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Mid-wave/Long-wave Infrared Dual-Octave Hyperspectral Imaging Spectrometer

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Abstract— SSGPO has developed a novel dual octave hyperspectral imaging spectrometer. To address the critical parameters of weight, volume and power consumption the system concept combines ultralightweight SiC optics and structures for front-end telescope and spectrometer, emerging dual-band FPA technology and micro dewar / electronics to form the sensor engine and a novel spectrometer design form which utilizes the first and second diffractive orders from a flat blazed grating.

An all aluminum ground demonstration spectrometer was designed, fabricated and tested. This cost effective hardware solution consisted of a 4-mirror spectrometer design form with a replicated flat blazed grating, f/2.35 at the slit and f/4 at the image plane. The optical design provided hyperspectral imagery in two spectral bands simultaneously, 3.5 to 6 microns (mid-wave infrared) and 7 to 12 microns (long-wave infrared) for a focal plane array format of 320 spectral bands and 240 spatial bands. The delivered hardware provided λ/10 RMS wavefront error at 3 microns.

The dual octave spectrometer provides a significant improvement in the weight, volume, and power requirements for hyperspectral imaging spectrometers. This development will enable next generation surveillance and reconnaissance optical instruments for space and air based platforms.

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1. INTRODUCTION

In this paper, a new spectrometer design will be presented-the dual octave hyperspectral imaging spectrometer (DOHIS). The introductory section will provide an overview of the DOHIS concept and it's attributes. Background information will be provided on hyperspectral instruments and dual-band focal plane array (FPA) technology. Following this background material, a brief review of diffraction theory will lead to a description of how the first and second diffractive orders are used to provide the dual octave spectrometer operation. A detailed discussion of the design and fabrication of a ground-based DOHIS demonstration instrument will then be presented followed by the measured performance of the fabricated spectrometer.

Dual-octave Hyperspectral Instrument System Concept— The DOHIS instrument is designed to provide significant improvements in mass, volume and power consumption. The space-based hyperspectral instrument concept consists of a lightweight SiC three mirror anastigmat (TMA) front end and structure with a four mirror spectrometer designed for dual octave operation. SiC materials provide high specific stiffness and high thermal stability which results in significant reduction in mass while maintaining image quality in stressing environmental conditions. The single spectrometer provides 320 spectral bands in the mid-wave infrared (MWIR) from 3.5 microns to 6 microns and 320 spectral bands in the long-wave infrared (LWIR) from 7 microns to 12 microns simultaneously. Dual band focal plane array technology allows the first and second diffractive orders to be utilized in the spectrometer optical design. This optical spectrometer design results in a number of critical system advantages:

- Spectrometer mass, volume and power for cooling reduced by up to 50% when compared to the traditional two channel approach.
- Elimination of beam splitting optics.

- Replacement of multiple FPAs with single Dual-band FPA.
- SiC front end provides significant improvements in lightweighting and thermal stability.
- SiC provides cost and schedule advantages over Be and glass based optics.

Using input from the Air Force Research Laboratories (AFRL-VSSS), a ground-based spectrometer was designed, fabricated, tested and delivered which demonstrates the dual-octave spectrometer concept. The design utilized a Janos Technologies catadioptric front end and an IR Labs dewar. A four mirror, flat grating, all aluminum spectrometer was designed with f/2.35 at the slit and f/4 at the image plane. The demonstrated WFE was 0.6 waves P-V at 3 microns (0.12 waves RMS at 3 micron) which was near the optical design residuals. The spectrometer measured 7.1" x 4.85" 5.05" and was delivered to AFRL-VSSS mounted in the IR Labs dewar.

A number of technology developments have been integrated resulting in improved performance, lengthened lifetimes and reduced cost associated with the next generation of infrared surveillance satellites. AFRL is pursuing several technology developments in order to research theses objectives. SSGPO has utilized these technology developments in this program.

- <u>Dualband Focal Plane Array Technologies:</u> Dual waveband FPA technologies reduce packaging requirements, eliminate image quality issues associated with beamsplitters or channel-to-channel misalignment, and eliminate data processing requirements associated with scene re-griding or spatial interpolation.
- <u>Compact Electronics:</u> Innovative electronics packaging concepts are required to reduce the power, volume and mass requirements associated with the present state of the technology.
- <u>Microdewar Coolers:</u> High efficiency microdewar technology reduces power, mass and volume resulting in a highly compact instrument.
- <u>Improved Structural/Optical Materials:</u> Exotic optical and structural materials are being applied in order to reduce the payload mass, and in this way reduce the launch costs associated with these sensors.
- <u>Multi-Functional Instrument Concepts:</u> Innovative optical and mechanical designs are required in order to allow multiple data sets to be obtained from a single instrument payload.

