The AEOS Spectral Imaging System

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In the past decade there has been an explosion in the exploitation of spectral, polarimetric, and wavefront diversity techniques applied to a number of scientific imaging and non-imaging problems. Utility of these methods is demonstrated in prior research and in many cases has resulted in the development of deployable systems. By combining the instruments with high performance algorithmic processing, end-users are provided with automated information extraction and enhanced capabilities for the tasks of discrimination, classification and identification. These techniques are successfully exploited today in the studies of earth resources, biological interactions, astronomy, manufacturing process control and military intelligence gathering among others. In this paper, I describe a system that has been developed at the Advance Electro-Optical System (AEOS) which achieves high spatial resolution, high spectral resolution, and high sensitivity simultaneously, permitting broad control of spatial, spectral and sensitivity parameters for optimization of timeline and feature extraction. Interest in enhancing spectral resolution to extract hidden spectral features is one area of current research that can benefit from this system [1].

The AEOS Spectral Imaging System (ASIS) is a multi-spectral compensated imaging capability integrated with the 3.6m AEOS telescope located at the Maui Space Surveillance Complex (MSSC). The optical implementation, sensors and processor architecture developed over the course of the past two years are described in this paper. The versatile implementation permits high sensitivity narrow-band, diffraction limited, compensated Adaptive-Optics (AO) imaging. ASIS was designed to achieve highly synchronized multi-channel image data acquisition in the visible (VIS), near infrared (NIR) and short wave infrared (SWIR). Field de-rotation and Atmospheric Dispersion Compensation (ADC) permit high performance imaging and multi-frame processing from zenith down to near horizon. Additionally, the ASIS optical layout incorporates access ports for accommodation of auxiliary instruments and can support AO compensated data collections for other modalities. ASIS is currently being utilized to validate Model Based Spectral Image Reconstruction (MBSIR) techniques [2,3]. ASIS also provides a convenient optical interface with AEOS to host an imaging Stokes polarimeter being utilized in a complementary area of research.

Keywords: Spectral imaging, Multi-spectral, Hyper-spectral, Visible, NIR, SWIR, AEOS, ASIS, MBSID

1.0 Background and History

In early 2004, a kick-off meeting was held to develop the initial optical concepts for a system that could be integrated with the AEOS to provide narrow band high spatial resolution adaptive optics (AO) compensated imagery. The desired system would be required to synchronize and record two narrow spectral bands of compensated imagery on two sensors simultaneously. Agile band pass selection, image integration, and data acquisition at frame rates up to 5Hz would need to be accommodated by the processing system and hardware elements.

Additional driving requirements that were considered in developing the design are listed below:

1. 300 μrad Full Field of View
2. 400 nm to 3000 nm Spectral Range
3. Capability for Rapid FOV Change
4. 0.1 μrad IFOV for Narrow FOV
5. Diffraction Limited
6. Telecentric
7. Atmospheric Dispersion Compensation (ADC)
8. Field De-Rotation
9. Radiometric Threshold Sensitivity ($M_v = 6.0$)

Initial concepts and cost estimates indicated that all requirements and features could not be accommodated at the initial project funding level. The ADC, Field De-Rotator and Multiple Fields of View were eliminated from the initial baseline, however, the design solutions were constrained during optimization to afford straight forward functional capability enhancement through a proposed spiral demonstration and development path. A small funding increment was added to enable the purchase of cameras with sufficient sensitivity to meet the specified radiometric requirement.

The initial implementation of ASIS was completed in August of 2004 with successful data collections occurring shortly afterwards. ASIS has now undergone two incremental levels of functional enhancement and capability demonstration through additional funding and customer support. In late 2004 through January of 2005, a temporary configuration permitted demonstration that signal losses due to the linear polarization selectivity of the filters implemented in the design could be recovered by the addition of a polarizing beam splitting (PBS) cube in the optical path. In this new configuration, orthogonally polarized image components would be imaged simultaneously on two synchronized sensors with orthogonally polarized filters. Following the successful demonstration of this polarization splitting concept, funding was secured to further develop an optimized optical design to implement PBS configuration and procure the required components. Funding and approval to proceed with the ADC and de-rotator design were also secured at this time.

