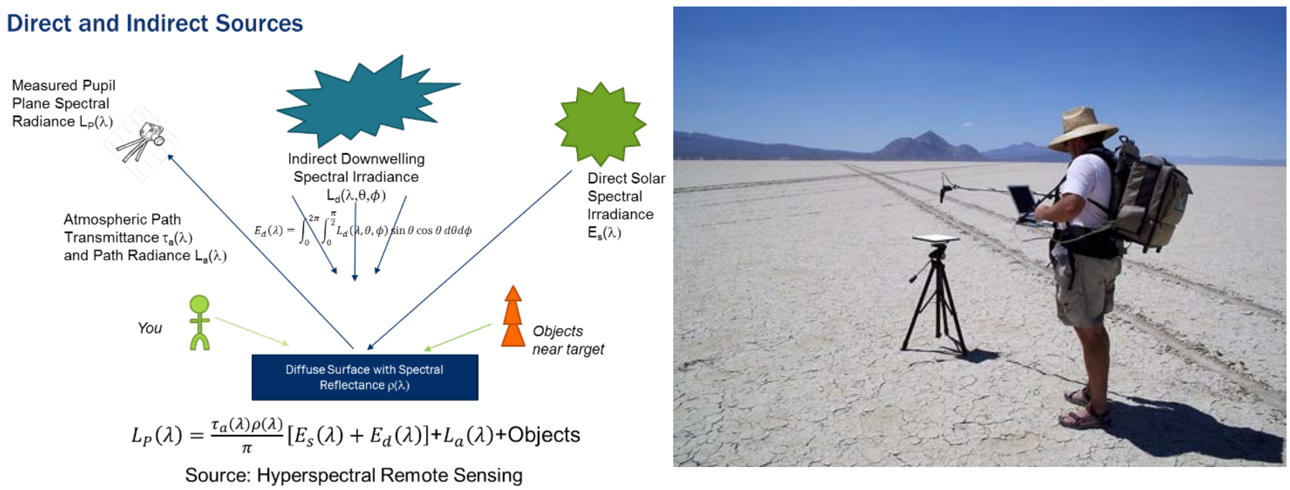

Figure 17: Targets used for Ground Truth and Validation of Space and Airborne Measurements[42]

The calibration target must be appropriately sized to the imaging application using the following parameters, that is, it must be large enough to be "seen" during flight observation:[42]

- Ground Sample Distance (GSD) must be known
- iFOV of the system must be known
- Pixel Pitch of the FPA must be known
- At least 7-12 pixels (more is better) must be filled by the target to get a calibrated center pixel image of the target.
- A reflectivity value similar to the intended target, or one that will not saturate the image should be selected.

While a high reflectance target will give an abundance of signal in most cases, high reflectance levels may saturate the imager in certain bands. Additionally, most real world targets are not highly reflective but more in the 20% to 70% regime. So, in reality it would be ideal to have a range of targets giving identical (spectrally flat) signatures over the wavelength range of interest that would span a large dynamic range. A group of identically sized targets of 2%, 20%, 50%, 75% and 99% reflectivity would give good linear spacing and provide the ability to test the camera response through a valuable set of ranges and SNR scenarios. If a user can pick only one target, then the reflectance value should be similar magnitude to the average scene reflectance.

Solar illumination introduces noise because light from the sun scatters as it travels through the earth's atmosphere. This scattered light may then be reflected by the source into the detection sensor. Adding another layer of complexity the absorption properties of the atmosphere change with the time of the day and the weather. For example, crepuscular light is more greatly absorbed, and the distribution of this absorption is shifted towards longer wavelengths. As a source itself, the position of the sun in the sky, as defined by the solar zenith angle, changes how and which parts of the object of interest are illuminated. This alters the signal produced by the object. When applicable, the effects of solar illumination must be taken into account during modeling. Programs like MODTRAN provide these calculations.[43]

6.2 Flight considerations: Down-welling Irradiance, Spectrum, BRDF and Image Evaluation:

DOWNWELLING & BRDF INFORMATION: In addition to a target, or in the absence of a target, if the user has the ability to radiometrically measure the solar spectrum reflected from the target in real time, commonly referred to the down-welling irradiance, then this radiometric baseline can be tied to the gathered HSI information. In the most extreme cases, the down-welling, up-welling would be measured in real time as observation and BRDF of the intended (if stationary) target would be known to compensate for observation.

To get an absolute number radiometrically one must deal with the complexity of figure 17. This figure shows how many data sources would need to be gathered to tie together an absolute response; practically, today such a model is too expensive and time consuming for most HSI users. So, practically, an absolute response is not nearly as important as a spectrally "gray" response; that is, no systemic spectral function across the entire bandwidth of the instrument. A little offset is fine, but no slope or smile across the spectrum. If the target is large enough to fill sufficient pixels, then another valuable, practical use of the target would be to partially flat field the imager with a known value.