The traditional approach for achieving hyperspectral imagery in several wavelength regions simultaneously involves multiple FPAs, and equal number of dispersive elements (e.g., gratings or prisms), and dichroic beamsplitters. This approach has obvious size, weight, and power penalties. The DOHIS concept for space-based applications integrates the emerging dual band FPA, compact electronics and microdewar coolers technologies with lightweight SiC optics and a single channel spectrometer design to provide improved performance and reduced cost, complexity, power consumption, and mass.

Hyperspectral Grating Imaging Spectrometers—SSGPO has developed multiple hyperspectral imaging spectrometers for space-based and airborne flight systems. Primarily SSGPO has been working with a novel hyperspectral imaging instrument design based on a Grating Imaging Spectrometer (GIS) concept. The GIS concept is based on a modified Offner 1:1 reimager, a layout of the concept is shown in Figure 1. A conventional Offner system is a 1:1 reimager based on a pair of concentric spherical reflectors. The all reflective nature of the design results in a very high throughput, and the symmetry of the design yields very good distortion and image quality performance. In the GIS configuration the convex spherical secondary of the Offner is replaced with a convex blazed grating. The grating disperses the energy which is reflected from the secondary resulting in a final image which contains both spectral and spatial information.

The Offner design form, however, has two drawbacks when we consider the requirements for the present dual-octave spectrometer operating in the MWIR/LWIR. First, the Offner is a 1:1 imaging design; there is no image magnification from the spectrometer slit to the image plane. This limits the design of the front-end telescope, implies a re-imaging system to provide the correct f/number for the Offner spectrometer, or possibly places requirements on the spectrometer design which may be prohibitive. In each of these cases, the complexity and therefore mass of the system is increased.

The second drawback pertains to the spectral bands of operation. The Offner design requires the fabrication of a grating on a curved substrate. As the wavelength of operation approaches the LWIR it becomes increasingly difficult and costly to fabricate the grating with the required groove depth and quality. A design utilizing a more conventional flat grating can provide cost advantages and possibly improved performance.

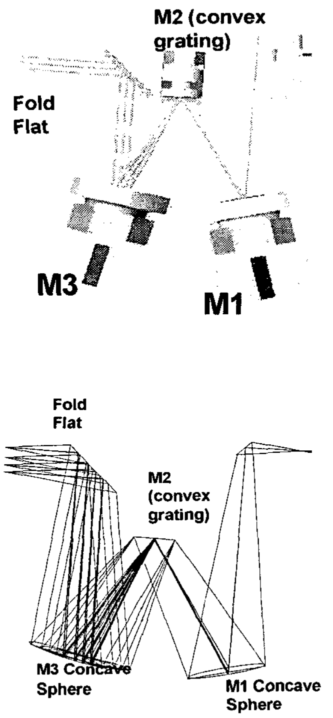

Figure 1 - Grating Imaging Spectrometer Concept

The remainder of this section provides a review of three of SSGPO's flight hyperspectral imagiing spectrometers and highlights some of the areas where a four mirror design form used for the DOHIS system could provide advantages over the Offner design. The four-mirror design will be presented in Section 2

HYPERION—Hyperion is an imaging spectrometer designed and produced by SSG for NASA's New Millennium program. A photo of the Hyperion instrument is presented in Figure 2, the optomechanical layout is presented in Figure 3, and the optical design, uses two different GIS modules to provide VNIR and SWIR hyperspectral data. The collecting telescope is an all reflective triplet which is mated to a finite conjugate relay system. This front end required a modified 1.3x Offner relay to be implemented in the GIS module. The system provides excellent wavefront and distortion performance.

It should be noted that the Hyperion instrument and the EO-1 payload launched successfully from Vandenberg AFB on Tuesday, November 21, 2000. The Hyperion instrument is functioning perfectly, and early reports indicate that the hyperspectral data obtained from the instrument represent the highest quality hyperspectral information ever obtained from space. More up to date information can be obtained by visiting NASA's web site: http://eo1.gsfc.nasa.gov/News/NewsEvents.html.