The complete bench was re-configured to accommodate the de-rotator, ADC and PBS elements during the spring of 2005. The new layout also moved the sensors to the aft end of the bench so the heat dissipation would not interfere with the incoming AEOS compensated light. During the lengthy procurement process for the PBS cube, ADC glass and de-rotator components, software was developed and re-configured to support the new functionality. The PBS cube was received in August, and shortly after integration of the new components, ASIS collected the first spectrally sequenced images of the Hubble Space Telescope simultaneously on the two orthogonally polarized visible sensor channels.

2.0 Optical Path Description

The ASIS optical path is comprised of functional elements that yield the required functionality for field de-rotation, atmospheric dispersion compensation, spectral band separation, spectral filtering and image scaling. The complete optical path for the baseline system is described in the following paragraphs.

The AEOS telescope directs light to an experiment room via a rotating flat mirror (M7). The light directed to the experiment room is intercepted by two input turning flats on the ASIS optical bench. These two flats are referred to as Input Turning Flat 1 and 2, or, ITF-1 and ITF-2. The purpose of ITF-1 and ITF-2 is to provide tilt and translation degrees of freedom to permit accurate registration of the 4 inch diameter AEOS exit pupil to the ASIS Input Telescope. A 16-Inch diameter commercially available Ritchey-Chrétien Input Telescope is utilized in a sub-aperture off-axis configuration in conjunction with a third concave mirror to yield a 5X all-reflective pupil reduction telescope with an exit pupil of approximately 20 mm diameter. This front-end solution provides a very cost effective approach for the required diffraction limited performance from 400 nm to 3000 nm with a 1.0 arc-min full Field of View (FOV).

The compact collimated ray bundle is then folded and de-rotated by a K-mirror de-rotation assembly. After de-rotation, the beam path is separated into two channels by a dichroic beam splitter that reflects 400 nm to 950 nm light and transmits light 950 nm and above. The transmitted light, commonly referred to as the “SWIR Channel”, is not utilized in the current sensor architecture but is available for planned future growth. The reflected visible to near-IR light (400-950 nm) is passed through a pair of counter rotating dispersion prisms that provide compensation for the differential bending of light at different wavelengths that results from the atmosphere. Left uncorrected, the atmospheric dispersion results in substantial field position shift with wavelength and for wide band imagery, blurring of the image and consequently loss of resolution in the elevation axis.

At this point, all the visible through near-IR light entering the AEOS telescope has been AO compensated, de-rotated into the required reference coordinate system and corrected for atmospheric dispersion. The remaining optics permit the integration of an LCTF which is an optically thick device that requires careful consideration for integration into a high performance imaging system. The LCTF mechanism was initially chosen for experimental versatility, ease of implementation, response time and cost effectiveness for the planned experiments. A custom lens design was developed that permitted placement of the LCTF in the converging ray-bundle prior to the formation of an intermediate telecentric image plane while preserving the unvignetted 1.0 arc-min full FOV. This approach was chosen to permit future FOV selection via telecentric relay(s) with the required magnification(s). The resulting optimized intermediate imaging lens and relay combination are highly corrected and coated for exceptional performance from 400 nm to 1100 nm. The relay utilized in the baseline optical configuration yields the narrow field requirement of approximately 50 micro-radians mapped to the sensor detector.

To achieve the required performance and compatibility with the available pass bands of commercially available LCTF's, the 400 nm to 950 nm optical path is split into two channels by a second dichroic beam splitter. The wide spectral coverage yielded by the intermediate imaging lens and relay design permit commonality for the resulting visible (VIS) and near-infrared (NIR) sensor channels. The resulting VIS channel provides spectrally agile imaging from 400 nm to 700 nm while the NIR channel provides spectrally agile imaging from 700 nm to 950 nm. Since the initial build up of the ASIS optical path, the VIS path has been split into two channels and a similar split of the NIR channel is planned to be implemented in late 2006. As discussed in the introductory section of this paper, a PBS cube facilitates the split of the VIS and NIR un-polarized light into orthogonal polarization components that can be aligned with the polarization of each LCTF. The PBS cube is installed in the former location of the LCTF prior to formation of the intermediate image plane. In order to preserve the performance of the original optical design, the PBS cube was specified to precisely match the optical thickness and dispersion characteristics of the LCTF for which the intermediate imaging lens had been originally optimized. The 4-channel baseline configuration of ASIS is illustrated by the optical layout shown in Fig. 1.

