Survey and Analysis of Fore-Optics for Hyperspectral Imaging Systems

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ABSTRACT

Applications for imaging spectrometers are expanding to cover a broader spectral range with higher fidelity, often from the VNIR to the SWIR with one common aperture. These fore-optic systems range from short focal length refractive optics for micro-UAV platforms, to large all-reflective telescopes for surveillance systems. Off-the-shelf lenses and standard prescription telescopes typically do not have the telecentricity and color correction performance to meet fore-optic system requirements for low distortion and broadband operation. This paper evaluates several wide- and narrow-field VIS-SWIR fore-optics designs, describes the effects of fore-optics aberrations on spectrometer performance, and outlines the effects of these constraints on aperture, spectral coverage, and optimal packaging.

Keywords: Hyperspectral, Offner spectrograph, all-reflective, imaging spectrometer, three-mirror anastigmat, TMA, telescope

1. INTRODUCTION

Significant advances in hyperspectral imaging (HSI) have been obtained through improvements in optical designs, manufacturing technologies, and diffraction gratings, with emphasis on the core spectral technology or “spectral engine”, but not necessarily with a corresponding development of fore-optics design. HSI’s strength is in exploiting high fidelity spectral signatures with complex algorithms for detecting faint and sub-pixel targets, or characterization of mixed pixel backgrounds. These science requirements, however, can drive very tight optical system performance and alignment stability requirements. In particular, the requirements of the fore-optics telescopes and lenses can make their design and manufacturing more difficult than the spectral engine itself. This paper will explain the differences between conventional imaging optics and HSI fore-optics, the derivation of their specifications, and the impact of artifacts on system performance and calibration stability.

2. DISCUSSION

The basic functionality of an HSI sensor is the separation or encoding of the spectral content, temporally or spatially, in a form which can be recorded and analyzed by a detector and processor. The survey of technologies in Figure 1 records the distinct advantages and disadvantages based on its parameters determined by system requirements and Concept of Operations (ConOps.) The optimal method of separation (dichroic filters, liquid crystal, gratings) or encoding (interferometric, Hadamard), is determined by constraints on packaging, detection sensitivity, radiometric accuracy, and stabilization requirements. Stabilized ball turret systems will have a stronger weighting toward compactness, while “strap-down” push-broom surveying sensors tend toward calibration accuracy. Snapshot systems acquire the full-spectrum simultaneously for their entire field-of-view, whether a slit or two-dimensional aperture. Snapshot sensors also are optimized for fast moving targets and push-broom scanning systems, with less rigorous stabilization requirements.

Staring systems acquire the full two-dimensional field of view, and either encode spatially such as done with a CTIS instrument or Hadamard Transform instrument, interferometrically as in a DASI or Michelson interferometer, or temporally through an AOTF or LCNTF. Staring systems have the advantage of performing two-dimensional image processing with good registration, but suffer from spectral cross-talk for scenes moving faster than their acquisition times. As an example of simplicity versus performance, LVF spectrometers are the simplest and most robust, integrating a narrow spectral filter directly each detector column, but are also the least sensitive, since the out-of-band light for a single pixel is not utilized. Imaging interferometers make for excellent background characterization instruments with high throughput (Jacquinot advantage), but are not suitable for small or high-vibration platforms.

Other publications cover the Signal-to-Noise (SNR) ratio and other metrics more completely than what we will discuss.

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Here. What is important to remember, however, is that all of these systems must transform the optical signal at long conjugates to a real or virtual image, and this image must be separated or encoded by the spectral engine with minimum sensor artifacts. The fore-optics discussed by this paper perform this key functionality.

HSI systems are more challenging than monochrome or 3-band color systems for their higher spectral fidelity and calibration stability, while also maintaining high image quality. These system level requirements lead to tight optical performance specifications for telecentricity, focus, axial and lateral color, field curvature, specific aberration allotment, and stray light. For systems without a field stop or slit, such as tunable filters, these principles still hold, but must be translated in the temporal domain. Whereas grating-based systems require low cross-talk within a camera frame between two spectra lines, tunable filters require low cross-talk between two spectral frames separated in time. For the sake of brevity, the examples presented will limit the discussion to slit-based spectrographs. These examples exemplify the principles of HSI fore-optics design, and are not rigorously optimized for particular performance goals.