SPECTRAL TARGETS: A more rare case would be to use an absorptive target giving sharp molecular lines for wavelength alignments of the spectrograph. It is rare, because unless the HSI had been damaged, it would be unusual for spectral drift to occur. Such spectral signature targets may be more appropriate in looking for actual signatures; that is, embedding known spectrum into neutral targets. However, it is a test to give as it could be useful in certain applications like geological target identification. There are also special rare earth oxide (REO) wavelength targets that can be used to develop spectral verification for the HSI instruments.

BAND RADIOMETERS, SPECTRAL RADIOMETERS & SPHERES IN THE FIELD: For extreme cases in the field where the camera may be subjected to long term use or physical abuse, the targets may not be able to adequately set scene radiance due to baseline variation of the instrument. Remote sensing groups have come to heavily rely on banded field radiometers for absolute validation of ground sites. Spectrometers, while less stable, also have a valuable place in the ground truth validation. In some cases, small portable integrating sphere have also been helpful in re-establishing calibration coefficients and detecting changes in instrument baselines.[35],[44]

“BORROWING” FROM NATIONAL IMAGERY INTERPRETABILITY RATING SCALE (NIIRS): More advanced and accepted techniques for more qualitative image acquisition are available in NIIRS techniques and have been employed in HSI targeting scenarios. The relative priority of different sensor specifications is application specific. Nevertheless, the potential cost savings which would arise from using a common sensor for multiple applications drives the desire to determine the relative importance of different performance measures. Several efforts have been made to generalize the utility of spectral data.[45]

For visual imagery, the NIIRS provides a scale of data utility. Although originated by the intelligence community, NIIRS also has a civil counterpart which covers non-military urban/industrial, natural resource, and agricultural applications. The Generalized Image Quality Equation (GIQE) aims to provide an objective equation for determining NIIRS, and a Spectral Quality Equation (SQE) has been proposed which builds on this by adding the number of channels to the common measures of resolution and signal-to-noise ratio.[46]

The creators of the SQE admit that its usage is highly context dependent, and therefore, they have pursued measures for some of the most common hyperspectral use cases such as subpixel object identification, terrain classification, and material identification. As such measures develop, they may be used to guide the prioritization of different aspects of hyperspectral system calibration. Work still continues in this area and needs further study.

7.0 CONCLUSION:

The authors of the paper have put forward a collection of techniques, comments, terms, references and processes that may serve as an introduction to the concepts of proper selection and characterization of hyperspectral instruments. The concepts discussed represent a "good faith effort" to encompass this very complex field and instrument testing. This paper is intended to serve as an invitation and a challenge to interested parties in the HSI industry to use this collected input as a potential foundation for the formation of new standards groups. If left unchecked and ungoverned without standards, HSI technology and the developing industry could be slow to reach its full potential due to disparate techniques and unbounded interpretation of instrument and application performance. The promise of HSI has reached the stage where cooperation among interested parties to offer customers performance-driven measurement metrics and absolute uncertainty on instrument specifications could be of great benefit.

DISCLAIMER: This is a scientific issue paper trying to outline items for current and future discussion within the subject of proper use of HSI for remote sensing measurement and analysis. It is NOT the intention of the authors to make any specific recommendations or endorsements. The USGS as a governmental organization does not endorse any commercial entity or solution. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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[45] http://www.isprs.org/proceedings/XXXVII/congress/1_pdf/01.pdf (NIIRS)

[46] http://fas.org/irp/imint/niirs.htm

[47] http://www.cie.co.at/publ/abst/15-2004.html

[48] http://spie.org/publications/spie-digital-library

[49] http://www.spectir.com/tools-resources/glossary-of-terms/

[50] http://www.nist.gov/alphasiteindex.cfm

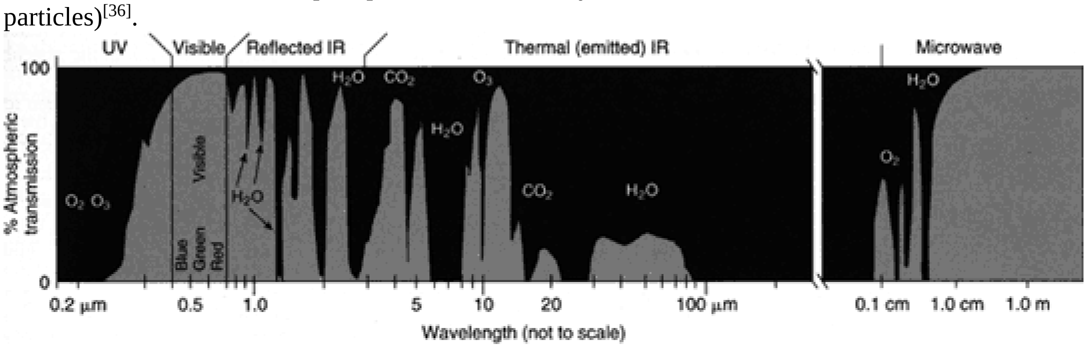
[51] http://speclab.cr.usgs.gov/contents.html