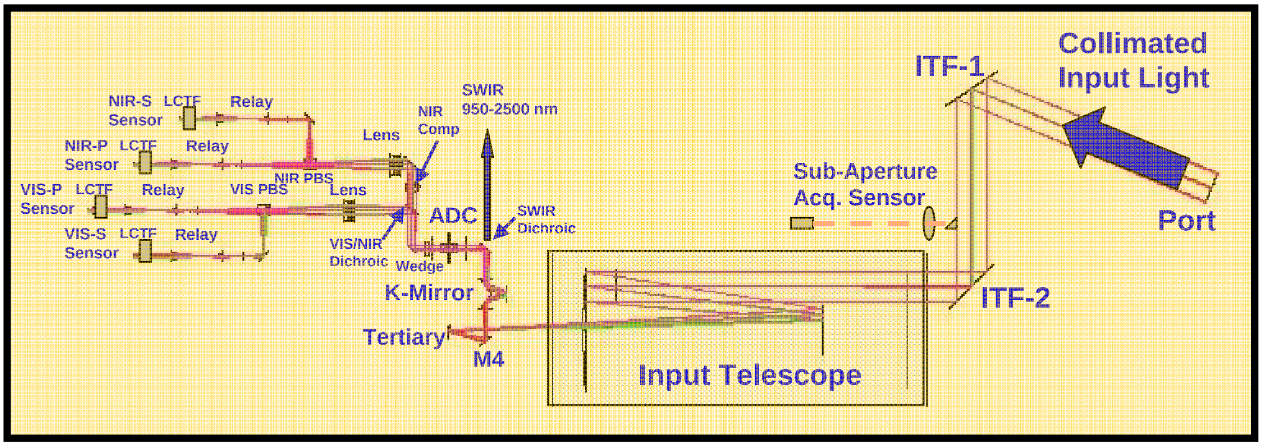

Figure 1 ASIS Baseline 4-Chnnel Optical Layout

While the optical layout of ASIS is relatively straight forward, the success in performing algorithmic processing and advanced reconstruction techniques relies on accurate modeling, measurements, and calibration of the spectral-polarimetric transmission function of the system elements to adequately define the overall transfer functions. Calibration of the spectral response and noise characteristics of the sensors is an essential requirement to achieving the required end-to-end spectral and polarimetric calibration of the system.

3.0 Sensors

From the initial requirements definition for ASIS, it became clear very early on that high sensitivity sensors would be required to achieve temporal sampling requirements with sufficient Signal-to-Noise Ratio (SNR) given the large transmission losses due to optical path, LCTF filter absorption characteristics, and the inherent LCTF linear polarization selectivity. For the most severe object radiometry cases, it was found that an imaging sensor with near single photon noise characteristics was required. After a comparison of several available sensor technologies and evaluation of performance with the candidates, the Andor iXon 887 camera with back-side illuminated Focal Plane Array (FPA) was selected as the sensor.

A distinguishing feature of the iXon camera is the utilization of an Electron Multiplying Charge Coupled Device (EMCCD). An EMCCD is an evolutionary variant of the common CCD where signal charge can be routed through a “gain register” before being sensed by the on-chip amplifier stage to yield the conversion of signal charge to voltage. The gain register is a series of discrete cells similar to a standard readout register but in which the transferred charge is immersed in a relatively strong electric field. The acceleration of the electrons within this field during charge transport results in a small probability of electron collisions with the crystalline lattice to yield “impact ionization”. Impact ionization results in the creation of additional electron-hole pairs. If the resulting additional charge is transferred to the next cell prior to recombination, then a gain results. The actual probability of ionization and recombination are very small. However, a large number of transfers results in a multiplicative effect, and when ionization rates and recombination rates are properly controlled by design, a substantial gain can be realized with very low excess noise. The “multiplied” charge at the output of the gain register is converted to a voltage by an output amplifier similar to a standard CCD output. If the signal charge has been multiplied such that the charge due to a single detected photon is equal to the charge equivalent readout amplifier noise, the EMCCD gain has essentially overcome the electrical noise of the output amplifier to yield near single photon sensitivity.

