Advances In The Opto-mechanical Design And Alignment Of The Hehsi Imaging Spectrometer Based On A Sagnac Interferometer

2005

Michael Stuart Schreiber
University of Central Florida

Find similar works at: http://stars.library.ucf.edu/etd

University of Central Florida Libraries http://library.ucf.edu

Part of the Mechanical Engineering Commons

STARS Citation

http://stars.library.ucf.edu/etd/389

This Masters Thesis (Open Access) is brought to you for free and open access by STARS. It has been accepted for inclusion in Electronic Theses and Dissertations by an authorized administrator of STARS. For more information, please contact lee.dotson@ucf.edu.
ADVANCES IN THE OPTO-MECHANICAL DESIGN AND ALIGNMENT OF THE HEHSI IMAGING SPECTROMETER BASED ON A SAGNAC INTERFEROMETER

by

MICHAEL STUART SCHREIBER
B.S. Brigham Young University, 2001

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the Department of Mechanical, Materials and Aerospace Engineering in the College of Engineering and Computer Science at the University of Central Florida Orlando, Florida

Spring Term
2005
ABSTRACT

The High Efficiency HyperSpectral Imager (HEHSI) is a Fourier Transform hyperspectral imager based on a Sagnac interferometer. This thesis research concentrates on the design upgrade and calibration of HEHSI from a proof of concept instrument to a prototype field instrument. Stability is enhanced by removing degrees of freedom and alignment is enhanced by providing for in-situ adjustments. The use of off the shelf components allows for reduced development time and cost constraints. HEHSI is capable of multiple configurations to accommodate sensors and optics with specialized capabilities for multiple wavelength ranges and viewing conditions. With a spectral response of 400 to 1000 nanometers in the visible and very near IR as well as 900 to 1700nm in the Near IR. Creation and use of a real time feedback alignment utility allow quantifiable signal comparison and image alignment. Advances allow for HEHSI to remain aligned during data collection sessions and confirmation of alignment through quantitative measures.
ACKNOWLEDGMENTS

I would like to thank Dr. Ham for his guidance that he has given me in being my thesis advisor. I would like to thank Dr. Art Weeks and Dr. Hyoung Jin “Joe” Cho for being on my thesis committee. I would like to acknowledge Dr. R. Glenn Sellar for his hard work and determination on HEHSI and increasing my knowledge on the entire subject of light, interference patterns, the Fourier transform, and spectrometry more than I will ever know. I would like to acknowledge Anand S. Arabatti, Pete Reardon, Jimmy Davis, and Danli Wang for their work on the HEHSI project.

I will thank my wife Kara Michelle Schreiber for my motivation to pursue a graduate degree, and for being my wife. I will thank my daughters Abby and Natalie for giving me many things to do instead of research. I will thank my parents for letting me be such a free spirit and curious scientist. I know that by myself I have achieved nothing without help.
# TABLE OF CONTENTS

LIST OF FIGURES ........................................................................................................... viii

LIST OF TABLES ........................................................................................................... xv

LIST OF ABBREVIATIONS ........................................................................................... xvi

CHAPTER ONE: INTRODUCTION ................................................................................. 1

1.1 Imaging Spectrometry ......................................................................................... 2

Classifications of Imaging Spectrometers ................................................................. 8

1.2 HEHSI Mark II .................................................................................................... 11

Physical description of the Mark II ........................................................................... 12

Sagnac Interferometer Basics ................................................................................. 15

Data Collection ........................................................................................................... 34

CHAPTER TWO: REQUIREMENTS AND CONSTRAINTS ....................................... 38

2.1 Objectives for the Mark III ............................................................................... 38

2.2 Tolerances .......................................................................................................... 40

Mirror tolerance ........................................................................................................ 40

2.3 Alignment .......................................................................................................... 46

2.4 Stability ............................................................................................................. 47

2.5 Vignetting ........................................................................................................... 48

2.6 Multiple Configurations - VIS/NIR ................................................................. 52
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center Central Fringe in Region of Interest</td>
<td>72</td>
</tr>
<tr>
<td>Calibrate to Known Source</td>
<td>73</td>
</tr>
<tr>
<td>Align Fringes to CCD</td>
<td>75</td>
</tr>
<tr>
<td>CHAPTER FIVE: CONCLUSIONS</td>
<td>87</td>
</tr>
<tr>
<td>5.1 Conclusions</td>
<td>87</td>
</tr>
<tr>
<td>5.2 Future Development</td>
<td>88</td>
</tr>
<tr>
<td>APPENDIX A DATA IMAGES</td>
<td>89</td>
</tr>
<tr>
<td>APPENDIX B PROGRAM CODE</td>
<td>126</td>
</tr>
<tr>
<td>MATLAB Code for Broadband Interference Pattern</td>
<td>127</td>
</tr>
<tr>
<td>MATLAB Code for Cosine Interference Patterns</td>
<td>128</td>
</tr>
<tr>
<td>LIST OF REFERENCES</td>
<td>129</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 1  AVIRIS Hyperspectral Image of Moffett Field, Mountain View, CA. Datacube with pixels in the x-y planes and voxels in the $\lambda$ direction. ............................... 3

Figure 2 Spectral imager classifications. ................................................................. 4

Figure 3: Classification of Imaging Spectrometers. ................................................. 8

Figure 4 The view of the Mark II instrument with the and cover in place. Openings were provided for light entrance and cabling. ................................................................. 12

Figure 5  The interior view of the Mark II instrument with the camera and cover removed. Showing the large base plate, the invar (shiny) locating plate, beamsplitter and mirror mounts, and the L shaped camera mount bracket .................................. 13

Figure 6  Visible/NIR HEHSI Mark II mounted on a tripod in field use on balcony...... 13

Figure 7 showing the triangular Sagnac’s mirrors in a purely symmetric position....... 15

Figure 8 Triangular Sagnac’s mirrors are offset from a purely symmetric position..... 16

Figure 9 This illustrates the separation of the output rays similar to Fig. 8 but with a different mirror offset of .4 units giving the displacement of the exiting parallel rays a displacement of .6123 units.................................................................................... 17

Figure 10 Family of hyperbola shown above where $b=100$. Notice the functions look parallel at the center. This region is where the Fourier transform can be used to find the frequency of the pattern. ..................................................................................... 21
Figure 11 Family of hyperbola shown above b=50 .......................................................... 22
Figure 12 Family of hyperbola shown above b=25 .......................................................... 23
Figure 13 Family of hyperbola shown above b=10 .......................................................... 24
Figure 14 Family of hyperbola shown above b=5 ............................................................ 25
Figure 15 Family of hyperbola shown above b=1 ............................................................ 26
Figure 16 Image taken with color camera through Mark III Sagnac interferometer setup.
................................................................................................................................... 27
Figure 17 Showing how the interference patterns of different wavelength have different
periods. The Fourier transform is used to deconvolute this superposition. ............. 28
Figure 18 Synthetic broadband interference pattern produced in MATLAB. .............. 28
Figure 19 Five aluminum pads used for alignment of the beamsplitter and mirrors in the
Mark II HEHSI instrument. ...................................................................................... 30
Figure 20 illustrates the five aluminum pads used in conjunction with a ¼ -20 screw
holding the mount to the invar plate for alignment of the beamsplitter and mirrors in
the Mark II HEHSI instrument. ................................................................................ 31
Figure 21 Pads as obstructions......................................................................................... 33
Figure 22 Showing how only one of the parallel rays can be clipped at any aperture.2 .. 33
Figure 23 Target board with colors to demonstrate HEHSI abilities............................ 35
Figure 24 Captured image with interference pattern showing vertical fringes............ 35
Figure 25: Images in the (x,y,λ) hyperspectral data cube. Images appear backwards due
to processing.1 ........................................................................................................... 36
Figure 26 Showing spectra of different regions of the image. Red is on the left, blue is
on the right of the graphs. The small square is a 50% reflectance target. The small
circle is a WCS target. 1 ................................................................. 37

Figure 27 Showing pixel ratios for a column of pixels 1, 8, 64, and 512 tall by 1 wide to
scale, respectively. Misalignment shown for angle θ1 not to scale. .................... 42

Figure 28 Shows an unfolded Sagnac interferometer beam path. ......................... 43

Figure 29 Rotation of one of the mirrors in the Sagnac interferometer produces a vertical
offset. ........................................................................................................... 44

Figure 30 Illustrates a larger field of view can be achieved with at shorter beam path... 50

Figure 31 (a) Layout of a right-angle triangular Sagnac interferometer showing the ..... 51

Figure 32 Aspect ratio for a right-angle-triangular Sagnac interferometer limited by .... 52

Figure 33 Thorlab Ultrastable Kinematic mirror mounts. ....................................... 59

Figure 34 Newport beamsplitter mount.(left) and modified Newport beamsplitter mount
used in HEHSI (right). .................................................................................. 59

Figure 35 The HEHSI Mark III functioning in the field........................................... 61

Figure 36 HEHSI Mark III with lid and camera mount removed......................... 61

Figure 37 Indigo Alpha with Optec 100mm lens (top), Qimaging Retiga 1300 with
Schneider 70mm Telexenar f2.2 lens (bottom).............................................. 62

Figure 38 Basic Configuration of Spectrometer ................................................. 66

Figure 39 Interference patterns of monochromatic light (left) appear as a cosine function.

Interference patterns of broadband white light (right) appear as sinc² function.... 67

Figure 40 A 633nm red HeNe interference pattern and real time Fourier transform
channel designation................................................................. 74
Figure 41  Modulation and highest pixel values after averaging across all rows in the region of interest. The fringes are not aligned to the CCD. The highest signal is 65 DN............................................................................................................................. 75

Figure 42  Shows the interferogram and the resulting spectrum after averaging across all rows in the region of interest. The fringes are aligned to the CCD when the signal in the spectrum is maximized. The highest pixel signal is 90 DN. Which illustrates a greater degree of alignment than Figure 41 with a signal of 65 DN............................. 76

Figure 43  Inconel beamsplitter profiles showing limits of performance.19, 20 ............... 78

Figure 44  1/4 -20 screws allow for alignment of camera to interferometer. ................. 80

Figure 45  Labview utility G code (Graphical Programming Environment). ROI select (top), continuous update with front panel (bottom).................................................. 82

Figure 46  LabVIEW utility front panel user interface..................................................... 83

Figure 47  Labview utility with HEHSI Mark III aligned with a 632nm HeNe laser in band 43...................................................................................................................... 84

Figure 48  LabVIEW utility with white light. FT showing light in bands 23 through 41. Histogram peak at central fringe is 80 DN. .............................................................. 85

Figure 49  HeNe at the Nyquist limit of a ROI that is 512 in the y direction..................... 91

Figure 50  Peaks in fluorescent light showing up in bands 92 (red) 104 (green) and 113 (blue). Green peak at value of 11 DN................................................................. 92

Figure 51  Peaks in fluorescent light showing up in bands 45 (red) 49 (green) and 54 (blue). Green peak at value of 28 DN................................................................. 93

Figure 52  Peaks in fluorescent light showing up in bands 140 (red) 154 (green) and 170
(blue). Red peak at value of 3 DN. ................................................................. 94

Figure 53  Fluorescent light past the Nyquist limit. No peaks show. ................. 95

Figure 54  HeNe peak in band 43. Peak is 515 DN. .............................................. 96

Figure 55  HeNe peak past Nyquist limit. Aliased. ............................................. 97

Figure 56  ROI taken from image with rectangle selection tool in LabVIEW G code.