[52] http://www2.isprs.org/commissions/comm6/wg2/resources/acronyms.html

APPENDIX I – HSI-SPECIFIC GLOSSARY OF TERMS:

As airborne hyperspectral, thermal mapping, and new technologies have developed over past decades, so has the terminology used in their description. The following glossary is by no means complete, but covers many of the concepts and terms specifically related to our imaging technologies. In addition to edits and definitions by the authors, the definitions below were developed from source material from SPIE, SpecTIR, NIST, USGS, and ISPRS [48 – 52]

ABSORPTION: Some types of electromagnetic radiation easily pass through the atmosphere, while other types do not. The ability of the atmosphere to allow radiation to pass through it is referred to as its transmissivity, and varies with the wavelength/type of the radiation. The gases that comprise our atmosphere absorb radiation in certain wavelengths while allowing radiation with differing wavelengths to pass through. The areas of the electromagnetic spectrum that are absorbed by atmospheric gases such as water vapor, carbon dioxide, and ozone are known as absorption bands. In the figure, absorption bands are represented by a low transmission value that is associated with a specific range of wavelengths. Most remote sensing instruments on aircraft or space-based platforms operate in one or more of these spectral windows by making their measurements with detectors tuned to specific frequencies (wavelengths) that pass through the atmosphere. When a remote sensing instrument has a line-of-sight with an object that is reflecting sunlight or emitting heat, the instrument collects and records the radiant energy. While most remote sensing systems are designed to collect reflected radiation, some sensors especially those on meteorological satellites directly measure absorption phenomena, such as those associated with carbon dioxide (CO_2) and other gases. The atmosphere is nearly opaque to electromagnetic radiation in part of the mid-IR and all of the far-IR regions (2.5 um to 14 um). In the microwave region, by contrast, most of this radiation moves through unimpeded, so radar waves reach the surface (although weather radars are able to detect clouds and precipitation because they are tuned to observe backscattered radiation from liquid and ice particles)[36].



ABSORPTION BAND: The wavelength interval within which electromagnetic radiation is absorbed by the atmosphere or by other substances is the absorption band.

ATMOSPHERIC CORRECTION: The process of attempting to remove atmospheric-related effects such as path radiance, from the measured radiance to leave a signal that is more closely related to surface characteristics. All atmospheric layers contain molecular gases, aerosol particles, and water vapor, and information about these constituents may be extracted from hyperspectral imagery by using specially designed radiative transfer algorithms, such as MODTRAN.[43] It follows that these algorithms can be used to characterize the atmosphere, subtract the atmospheric effects and calculate spectral surface reflectance, with atmospheric effects minimized to aid in material identification and ground-cover classification.

BANDS (Also referred to as BANDWIDTH, NUMBER OF BANDS, NUMBER OF SIMULTANEOUS BANDS): A band is discrete portion of the electromagnetic spectrum over which data are acquired by a sensor. As related to an HSI Instrument, the width of a selected spectral band or channel, in nanometers (nm), is typically measured as the Full Width Half Maximum (FWHM) of the band spectral response. The number of bands refers to the total number of bands that can technically be captured by the sensor and equals the full range of the sensor divided by the minimum bandwidth, among other technical considerations. The number of simultaneous bands is the total number of bands that can be collected at any one time. For example, there are sensors that can collect 200+ bands across the solar reflected spectrum, but each band must be individually "tuned," and the sensor can only collect 15 individual bands at any one time. This type of sensor has useful applications, but calling it hyperspectral is problematic for most imaging researchers. Prospective purchasers of such a system should be keenly aware of this type of limitation.

BINNING: Binning is the averaging of neighboring pixels in the spatial and/or the spectral axes. Binning will reduce the frame size (by reducing spatial and/or spectral resolution), and increase the signal to noise. Many cameras perform binning inside the camera, thus the reduced amount of data to be communicated increases the maximum frame rate.

CALIBRATION: For hyperspectral imaging, calibration is the test of the sensor and its component wavelengths against a reflectance target of known dimensions and accuracy. Typically targets of known spectral reflectance and absorption are used to evaluate a response of the imaging sensor and to measure secondary issues such as stray light and signal to noise ratios.

CCD ARRAY: A Charge Coupled Device (CCD) is a light-sensitive, silicon-based semiconductor device. Comprised of an array of light-sensitive photocells, the CCD measures the incoming light and converts it to an electrical charge for each cell or pixel, which may then be measured and recorded. In a CCD sensor every pixel's charge is transferred through a very limited number of output nodes (often just one) to be converted to voltage, buffered, and sent off-chip as an analog signal. Using this design, all of the pixel can be devoted to light capture, and the output's uniformity (a key factor in image quality) is high. It is one of two basic digital image capture technologies; the other is Complementary Metal Oxide Semiconductor (CMOS).