Other desirable features of the iXon cameras include an integral cooling manifold for chilled water, a shutter, selectable on-chip pixel binning, selectable readout rates, selectable vertical transfer timing and driver compatibility with Linux. Additional characteristics for the Andor iXon 887 camera can be found in Appendix A.

The EM gain process is substantially temperature dependent and requires much colder temperatures than traditional CCD cameras to achieve beneficial gain. Andor has packaged the EMCCD FPA in a vacuum dewar with a heat pipe to a multi-stage Thermo-Electric Cooler (TEC) which is capable of achieving stable FPA temperatures of -75C with fan cooling and -100 C with chilled water.

Finally, the Andor iXon 887 camera permits selection of a conventional CCD readout mode or the EM gain register readout. This feature permits correlation of EM gain characteristics with the linear behavior of an on-chip conventional read-out. The performance characteristics achieved with the iXon cameras is the subject of planned future publications.

4.0 Processing and Control Architecture

ASIS is currently a self-contained processing system with no connections to the AEOS facility other than power. The absence of mount and time information from the facility required a local time base and simulation capability to realize the required system functionality. An accurate estimate of mount position is an essential requirement to achieving the required image de-rotation modes of operation and atmospheric dispersion compensation. An IRIG-B time generator that is manually synchronized prior to a data collection mission is utilized for system time. For stellar objects, azimuth and elevation of an object are computed based on system time. Azimuth and elevation of satellites are pre-computed and tabulated in text based Mission Input Files which are loaded onto the system prior to a data collection mission.

Processing and control for ASIS was architected using three PC's configured with the Linux operating system. Two of these processing elements operate as channel servers and provide the necessary coordinated control of filters and sensors to perform synchronized data acquisition. Each of these channel servers contains an IRIG-B time reference and can support up to two sensors and two filters, providing full rate data acquisition for a total of four channels. The third processing element in configured as a workstation and provides the display interface and user input function to the system operator. Communication of the work station processor with the channel server processors is implemented via Gigabit Ethernet through a Gigabit switch.

ASIS also utilizes an embedded motion controller that is programmed with mission specific motion control data. Motion control profiles are synchronized with IRIG-B time reference to facilitate image de-rotation and atmospheric dispersion compensation.

While an attempt was made to maximize the use of commercial off-the-self (COTS) hardware, an in-house solution was required to coordinate the accurate synchronization of multiple sensors. The Sensor Synchronization Unit (SSU) was constructed to provide the required signal conditioning and logic to coordinate the Arm, Trigger and Fire signals from each sensor via interrupt control on the channel servers. The SSU provided the hardware "glue" providing feedback to the software state and transition control elements required to achieve precise integration time synchronization and ability to operate multiple channels with independent integration times. The ASIS system block diagram for two sensor channels is illustrated in Fig. 2.