632nm red HeNe laser light in band 43. ............................................................ 98

Figure 57  Screen shot for ROI rectangle selection tool in G code. HeNe interference

pattern is visible with vignetted edges. ............................................................... 99

Figure 58  Shows an off axis view of white light where the interference pattern exhibits

hyperbolic traits. ............................................................................................... 100

Figure 59  Closeup of HeNe fringes. Peak is in band 10 with a secondary peak in band

21 ..................................................................................................................... 101

Figure 60  Broadband light with fringes aligned to CCD. Central fringe in histogram

shows 6320 DN. FT shows light in bands 30 through 51. (set1) ....................... 102

Figure 61  Broadband light not aligned to CCD. (set 1) ..................................... 103

Figure 62  Broadband light not aligned to CCD. (set1) ....................................... 104

Figure 63  Broadband light not aligned to CCD. (set1) ....................................... 105

Figure 64  Broadband light aligned to CCD. (set 2) .......................................... 106

Figure 65  Broadband light not aligned to CCD. (set 2) ..................................... 107

Figure 66  Broadband light not aligned to CCD. (set 2) ..................................... 108

Figure 67  Broadband light aligned to CCD. (set 3) .......................................... 109

Figure 68  Broadband light not aligned to CCD. Rotated about zero point. (set 3) ...... 110
Figure 69  Broadband light not aligned to CCD. Rotated about zero point. (set 3) ..... 111

Figure 70  Broadband light aligned to CCD. Histogram peak of central fringe showing 3100 DN and FT peak at band 62. (set 5).............................................................. 112

Figure 71  Broadband light showing small modulation in upper window even though not aligned. This shows aliasing as the fringes have shifted past each other in the y direction because of the angle of rotation. Histogram peak at 2350 DN with no notable peak in FT bands. (set 5).............................................................. 113

Figure 72  Blue LED showing small modulation in upper window even though not aligned. Notice central fringe cannot be identified readily with crooked fringes. (set 6)............................................................................................................................. 114

Figure 73  Blue LED showing large modulation in upper window while aligned. (set 6)............................................................................................................................. 115

Figure 74  Blue LED showing large modulation in upper window while aligned. (set 6)............................................................................................................................. 116

Figure 75  Rotating around zero point with blue LED light. Looking at how the central fringe is not apparent with crooked fringes. (set 6)............................................................. 117

Figure 76  Rotating around zero point with blue LED light. (set 7).............................. 119

Figure 77  Rotating around zero point with blue LED light. Looking at how the central fringe is not apparent with crooked fringes. (set 7)............................................................. 120

Figure 78  Rotating around zero point with blue LED light. Looking at how the central fringe is not apparent with crooked fringes. (set 7)............................................................. 121

Figure 79  Rotating around zero point with white light. Looking at how the central fringe
is not apparent with crooked fringes. (set 8).......................... 122

Figure 80  Rotating around zero point with white light. (set 8).......................... 123

Figure 81  Rotating around zero point with white light. Looking at how the central fringe is not apparent with crooked fringes. (set 8).......................... 124

Figure 82  Rotating around zero point with white light. Looking at how the central fringe is not apparent with crooked fringes. (set 8).......................... 125
LIST OF TABLES

Table 1  Bands and the wavelengths / wavenumbers they represent in a processed 512 element HEHSI image. ................................................................. 6

Table 2  Summary of some HyperSpectral airborne imaging spectrometers. 10, 12 ............... 9

Table 3  Camera detector sizes. .............................................................................. 53
LIST OF ABBREVIATIONS

λ Greek letter Lambda, variable used to represent wavelength
AR Anti-Reflective
CCD Charge Coupled Device
FOV field of view
FT Fourier Transform
HDF File extension for IDL computer language. HDF file contains information relative to an image data cube.
HEHSI High Efficiency HyperSpectral Imager
HeNe Helium-Neon
IDL Interactive Data Language. Computer programming language for image processing.
IR Infrared
m meter
NIR Near Infrared
nm nanometer, 10⁻⁹ m
Pixel Picture Element, the smallest distinguishable part of a 2D image.
ROI Region of Interest
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>SWIR</td>
<td>Short Wave Infrared</td>
</tr>
<tr>
<td>µm</td>
<td>micrometer, $10^{-6}$m</td>
</tr>
<tr>
<td>UV</td>
<td>Ultra Violet</td>
</tr>
<tr>
<td>VNIR</td>
<td>Very Near Infrared</td>
</tr>
<tr>
<td>WCS</td>
<td>Wavelength Calibration Standard</td>
</tr>
</tbody>
</table>
CHAPTER ONE: INTRODUCTION

The pursuit of advances in the opto-mechanical design of the imaging spectrometers based on a Sagnac interferometer is pushed by the ongoing research with the HEHSI instrument. Hyperspectral imagers have applications in remote sensing. Imaging in the visible, near-infrared, mid-infrared and longwave infrared is possible using optics and sensors which work in their respective range of wavelengths. Hyperspectral imagers differ from point spectrometers in the fact that they collect an entire spectrum for every pixel in an image\textsuperscript{22}. Hyperspectral imagers can also be used for detection of significant changes in geophysical structures, plant life, and marine environments.\textsuperscript{21} Such spectral information can locate minerals, monitor the state of terrestrial and marine vegetation, and water quality. Hyperspectral imagers also have military applications in the ability to distinguish camouflage from vegetation in the near infrared. The HEHSI (High-Efficiency HyperSpectral Imager) is a windowing class, along track scanning Imaging Spectrometer.\textsuperscript{2} The HEHSI Mark II instrument and its abilities will be discussed. Also discussed will be the need for advances from the HEHSI Mark II to an upgraded instrument the HEHSI Mark III.
1.1 Imaging Spectrometry

Imaging spectrometers and imaging spectrometry offer advantages over other types of spectrometers and imagers. Hyper spectral imagers can be compared and contrasted to both spectrometers and imagers and show marked differences in how they identify data. Spectrometers deal with the spectra of a sample. There are different applications for spectrometers as well as differing types of spectrometers. Spectrometers differ from Imaging spectrometers as they do not contain image data in the resulting data. For a single sample with a spectrometer, a single spectra will result. Imaging spectrometers will provide a spectra for every element in the image. Imaging spectrometer data sets contain large amounts of data due to the fact that there are hundreds or thousands of elements or pixels in an image. Each pixel in the image will have its own spectra rather than a single spectra as a non-imaging spectrometer would produce. Shown is a 3D data cube. Each layer represents one band of wavelength. Such is the output of a hyperspectral imager. With the x and y dimensions being the image plane and the spectral data in the \( \lambda \) dimension.
FIGURE 1  AVIRIS Hyperspectral Image of Moffett Field, Mountain View, CA. Datacube with pixels in the x-y planes and voxels in the $\lambda$ direction. 

Imaging spectrometers are useful when spatial resolution is necessary. Instances where spatial resolution comes into play include: quality control where defective items display have spectral characteristics, geography where certain spectral characteristics indicate traits and features of a particular region, biology in distinguishing microscopic cells of interest containing a certain spectra from other cells, astrology where remote sensing may be the only way to collect data of extra-terrestrial bodies and their features. All of these areas produce niches where imaging spectrometers can collect valuable data that would not be available with non-imaging spectrometers.

Spectral imaging also has other classifications such as multi-spectral imagers and hyper-
spectral imagers. The distinction between multi and hyper spectral imagers amounts to the number of bands that the detected radiation can be divided into by wavelength and/or wave number and the width of the bands. Hyperspectral imagers will demonstrate >30 bands in the visible region, while in other regions Hyperspectral classification may not need to have as many as 30 bands, but may be determined to be Hyperspectral by the width of the individual bands. An example of this would be to have a spectrometer that only looked into the wavelength of 500nm to 550nm and perceived 10 bands within that range of wavelengths. Such a spectrometer could be considered hyperspectral without having 30 bands. As shown in figure 2 hyperspectral bands are much narrower than the bands perceived by a multispectral instrument, and in the same manner ultraspectral bands have a narrower band width than hyperspectral. With an increase in bands and narrower band widths the definition of a spectral profile is increased.

Figure 2 Spectral imager classifications.
A challenge involved with imaging spectrometers is that not only does it involve collecting the spectral information, it involves collecting spectral information for each pixel. With images with hundreds of thousands of pixels (512 x 512) to over a million (1024 x 1024) pixels, the spectral imaging becomes a larger task in data storage and data processing. This is a trade-off between imaging and non-imaging spectrometers. It is much easier for a non-imaging spectrometer to increase in spectral resolution because it does not have the burden of the image with all of its pixels.