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Figure 1. Hyperspectral Imaging Technologies

2.1. FIRST ORDER PARAMETERS AND TELECENTRICITY

The first-order parameters examined here for HSI systems are focal length, f-number, field stop size, pupil positions, and focus. In airborne applications, nadir viewing push-broom systems have focal lengths on the order of 12-75 mm depending on planned altitude, instantaneous field-of-view (IFOV), and pixel pitch. Current airborne systems such as the Ocean PHILLS operate between f/2.8 and f/4, although the spectrograph is designed at f/2. The entrance slit defines the field of view and is scanned to acquire the full two-dimensional scene. The slit width is determined by the effective detector pixel size multiplied by the spectrograph magnification. Widening the slit width increases the useful system throughput, but only if an anamorphic fore-optic is implemented to retain the square IFOV. Increasing the slit width in this manner also reduces the spectral resolution, although for most airborne systems the pixels are binned on the detector by 2 or 4 already to increase SNR, and therefore would not incur any disadvantages. The most significant problem with using anamorphic lenses, such as based on a Cinamascope lens, is that the throughput gain by making the slit wider is lost in f-number (approximately one f-stop), when trying to design with toroidal lenses or prisms with manufacturability in mind.

The Offner spectrometer (Figure 1) represents an increasingly accepted imaging spectrograph for its low distortion, low f-number and large field size, and is shown here as our primary example. For the Offner spectrometer, the first requirement levied on the fore-optics design is pupil matching, which infers telecentricity (entrance pupil located approximated at infinity.) The slit defines the spectrograph field, with the spectra dispersed along each detector row and the scene spatial information imaged along the detector columns. The metric for specifying the tolerance is the chief ray angle, typically 0.2 to 1 degree for <10% vignetting, depending on spectrometer’s focal length. In the lens design process, the starting points selected are at two different ends. The first design form is a double Gauss, with an added field lens group. This starting point emphasizes initially correcting the Seidel aberrations, and then adding elements and changing glasses for telecentricity and color correction. The second design starting point is an inverted eyepiece design (or reverse telephoto) which inherently has an external pupil but with significant coma and lateral color. Adding lenses
and splitting elements is performed incrementally during the design, for both color and aberration correction. At moderate focal lengths (25-100 mm), a Huygens eyepiece was the starting point, with singlets replaced with achromats. For short focal lengths (<25 mm), a reverse telephoto (similar to an Erfle eyepiece) with a negatively powered first element was selected to maintain minimum glass thicknesses. Since spherical aberration does not tend to dominate, aspherizing lenses did not seem to improve performance during lens design optimization.

Figures 3 and 4 show a comparison layout of two of the lenses discussed: the double Gauss and the inverted eyepiece. In the double Gauss, the additional three field group lenses match the spectrograph pupil and the doublets are optimized for the axial and lateral color correction. The inverted eyepiece design has an external entrance pupil set at front focal position of the lens, thus guaranteeing image space telecentricity. For airborne applications, usually the distortion will be relaxed, since the images are usually geo-rectified in post-processing to account for aircraft motion. Coating transmission performance limits the surface count and maximum ray angles. HSI systems in the VNIR and SWIR are generally driven to wideband performance (400-1000 nm, 1000-2500 nm respectively.) As the spectral range increases, the average coating losses increase as there are more layers on the thin film stack to meet the spectral range. The second impact of coating losses is the increase in scattered light as explained in the last section. Polarization has not been analyzed for these design types, although is expected not to be a problem since the polarization of the spectrograph’s grating and mirrors most likely dominate (< 5%).
It is not always feasible under program budgets to design and fabricate a custom lens in the schedule provided. In this case, commercial-of-the-shelf (COTS) lenses replace custom optics. This requires floating the fore-optics stop and letting the spectrograph determine the system aperture. For example, a Schneider Cinegon f/1.4, 25-mm focal length lens has sufficient color correction and transmission over 450-1000 nm to drive a broadband f/2.8 spectrograph. Although this will introduce additional stray light due to mismatched pupils, it is a viable low-cost alternative. A third alternative for meeting the telecentricity requirement is combining a COTS lens with a custom field lens. For Nikon F-mount lenses there is sufficient back working distance to put the field lens prior to the slit, whereas for C-mount lenses the tight working distance necessitates putting the field lens after or on the slit substrate itself.