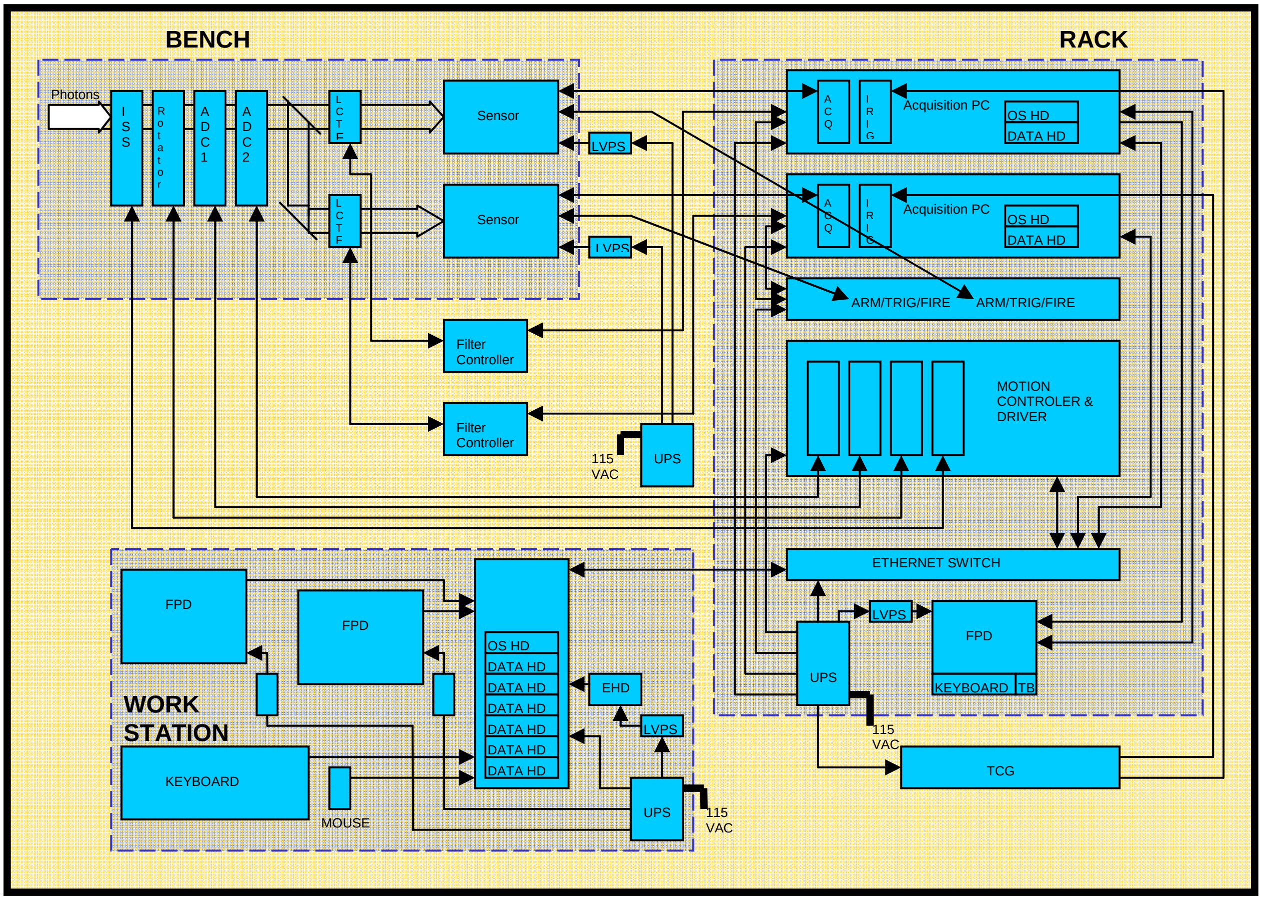

Figure 2 ASIS System Block Diagram

5.0 AEOS Installation

The optics and sensors of the ASIS system are installed on a 5x12 foot optical bench located in Optics Room 5 of the AEOS facility. All electrical signal interconnections to the bench electronics are contained in a single cable harness that runs to a 24U rack enclosure located against the back wall of the lab. A work station is located next to the rack that provides all the necessary user interfaces for control of the system and display of images and parametric data. The work station can be located remotely in the outer room of other locations via extension of the Gigabit Ethernet link between the work station and rack. Figs. 3-5 show hardware elements on the aft end of the bench, rack assembly, and user interface displays, respectively.