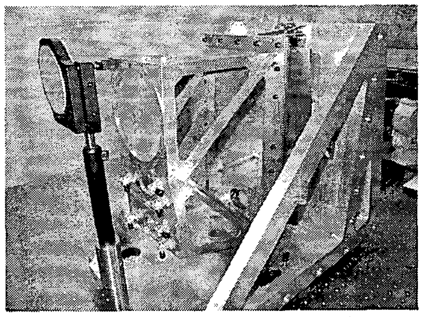

Figure 2 - Hyperion Hyperspectral Imager

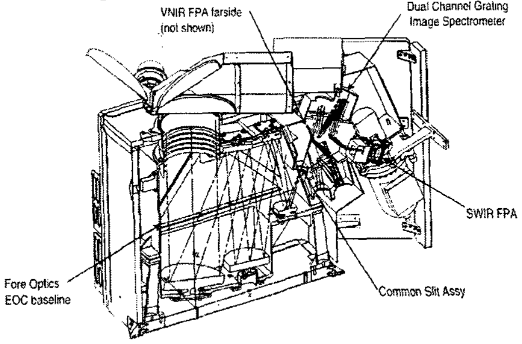

Figure 3 - Hyperion Opto-Mechanical System Layout

WARFIGHTER—In this application an imaging spectrometer capability needed to be added to an existing design developed to provide high-resolution, pan-chromatic, visible wavelength imaging. The foreoptics design was a three mirror anastigmat (TMA). The TMA forms a real exit pupil forward of the final image (non-telecentric). In addition, the TMA F-number did not match the F-number for the spectrometer system. Yet it was desired to use the Offner relay for the spectrometer.

A design solution was developed by implementing an intermediate relay to mate between the TMA and the Offner relay. The intermediate image was able to form a telecentric exit pupil to feed into the Offner relay, and the magnification of the intermediate relay was chosen such that the Offner could be designed at its conventional 1:1 magnification. A photo of the Warfighter instrument, integrated to the TMA fore-optics, is presented in Figure 4 and in Figure 5 the GIS optical layout is presented along with the intermediate relay optics.

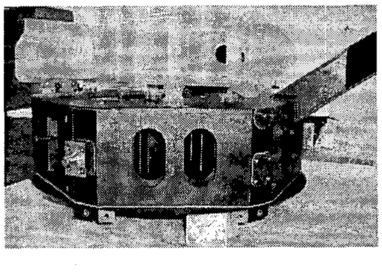

Figure 4 - Warfighter Instrument

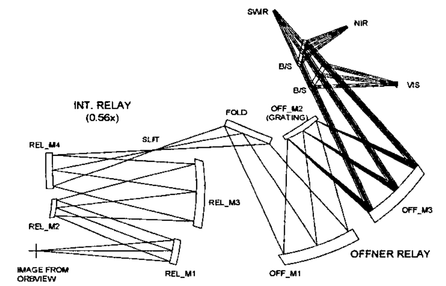

Figure 5 - Warfighter Spectrometer Optical Design

HYLITE—The HYLITE program was recently completed and the instrument delivered. A rendered layout of the instrument is shown in Figure 6, in Figure 7, a close up of the spectrometer optics is presented. The front end is a classic TMA comprised of three off-axis conic section reflectors. The front end images down to a slit and the slit is reimaged with a 1:1 Offner-type GIS. This is a fairly fast spectrometer (F/2.0) which has been optimized to operate from 7.95 – 11.05 microns.

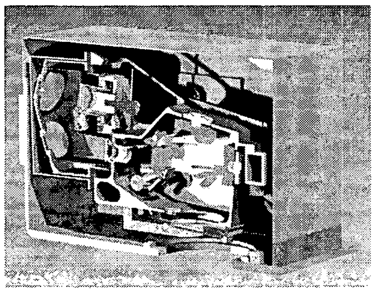

Figure 6 - HYLITE IR Hyperspectral Instrument

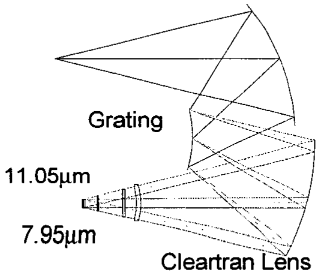

Figure 7 - Close up of HYLITE Spectrometer

Dual-Waveband Focal Plane Array Technology—DRS Infrared Technologies, Inc. has been developing a stacked multicolor focal plane array for the Air Force's High Operating Temperature Staring Array (HOTSTAR) program. The hyperspectral instrument concept presented here provides an ideal design configuration to be used with this innovative DRS focal plane array.

DRS Single Band FPAs—Several scanning and staring FPAs are currently in production at DRS. The single band staring array family, as shown in Figure 8, is based on the high density via interconnected photodiode (HDVIP™) structure.

The HDVIP^{TM} technology has also been utilized to fabricate two color IRFPAs by simply stacking two individual monocolor HDVIP™ FPAs on top of each other, as shown in Figure 9. The key feature of this structure is that it is a straightforward extension of the DRS mono-color technology.