Focus may be the simplest and sometimes most overlooked of the first-order lens parameters for HSI systems. The challenge with focus is the impact on throughput and calibration accuracy, as a function of object distance and sensor temperature. With changes in temperature, the lens barrel and optics expand at different rates. Even with refocusing, these change the aberration balancing of the optic, and thus the amount of light that makes it through the slit—a calibration change. Additionally there are two focus actions: the lens focuses on the slit, and the spectrograph focuses the spectra on the detector, both having wavelength dependant field curvature and aberrations (Figures 5 and 6). Thus, for radiometrically calibrated systems without auto-focus, it may be preferable to weight the lens design optimization function for a uniform throughput over the thermal focus range, even with a slight MTF loss.

### 2.2. AXIAL AND LATERAL COLOR

High spectral fidelity is a key requirement for an HSI system to maintain high detection sensitivity without the need for re-calibration. The first aberration examined here is axial color, which is the difference in the axial focus position with wavelength (Figure 8). When significant axial color exists, the spectral transmission through the slit will vary depending on the focus setting with object distance, pressure and temperature. This can be corrected only by having a calibration matrix for the full range of operation. For light transmitted through the slit, there still exists a difference in focus for each wavelength, which is partially compensated by tilting the focal plane. Actively tilting the detector for axial color however, causes a spectral shift, and thus requires a spectral recalibration.

The second chromatic aberration, lateral color, affects the optical performance more significantly because it is difficult to control in telecentric optics, as mentioned previously. Lateral color is the change in magnification with wavelength, and when dispersed along the detector rows becomes spectral keystone distortion. Such tight requirements stem from the inherent nature of HSI algorithms looking for spectral anomalies, where any slight spectral cross-talk could be seen as a new spectral mixture. This new spectral mixture greatly increases the dimensionality of the end-member space, thus making hyperspectral image compression less efficient. Typical specifications for keystone distortion are 0.1-pixel, or
2-microns for a 20-micron detector pixel. Optically compensating keystone in the spectrometer is possible by adding a refractive wedge or powered element near slit or the detector, but this element then becomes a potential stray light source.

![Figure 7. Field Curvature for double Gauss with Field Group](image)

![Figure 8. Lateral Color vs. Field](image)

In the selection of glasses during the design, the typical methods entail using Calcium Fluoride and low dispersion glasses, along with the short flints separated from the dispersion glass line (KZFSx, KZFSNx.) Low index elements, however, cause more elements to be needed for aberration balancing and field flattening. For this reason, telecentric color-corrected lenses may have twice the optical elements than an equivalent focal length photographic objective. Other methods are under investigation for color correction, but are not without limitations. Adding diffractive optical surfaces for color correction is a standard practice with infrared systems, but is impractical for visible optics since most applications require more than one octave of spectral range.

### 2.3. FIELD CURVATURE AND ZONAL ASTIGMATISM

Field curvature causes a loss of transmission through the slit with field. As mentioned previously, this can be corrected with a field flattener lens immediately before the slit, or by curving the slit toward the fore-optic. However,
incorporating optics near field locations must be taken with great care, to avoid ghost reflections. Ghost reflections are caused by either the broad band anti-reflection coatings especially operating near their cut-offs or by the reflectivity of the black area around the slit itself.

A more visually apparent aberration is zonal astigmatism. For large fields, even though the astigmatism may be well-behaved on-axis and at 0.7-field, it may be out of specification in-between or at the edges. Astigmatism itself would not be too damaging since the light would still transmit through the slit, but when incorporated with field curvature, no best sagittal or tangential focus exists for any field location. Astigmatism with the inherent field curvature may also be introduced through tilt misalignment of an element. This is visually apparent as a point image “corkscrews” through focus (Figure 10.) The spectral dependence of the astigmatism causes the same throughput loss as axial color, only with field dependence.