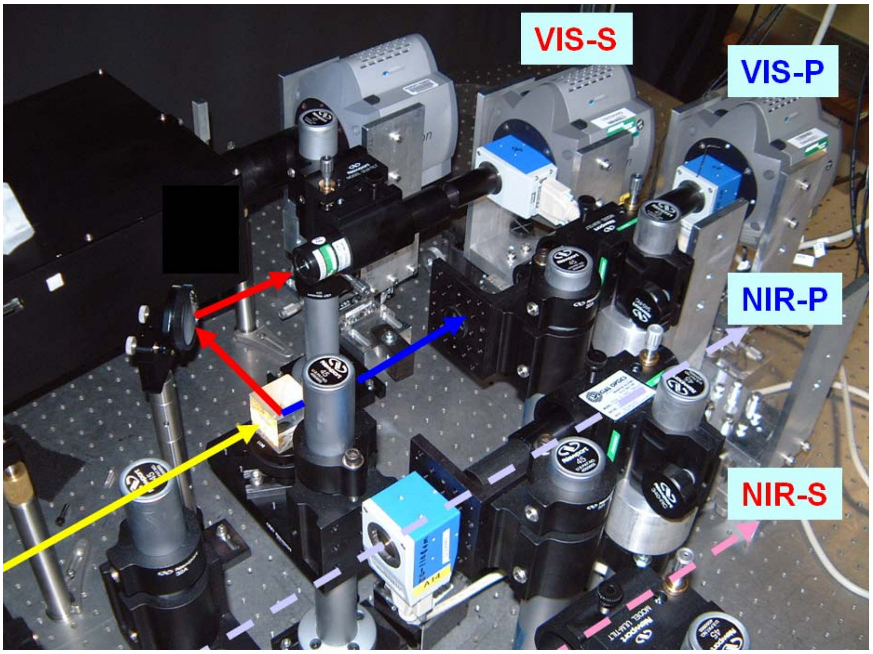

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Figure 3 ASIS Hardware on Bench

Figure 4 ASIS Rack

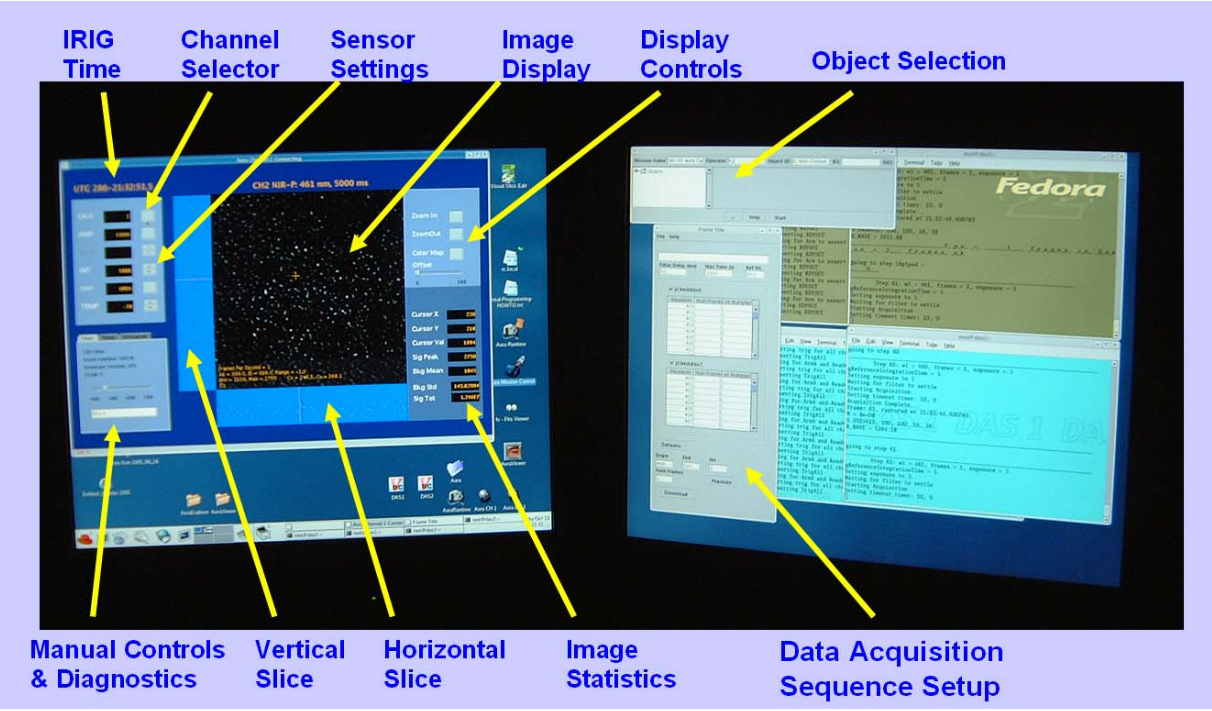


Figure 5 ASIS User Interface Displays

6.0 Characterization and Calibration

Calibration of system optical and electro-optical performance characteristics is critical for any type of quantitative data analysis. Calibration and characterization of the ASIS system is an ongoing effort. Most critical is the spectral-radiometric response characterization of each channel. The effort required to determine the spectral response is divided into a number of sub-tasks to characterize major sub-system components. These components are summarized as follows:

1. AEOS System Spectral Transmission
2. ASIS Bench Optics Spectral Transmission
3. Filter Spectral Transmission
4. Filter Effective Bandwidth at Center Wavelength
5. Detector Spectral Quantum Efficiency
6. AEOS Polarization Transmission
7. ASIS Bench Optics Polarization Transmission

The program goal is to provide 1 nm resolution characteristic curves for each of the listed system components. The LCTF's utilized in ASIS were rigorously characterized for transmission and band pass characteristics with 0.1 nm sampling. Initial AEOS spectral transmission curves for the visible pass band were generated by performing 1.0 nm sampling spectral scans facilitated by the ASIS LCTF's in conjunction with an integrating sphere source. Spectral transmission curves for the ASIS bench are currently derived from measured coating, dichroic beam splitter, and PBS cube data, provide by the vendors. A vendor supplied Quantum Efficiency (QE) curve is also currently being utilized to evaluate end-to-end system performance. At the writing of this paper, efforts were underway to begin sensor level characterization with QE, Noise and Conversion Gain data products to be forthcoming. The calibrated sensors will permit the further anchoring of the ASIS bench transmission curves as well as the overall system spectral response.

In addition to component and sub-system characterization and calibration efforts, an end-to-end calibration effort that utilizes stars with known spectral radiometric curves is underway. Other calibration efforts include indexing the de-rotator coordinates to the sky coordinates, indexing the two ADC prism pairs to the local projection of the elevation axis, sensor FPA rotational mapping residuals, sensor FPA plate scale, sensor gain versus settings and sensor noise versus settings.

7.0 Conclusions

ASIS realizes unique capabilities for temporally correlated narrowband multi-spectral AO compensated diffraction limited imagery acquisition on multiple sensor channels. The flexible processing and control architecture enables the system to be optimized for data collection with respect to of a variety of signature metrics. ASIS was utilized successfully to demonstrate the feasibility of spectral feature enhancement through application of Model Based Spectral Image Reconstruction (MBSIR). There is clearly significant potential to spectrally discriminate and classify resolved extended object features accessible only through AO compensated imagery. For applications in which spatial resolution is not critical, sensors can be operated in a pixel binning mode to substantially increase sensitivity and temporal sampling. ASIS can be configured with filter wheels in lieu of LCTF's permitting temporally correlated wide band imaging for greater radiometric sensitivity or anchoring to established photometric correlation techniques. ASIS currently provides an insertion port for an imaging Stokes polarimeter integrated on the bench and has a convenient insertion point for a pupil-plane image sensor. The SWIR port provides a compensated 20 mm pupil that yields photons from 950 nm to beyond 2500 nm. The flexibility and the diversity of techniques that can be exploited with ASIS will undoubtedly bring forth a myriad of valuable results in the coming years.

8.0 Acknowledgments

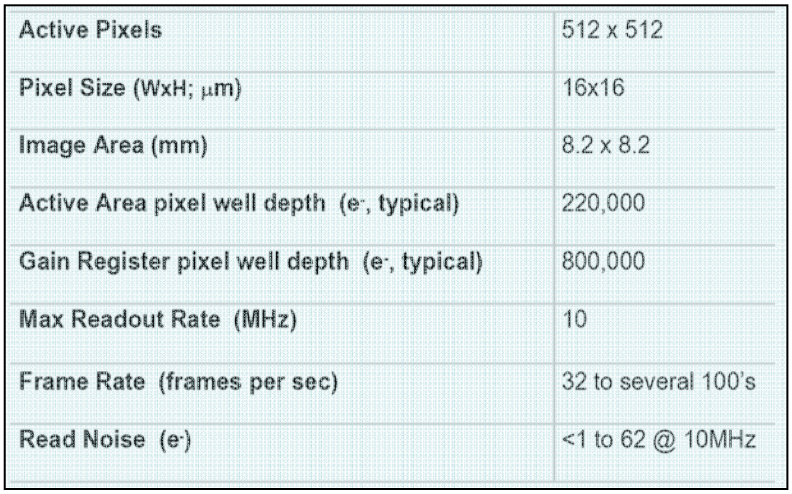
The author would like to thank the Air Force Research Laboratory (AFRL) Detachment 15 in supporting this project and several key individuals whom have contributed to the successful development of the ASIS system. First and foremost is Laura Ulibarri, AFRL/DESA, whom has provided much encouragement and assistance in facilitating my success in leading this project. Brian Thill, AFRL/DESM, who provided me with much insight into the operations at the Maui site and assisted me with programmatic details in the initial phase of the project. Travis Blake, AFIT/ENG was extremely valuable in obtaining a high fidelity LCTF characterization, generation of presentation material to support key project decision points, and reduction of data to estimate spectral transmission of the system. Dave Briscoe of Northrop Grumman Information Technology provided useful recommendations and insight in the early phases of the project and much needed assistance in the radiometric calibration of the sensors. Bruce Stribling of Boeing-LTS generated initial inertia and customer interest to support this project. And finally, a spectral imaging system without software is just a collection of expensive parts. Much thanks to the persistent efforts of Gary Eckert of Boeing-LTS who developed all aspects of the software to realize the current capabilities of ASIS.