The dual stack FPA uses standard LPE production material with CdTe interdiffused passivation, the same diode formation process. Differences are the lamination of the second HgCdTe layer and the insulated via to provide pass through contact from the top layer to the silicon ROIC. The HDVIP™ multicolor structure possesses a number of important advantages over other approaches. One of the most important advantages of the DRS approach is that it permits independent readout of each color separately and simultaneously. This greatly simplifies ROIC design and avoids the use of noisy signal subtraction circuitry. Due to the criticality of the ROIC in determining the ability to shrink the cell size down to 20 µm, the simpler design made possible by the DRS HDVIP™ architecture is of key importance. Another key advantage of the DRS approach is the inherent reliability of the laminated structure to thermal cycling. Lastly, the use of production LPE HgCdTe in the DRS approach completely eliminates risk associated with material growth.

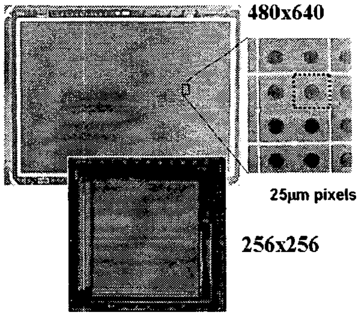

Figure 8 - 25 µm pitch 480x640 and 40 µm pitch 256x256 FPAs. Insert shows HDVIP^{tm} pixels with via interconnect and distributed substrate contact grid

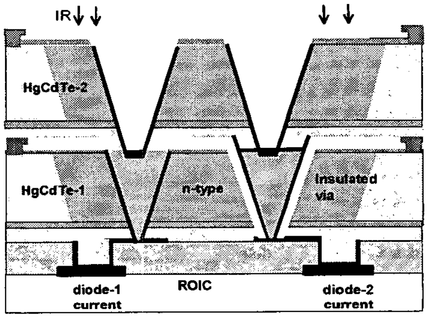

Figure 9 - Stacked Two Color HDVIP^{TM} Unit Cell

Dual-Octave Concept Implementation—The core of the dual-octave spectrometer concept is based on diffraction characteristics of blazed surface gratings. A typical blazed grating structure is shown in Figure 10.

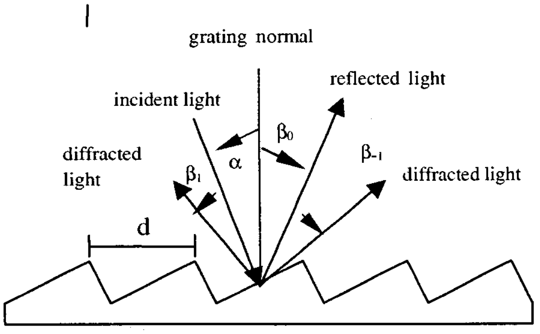

Figure 10 - Blazed Diffraction Grating. [1]

The grating equation for this grating is given by [1]:

$$m\lambda = d\,(\sin\alpha + \sin\beta)$$

where:
- m = diffraction order
- λ = wavelength
- d = groove spacing
- α = angle of incidence
- β = angle of diffraction for mth order

If we choose $2\lambda_2 = \lambda_1$ we see that the angle of diffraction for m = 1 at λ_1 and m = 2 at λ_2 are equal. When we consider an all reflective grating imaging spectrometer, the light incident at a specific location in spectral direction of the image plane will contain radiation at λ and 2λ. By employing a dual-band FPA at the image plane allows the simultaneous detection of hyperspectral information over two octaves. If we consider the MWIR (3.5 microns to 6 microns) and LWIR (7.0 microns to 12 microns) spectral regions, we can design an optical system which provides dispersion of radiation in each of these bands without spectral crosstalk. These two bands correspond with the spectral sensitivity of dual-band FPAs currently under development. A representative sensitivity curve is shown in figure 11.

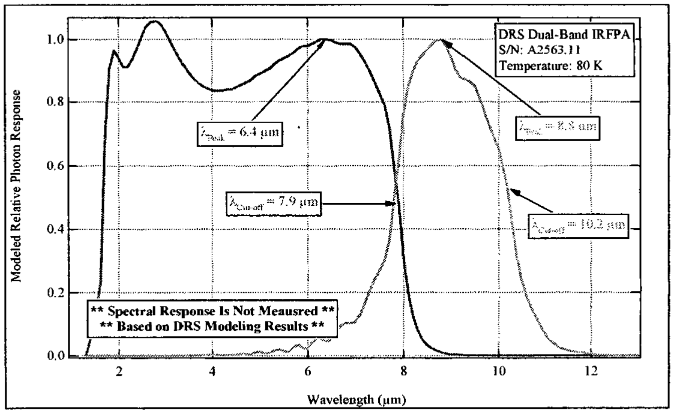

Figure 11 – Modeled spectral sensitivity of DRS FPA at 80K.