The HEHSI imaging spectrometer is a hyperspectral imaging spectrometer when used at the higher levels of its ability, if used at lower levels it could be used as a multispectral imaging spectrometer. The threshold that HEHSI crosses to be in the hyperspectral range involves the number of recorded data pixels that contain images with interference pattern modulation. As the number of pixels in the image grows larger the number of bands that can be detected will grow. The increase of spectral bands is from the higher resolution of the image allowing the collection of more data in the along-track direction of the image. The number of pixels in the along-track direction has a direct relationship on the number of bands that the Fourier transform will resolve. The wavelengths that can be detected will be limited by the detector array and optics of the system, but the number of bands will grow as detector size in pixel width grows.
<table>
<thead>
<tr>
<th>HDF Band Numbers</th>
<th>Actual Band Number</th>
<th>HeNe Wavelength (nm)</th>
<th>Final Wavenumber</th>
<th>Final Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>9630.50723</td>
<td>1038.366906</td>
<td>989.4293059</td>
</tr>
<tr>
<td>2</td>
<td>31</td>
<td>10106.83627</td>
<td>944.8968903</td>
<td>904.2004699</td>
</tr>
<tr>
<td>3</td>
<td>32</td>
<td>10583.16532</td>
<td>866.8648649</td>
<td>832.4902668</td>
</tr>
<tr>
<td>4</td>
<td>33</td>
<td>11059.49436</td>
<td>800.7378641</td>
<td>771.3186373</td>
</tr>
<tr>
<td>5</td>
<td>34</td>
<td>11535.82341</td>
<td>743.9845361</td>
<td>718.5214686</td>
</tr>
<tr>
<td>6</td>
<td>35</td>
<td>12012.15245</td>
<td>694.7436823</td>
<td>672.4892254</td>
</tr>
<tr>
<td>7</td>
<td>36</td>
<td>12488.4815</td>
<td>651.6162528</td>
<td>632</td>
</tr>
<tr>
<td>8</td>
<td>37</td>
<td>12964.81054</td>
<td>613.5302869</td>
<td>613.5302869</td>
</tr>
<tr>
<td>9</td>
<td>38</td>
<td>13441.13959</td>
<td>596.0762091</td>
<td>596.0762091</td>
</tr>
<tr>
<td>10</td>
<td>39</td>
<td>13917.46863</td>
<td>579.6506024</td>
<td>579.6506024</td>
</tr>
<tr>
<td>11</td>
<td>40</td>
<td>14393.79768</td>
<td>564.0710153</td>
<td>564.0710153</td>
</tr>
<tr>
<td>12</td>
<td>41</td>
<td>14870.12672</td>
<td>553.310153</td>
<td>553.310153</td>
</tr>
<tr>
<td>13</td>
<td>42</td>
<td>15346.45577</td>
<td>522</td>
<td>522</td>
</tr>
<tr>
<td>14</td>
<td>43</td>
<td>15822.78481</td>
<td>497.2713178</td>
<td>497.2713178</td>
</tr>
<tr>
<td>15</td>
<td>44</td>
<td>16299.11385</td>
<td>485.7652503</td>
<td>485.7652503</td>
</tr>
<tr>
<td>16</td>
<td>45</td>
<td>16775.4429</td>
<td>474.7796053</td>
<td>474.7796053</td>
</tr>
<tr>
<td>17</td>
<td>46</td>
<td>17251.77194</td>
<td>464.2798552</td>
<td>464.2798552</td>
</tr>
<tr>
<td>18</td>
<td>47</td>
<td>17728.10099</td>
<td>454.2344611</td>
<td>454.2344611</td>
</tr>
<tr>
<td>19</td>
<td>48</td>
<td>18204.43003</td>
<td>444.6145553</td>
<td>444.6145553</td>
</tr>
<tr>
<td>20</td>
<td>49</td>
<td>18680.75908</td>
<td>435.3936652</td>
<td>435.3936652</td>
</tr>
<tr>
<td>21</td>
<td>50</td>
<td>19157.08812</td>
<td>426.5474695</td>
<td>426.5474695</td>
</tr>
<tr>
<td>22</td>
<td>51</td>
<td>19633.41717</td>
<td>418.0535844</td>
<td>418.0535844</td>
</tr>
<tr>
<td>23</td>
<td>52</td>
<td>20109.74621</td>
<td>410.7160547</td>
<td>410.7160547</td>
</tr>
<tr>
<td>24</td>
<td>53</td>
<td>20586.07526</td>
<td>403.3785743</td>
<td>403.3785743</td>
</tr>
<tr>
<td>25</td>
<td>54</td>
<td>21062.4043</td>
<td>396.0410436</td>
<td>396.0410436</td>
</tr>
<tr>
<td>26</td>
<td>55</td>
<td>21538.73335</td>
<td>388.7035139</td>
<td>388.7035139</td>
</tr>
<tr>
<td>27</td>
<td>56</td>
<td>22015.06239</td>
<td>381.3669842</td>
<td>381.3669842</td>
</tr>
<tr>
<td>28</td>
<td>57</td>
<td>22491.39144</td>
<td>374.0304546</td>
<td>374.0304546</td>
</tr>
<tr>
<td>29</td>
<td>58</td>
<td>22967.72048</td>
<td>366.6939251</td>
<td>366.6939251</td>
</tr>
<tr>
<td>30</td>
<td>59</td>
<td>23444.04952</td>
<td>359.3573955</td>
<td>359.3573955</td>
</tr>
<tr>
<td>31</td>
<td>60</td>
<td>23920.37857</td>
<td>352.0208658</td>
<td>352.0208658</td>
</tr>
</tbody>
</table>

Table 1  Bands and the wavelengths / wavenumbers they represent in a processed 512 element HEHSI image.

Example: When using the Fourier transform to deconstruct an interference pattern taken from HEHSI data in the 400nm to 1000nm wavelength range:

A detector array of 128 elements can detect 64 bands of which around 8 are useful. A
detector array of 256 elements can detect 128 bands of which around 16 are useful. A detector array of 512 can detect 256 bands of which around 31 are useful as shown in Table 1. The useful bands are determined by the ability of the CCD sensor. Bands that represent wavelengths that the sensor cannot detect are not considered useful. The HDF band numbers are assigned to the bands that are useful and these bands with their wavelength definitions are carried over to an HDF file that is used in IDL and ENVI as a correlating information file that accompanies the image data cube. The Retiga camera was sensitive from 400nm in band 60 to around 1000nm in band 30. Although bands 1 through 29 exist they represent wavelengths further in the infrared that the camera cannot sense, the same is true of the ultraviolet in bands 61 through 256. HEHSI has 31 useful bands in the visible wavelength range and because of this resolution is classified as hyperspectral.
Imaging spectrometer examples fall into the categories of Bandpass, Dispersive and Interferometric. Bandpass Imaging spectrometers use a series of filters in order divide the radiation from the source into its separate bands. Dispersive Imaging spectrometers will use a prism in order to separate the radiation into its separate bands. Interferometric Imaging interferometers will use an interferometer to separate the radiation into its bands. The HEHSI instrument is an interferometric imaging spectrometer and uses a Sagnac interferometer to create an interference pattern to be captured with the image. Spectral
information is collected by using the Hyperspectral imager to collect images which contain interference patterns. The spectral information can be extracted by deconvoluting the interference pattern with image processing software.

<table>
<thead>
<tr>
<th>Sensor (Agency)</th>
<th>Number of Bands</th>
<th>Spectral Range(nm)</th>
<th>Bandwidth FWHM(nm)</th>
<th>IFOV (mrad)</th>
<th>FOV (deg)</th>
<th>Data</th>
<th>Period of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAS (ASTER) (DAIS-2815) (GER)</td>
<td>1</td>
<td>760-850</td>
<td>90</td>
<td>1.0,2.5, or 5.0</td>
<td>28.8, 65, or 104</td>
<td>Image Cube (IC)</td>
<td>Since(s) 1991</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3000-5000</td>
<td>600-700</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>8000-12000</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AHS, Daedelus</td>
<td>48</td>
<td>440-12700</td>
<td>20-1500</td>
<td>2.5</td>
<td>86</td>
<td>IC</td>
<td>1994</td>
</tr>
<tr>
<td>AIS-1</td>
<td>128</td>
<td>990-2100</td>
<td>9.3</td>
<td>1.91</td>
<td>3.7</td>
<td>IC</td>
<td>1982-85</td>
</tr>
<tr>
<td>AIS-2 (NASA/JPL)</td>
<td>128</td>
<td>1200-2400</td>
<td>10.6</td>
<td>2.05</td>
<td>7.3</td>
<td>IC</td>
<td>1986-87</td>
</tr>
<tr>
<td>AISA (Karelsilva Oy)</td>
<td>1-286</td>
<td>450-900</td>
<td>1.56-9.36</td>
<td>1</td>
<td>21</td>
<td>IC</td>
<td>S1993</td>
</tr>
<tr>
<td>AMSS (Geoscan)</td>
<td>32</td>
<td>490-1090</td>
<td>170-240</td>
<td>2.1x3.0</td>
<td>92</td>
<td>IC</td>
<td>S1985</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2020-8500-12K</td>
<td>430-440</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td></td>
<td>550-590</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ARES (AIP)</td>
<td>75</td>
<td>2000-6300</td>
<td>25-70</td>
<td>1.17</td>
<td>3x3</td>
<td>IC</td>
<td>S1985</td>
</tr>
<tr>
<td>ASAS</td>
<td>29</td>
<td>455-873</td>
<td>15</td>
<td>0.8</td>
<td>25</td>
<td>IC</td>
<td>1987-91</td>
</tr>
<tr>
<td></td>
<td>62</td>
<td>400-1060</td>
<td>11.5</td>
<td>0.8</td>
<td>25</td>
<td>IC</td>
<td>S1991</td>
</tr>
<tr>
<td>AISAS (NASA/GSFC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVIRIS (JPL)</td>
<td>224</td>
<td>380-2500</td>
<td>9.7-12.0</td>
<td>1</td>
<td>30</td>
<td>IC</td>
<td>S1987</td>
</tr>
<tr>
<td>CASI (Itres Research)</td>
<td>288</td>
<td>400-1000</td>
<td>650</td>
<td>1.3,1.6</td>
<td>37.8</td>
<td>Profil e Image</td>
<td>S1990</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>nominal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CIS (China)</td>
<td>64</td>
<td>400-1040</td>
<td>10</td>
<td>1.2x3.6</td>
<td>80deg</td>
<td>IC</td>
<td>S1993</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>2000-2480</td>
<td>20</td>
<td>1.2x1.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>3530-3940</td>
<td>410</td>
<td>1.2x1.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>10.5K-12.5K</td>
<td>1000</td>
<td>1.2x1.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CHRISS,SAIC AHIS,(SAIC)</td>
<td>40</td>
<td>430-860</td>
<td>11</td>
<td>0.05</td>
<td>10</td>
<td>IC</td>
<td>1992</td>
</tr>
<tr>
<td></td>
<td>288</td>
<td>440-880</td>
<td>3</td>
<td>1</td>
<td>11.5</td>
<td>IC</td>
<td>1994</td>
</tr>
</tbody>
</table>