CLASSIFICATION: The process of assigning individual pixels in an image into one of a number of categories based on their reflectance characteristics. This technique is useful for determining land use and remotely mapping habitats, amongst other things.

CMOS: A Complimentary Metal-Oxide Semiconductor is a light-sensitive, silicon-based semiconductor device. Made up of an array of light-sensitive photocells, the CCD measures the incoming light and converts it to an electrical charge, which may then be measured and recorded. In a CMOS sensor, each pixel has its own charge-to-voltage conversion, and the sensor often also includes amplifiers, noise-correction, and digitization circuits, so that the chip outputs digital bits. These other functions increase the design complexity and reduce the area available for light capture. This is one of two basic digital image capture technologies, the other being a Charge Coupled Device (CCD).

CROSS TRACK: Cross Track defines a direction perpendicular to the direction of flight (`across the aircraft's track'). Across track spatial pixel resolution is related to the FOV of the instrument lens and the flying height of the aircraft or satellite.

DARK CURRENT: Dark Current is one of the additive components to the signal measured by a hyperspectral imaging instrument that is not target-related. These components are measured by the instrument during data collection and are removed during radiometric correction processing of the raw image data. Dark current is the current that flows in a photodetector when there is no optical radiation incident on the detector and operating voltages are applied.

DIFFRACTION GRATING: An optical device used for diffracting a beam of light into its wavelength components is the diffraction grating; it is the main component of line scan spectrographs.

DIGITAL NUMBER (DN): Digital Number refers to the output from an analog to digital converter or raw signal strength as indicated by a sensor.

DISTORTION: Distortion occurs when image magnification in an EO sensor optical system varies with position within the image, causing straight lines (generally conceptual rather than literal) in the object to be mapped into curved lines in the image.

DOWNWELLING IRRADIANCE: The amount of light or other radiant energy directed toward the earth's surface from the sun or the atmosphere, typically measured in Watts per meters squared ($W*m^{-2}$) is downwelling irradiance.

DRIFT (aircraft): The tendency of an aircraft to be unable to maintain the planned course over ground when flying in crosswind conditions unless corrections are made is called aircraft drift.

DRIFT (sensor): The tendency of an electronic sensor or device's known response to vary with internal or external changes such as temperature, electronic noise sources or physical shock to the instruments is called sensor drift.

D* (D-Star): D-Star is noise in an electronic sensor as defined by the following equation:

$$D^* = (A_{D^*}\Delta f)^{1/2}/NEP$$

Where A_D is the area of the detector in cm^2
Δf is the bandwidth of the electrical system reading the detector output in Hz
NEP is the Noise Equivalent Power in watts

EM RADIATION: Electromagnetic radiation is radiation such as visible light, microwaves, and infra-red, which is composed of interacting electric and magnetic fields. In general hyperspectral imaging involves the solar-reflected portion of the electromagnetic spectrum (400 nm – 2500 nm).

FLIGHT BLOCK: Flight block is an area on the ground identified during flight planning for which imagery data is to be acquired using either a single flight line or multiple and adjacent flight lines with side lap. It contains one or more areas of interest and should not be confused with Mosaic.

FLIGHT LINE: Flight line is typically used to refer to a single linear path (usually pre-planned) along which image data are acquired. A flight block is made up of multiple and adjacent flight lines with side lap. It should not be confused with a scan line. See also Flight Block.

FLYING ALTITUDE: Flying altitude is the required height at which the aircraft must fly to obtain a specified across-track pixel size. It varies according to the given field of view (FOV) of the instrument lens and can be specified for Above Ground Level (AGL) or Mean Sea Level (MSL). Pilots often require this value to be specified MSL, meaning that the both the height AGL and the average terrain height must be added together.

F-NUMBER: F-Number is the ratio of the focal length to the lens aperture. It is a measure of the light gathering capability of a lens; the smaller F-number the brighter the image.

FIELD OF VIEW (FOV) and INSTANTANEOUS FIELD OF VIEW (iFOV): The angle between two rays passing through the perspective center of a camera lens to the two opposite sides of the image area is known as the FOV. With the AISA instruments, the FOV defines the width of the area viewable through the lens in the across-track direction. This value may be measured in degrees or in pixels. The FOV directly influences the required flying height of the aircraft or platform for a given across-track pixel size. The iFOV is an important calculation in determining how much a single detector pixel can see in terms of FOV.