2. DESIGN AND FABRICATION

Design requirements—To demonstrate the dual-octave spectrometer concept, a ground-based spectrometer was designed and fabricated. A four mirror design with a flat grating was developed with f/2.35 at the slit and f/4 at the image plane. All optics were general aspheres. The optical design drivers included (1) use of a commercially available grating, (2) fixed f/# for the slit and image plane, and (3) an envelop which would allow the spectrometer to be mounted in a Government furnished dewar. The cost effective fabrication utilized an all aluminum system, and diamond turned optics with minimal post polishing. Optical testing and alignment were performed on the fully assembled spectrometer only; none of the individual optics were tested. The completed spectrometer was mounted in an IR Labs dewar supplied by AFRL to within mechanical tolerances and delivered to AFRL-VSSS. The system characteristics are shown in Table 1.

Table 1. First order properties for hardware demonstration

Bandwidth	MWIR/LWIR 3.5 μm to 6μm/7μm to 12 μm
Entrance Pupil	6.701”
Effective Focal Length	26.804”
Front-end F-number (Janos Hybrid)	F/2.35
F-number on FPA	F/4
Magnification	1 to 1.7
FPA Size	0.6299” x 0.4722”
Pixel size	50 microns
Field of view	±0.5 degrees
Grating Pitch	30 grooves/mm
Grating Blaze Wavelength	8.0 μm
Grating Blaze Angle	6.9 degrees
WFE (RMS)	<0.1 waves at 3.5 μm over entire FOV for MWIR/LWIR
Ensquared Energy	> 50% over entire FOV
MTF	Within 15% of diffraction limit (at Nyquist frequency)
Measured WFE (RMS)	0.09 to 0.12 waves at 3 μm for three field points
Dimensions	7.1” x 4.85” 5.05”
Weight	5.14 lbs.

Optical Design—The design for the fore-optics was based on the data obtained from Janos for their F/2.35 catadioptric lens. This design simulates the lens of choice to within the accuracy of the data provided. A four-mirror spectrometer design was selected (figure 12). The initial design was modified for volume (design fits in IR Labs dewar), grating, and field-of-view considerations. It was also constrained to minimize distortion (less than 0.5 pixels at the design-level) and wavefront error.

The spectrometer design was constrained to work with an off-the-shelf, flat reflective grating. SSG has designed and fabricated Offner spectrometers for a number of flight systems for visible through IR wavebands. As stated earlier the Offner design form requires a convex blazed grating. The implementation of the Offner design in the LWIR presents challenges in the fabrication of the convex gratings. The presently utilized process for creating convex gratings is an e-beam technique which generates a blazed grating on the surface of a convex sphere. When this process is applied to the requirements for LWIR systems, limitations in the implementation make it difficult to create the relatively large features. The critical aspects of the grating are the depth of the grooves in the diffractive grating, the ability of the technique to accommodate the sag of the convex grating substrate and accuracy of the grating profile. These elements effect the throughput and overall performance of the spectrometer. In addition, thermal characteristics of the substrate material need to be considered to minimize differences in coefficient of thermal expansion (CTE) and thermal conductivity which may effect the optical performance of the instrument at below ambient operating conditions. For these reasons and to enable cost effective demonstration of the dual-octave spectrometer, the design form utilized a flat grating.

The grating used in the design presented here has the following characteristics: pitch = 30 grooves/mm, blaze wavelength = 8.0 mm, blaze angle = 6.9°.

Figure 12 shows the optical design for the four-mirror spectrometer. All three mirrors are general aspheres. This design form allows the spectrometer to have magnification to account for the F/2.35 at the slit and F/4 at the FPA. This is not the case for the Offner design form which must have a magnification of 1. The four-mirror design form also allows for increased design flexibility which can result in decreased system size and complexity. Analysis of the trade between spectrometer size and performance indicates that the four-mirror design provides performance comparable to the Offner for a give spectrometer size and can also decrease the overall size of the instrument consisting of fore-optics and back-end spectrometer.

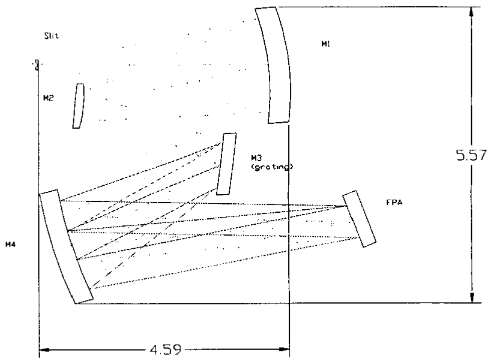

Figure 12 - Ray Trace of Optical Design for

Demonstration Hardware

Image Quality—The root-mean-squared wavefront error for this spectrometer design is less than 0.1 λ across the field-of-view for the wavebands of interest. Graphs of the design wavefront error as a function of field angle (for three different wavelengths) are shown in Figures 13 through 15. Error contributed by the fore-optics is not included in these calculations. The ensquared energy for this spectrometer design (fraction of energy from a particular field point falling within the area of a square, 50 mm pixel) is greater than 50% across the field-of-view for the waveband of interest This design has an MTF within 15% of a diffraction limited system (at the Nyquist frequency).