Continued on Next Page
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Channels</th>
<th>Wavelengths</th>
<th>Resolution</th>
<th>Spatial</th>
<th>Date</th>
<th>Primary Purpose</th>
<th>Acquisition</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAIS-7915 (GER/DLR)</td>
<td>32</td>
<td>400-1010, 1500-1780, 1970-2450, 3000-5000, 8.7K-12.7K</td>
<td>16-Oct</td>
<td>36, 36</td>
<td>3, 3.2, 5, or 5.0</td>
<td>64-78</td>
<td>IC</td>
<td>S1994</td>
</tr>
<tr>
<td>DAIS-16115 (GER)</td>
<td>76</td>
<td>400-1000, 1000-1800, 2000-2500, 3000-5000, 8K-12K, 400-1000</td>
<td>8</td>
<td>25, 16</td>
<td>3</td>
<td>78</td>
<td>IC</td>
<td>S1994</td>
</tr>
<tr>
<td>DAIS-3715 (GER)</td>
<td>32</td>
<td>360-1000, 1000-2000, 2175-2350, 3000-5000, 8K-12K</td>
<td>20</td>
<td>1000, 50</td>
<td>5</td>
<td>-45</td>
<td>IC</td>
<td>S1994</td>
</tr>
<tr>
<td>FLI/PMI (Moniteq)</td>
<td>288</td>
<td>430-805</td>
<td>2.5</td>
<td>1.3</td>
<td>70</td>
<td>Profile Image</td>
<td>1984-90</td>
<td></td>
</tr>
<tr>
<td>FTVHSI (Kestrel)</td>
<td>256</td>
<td>440-1150</td>
<td>67cm-1</td>
<td>0.8</td>
<td>15</td>
<td>IC</td>
<td>1996</td>
<td></td>
</tr>
<tr>
<td>GER-63 Channel Scanner (GER)</td>
<td>24</td>
<td>400-1000</td>
<td>25</td>
<td>125</td>
<td>2.5, 3.3, or 4.5</td>
<td>90</td>
<td>IC</td>
<td>S1986</td>
</tr>
<tr>
<td>HYDICE (NRL/ERIM)</td>
<td>206</td>
<td>400-2500</td>
<td>7.6-14.9</td>
<td>0.5</td>
<td>8.94</td>
<td>IC</td>
<td>1994</td>
<td></td>
</tr>
<tr>
<td>ISM (DESPA/IAS/OPS)</td>
<td>64</td>
<td>800-1600</td>
<td>12.5</td>
<td>3.3x11.7</td>
<td>40</td>
<td>IC</td>
<td>S1991</td>
<td></td>
</tr>
<tr>
<td>MAS (Daedalus)</td>
<td>50</td>
<td>547-14.5K</td>
<td>31-517</td>
<td>2.5</td>
<td>85.92</td>
<td>IC</td>
<td>S1992</td>
<td></td>
</tr>
<tr>
<td>MIVIS (Daedalus)</td>
<td>20</td>
<td>433-833, 1150-1550, 2000-2500, 8.2K-12.7K</td>
<td>20</td>
<td>8</td>
<td>2</td>
<td>70</td>
<td>IC</td>
<td>S1993</td>
</tr>
<tr>
<td>MIVIS (Daedalus)</td>
<td>8</td>
<td>433-833, 1150-1550, 2000-2500, 8.2K-12.7K</td>
<td>20</td>
<td>8</td>
<td>2</td>
<td>70</td>
<td>IC</td>
<td>S1993</td>
</tr>
<tr>
<td>MUSIC (Lockheed)</td>
<td>90</td>
<td>2500-7000, 6K-14.5K</td>
<td>25-70</td>
<td>0.5</td>
<td>1.3</td>
<td>IC</td>
<td>1989</td>
<td></td>
</tr>
<tr>
<td>ROSIS (MBB/DLR/GKSS)</td>
<td>84</td>
<td>430-830 ($\text{&amp;}2400$)</td>
<td>12-Apr</td>
<td>0.56</td>
<td>16 (32)</td>
<td>IC</td>
<td>S1993</td>
<td></td>
</tr>
<tr>
<td>SFSI (CCRS)</td>
<td>115</td>
<td>1200-2400</td>
<td>10.4</td>
<td>0.4</td>
<td>9.4</td>
<td>IC</td>
<td>S1994</td>
<td></td>
</tr>
<tr>
<td>SMIFTS (U. of Hawaii)</td>
<td>75</td>
<td>1000-5200, 3200-5200</td>
<td>100cm-1</td>
<td>0.6</td>
<td>6</td>
<td>IC</td>
<td>S1993</td>
<td></td>
</tr>
<tr>
<td>TRWIS-A</td>
<td>128</td>
<td>430-850</td>
<td>3.3</td>
<td>1</td>
<td>15</td>
<td>IC</td>
<td>1990</td>
<td></td>
</tr>
<tr>
<td>TRWIS-B</td>
<td>90</td>
<td>460-880</td>
<td>4.8</td>
<td>1</td>
<td>15</td>
<td>IC</td>
<td>1991</td>
<td></td>
</tr>
<tr>
<td>Instrument</td>
<td>Channels</td>
<td>Wavelengths</td>
<td>System</td>
<td>Resolution</td>
<td>Image Quality</td>
<td>Status</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------------</td>
<td>----------</td>
<td>-------------</td>
<td>--------</td>
<td>------------</td>
<td>---------------</td>
<td>-----------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hybrid VIFIS</td>
<td>30</td>
<td>440-640</td>
<td>14-Oct</td>
<td>1</td>
<td>IC</td>
<td>Test 1994</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(U. of Dundee)</td>
<td>30</td>
<td>620-890</td>
<td>14-18</td>
<td>1</td>
<td>31.5</td>
<td>IC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WIS-FDU</td>
<td>64</td>
<td>400-1030</td>
<td></td>
<td>1.36</td>
<td>10 &amp; 1</td>
<td>Test 1992</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WIS-VNIR</td>
<td>129,265</td>
<td>400-1000</td>
<td></td>
<td>0.66</td>
<td>19.1</td>
<td>IC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WIS-SWIR</td>
<td>81+90</td>
<td>1000-2500</td>
<td></td>
<td>0.66</td>
<td>12</td>
<td>IC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Hughes SRBC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 1.2 HEHSI Mark II

The HEHSI Mark II (Mark II) is the second version in the evolution of the HEHSI series instrument. It was built by a team of UCF undergraduate engineering students directed by R. Glenn Sellar. The Mark II was used for proof of concept and prototype development in research. The project goal was a small hyperspectral imager that would be placed in a small space satellite called a “getaway special” and be carried to earth orbit by a space shuttle where it would function. The Mark II would then collect data that could be processed to retrieve hyperspectral information. Although the project has not yet gone into space, advances were made to bring about the maturation of the HEHSI project.
Physical description of the Mark II

The Mark II is a custom made interferometer based on a triangular Sagnac Interferometer.

Figure 4 The view of the Mark II instrument with the and cover in place. Openings were provided for light entrance and cabling.
Figure 5  The interior view of the Mark II instrument with the camera and cover removed. Showing the large base plate, the invar (shiny) locating plate, beamsplitter and mirror mounts, and the L shaped camera mount bracket.

Figure 6  Visible/NIR HEHSI Mark II mounted on a tripod in field use on balcony.

The Mark II was used as a field instrument mounted on a rotation stage that rested on a tripod. Data was collected as the rotation stage moved, causing the field of view to scan
across the region of interest. The interference pattern was visible in the image as the data was acquired. Trade-offs existed between the amount of data captured and the quality of the spectral information extracted. By rotating the instrument at a slower angular velocity or increasing the camera frame rate more data is captured. This allows for oversampling of the data and through interpolation of the data during processing an advantage is achieved. Oversampling of the data also produces larger data sets. A data set captured with 8X oversampling is eight times larger than a data set that was not oversampled. This increases the processing time of the larger datasets and if the dataset becomes extremely large it becomes an issue for the computer resources and program resources to be able to handle the size of the data. In some cases the data set must be broken up into many smaller datasets that are processed one at a time. Environmental factors must also be considered when oversampling during data collection. Many things in a scene may change. The sun may move and change the position of shadows, clouds may move and influence lighting and shadows, cars and other moving objects may cross through the field of view, the moon and stars will move, and the increased time for data capture may limit the amount of data sets that can be taken in one session. These trade-offs exist and are factored in when determining how much oversampling to employ while collecting data.
Sagnac Interferometer Basics

Figure 7 showing the triangular Sagnac’s mirrors in a purely symmetric position.

The blue ray in figure 7 illustrates the path the ray would take in a purely symmetric setup. The Sagnac setup shown in Figure 7 shows a basic setup. Fringes will not exist in
this scenario. It implies a pattern where $b=0$ in equation 2. Because the CW and CCW rays are sitting right on top of one another no fringes will be visible or one large central fringe may appear but will come close to filling the entire field of view (FOV) and not show a fringe pattern but a single fringe. As the parallel exiting rays separation grows, the interference pattern changes. Shown in Figure 56 is an example of a monochromatic interference pattern as seen through a Sagnac interferometer.

Figure 8  Triangular Sagnac’s mirrors are offset from a purely symmetric position.

This illustrates the separation of the output rays as the triangular Sagnac’s mirrors are offset from a purely symmetric position. The green ray illustrates the clockwise beam, the red ray illustrates the counter clockwise beam, and the blue ray illustrates the
incoming path of the ray. One mirror is left in it’s symmetric setup while the other mirror is offset by .2 units. This gives the exiting parallel rays a separation of .3061 units.

Figure 9 This illustrates the separation of the output rays similar to Fig. 8 but with a different mirror offset of .4 units giving the displacement of the exiting parallel rays a displacement of .6123 units.

A linear relationship exists between the offset of the mirror and the separation of the parallel rays. The separation of the parallel rays due to the offset mirror determines the width of the fringes. In Figures 10 – 15 the curves represent the peaks of fringes in a monochromatic interferogram. The pattern displayed by a Sagnac and other two ray
interferometers appears linear much of the time, it is however hyperbolic. It appears more hyperbolic when the rays are close together (b is close to 0), and it appears that the fringes are linear and parallel when the rays are further apart (b>>0) on the scale of .125 inches being far apart. As b approaches 0 the interference pattern becomes more strongly hyperbolic. The Fourier transform will not be able to deconvolute a hyperbolic interference pattern and have the resulting data be meaningful unless the data is first processed to transform the hyperbolic interference pattern into a nominally parallel interference pattern. It has been determined that to avoid the hyperbolic effects of the interference pattern b should be as large as possible without aliasing the interference pattern with respect to the CCD and its range of working wavelengths. When the parallel rays are approximately .125 inches apart in a HEHSI setup including the Retiga camera with Schneider 2.2 Telexenar 70mm lens the interference pattern of 632nm wavelength light begins to alias. The 632nm light emitted from a red HeNe laser reaches the limit where the period of the interference pattern is two pixels wide. Moving the rays further than .125 inches apart will cause aliasing. The modulation appears very low when aliased compared to when not aliased. Figures 53 and 54 in Appendix A show aliased and not aliased HeNe interferograms respectively.
The group of equations (Eq. 1) arranged in Mathcad format show the general equation for the General equation of hyperbola. Using Mathcad a family of hyperbola was plotted in a way to illustrate the interference pattern seen through the Sagnac interferometer.

Eq. 2 is a simplified hyperbola formula shown in Mathcad format. Equation 2 was used
and plotted with independent variable having a vertical orientation in order to give a better graphical representation when plotted. The following variables show the numerical iterations and resolution in Figures 10 - 15.

\[
\begin{align*}
a &:= -20, -19.8 .. 20 \\
b &:= 100, 50, 25, 10, 5, 1 \\
y &:= -100, -99 .. 100
\end{align*}
\]
Figure 10 Family of hyperbola shown above where b=100. Notice the functions look parallel at the center. This region is where the Fourier transform can be used to find the frequency of the pattern.
Figure 11 Family of hyperbola shown above $b=50$
Figure 12 Family of hyperbola shown above b=25
Figure 13 Family of hyperbola shown above $b=10$
Figure 14 Family of hyperbola shown above $b=5$
Figure 15 Family of hyperbola shown above $b=1$
Figure 16  Image taken with color camera through Mark III Sagnac interferometer setup.

Figure 16 illustrates an interference pattern from a broadband (incandescent bulb) light source. The central fringe is shown by the white fringe in the middle. It also illustrates the superposition of other periodic fringes. The HEHSI instrument uses a monochromatic digital camera to acquire images. This image also shows the hyperbolic nature of the interference pattern when the parallel ray separation is small.
Figure 17  Showing how the interference patterns of different wavelength have different periods. The Fourier transform is used to deconvolute this superposition.