9.0 References

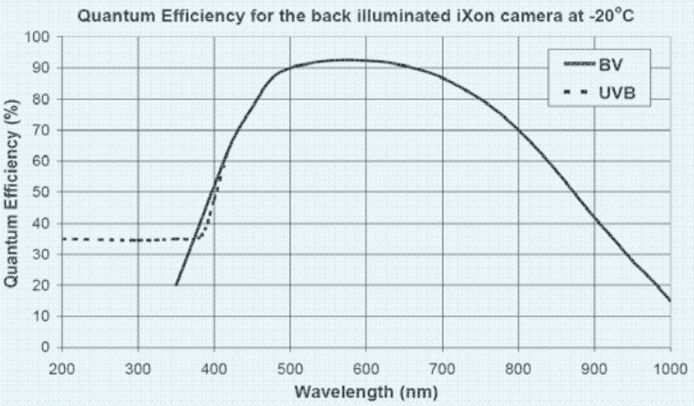
1. Travis F. Blake, Matthew E. Goda, Stephen C. Cain, and Kenneth J. Jerkatis, "Enhancing the Resolution of Spectral Images", *Proc. SPIE Int. Soc. Opt. Eng,* **6233**, 2006
2. Travis F. Blake, Matthew E. Goda, Stephen C. Cain, and Kenneth J. Jerkatis, "Model of the AEOS Spectral Imaging Sensor (ASIS) for Spectral Imaging Deconvolution", *2005 AMOS Technology Conference*
3. Travis F. Blake, Matthew E. Goda, Stephen C. Cain, and Kenneth J. Jerkatis, "Spectral Image Deconvolution Using Sensor Models", *Proc. SPIE Int. Soc. Opt. Eng,* **5896**, 2005

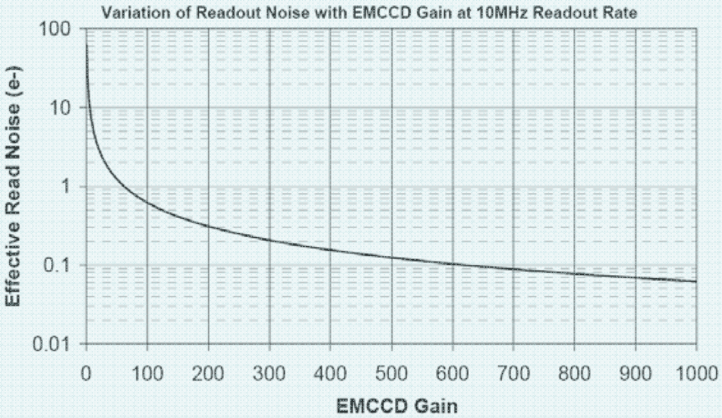
APPENDIX A

Characteristics of the Andor iXon 887 Camera †



Active Pixels	512 x 512
Pixel Size (WxH; μm)	16x16
Image Area (mm)	8.2 x 8.2
Active Area pixel well depth (e-, typical)	220,000
Gain Register pixel well depth (e-, typical)	800,000
Max Readout Rate (MHz)	10
Frame Rate (frames per sec)	32 to several 100's
Read Noise (e-)	<1 to 62 @ 10MHz





† Data taken from Andor Technology iXon 887 BI Data Sheet, issue p, rev 2, November 2003