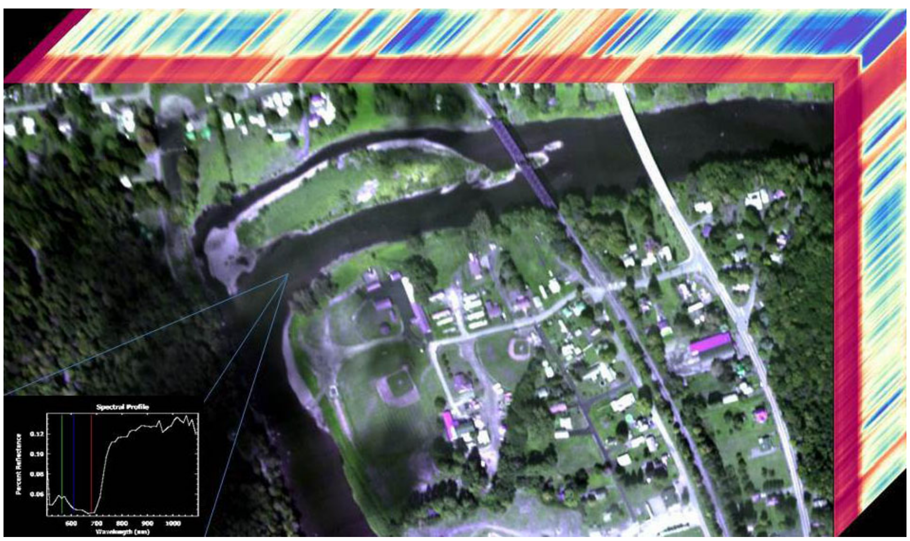
FWHM: Full width Half Maximum (FWHM) is the width of a spectrum curve measured between those points on the *y*-axis, which are half the maximum amplitude.

GROUND SAMPLE DISTANCE (GSD): The smallest visually resolvable unit (L x W) on the ground for a given pixel size is GSD.

GROUND TRUTH: Ground truth refers to relating direct field observations of ground surface phenomena to corresponding features in remotely-sensed data for verification of accuracy.

GYROSCOPICALLY STABILIZED MOUNT: A gyroscopically stabilized mount is a specialized platform mount used to provide precise, real-time motion compensation, leveling, and drift control to the installed image sensor head in the aircraft. It dampens aircraft vibrations and reduces attitude changes transmitted to the sensor head, providing imagery that is less prone to effects of smear or jitter. The mount incorporates three axis corrections (roll, pitch and yaw), from a precision GPS system, and can extend the operational survey window under conditions of turbulence. The use of a gyroscopically stabilized mount may also allow for faster survey flight speeds, if this is permissible within the imager's operational resolution constraints.

HYPERCUBE: The 3-D data set that results from a scan with a hyperspectral camera is a hypercube. The three dimensions are two spatial (x, y) and one spectral. The example below shows an image of the Upper Delaware River from the Civil Air Patrol's, Airborne Real-time Cueing Hyperspectral Enhanced Reconnaissance (ARCHER) sensor.



HYPERSPECTRAL: A sensor is classed as hyperspectral if it is capable of imaging an area in many (e.g., hundreds) of bands simultaneously.[42]

Category	Spectral Band Content	Spectral Resolution	Application	Example System
Multispectral	A few to dozens	20-100nm	• Multispectral classification of dissimilar materials • Military target detection & camouflauge ident. • Geological • Oceanography • Atmospheric	LANDSAT (NOAA) AVHRR (JPL) SPOT 3 (France)
Hyperspectral	Hundred to a few hundred	10-15nm	• Precise surface material identification • Environmental monitoring • Detection of selected gases • Atmospheric effects must be known to detect gases	HYDICE (NRL) AVIRIS (JPL) HIRIS FTS (LLNL)
Ultraspectral (Spectroscopy)	Several Hundred	1nm	• Gas Specied Detection • High resolution permits in-situ correction of atmospheric effects (water, ozone, etc)	Mostly ground based spectrographs Fourier-Transform spectrometers Coming to Space

HYPERSPECTRAL IMAGING (HSI): HSI is the process of measuring a complete spectrum at each spatial point of a sample with a hyperspectral camera. Hyperspectral sensors typically divide reflected or emitted energy in many, typically hundreds of narrow, contiguous bands, collectively called spectra, which often comprise a unique fingerprint of the material being sensed. Hyperspectral imaging, like other spectral imaging, collects and processes information from across the electromagnetic spectrum. The goal of hyperspectral imaging is to obtain the spectrum for each pixel in the image of a scene with the purpose of finding objects, identifying materials or detecting processes.

IMAGE ANALYSIS: Image analysis is the extraction of characteristic information inherent within the processed imagery for the imaged target. The information derived from spectral and/or spatial image analysis is used to produce value-added products used by decision makers for environmental and resource management. For HSI applications, image analysis involves the analysis of the spectroscopic fingerprint of each pixel, often relating it to a known spectral library or phenomenon.