The multiple interference patterns created by the multiple wavelengths superimpose one on top of the other. A broadband interference pattern will look similar to a sinc2 function. Depending on the intensity of different wavelengths in the broadband light the pattern will vary.

Figure 18  Synthetic broadband interference pattern produced in MATLAB.
Using Matlab an interference pattern can be created from user defined input. In Fig. 17 two such synthetic patterns are shown. The pattern on the left has a scale factor of ten, while the pattern on the right has a scale factor of one. The interference patterns are automatically scaled from 0 to 256 for the grey scale color based on the maximum and minimum values of the 2D array before writing the array to an image. Therefore these images are more helpful in their spatial representation than in the intensity they portray. Matlab code to recreate these images is given in the Appendix B.1 and B.2.

The setup of optical components in HEHSI has the angles of the Interferometer set at $45^\circ$, $45^\circ$, $90^\circ$ with the $90^\circ$ angle between the entrance and exit of the interferometer. The placement of the mirrors is guided by a large Invar plate that is precision machined to the reference angles defined for the initial rough alignment of the interferometer. The final precision alignment is then achieved by filing small amounts off of three aluminum pads located on the base of the mirror mounts and beam splitter mount. These aluminum pads can be seen in Fig. 19. Each mirror mount is machined from a single piece of aluminum and contains a two inch front surface mirror that is held in place by a retaining ring. The mirrors used were $\lambda/20$ flatness on the front surface and made of fused silica with a silver mirror coating. The beam splitter was made of .43 inch thick fused silica with an inconel beam splitter coating on one face and a broadband antireflection coating on the other surface. The mirror and beamsplitter mounts were attached to the invar plate by $\frac{1}{4}$-20 socket cap head screws that provided the clamping force to keep the mounts attached. The invar plate was fastened to an aluminum base plate that held the interferometer, the
camera with mount and the light shield. The camera mounting bracket is an L shaped piece of aluminum that allowed for the camera to rotate around the x and y axis for alignment purposes. The light shield was constructed of 3/16” black acrylic and allowed for light entrance and cable access.

Figure 19 Five aluminum pads used for alignment of the beamsplitter and mirrors in the Mark II HEHSI instrument.

The performance of the Mark II was good in laboratory settings and it enabled success in proof of concept research. The Mark II had shortcomings that made data collection in non-laboratory settings difficult and time consuming. The main difficulty included the alignment and the stability of the alignment. Alignment was difficult to obtain and routinely took over 4 hours to align the interferometer to a desired fringe pattern.
Figure 20 illustrates the five aluminum pads used in conjunction with a $\frac{1}{4}$ -20 screw holding the mount to the invar plate for alignment of the beamsplitter and mirrors in the Mark II HEHSI instrument.

Alignment of the Mark II was achieved by visually aligning the fringes to the CCD and counting the fringes. A set of 200 image frames was captured and a Fourier transform was performed over the 200 frames to show what band the HeNe laser (632 nm) fringes were in. After interferometer alignment was achieved, movement of the interferometer would cause a change in alignment. Changes in alignment were apparent in either the misalignment of fringes to the CCD, HeNe fringes changing bands, or other obvious changes such as the loss of fringes. This was due to optical parts being able to move or slide from their aligned configuration and was expressed in the fact that the interference pattern changed from its previous state.

Vignetting was a second shortcoming, and the reduction of vignetting was desired. With
the Mark II hardware, vignetting reduced the viewable image due to mechanical obstructions in the optical path. Although the obstructions did not cause data collection failures, there was a need to maximize the usable image by removing obstructions. Obstructions took two forms. The first obstruction was the front surface mounting pads in the mirror mounts and beam splitter mount. These pads blocked a portion of the mirror and obstructed the path of the beam. The area affected by the obstruction would be larger than the obstruction itself because it would affect the modulation of any ray that had its parallel ray obstructed. So the obstruction was not only the area of the obstruction but in addition to that the height of the obstruction perpendicular to the offset of the rays multiplied the distance of the offset was an additional area where image could be seen in the collected data but without modulation because only one of the parallel rays made it through the interferometer as shown in Figure 22. These obstructions are not at first visible because image is seen in the captured data, these regions have no modulation and will lower the SNR if used for determining spectra. The extremes of the interferometers image show how modulation is lost at the when the image gets closer to the edge of the beamsplitter or mirror (whichever is the limiting aperture) than the distance the parallel rays are offset. This loss of modulation can be seen at the edges of Fig. 16 where the opaque ground edge due to the thickness of the beamsplitter clips one of the two parallel rays.
Calibration was not available in the Mark II. Although the interference pattern could be seen in the image, it was a difficult task to try to change the length of the aluminum pads by the prescribed method of removing the mirror from the assembly, shortening a pad by filing it (with precision), replacing the mirror and mount back onto the assembly and continue the alignment process. Some alignment was achieved through over tightening the hold down bolt, but because of the coarseness of the thread (1/4-20) it was not a precision adjustment and caused some bending and flexing at the base of the optic mounts that was not desirable. Achieving an alignment that was straight and visible with
the Mark II was achievable, but not repeatable, but the ability to force a calibration so that the desired fringe spacing was attained was not available until the Mark IIb. The Mark IIb was a modification made to the Mark II by the addition of a precision adjustment screw with 100 TPI. This allowed for a degree of manipulation in moving one of the mirrors by gradually adjusting its position by tilting it from below and from behind. The advantages given the Mark IIb by adding the adjustment screw showed that the Mark III must also be adjustable in this way.

**Data Collection**

Data collection with HEHSI consisted of collected a set of digital images with the HEHSI rotating through the scene. The areas of interest would need to enter from one side pass through the interference pattern and then exit the other side. Figures 22 - 24 show an image captured by HEHSI and a processed data set. Notice how different areas of the scene are bright and dark when only a certain wavelength is represented in grey scale.
Figure 23 Target board with colors to demonstrate HEHSI abilities.

Figure 24 Captured image with interference pattern showing vertical fringes.
Figure 25: Images in the (x,y,λ) hyperspectral data cube. Images appear backwards due to processing.¹
Figure 26  Showing spectra of different regions of the image. Red is on the left, blue is on the right of the graphs. The small square is a 50% reflectance target. The small circle is a WCS target. ¹
CHAPTER TWO: REQUIREMENTS AND CONSTRAINTS

2.1 Objectives for the Mark III

The objectives for the design of a Mark III version of the HEHSI instrument include the areas of concern noted from experience with the Mark II and Mark IIb instruments and additional requests for improvement. The main goal in designing the Mark III was to allow the instrument to maintain an alignment through a series of field samples. Stability affected performance. Another objective was in-situ adjustment of the optics for modifying the interference pattern. The in-situ adjustments were not for performance but rather for convenience and speed. The basic routine of gathering field samples is mentioned below.

1. Rough calibration to attain interference pattern.
2. Fine calibration to produce desired interference pattern.
3. Capture initial 200 frames of HeNe interference pattern
4. Dismantle lab setup.
5. Move instrument to outdoor position.
7. Take data samples.
8. Dismantle field setup.
9. Return instrument to lab.

10. Setup instrument inside lab.

11. Capture final 200 frames of HeNe interference pattern

The outlined procedure is to provide a basis of operations through which the Mark III hardware should remain stable. Stable in this case would refer to the interference pattern that is captured in the initial 200 frames of HeNe and the final 200 frames captured. When compared the interferogram should remain aligned in both the peak of the HeNe wavelength should be in the same band when FT is applied to the 200 frames and fringes being aligned with the same angle with respect to the CCD of the camera. The need to demonstrate the mentioned procedure with results in both categories being agreeable to each other from the initial and final 200 frames of collected data comes from the need to believe that the data is reliable. If the results of the initial and final 200 frames produce similar results it can be assumed that the alignment of the instrument remained constant between the times the two samples were acquired. This gives confidence to the data recorded in step 7. And multiple data acquisitions taken in step 7 can be said to have identical alignments if the calibration remains constant. If the calibration cannot be held constant through a data collection sequence it cannot be considered reliable and any information taken from the processed data is questionable if not wrong. When the initial and final 200 frames do not produce agreeing calibrations it is not possible to determine when the alignment was disturbed, if it was in transporting the instrument or during acquisition. Changes in alignment are small and require a calibration reading to
determine if they have been altered. Maintaining a calibration at two points (start and finish) will raise confidence in the reliability of the data throughout the capture process as well as the information taken from the processed data.

2.2 Tolerances

Each optical element in HEHSI needs to be aligned to all other optical elements. Deviations from the desired position must reside in a margin of error that will not effect the outcome of the interference pattern. Multiple degrees of freedom in the HEHSI instrument are required to ensure that the optics can be aligned. The following parts have one or more degree of freedom. Mirror 1, mirror 2, beamsplitter, camera body, Fourier lens, lens aperture. Acceptable tolerances will be discussed in this section.

Mirror tolerance

The angles of mirrors are necessary adjustments for the positioning of the image. The two images (CW and CCW) need to be aligned in such a manor that the interference pattern can be both detected and aligned. In determining what amount of control is needed with the mirror adjustment mechanism we must look at the detector to see what kind of control is necessary. The following scenario depicts a detector ROI of 512x512 pixels with each pixel being 6.5um square. The mirror adjustment mechanism should be
able to attain a fringe pattern alignment to within $\frac{1}{2}$ of a pixel over 512 pixels. In order to specify the amount of accuracy needed we will use the following numbers as given.

- Beam separation = range from .01 to .1 inches (2.54 to .254 mm)
- Minimum incremental adjustment = 1.5 degrees for minimum manual adjustment made by turning fine adjustment screw by hand.
- Pixel size 6.5 x 6.5 um
- Path lengths of the interferometer diagonal path between mirrors assumed to be 5 inches for calculation purposes at center of mirrors. (5 inches approximates the distance between mirrors, which is not constant, and is less than 5 inches. A larger number will require tighter tolerances and not undershoot the requirements of the system.)
- Maximum angular misalignment of fringes and CCD should be $\frac{1}{2}$ pixel over the 512 pixel length of the ROI. Shown in Figure 27.

As shown in Fig. 27 and Eq. (3) the maximum angle of misalignment for CCD’s with square pixels oriented in a equally spaced square pattern such as with the Retiga and Dalsa cameras is $\theta_1 = .0559^\circ$. In Fig. 27 $\theta_1$ illustrates the angle that the alignment of the interference fringes to the CCD can be misaligned, not to scale.
Figure 27 Showing pixel ratios for a column of pixels 1, 8, 64, and 512 tall by 1 wide to scale, respectively. Misalignment shown for angle $\theta_1$ not to scale.

$$\tan \theta_1 = \frac{O_1}{A_1} = \frac{.5}{512}$$

$$\theta_1 = 0.05595289^\circ$$

Eq. (3)
Figure 28  Shows an unfolded Sagnac interferometer beam path.