The effect of field curvature is an effective loss of depth-of-focus for maintaining calibration. Figure 10 shows the combination of field curvature and astigmatism causing non-uniform throughput dependence with field. As focus changes with temperature, these curves can either monotonically decrease, or flip as one wavelength comes into best focus and another goes out of best focus.

From a system engineering viewpoint, the fore-optics and spectrograph manufacturers are typically two separate organizations, with the two designs and hardware merging during the project time-line. The challenge for the integrated product team is to build in enough flexibility into the design and schedule so that some compensation of the fore-optics aberrations can be performed by the spectrograph, and vice versa. For optimal imaging performance, the focus and tilt compensators should be done both at a subsystem level and to a lesser extent at the integrated system level. Compensating during manufacturing requires a firm grasp of the optical design, and should be simulated during the system tolerance analysis. For example, the zonal astigmatism of the fore-optics may be partially compensated by the spectrograph. For the Offner spectrograph, this is performed by slightly tilting up in the primary (the first mirror after the slit) and tilting down tertiary mirror (the mirror just before the detector.) As a last system design note: as with all high-quality systems, but particularly due to HSI’s tight chromatic correction, the glass melt data should be used in the final optical design, and coating witness samples be verified for transmission performance.
2.4. TRANSMISSION AND STRAY LIGHT

The transmission requirements further limit the design form and performance, with values in the range of 65-75% for refractive optics, and 90-95% for all-reflective optics. HSI systems in the VNIR and SWIR typically cover more than one octave of wavelength ranges, limiting the average anti-reflection coating average loss to 0.75-1.5%. As the spectral range and angular extent increase, the coating losses increase, thus limiting the number of surfaces in order to meet the transmission specification. The second effect of coating losses is the increase in scattered light from three specific sources. The first is in-field scatter, or veiling glare, due to the cumulative coating Fresnel losses. Veiling glare can be partially accounted for by a frame-by-frame offset in image processing if sufficiently uniform. Out-of-field scatter for HSI systems corrupts the data more significantly, creating spectral artifact which may confuse the algorithms. In coastal remote sensing, this artifact creates situations such as overestimating sandy bottom type classification, when what is truly being observed is the stray light from an out-of-field coastal beach zone. The third stray light artifact particular to HSI systems is the slit-optic-slit ray path. The light reflects from the slit coating, to the curve last element (typically only a few millimeters from the slit), and then back through the slit. For photolithographic slits, the reflectivity of the black area around the slit itself is usually a metal oxide. Blackened nickel or blackened chrome slits are 3-5% reflective, significantly higher than 0.5-1.5% for most broadband antireflection coatings. A painted mask surrounds the slit, but can only be manufactured to be located within +/-0.05 mm of the slit edges. The stray light analysis for a 5% reflective slit in Figure 11 shows two ghost images for the last optical element approximately 10 times more significant than the veiling glare background. Air slits are a viable alternative although they are generally more jagged (1-2 microns) and trap dust. The image striping due to dust and slit acuity variations are a leading cause of calibration errors as thermal and mechanical changes causes the slit to move around.

Prior to proceeding to the discussion of all-reflective optics, it is worth a brief summary up until this point. The particular challenge that the HSI system designer faces is that the requirements of image quality, telecentricity, color correction, and high SNR (high transmission, large aperture), must be traded against less understood parameters of stray light, radiometric calibration stability, and ultimately Receiver-Operator Curve (ROC) performance (probability of detection vs. false alarms.) The table in Figure 12 gives some starting points for values to assign to an initial lens specification. These metrics may loosen by a factor of two if the system is a 640-pixel spatial format with 20-nm bands using only change detection algorithms, or tighten by a factor of two for a 1280-pixel spatial format, with 2-nm bands, expecting full radiometric and spectral position calibration. Scene-based sensor modeling simulations are currently in progress to reduce the ambiguity in design trades to better statistical metrics.
2.5. ALL-REFLECTIVE FORE-OPTICS DESIGNS