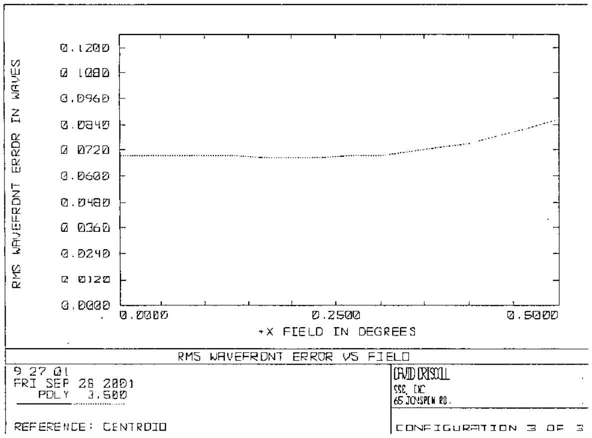

Figure 13 - RMS Design Wavefront Error at 3.5 Microns

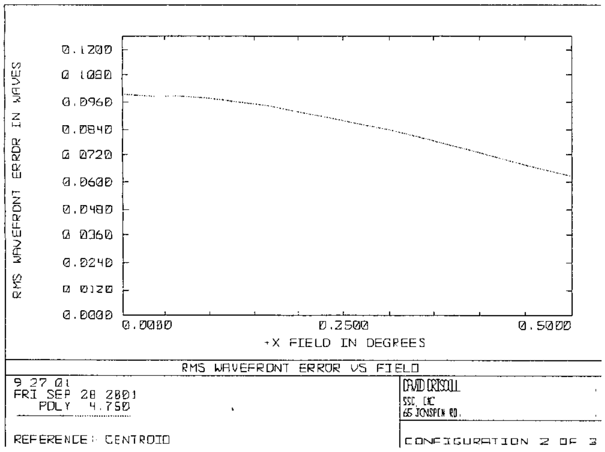

Figure 14 - RMS Design Wavefront Error at 4.75 Microns

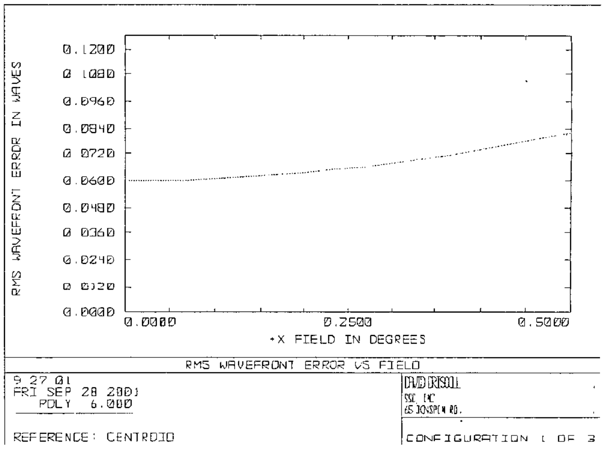

Figure 15 - RMS Design Wavefront Error at 6.0 Microns

System Hardware—The system hardware consists of three diamond turned aluminum mirrors, an off-the-shelf flat grating (Thermo RGL, Rochester, New York), an aluminum housing, spectrometer slit and housing and mounting plates and shims. Figure 16 shows the opto-mechanical design and Figure 17 shows the as fabricated components and final assembled spectrometer. Figure 18 shows a mechanical drawing of the entire system including the fore-optics (Janos Technologies, Townshend, VT) and dewar (IR Labs, Tucson, AZ).