(a) symmetric path going CW.  (b) symmetric path going CCW.  (c) mirror D offset .2 units for a CW path.  (d) mirror D offset .2 units for a CCW path.  (e) showing how mirror C can create a vertical offset of parallel rays if rotated about horizontal axis.
Angles of mirrors in Figure 23 are around Y axis.

\[ e = \text{offset} \]
\[ \tan \theta_4 = \frac{e}{d} \]
\[ \theta_4 = a \tan \left( \frac{e}{d} \right) \]
\[ d = (.1,.01) \]
\[ \theta_4 \leq \theta_1 \]
\[ e = d \times a \tan (\theta_1) \]
\[ e = (5.595 \ E - 3.595 \ E - 4) \]

Figure 29 Rotation of one of the mirrors in the Sagnac interferometer produces a vertical offset.

The offset shown as ‘e’ causes a rotation of the fringe pattern. The rotation produced by a given offset ‘e’ is larger when the parallel beams are closer in the horizontal distance ‘d’ because the patterns slope changes more quickly for a given change in \( \theta_3 \) because of the direct relationship between ‘e’ and ‘d’ on the slope.
\[ CD = 5.0" \]
\[ a_3 = 2.5" \]
\[ \tan \theta_2 = \frac{e}{CD} \]
\[ \theta_2 = (6.411 E - 2 \text{ deg}, 6.411 E - 3 \text{ deg}) \]
\[ \theta_2 = 2 \times \theta_3 \]
\[ \tan \theta_3 = \frac{o_3}{a_3} = \frac{o_3}{2.5} \]
\[ \tan(\theta_2/2) = \frac{o_3}{a_3} = \frac{o_3}{2.5} \]
\[ o_3 = a_3 \times \tan(\theta_2/2) \]
\[ o_3 = 2.5 \times \frac{e}{CD} \]
\[ o_3 = (1.398 E - 3, 1.398 E - 4) \]
minimum angular adjustment = 1.5°
\[
\frac{360 \degree}{1.5 \degree} = 240
\]
\[ \frac{240}{o_3} = TPI = \text{threads per inch} \]  
Eq.(5)  
\[ TPI = (2.98 TPI , 29.8 TPI ) \]

Eq. (5) shows what TPI a fine adjustment screw must have to accommodate the mirror actuation. 30 TPI or greater must be used to control the alignment of the fringe pattern.

Calculations show that for a beam offset of .1 inches adjustment increments of .0139 inches (1.5 deg of 3 TPI adjustment screw) are capable of aligning to ½ pixel over 512 pixels. For an offset of .01 inches, an adjustment increment of .00139 is capable of aligning to ½ pixel over 512 pixels(1.5 deg of 30 TPI adjustment screw). When the
offset is 0 the beams are directly on top of each other and there is no interference pattern. As the beams separate the interference pattern becomes more detectable and the fringes change from a few large wide fringes detectable at small beam separations to more thin fringes at larger beam separations. These levels of adjustment will allow the pattern to be aligned in-situ.

2.3 Alignment

In order to design for the HEHSI Mark III desired improvements over the existing Mark II instrument must be realized. These include changes that will emphasize strengths and overcome flaws in the Mark II. Descriptions of areas that must be designed for to improve alignment and alignment procedure are as follows. Alignment of the HEHSI Mark II instrument is achievable, but difficult. Alignment of the Mark II was achieved by visually aligning the fringes to the CCD by visual inspection of monitor output and counting the fringes shown on the monitor. A set of 200 image frames was captured and a Fourier transform was performed over the 200 frames to show what band the HeNe laser (632 nm) fringes were in. Changes in alignment were apparent in either the misalignment of fringes to the CCD, HeNe fringes changing bands, or other obvious changes such as the loss of fringes. To achieve an alignment that is satisfactory with the Mark II can take one or more hours due to the difficulty in controlling the mirror adjustments and calibration due to the use of visual inspection of the interference pattern on a computer monitor. Starting from a totally unaligned state can take 4 or more hours
with the Mark II. Visual inspection causes eye strain after a short amount of time and the
calibration is only as good as the vision of the person performing the alignment. The
qualitative alignment needs to be succeeded by a quantitative method that will allow for
consistent calibration and alignment regardless of the operators vision. There is also the
need for the alignment to take place in less than one hour consistently.

2.4 Stability

Descriptions of areas that must be designed for to improve stability of alignment are as
follows. After observing the Mark II interferometer and its sensitivity to movement and
vibration it was determined that the cause of the instability was due to the way the
mirrors and beamsplitter were held inside their respective mounts. Although the mounts
were designed in a way that would ideally hold the optics without freedom to move, the
threads in the retaining rings used to clamp the optics against the pads used to hold them
were not able to conform to the surface of the optics. In practice the mounts were not
able to perform well enough to keep the optics stable during transportation to collect field
data. Retaining rings alone were not enough to stabilize the optics. Part of this was due
to the fact that the torque applied to a threaded retainer cannot be relied upon to produce
a specific preload.\textsuperscript{6} This allowed for the optics to be stable in one position until
disturbed. When disturbed the optics would leave the original position and settle in a
new position. This source of instability was verified on the Mark II by placing visco-
elastic rubber (sorbathane) around and behind the optics to provide constant pressure.
The beamsplitter only received sorbathane around the edges as its back surface could not be obstructed. The instabilities of the Mark II due to the optics moving in their mounts were solved when the optics were reinforced with the sorbathane.

After identifying the cause of the instabilities of the optics moving in their mounts, it is necessary that the mounts for the Mark III are not subject to this same condition. Future mounts must be able to immobilize the elements of the interferometer. Use of elastic mounting pads or spacers can be used for providing continuous pressure against the optics without causing high stress concentrations that could occur with harder materials such as metal set screws. Economically, small mirrors can be installed in commercial mounts with parallel rods for the mirror to rest on with a nylon tipped clamping screw. Excessive screw force would cause distortion and should be checked interferometrically after assembly. Distortion of the optics due to clamping force would be apparent if monochromatic fringes did not appear to be straight. Curves in the pattern would reveal that the surface of the optic was no longer flat due to distortions caused by clamping.

### 2.5 Vignetting

Descriptions of areas that must be designed for to improve the field of view due to vignetting are shown in figure x. The pads of the optic mounts in HEHSI Mark II and the edge of the beamsplitter mount should be adjusted to allow for fewer obstructions and a shorter beam path through the interferometer. Figure 30 shows how shortening the path
distance through the interferometer can reduce vignetting by having a shorter length to length to aperture ratio.
Figure 30  Illustrates a larger field of view can be achieved with a shorter beam path.
Figure 31  (a) Layout of a right-angle triangular Sagnac interferometer showing the beamsplitter cube and two mirrors; (b) unfolded layout of the same interferometer; (c) angle at which vignetting reaches 100%.2
Area where rays will be clipped if beam path were to be any smaller is determined by the size of the beamsplitter.

Figure 32  Aspect ratio for a right-angle-triangular Sagnac interferometer limited by vignetting of the beam between the two mirrors. ²

2.6 Multiple Configurations - VIS/NIR

The instrument will be used for multiple configurations. Two main configurations will be based on two current cameras. The QImaging Retiga 1300 Visible/ Very Near IR (Retiga) camera and the Indigo Systems Alpha Near IR (Alpha) camera will be two components that will drive the Configurations of the Mark III instrument. The Retiga is sensitive from 400-1000nm while the Alpha is sensitive from 900-1700nm. The difference between the two cameras range of detection will be the basis for needing to change the alignment of the interferometer. Aligning the mirrors so that the lower end of the range (400nm Retiga, 900nm Alpha) Is close to the Nyquist limit so that more fringes can be detected. Another change in configuration between the Alpha and the Retiga is
the detector size. The Alpha has fewer pixels with the pixel size being larger.

<table>
<thead>
<tr>
<th>Camera</th>
<th>Columns</th>
<th>Rows</th>
<th>Pixel size</th>
<th>Bit depth</th>
<th>Detector Size</th>
<th>512x512 size</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>QImaging Retiga 1300</td>
<td>1280</td>
<td>1024</td>
<td>6.5x6.5µm</td>
<td>12 bits</td>
<td>8.32x6.65mm</td>
<td>3.32x3.32mm</td>
<td>400-1000nm</td>
</tr>
<tr>
<td>Dalsa Dalstar 1M30</td>
<td>1024</td>
<td>1024</td>
<td>12x12µm</td>
<td>12 bits</td>
<td>12.3x12.3mm</td>
<td>6.15mm x 6.15mm</td>
<td>400-1000nm</td>
</tr>
<tr>
<td>Indigo Alpha NIR</td>
<td>320</td>
<td>256</td>
<td>30x30µm</td>
<td>12 bits</td>
<td>9.6x7.68mm</td>
<td>Limited to 320x256 at 9.6x7.68mm</td>
<td>900-1700nm</td>
</tr>
</tbody>
</table>

Table 3 Camera detector sizes.

The differences between the two cameras in ability and size require the interferometer setup to have the ability to accommodate both cameras in alignment. The constraints of alignment will be driven by the Retiga as it has smaller pixels and more elements in the CCD array. While the vignetting which is already being minimized by shortening the beam path will be more noticeable on the Alpha due to its larger CCD array. A lens with higher focal length would be necessary to reduce the effects of vignetting without changing all the optics (mirrors, beamsplitter, and mounts) to a larger size in order to accommodate the larger CCD array.
2.7 Accessibility

Descriptions of areas that must be designed for to improve accessibility to adjustment mechanisms for purposes of alignment and focusing are as follows. The screws on the Mark II are hard to access. When accessing the screws to tighten the mounts to the invar during alignment, the tools used to tighten the screws obstructed the path of the beam. The obstruction of the beam path during adjustment made the alignment process difficult due to the need to remove the screw driver to see if an adjustment caused the alignment to improve or degrade. The aluminum pads shown in Figure 19 that were used for fine adjustment were less accessible during adjustment due to the fact that the pad to be filed down must be removed from the instrument to be adjusted. The pads were also only adjustable in one direction. They could be filed smaller but not made larger. In order to remove the pad, the mirror or beamsplitter mount to which the pad was attached must first be removed. The camera and lens being located inside the black acrylic housing prevent the adjustment of focus and iris aperture while the cover is in place. Adjustments to the focus and iris would be more convenient if they were accessible while the cover was in place. The placement of the hardware in the Mark II is not convenient to adjust and as such is an obstacle for adjustment should be avoided in the mark III.

The mark III should take consideration of the obstacles for adjusting in the mark II and
allow for access to adjustment to be available without obstructing the path of light used to help guide the alignment. Removal of the optics should not be required in the mark III as it is time consuming and can cause a misalignment while trying to align the instrument. Such presents a conflict in interest between aligning and misaligning and should be avoided. Optics should remain in place with the beam path unobstructed in order to ascertain if an adjustment made to the alignment is an improvement during adjustment. This will facilitate alignment in both the number of steps in procedures necessary to make adjustment and the amount of time required to make the adjustment. In the Mark III adjustments should be able to be made while all covers are in place. This will remove the opportunity for cover removal process to disturb the optics and increased accessibility.
CHAPTER THREE: DESIGN

3.1 Beam Path

The beam path for the mark III should be as short as possible to reduce the effects of vignetting and to aid in alignment. The beam path should not be shortened to the extent that the beam splitter or beam splitter mount will clip the 45° portion of the Sagnac’s triangle.