IMAGE DATA: Image data are radiance measurements of the target as measured and recorded by an instrument from reflected or emitted radiation in the visible, NIR, SWIR, MWIR, or LWIR portions of the electromagnetic spectrum.

IMAGING SPECTROMETER: An imaging spectrometer is an instrument that splits incoming light into many, often hundreds, of narrow contiguous bands for each pixel in the scene and creates a registered stack of images. Imaging spectrometers are used in hyperspectral imaging and imaging spectroscopy to acquire a spectrally-resolved image of an object or scene, often referred to as a data-cube due to the three-dimensional representation of the data.

INTEGRATING SPHERE: An integrating sphere is used in the spectral and spatial calibration of the AISA family of instruments. The definition from the Photonics Dictionary (www.labsphere.com) is ”A hollow sphere coated internally with a white diffusing material and provided with openings for incident beam, specimen, and detector used for measuring the diffuse reflectance or transmittance of objects.”

IRRADIANCE: Irradiance is an entity of flux that describes a point source or a source of a fixed size and distance such as the Sun when viewed from Earth. When irradiance includes wavelength dependence, it is called spectral irradiance. Generalized units of spectral radiance are Watts*cm^{-2}*μm^{-1} or Photons*sec^{-1}*cm^{-2}*μm^{-1}.

KEYSTONE: Keystone refers to a change in optical magnification with wavelength. It is a measure of the spatial shift between pixels at different wavelengths. Keystone and its spectral equivalent, Spectral Smile, are present to varying degrees with push broom-style instruments using diffraction gratings. See also Spectral Smile.

MERCURY CADMIUM TELLURIDE-MCT-Focal Plane Array (FPA): An MCT FPA is a two-dimensional detector array for the short-wave (SWIR) to long-wave infrared (LWIR) region. The MCT SWIR camera detects light in the 0.9 um to 14 um range (model dependant). Mid-infrared MCT arrays also are used for hyperspectral imaging in the 3 um to 5 um bands.

MODULATION TRANSFER FUNCTION: The modulation transfer function (MTF) is the magnitude response of the optical system to sinusoidal targets of varying spatial frequencies. When analyzing an optical system in the frequency domain, the imaging of sinewave inputs is considered rather than point objects. While figures of merit such as contrast, sensitivity, and resolution give an intuitive indication of performance, the MTF provides a comprehensive and well-defined characterization of optical systems.

MULTISPECTRAL: A sensor is multispectral if it simultaneously acquires images of the same area in a number of different wavelength ranges (bands).

MULTISPECTRAL IMAGE: A multispectral image is an image that contains intensity information at more than one wavelength. A Red/Green/Blue image is a multispectral image because it includes information from three different wavelengths. The term hyperspectral image is used when many wavelengths covering an entire wavelength region (visible, NIR, etc.) are included.

MWIR: Mid-Wave Infrared (MWIR) is a spectral region covering infrared wavelengths between ~3 to 5 microns mostly defined by the atmospheric transmission windows due to water vapor. The hyperspectral SEBASS sensor contains both MWIR & Long-Wave Infrared. It is typically used for atmospheric analysis or acquisition of thermal targets like jet exhaust or engine emission.

NADIR: Nadir refers to the point on the ground located vertically below the center of the objective lens.

NEAREST NEIGHBOR: Nearest neighbor is a means of resampling where the DN value for the pixel to be mapped is assigned based on the DN of the closest pixel in the input image. The nearest neighbor approach has the benefit over other methods (e.g., bilinear interpolation and cubic convolution) in that it does not alter the original input pixel values and is computationally simple. See also Resample. It is often used with correcting or assigning recalculated values to pixels after some transformative process.

NIR: Near Infrared (NIR) is the shortest wavelength of the infrared region, nominally 750 to 1200 nm.

NIST SIRCUS: National Institute of Standards and Technology (NIST), Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) is a reference facility for the calibration of detectors and radiometers for spectral irradiance responsivity and spectral radiance responsivity across the UV, visible, and much of the infrared spectrum. SIRCUS uses continuously tunable lasers coupled into integrating spheres as a spectral irradiance or radiance source. The availability of lasers ultimately determines the spectral coverage available on SIRCUS while the ultimate uncertainties achievable are determined by the quality of the reference standard irradiance detectors. The high power and wavelength stability of the laser-based sources enable large aperture instruments, from remote sensing instruments to astronomical telescopes and detector array-based imaging systems, to be characterized and calibrated. This facility is often used to calibrate HSI instruments.

NOISE: Spurious, unwanted energy generated internally within an electronic system or sensor or from outside interference is called noise. It is unpredictable, random variations in the measured signal from moment to moment or from measurement to measurement. Noise tends to limit the useful range of a system. See also Signal-to-Noise Ratio.