When image quality, transmission and stable calibration are of greater concern than size and cost, the obvious choice for eliminating color aberration is an all-reflective fore-optic. Especially for common aperture VNIR and SWIR systems, the spectral range is too wide for any refractive design with anti-reflection coatings to be practical. Modified Ritchey-Chrétien (R-C) Cassegrains are the first choice for a compact, low-cost, long focal length design, with minimal refractive elements. The R-C on-axis aspheric mirrors can be easily generated and polished, or they can be diamond-turned in metal when a snap-together construction is desired to reduce alignment costs. The main advantage of the R-C with glass optics, compared to off-axis designs, is improved manufacturability from an axi-symmetric optomechanical design. Light-weighted glass mirrors are still the most economical way to obtain satisfactory weight, low surface roughness and wavefront error, without significant up-front costs. However, when comparing with metal optics and silicon carbide, this gap closes when taking into account the optomechanical mounting and system operation costs (recalibration frequency, weight impact).
The disadvantages of the R-C, compared to an off-axis design, are an obscured aperture, baffle complexity, and increased primary size for the same pupil area. In the R-C, additional optics must be incorporated after the secondary, to meet telecentricity and field flattening (Figure 8). Obscured apertures are also not permissible for infrared systems with narcissus constraints (warm optics emissions), since the detector will see the emitted flux reflected back from the secondary. Even for the SWIR, a narcissus analysis is recommended for wavelengths greater than 2.35-microns. Three-mirror anastigmat telescopes (Cooke triplet) designs are ideal for HSI systems since they can meet image quality, field curvature, and telecentricity, and provide sufficient places for stray light baffles without additional optics. As a conceptual design example, an all-reflective three-mirror anastigmat (TMA) telescope is illustrated in Figure 9, with a 360-mm focal length and f/3 aperture. The off-axis hyperbolas and two higher-order prolate ellipses correct the 3rd- and 5th-order aberrations, with an rms spot-size of <5 microns across a 3-degree field of view. A manufacturability and material analysis of this telescope to achieve this performance is in progress.
widen the slit without changing the IFOV. For a slit width of twice the pixel size, the along-track focal length would be half the cross-track focal length, thus an anamorphicity requirement of 2X. Other ratios are possible based on the packaging and optical performance and fabrication capabilities. The key considerations for a modified Schwarzschild objective explained in the references are manufacturing of the off-axis elements and toroidal sections. Single point diamond turning (SPDT) technologies are suitable to this type of problem. Off-axis toroids could be fabricated on a slow-servo tool with the work-piece axis parallel to the spindle, and the diamond tool moving in-and-out parallel to the spindle axis. On-axis toroids most likely would be turned on a fixed-tool B-axis SPDT machine, with the diamond tool moving around the work-piece vertex perpendicular to the spindle axis. With progress in optics metallurgy, fewer fabrication steps will be needed as the surface finishes straight from the SPDT machine start to regularly reach < 5-20 angstrom. New SPDT machining capabilities, Computer Numerically Controlled polishing, and snap-together alignment are making the all-reflective TMA and Schwarzschild Objective more economical options for HSI fore-optics.

| Refractive | Double gauss with field group | Modified COTS | More elements |
| Huygens Eyepiece | Compact, Low-cost | Non-symmetric |
| Telephoto | Wide-field | Non-symmetric |
| Reflective | Ritchie-Chrétien | Compact | Obscured, additional optics |
| Three Mirror Anastigmat | High image quality, coaxial alignment | Narrow field, large volume |
| Schwarzschild Objective | Wide-field | Field flattener needed, steep aspheres |

Figure 11. HSI Design Form Summary Table

3. CONCLUSIONS

Fore-optics for hyperspectral systems require special considerations not typically addressed in COTS or standard designs. The addition of telecentricity adds additional elements and forces using larger size optics, thus reducing transmission and increasing complexity. Axial and lateral color requirements limit the glass selection to lower dispersion/lower index glasses, thus increasing the field curvature and decreasing calibration stability with sensor temperature. The astigmatism and field curvature for large field systems also force tight temperature stability requirement to maintain a stable radiometric calibration. These combined issues make all-reflective systems more attractive for narrow field applications, and are becoming more practical for wide field applications, as single-point diamond turning and computer polishing manufacturing technologies continue to reduce the cost of off-axis aspheric and toroidal mirrors.
REFERENCES