3.2 Modularity

The instrument is to be designed with modularity in mind order to facilitate smooth transitions through multiple configurations of the instrument. Modularity will include the ability of the instrument to use multiple cameras with multiple lens configurations, allowances for apertures and light baffles at the entrance, and the options for fore-optics that will be placed between the entrance aperture and the target. To allow for the many different configurations that are possible is difficult because of the lack of foreknowledge concerning components that may be desire in future configurations. The design will
allow the separation of the interferometer assembly, camera, and fore-optics is desired and will allow for interfacing different components in a straightforward manner. A flat bulkhead is used to make the modular interface straightforward. Any camera should be able to interface with the interferometer housing with bolt holes in a simple rectangular configuration.

3.3 Components

The instrument for reasons of price and replacement of parts will use off the shelf components. Off the shelf components although not optimized for use in this instrument allow development with greater speed. Components although not custom made for HEHSI are selected for optimal performance.

Mirrors

Standard $\lambda/20$ mirrors are available OTS in sizes up to 2” circular. These mirrors will be used and are available from a wide variety of suppliers. Larger $\lambda/20$ mirrors are not commercially available. This will drive the size of the mirror mounts as well.
**Beamsplitter**

Commercial beamsplitters are available in many varieties. Broadband beamsplitters with 50/50 transmission reflection ratios are not common. The best choice for this is a Inconel plate beamsplitter on fused silica. Inconel can have a flat broadband profile as shown in Figure 39. However it must be used at a 45° angle to perform as specified.

**Mirror mounts**

Mirror mounts chosen are the Thorlabs 2” Ultra-stable kinematic mounts. They provide 80 TPI adjustment screws and have nylon tipped set screws to hold the optic in place. The optic rests on two positioning edges (rods) that are machined into the body of the mount. The stiff springs that appose the adjustment screws provide a stable working environment. The adjustment screw tips seat in a cone, rod, and flat configuration for stability.
Figure 33 Thorlab Ultrastable Kinematic mirror mounts.

Beam splitter mount

Figure 34 Newport beamsplitter mount (left) and modified Newport beamsplitter mount used in HEHSI (right).
The beamsplitter mount chosen was a Newport Ultima 2” model (Fig. 34) that had a nylon tipped screw as well as open side. The open side of the mount allowed for shorter path lengths without clipping rays. The mount was modified by removing the back portion of the mount including the half that holds the adjustment screws and placing holes in the bottom of the mount to rigidly mount it to the HEHSI housing. No adjustments will be made to the placement of the beamsplitter as it will be a datum by which all other components will be adjusted to.

Housing

A custom housing made for HEHSI will mount the Sagnac components, mirror mounts, beamsplitter mount, and the respective optics. It will also have mounting surfaces for the camera brackets that will attach to it and fore-optic attachment points.
Figure 35  The HEHSI Mark III functioning in the field.

Figure 36  HEHSI Mark III with lid and camera mount removed.
Lens

The foremost lens used with HEHSI is the Schneider 70mm Telexenar f2.2 (shown in fig. 37 attached to the Qimaging Retiga 1300 camera). It demonstrates the capabilities that HEHSI needs in being corrected for wavelengths 400nm – 1000nm. It is also useful in the NIR up until 1500nm where the AR coatings in the lens will prohibit use further into the IR. The limitation due to the AR coatings was found after using the Indigo Alpha camera with HEHSI. The fact that it is corrected for these wavelengths is rare and the 70mm Telexenar’s other competitor was the 35mm Telexenar also sold by Schneider. The lens has manual focus and manual iris. Versions of this lens with electric iris are also available. An additional lens was added later for the Alpha with 900nm – 1700nm wavelength correction. This lens was made by Optec S.R.L. The Optec lens was a 100mm lens. The longer focal length helped reduce vignetting that was already exaggerated by the larger pixel sizes on the Alpha’s CCD.

Figure 37  Indigo Alpha with Optec 100mm lens (top), Qimaging Retiga 1300 with Schneider 70mm Telexenar f2.2 lens (bottom).
3.4 Mounting Points / Stability

From the modular design of the instrument there is a need to make sure that the different modules with their housings are able to securely mate with one another so that instabilities do not occur. Mounting points had a large rectangular ¼-20 bolt pattern consisting of 4 bolts. This was sufficiently strong to attach any camera with bracket to the interferometer portion of HEHSI.

3.5 Adjustments

Each of the components in the HEHSI Instrument has multiple possible degrees of freedom. It is possible to remove some degrees of freedom in order to force alignments to be made using the other available adjustments. It is necessary to determine which degrees of freedom will stay and which will be removed. Removal of DOF’s will help constrain the system and remove areas where misalignments can occur.
CHAPTER FOUR: ALIGNMENT PROCEDURES

4.1 Introduction

Optimization of camera focus for higher modulation and higher signal to noise ratio along with adjustment of mirror alignment for spectral scale control and central fringe placement will allow for the highest quality of data. Methods for achieving the optimal alignment states are developed in order to give feedback on quality of alignment and facilitate the speed at which the alignment can be reached. Experimental results show the effectiveness of these methods in achieving the optimal alignment in a Sagnac interferometer based hyperspectral imager. Optimal alignment of a hyperspectral imager allows for repeatability in calibration. Optical alignment can also prevent reduction in signal modulation by focusing the lens correctly on the interference pattern. Data captured will be of higher quality when all optics are aligned optimally.

The current method for aligning the Sagnac interferometer in the HEHSI Mark II uses manual adjustment of mirror actuators and lens focusing. Feedback for alignment is provided by a real time histogram of signal levels and by visual observation of displayed image with non-real time Fourier transform over a region of interest being performed.
Current improvements allow for real time feedback of alignment parameters. Quantitative parameters enhance the ability to align over qualitative judgments based on visual inspection from a video display.

### 4.2 Alignment of System

Alignment of the HEHSI hyperspectral imager incorporates the alignment of the interferometer and the camera. Using image processing to optimize the alignment of these integral parts produces a quantitative approach to acquiring quality data.

#### Fourier Transform Hyperspectral Imager

The Sagnac interferometer uses a beam splitter to divide incoming light into two paths. When the light exits the interferometer the two paths have a horizontal offset and are recombined with a lens creating an interference pattern at the CCD. The Fourier transform can decompose the interference pattern into a spectrum for each individual pixel. Alignment of the optics in the interferometer, which includes two mirrors and a beam splitter, is vitally important to quality of the data.
Misalignment in any of the degrees of freedom will cause a change in the interference pattern. Changes could include reduction of usable signal, which reduces the signal to noise ratio. Addition processing may be required to correct for changes in alignment that change the interference pattern from its optimum. Processing time can take hours to days depending on the size of the dataset that must be processed. By aligning the camera and interferometer correctly, processing time can be shorter. By having the central fringe aligned to the CCD, processing that would rotate the scanning velocity of a target into the coordinate system of the fringes can be avoided. This paper discusses the process and algorithms to insure an optimal optical alignment of both interferometer and camera. A feedback loop is composed of the digital camera, and a computer running National Instruments LabVIEW. The image is analyzed in LabVIEW and evaluated based on its characteristics of focus and alignment.

Figure 38  Basic Configuration of Spectrometer

Incremental changes to the focus and alignment will be made until a position is found that receives the highest evaluation in both focus and alignment. Evaluation and
weighting algorithms determine which adjustments are made first and keep the alignment process converging toward the optimum. The interference pattern in a Sagnac interferometer is in focus only when the camera is focused at infinity (Steel). Because of this the process of focusing the lens of the camera through the interferometer is different than with normal cameras focusing on a target. The camera lens focusing through the interferometer does not focus on the target in front of the spectrometer. The camera focuses on the interference pattern generated by the interferometer, which is at an infinite distance.

Figure 39 Interference patterns of monochromatic light (left) appear as a cosine function. Interference patterns of broadband white light (right) appear as sinc² function.

Different approaches to finding the optimal focus at infinity are discussed. Improper alignment of the angle of the mirrors may cause the spatial frequency in the interferogram corresponding to the shorter wavelengths to exceed the Nyquist limit. This occurs when the period of the interference pattern is less than two pixels per fringe. This extreme must be avoided for the wavelengths of interest. Optimal mirror placement can reduce the
effects of vignetting by shortening the distance light must travel through the interferometer. This allows for the camera to be able to use more of its field of view. Moving the mirrors closer to the beam splitter allows for a shorter path. If the mirrors are moved too close to the beam splitter they will have light rays clipped by the beam splitter as shown in Figure 33. An optimal distance is found between mirrors and beam splitter to reduce vignetting. Placement of the central fringe within field of view is necessary for extraction of spectra from the interference pattern.

Focusing of the lens is a single degree of freedom. Multiple additional degrees of freedom must be exploited in positioning the mirrors in their optical locations. Each mirror has three degrees of freedom for a total of six degrees of freedom for two mirrors. The mirrors must be adjusted in the correct order in order to reach the optimal position. As alignment converges on the optimal position the process for alignment cycles through the various criteria, making sure that all criteria for alignment converge.

Efficient Hyperspectral Imaging using HEHSI requires that the optics be aligned so that collected data will contain as much usable information as possible. The images must contain an interference pattern in order to extract spectral data from the images. By resampling a series of acquired images and performing a Fourier transform over them, the spectral content of each pixel can be found. In order to extract the most information from the interference patterns contained in the images, optimal alignment should be achieved.
Working with HEHSI creates the need for a set of algorithms in order to insure that alignment and calibration are carried out in a standardized procedure. Following a standardized procedure adds confidence that when comparing data acquired from different spectrometers or at different times and different locations, they will align spectrally. If standardized procedures are not followed, different states of alignment and calibration may be reached, and the spectrum from one dataset may not align with the spectrum from another dataset. With this in mind a procedure for aligning a Fourier transform imaging spectrometer will be outlined.

4.3 Procedure for Alignment

The following procedure steps will allow for a repeatable calibration of the current Sagnac interferometer based Fourier transform hyperspectral imager.

Interferometer Setup

The Sagnac interferometer should be setup with the beam splitter at 45 degrees to both incoming and outgoing chief rays. The Inconel (inconel is a sputtered on beamsplitter coating) beam splitter coating is optimized to provide a 50:50 ratio for transmitted and reflected light when used at 45 degrees. As the path of the chief ray departs from the
optimal angle of 45 degrees the transmitted and reflected light will stray from a 50:50 ratio and thus reduce the modulation of the interferogram.\textsuperscript{2, 16, 19, 20}

\textbf{Align Offset Images}

Focus camera lens on an object in the field of view. The camera will later be focused at infinity in step 3, but for step 2 the camera should focus on a target to allow for image alignment. Align the mirrors so that the dual images created by clockwise and counterclockwise paths lay on top of each other. The two images must be superimposed, one on top of the other, with a slight offset. This will allow for the viewing of the interference pattern in step 3.