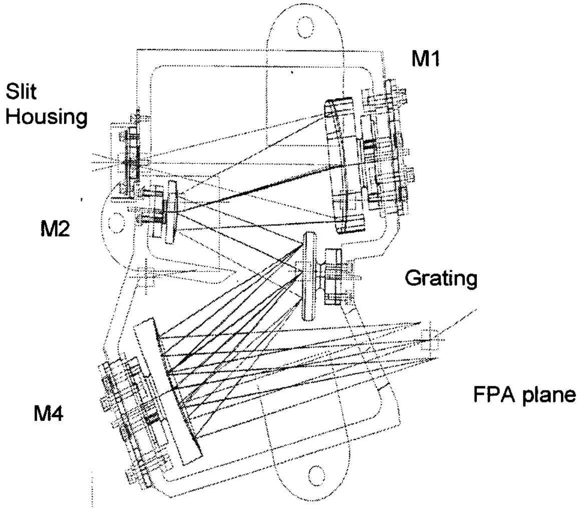

Figure 16 – Dual Octave spectrometer Opto-mechanical design

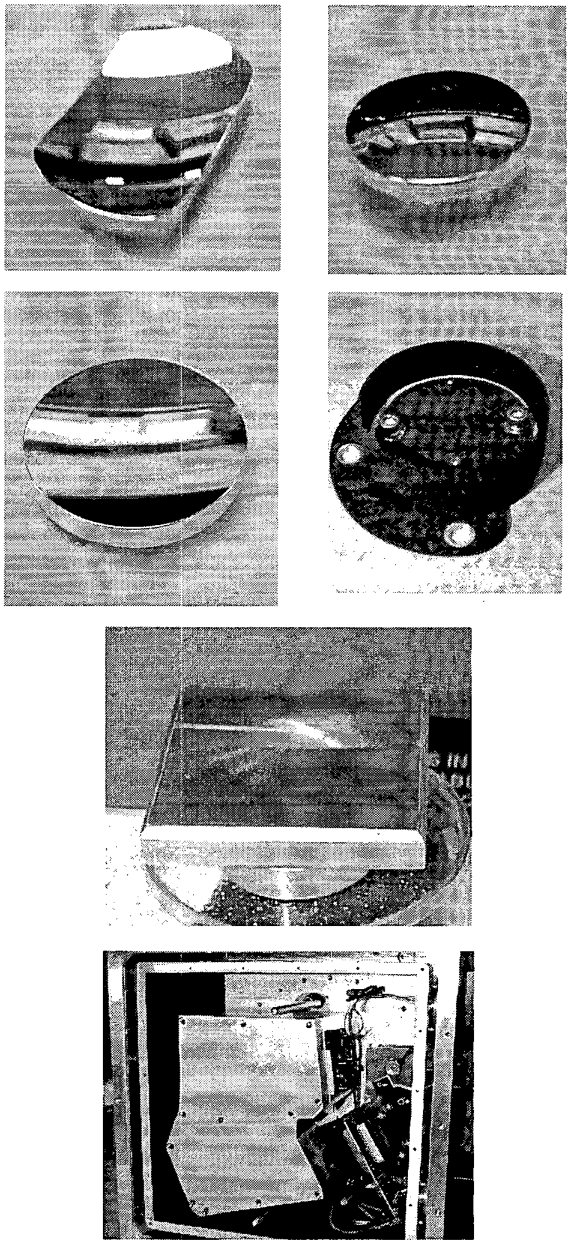

Figure 17 – Components for dual octave spectrometer. From top left: M1, M2, M4, Slit housing, flat grating and assembled and aligned spectrometer mounted in Dewar.

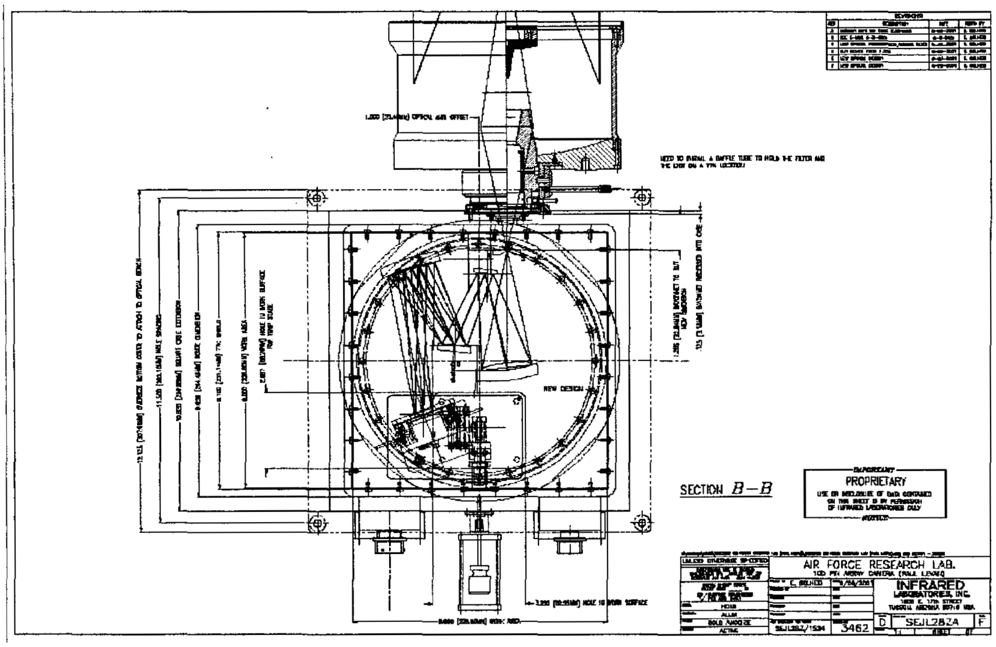

Figure 18 -. Mechanical Drawing of entire dual octave spectrometer system including fore-optics and dewar.