PASSIVE REMOTE SENSING: Remote sensing techniques or technologies that measure naturally reflected or radiated energy in order to make inferences about the surface without physical contact is called passive remote sensing. The key difference between these technologies and those of active remote sensing systems lies in the origin of the measured energy. While active systems actively emit energy towards an object and then measure what returns, passive systems measure naturally occurring energy from the sun that is reflected or emitted from an object.

PITCH ANGLE: Pitch angle is the vertical angle formed between the aircraft’s longitudinal axis and the horizontal plane. Fixed wing aircraft often have a positive pitch angle (nose up) during normal flight.

PIXEL: Pixel is short for picture element. It is the smallest visual element that a digital image can be divided into. The resolution of the image is dependent on the number of pixels it contains. For an image with a given physical dimension the more pixels that are used the higher the resolution. See also Resolution.

PIXEL PITCH: Pixel pitch refers to the spacing between the center-on-center distance of each pixel in an array. Typically symmetric spacing is employed but can be asymmetric in rare cases.

POINT SPREAD FUNCTION: The point spread function (PSF) describes the response of an imaging system to a point source as seen by the FPA. A more general term for the PSF is a system's impulse response; the PSF being the impulse response of a focused optical system.

PUSHBROOM SCANNER: A sensors that uses a line of detectors to scan a two dimensional scene is a pushbroom scanner. The ground swath covered in a single pass of the instrument is related to the chosen pixel size and the number of pixels in each row of the sensor array. Pushbroom scanners rely on the forward motion of the platform relative to the imaged target to provide a recognizable image that is built up scan line by scan line according to the chosen integration time.

RADIANCE: Radiant intensity or radiance is energy per unit projected area and is typically measured in watts*steradian^{-1}*m^{-2} (SI Units). In radiometry, radiance is the radiant flux emitted, reflected or transmitted by a surface, per unit solid angle per unit projected area, and spectral radiance is the radiance of a surface per unit frequency or wavelength, depending on whether the spectrum is taken as a function of frequency or of wavelength.

RADIOMETRIC CORRECTION: Radiometric correction is one of a set of radiometric calibration techniques that is applied during remote sensing data processing and includes corrections related to the sensitivity of the remote sensor, topography and sun angle, and atmospheric scattering and absorption. Under most circumstances the term radiometric correction generally implies that two major processes have been performed on raw image data: correction and calibration. Radiometric correction involves the removal of additive instrument-related components (dark current, etc.) from the raw image data. This leaves only the actual target-related component of the signal. Correction, for instance, can be used to scale the raw image data from 12 to 16 bits in dynamic range in typical instruments. Radiometric calibration involves the application of instrument and aperture-specific coefficients (contained in the *.rad files generated during instrument calibration) to the raw image data, converting it from raw DN to units of radiance. See also Rad File and Radiance.

RADIOMETRIC RESOLUTION: Radiometric resolution determines how finely a system can represent or distinguish differences of intensity and is usually expressed as a number of levels or a number of bits, for example 8 bits or 256 levels that are typical of computer image files. The higher the radiometric resolution, the better subtle differences of intensity or reflectivity can be represented, at least in theory. In practice, the effective radiometric resolution is typically limited by the noise level, rather than by the number of bits of representation

REFLECTANCE: Reflectance is the ratio of a given wavelength of light reflected by a surface to the light incident on a surface for a given geometry and expressed as a percentage. To arrive at a measure of reflectance, the instrument radiance data must be atmospherically corrected to remove as much of the effect of the atmosphere as possible. Reflectance of the surface of a material is its effectiveness in reflecting radiant energy. It is the fraction of incident electromagnetic power that is reflected at an interface. The reflectance spectrum or spectral reflectance curve is the plot of the reflectance as a function of wavelength, against a standard reflectance substance, such as Spectralon, termed “relative” reflectance. If the data has been corrected for the absorbing properties of the reference material, it is termed “absolute” reflectance.

REFLECTED LIGHT: Light reflected off a ground target and passively sensed and measured by the imagers is referred to as reflected light.

REFRACTION: Refraction is the change in direction of travel of an electromagnetic wave as it passes between two areas which have a different refractive index.

REMOTE SENSING: Remote sensing is the acquisition of information of an object or phenomenon by the use of device(s) that is not in physical or intimate contact with the object (such as by way of aircraft, spacecraft, satellite, or ship). Hyperspectral cameras may be used in ground-based or airborne remote sensing applications.

RESOLUTION: Resolution defines the smallest ground element that can be identified in the imagery. The smaller the pixel size, the higher the resolution of the data. High resolution capabilities are aircraft and speed dependent.

SCAN LINE (FRAME): Data collected during one frame time of sensor are scan line data. A scan line may be visualized as having one spatial dimension and one spectral dimension. A pushbroom sensor's image is made up of a continuous series of many scan lines or frames, successively built up throughout the data acquisition in a `waterfall' style display. A single flight line can be made up of thousands of scan lines. It should not be confused with the term flight line.