3. RESULTS

The wavefront for the spectrometer was measured using phase shift interferometer and data was reduced by Opticode Phase Analysis Software. In double pass configuration at 632.8 nm HeNe wavelength, 11-th order was measured at three locations corresponding to the lower, middle, and upper field points in the image plane (top, center and bottom of the detector). This was achieved by rotating and translating the spectrometer using slit edge and mirrors masks as the reference points.

Visible wave interference was inspected at 15-th and 16-th orders to verify its quality and proper location. Due to the contrast and small amount energy in the double pass configuration, quantitative wavefront values could not be measured.

With spectrometer and the laser unequal path interferometer (LUPI) in place, magnification of the system was measured by translating laser in the slit direction by known amount and measurement the new location of the retro-ball in x-, y-, and z-directions. The actual magnification given by image height/object height was measured to be 1.700±0.007, which is the nominal value.

Table 2. Dual octave demonstration hardware measured performance.

	11-th order center peak-to-valley	11-th order top peak-to-valley	11-th order bottom peak-to-valley	15-th order center P-V (estimated)
Wavefront Actual @ 632.8 nm	2.90	3.20	2.80	4.00
Wavefront Nominal @ 632.8 nm	3.57	2.77	2.77	3.10
Delta	-0.67	0.43	0.03	0.90
Wavefront Actual @ 3 micron	0.61	0.67	0.59	

	11-th order center RMS	11-th order top RMS	11-th order bottom RMS	15-th order center RMS
Wavefront Actual @ 632.8 nm	0.56	0.54	0.45	
Wavefront Nominal @ 632.8 nm	0.45	0.34	0.34	0.6
Delta	0.11	0.2	0.11	
Wavefront Actual @ 3 micron	0.12	0.11	0.09	

4. SUMMARY

In this paper, a new hyperspectral spectrometer design was presented. The dual-octave hyperspectral imaging spectrometer results from the integration of a unique spectrometer implementation which utilizes the first and second diffractive orders and emerging dual-band FPA technologies. Simultaneous hyperspectral information is achieved in two spectral bands in a compact and efficient instrument. An all aluminum ground-based demonstration spectrometer unit was designed and fabricated for the MWIR (3.5 microns to 6 microns) and LWIR (7 microns to 12 microns) with λ/10 RMS performance at 3 µm. Future space and airborne remote sensing applications will benefit from combining the dual octave spectrometer with lightweight, thermally stable SiC materials and advanced microdewar and drive electronics for a compact, lightweight, power efficient hyperspectral instruments.

REFERENCES

[1] Christopher Palmer, *Diffraction Grating Handbook*, Thermo RGL (2002).

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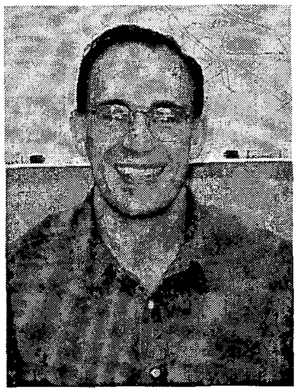
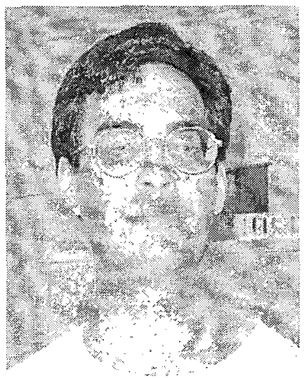


***Jay Schwartz** is the Senior Manager of R&D at SSG Precision Optronics. The R&D group investigates advanced technologies, processes and materials for high precision optical instruments. He has over 10 years experience in U.S. Government funded research and development of noval optical materials and devices, and unconventional communications systems. His education includes an M.S. degree in Electro-Optics from Tufts University and a S.B. in Engineering Sciences from Harvard University.*



***David Driscoll** is an optical systems engineer and has nine years of experience designing and assembling optical systems. He has served as the project lead of airborne hyperspectral instruments. Additionally, Mr. Driscoll has experience with electro-optic devices, laser systems and thin film technologies. He received an M.S Optics, BA Physics from Cornell University.*

***Jerzy Kocjan** is a Senior Engineer at SSGPO. For over five years Mr. Kocjan has worked at SSG on various space and ground optical systems as an optical test engineer and project engineer. He has over 10 years previous experience in optical engineering and manufacturing, medical implants engineering. He had also worked on NSF founded, small business innovation grants. He has received an MS in Applied Physics; BS in Physic; AS in Civil Engineering.*