SCATTERED LIGHT: Light scattered internally within the optical train of a VNIR system is scattered light. This light is scattered by reflections from the edges of optical components or mounts, or from irregularities on the optical surfaces. Scattered light is one of the additive components to the signal measured by the HSI instrument that is removed during radiometric correction.

SCATTERING: The multiple reflection of electromagnetic radiation off surfaces or particles is scattering. This leads to a decrease in the energy being transmitted.

SIGNAL-TO-NOISE RATIO (SNR): SNR or S/N is a measure used in science and engineering that compares the level of a desired signal to the level of background noise. It is defined as the ratio of signal power to the noise power from the sensor as well as noise contributed from the electronics, often expressed in decibels. The SNR ratio is the signal of the target information to the signal measured by an instrument to the undesirable noise present in the signal.

SMILE: The spectral smile, also known as a smile or frown curve, is a spectral distortion that is typically found in pushbroom sensors. It is a shift in wavelength in the spectral domain that is a function of cross-track pixels (column) in the swath and measures spectral distortion or wavelength shift in the across-track direction of the array. As a result, the sensor does not respond to exactly same wavelength across an individual scan line. Typically this distortion is low, on the order of ±0.25 to ±0.8 pixels (depending on the sensor type) and is ameliorated during calibration. The term arises from the general appearance of a plot of wavelength versus spatial pixel, which approximates the curve of a shallow smile with upturned ends. Spectral smile, and its spatial equivalent, Keystone, are present to varying degrees with pushbroom-style instruments using diffraction gratings. See also Keystone.

SPECTRAL BAND: A spectral band is a band in the spectrum defined by an upper and lower wavelength. It is sometimes referred to as a channel or band and is a set or user-defined range of contiguous rows on the sensor used to measure reflected or emitted radiation.

SPECTRALON: Spectralon is a brand name and registered trademark of Labsphere, Inc. for a low density form of sintered Poly Tetra Fluoro-Ethylene (PTFE). PTFE is a fluoropolymer, which has very high diffuse reflectance over the ultraviolet, visible, and near-infrared regions of the spectrum (0.25 um to 2.5 um). It exhibits highly Lambertian behavior and can be machined into a wide variety of shapes for the construction of optical components such as calibration targets, integrating spheres and optical pump cavities for lasers.

SPECTRAL SIGNATURE: Spectral signature is the unique profile for a specific target type (e.g., minerals, water, tree species, grass, concrete, etc.) based on its measured spectral response across a portion of the electromagnetic spectrum. The difference between unique spectral signatures often provides the basis for powerful analysis techniques to be used in extracting useful information from hyperspectral image maps.

SPECTROMETER: A spectrometer is any instrument used to probe a property of light as a function of its portion of the electromagnetic spectrum, typically its wavelength, frequency or energy. Technically, a spectrometer can function over any range of light, but most operate in a particular region of the electromagnetic spectrum.

SPECTROSCOPY: Spectroscopy is the study of light as a function of wavelength (spectrum) which has been transmitted, emitted or reflected from a solid, liquid or gas sample.

SPECTRUM: Spectrum is the intensity of light as a function of wavelength, which can be displayed on an emission, reflectance, absorption, or transmission scale.

SPECTRAL STRAY LIGHT: Spectral stray light, not to be confused with scatter light, is the signal produced by one wavelength in a spectral array that was not from the intended wavelength.

STARING ARRAY (HSI): A staring array is a type of camera or method of hyperspectral imaging in which the object and camera are stationary and the entire object is imaged at the same time. To acquire spectral information at multiple wavelengths, a tunable filter is used to scan through the wavelengths.

STRAY LIGHT: Light in an optical system, which was not intended in the design, is stray light. The light may be from the intended source, but it follows paths other than intended, or it may be from a source other than the intended source. This light will often set a working limit on the dynamic range of the system; it limits the signal-to-noise ratio or contrast ratio, by limiting how dark the system can be.

SWIR: Short-Wave Infrared is a spectral region covering infrared wavelengths nominally between 1.0 um to 2.6 um.

VICARIOUS CALIBRATION: Vicarious calibration is the process of validating remote sensing measurements by acquiring in situ measurements on ground targets simultaneous with or close to the time of instrument measurement.

VISIBLE WAVELENGTHS: Spectral wavelengths of light visible to the human eye are visible wavelengths and usually range between approximately 400 to 700 nm. International standards define the full visible range as 380-830nm.[47]

ZONG METHOD: A method developed by Yuqin Zong at NIST to correct a spectro-radiometer's response for measurement errors arising from the instrument's spectral stray light. By characterizing the instrument's response to a set of monochromatic laser sources that cover the instrument's spectral range, one obtains a spectral stray light signal distribution matrix that quantifies the magnitude of the spectral stray light signal within the instrument.[21]