\textbf{Focus Camera on Interference Pattern}

Focus camera lens at or near infinity. This change in focus of the camera is necessary to be able to see the interference pattern. Do not focus on a target in the field of view. Focusing the lens at infinity allows for the parallel rays that were established by splitting the incoming light with the beam splitter to focus at the camera’s CCD. In order to determine when the camera lens is at its’ optimal focus use the brightest pixel in the interference pattern.
Using LabVIEW it is possible to find the pixel with the highest signal (or ‘brightness’) in a region of interest. After acquiring the image a LabVIEW VI (virtual instrument) will poll the image and return the largest pixel value from the region of interest. This technique of using the highest signal, which will occur in the center of the central fringe when using a flat field and white light, will give a value that will be used to find the optimal focus of the lens. Using this functionality to acquire real time images from the camera and display quantitative information pertaining to the signal levels enables focusing of the camera lens to a higher precision than that achievable by visual inspection of the images output to a display device. With a flat field in the region of interest it is important that the brightest pixels are not saturated when the interference pattern is in focus. This must be done to insure proper radiometric calibration. When the interference pattern comes into focus using white light the center bright fringe will be approximately twice as bright as when viewing the same target when the interference pattern was not in focus. The dark fringes will not have their signal go to zero with white light, but if illuminated with monochromatic light the value of the center of the dark fringes should ideally approach zero. Monochromatic light will not, however, produce zero signals because of the integration of the interferogram across the pixel. If completely destructive interference were to take place at one location on the pixel the surrounding locations would not have only partially destructive interference due to the function of the interference pattern itself.
**Align Central Fringe to the Zero Path Difference**

Align the central fringe to the zero point. The interference pattern will appear without the center fringe being aligned to the zero path difference point. By rotating a mirror about its X axis the fringe pattern will rotate. When the fringe pattern rotates, it can be seen that there is a center of rotation. Ideally the center of rotation will be a point on the center fringe of the interference pattern produced when viewing white light. In order to force the central fringe to coexist on the center of rotation both mirrors must be aligned to the beam splitter with equal angles. By visual inspection a center of rotation can be judged.

Multiple iterations of adjustment must be made to insure that the central fringe coincides with the center of rotation.

**Center Central Fringe in Region of Interest**

Now that the central fringe of the interference pattern is aligned to the center of rotation, alignment of the camera can be made to the interference pattern. Care should be taken to make sure that the interference pattern resides so that the vignetting from the system is minimized. The central fringe should also reside in the center of the image where aberrations due to the lens are the smallest. Depending on the region of interest to be captured this may be more or less difficult. If the camera has a frame size of 1280 x 1024
pixels, and the only a 512 x 512 region of interest is to be captured, then there is more
freedom than if the camera needs to capture all 1280 x 1024 pixels in each frame.26

**Calibrate to Known Source**

The hyperspectral imager can now be spectrally calibrated. This can be done by using a
monochromatic light source of known wavelength such as a 633 nm HeNe laser. The
laser beam should pass through a beam expander and a diffuser in order to produce
somewhat uniform illumination across the field of view. Other light sources can also be
used for calibration as long as they have known spectral characteristics such as an
absorption line or an emission line. The frequency of the interference pattern within the
region of interest can now be calibrated. By translating the mirror toward or away from
the beam splitter along the mirrors Z axis without allowing any change in the rotation
about the X or Y axis of the mirror the frequency of the interference pattern will grow or
shrink.
Figure 40  A 633nm red HeNe interference pattern and real time Fourier transform channel designation.

A LabVIEW interface is used to produce a real time graphical display of the Fourier transform of a row or column (depending on camera orientation) of the acquired image. This display creates feedback that shows the current frequency of the fringes created by the monochromatic light source inside the region of interest. With feedback, adjustments can be made that will place the peak of an emission source at the desired frequency. For example, a red HeNe laser could repeatedly be placed at a frequency of 43 fringes over a 512 x 512 pixel region of interest.
Align Fringes to CCD

Align the interference pattern to the CCD array. The interference pattern should be aligned parallel to either the rows or the columns of the CCD. LabVIEW can be used to align the interference pattern to a precision beyond that possible with only visual inspection. By acquiring real time images LabVIEW can process them to show when the fringes are aligned to the CCD. To accomplish this, the pixels in the region of interest are averaged along rows (or columns) in the direction that is parallel with the fringes. The result is a single one-dimensional array that contains the average profile of the region of interest. Taking the pixel with the highest signal and comparing it to the signal from the other pixels while the mirror is being adjusted will indicate when the mirrors are most accurately aligned to the CCD.

Figure 41  Modulation and highest pixel values after averaging across all rows in the region of interest. The fringes are not aligned to the CCD. The highest signal is 65 DN.
When the fringes are not aligned parallel to a row or column of the CCD the measured modulation of the interferogram will be reduced. Optimal alignment is achieved by driving the angle of the mirrors to maximize the modulation in the interferogram, which in turn maximizes the signal in the resulting spectrum.

Figure 42  Shows the interferogram and the resulting spectrum after averaging across all rows in the region of interest. The fringes are aligned to the CCD when the signal in the spectrum is maximized. The highest pixel signal is 90 DN. Which illustrates a greater degree of alignment than Figure 41 with a signal of 65 DN.

Rough alignment is an important starting point after which fine alignment can take place. Rough alignment is performed with a HeNe laser for Vis/NIR optics. MWIR optics can also aligned roughly with a HeNe laser even though they do not transmit as well in the visible range. There are two parts to the rough alignment
1. Align optics to a nominal 45°, 45°, 90° triangle in the interferometer housing.

2. Create a real visible interference pattern from the two HeNe beams exiting the Mark III entrance aperture.

Mechanical parts are designed for a 45°, 45°, 90° Sagnac setup. Deviating from the proposed setup will cause one or more of the following effects:

1. Reduce clear aperture / Increase vignetting from beamsplitter

2. Remove beamsplitter from its 50% Transmission / 50% Reflection angle of 45°.

3. Misalign the Interferometer with respect to the camera.
Figure 43  Inconel beamsplitter profiles showing limits of performance.\textsuperscript{19, 20}

The housing is designed to place the beam splitter and mirror mounts in their nominal locations. Rough alignment is manual adjustment of the mirror mounts in order to create an interference pattern. The quality of the interferogram will be the scope of fine adjustment of the interferometer. Care needs to be taken to avoid moving the housing with respect to the incoming beam during rough alignment once a good nominally perpendicular angle is made.

The visual inspection of the rough alignment should start with the laser entering the housing perpendicular to the housing and at 45° to the beamsplitter. The laser should pass through the center of the beamsplitter. Rough alignment of the interferometer is complete when an interference pattern can be seen from the exiting rays interfering with each other. 50% of light that enters the interferometer will exit through the entrance. For visibility and accessibility and to avoid removing the camera it is easiest to rough align using the laser beams exiting the entrance aperture. The exit beams should be parallel to
the inbound beam if the in beam is perpendicular to the housing. By manually aligning the mirrors the exit beams can be made to converge to an approximate point. When the two beams are parallel with a small offset, an interference pattern will appear.

Fine Alignment takes over where rough alignment leaves off. Once rough alignment has established a 45°, 45°, 90° triangle beam path and created an interference pattern fine alignment can begin. Fine alignment uses the camera to display the interference pattern and all qualitative judgments on the interferogram will be done based on the output from the camera. Initial alignment techniques involved a visual analysis of the camera output on a computer screen. The first step in fine alignment is to look at a broadband light source with the instrument. Such targets as a white wall illuminated by an incandescent bulb or other source can be used. Adjustments to position the interference pattern will be made while looking at the interferogram displayed on the screen. The first part of fine adjustment will be to force the central fringe of the interference pattern to the center of the CCD. This should be done first by moving the camera mount and second by moving the mirrors. The camera mount provides a gross adjustment that could (if far enough out of alignment) cause the removal of the beam path from 45°, 45°, 90° if the adjustment were made by moving only the mirrors and not the camera mount.
To aid in the quantitative analysis of the fringe quality an alignment program was created using National Instruments LabView software (Labview). The program’s usefulness helps in determining the alignment in a way that the human eye cannot. The program can give numerical values which indicate a degree of alignment. The program can also help in optimizing the focus. Figures in Appendix A illustrate screen shots taken from the alignment utility.
START

Acquire Streaming Image Data

i=0 or i>0

i=0 or i>0

i>0 Output 2D image of ROI to front panel.

i>0 Output 2D image of ROI to front panel.

Output graph 1D array as histogram showing modulation.

Sum pixel values of 2D array into 1D array along fringe direction.

Perform Fourier Transform over 1D array.

Output graph of 1D array of FT as wavelength bands.

Stop or continue open loop

STOP
Figure 45  Labview utility G code (Graphical Programming Environment). ROI select (top), continuous update with front panel (bottom).
Figure 46  LabVIEW utility front panel user interface.
Figure 47  Labview utility with HEHSI Mark III aligned with a 632nm HeNe laser in band 43.
Figure 48  LabVIEW utility with white light. FT showing light in bands 23 through 41. Histogram peak at central fringe is 80 DN.

The program first captures a single frame of 12 bit data from the camera. The data is placed in a 2D array variable. The 2D array is both output to the screen and averaged in the cross track direction. The cross track direction is parallel to the fringes. The average is output into a 1D array. There are two reasons for averaging in the cross track direction. The first reason is that when using laser light to illuminate the instrument with monochromatic light there is laser speckle. Laser speckle causes the interferogram to
have hot spots that show up as noise. By averaging in the cross track dimension the noise
is averaged out and a cleaner 1D interferogram results. The second reason is for speed.
With previous alignment routines 200 frames of laser light were acquired and averaged in
the k direction (x and y represent the image and k represents the frame #). This method
of averaging over 200 frames could not promote a real time response for alignment
purposes. If the camera ran at 20 frames per second, the averaged array would become
available every 10 seconds. Using the utility in real time is an advantage over non-real
time because it allows the user to become familiar with the adjustments being made by
using real time feedback to determine the result of each incremental adjustment to the
alignment of the interferometer. This real time feedback allows the users to familiarize
themselves with the instrument faster than if each adjustment took 10 or more seconds to
give feedback pertaining to the adjustment.

The 1D array is displayed in the upper left corner graph. This graph displays the average
pixel intensities of the 2D array. The average intensities then have a FFT performed
across the 1D array and the spectrum of the 1D array is output as the lower left corner
graph. This graph shows the spectra of the entire 2D array. It does not perform any
spectral imaging as it is useful only with a flat field input. If spatially modulated images
were viewed the calibration would not be representative of any part of the image, but
would represent the average of the entire image.
CHAPTER FIVE: CONCLUSIONS

5.1 Conclusions

By implementing a standard procedure to align a hyperspectral imager, repeatable
calibration can be achieved. The use of quantitative feedback in the alignment is very
important due to the limitations of aligning an interferometer by visual inspection alone.
LabVIEW facilitated the acquisition and analysis of real time images providing a tool to
gain the feedback that was necessary to accomplish optimal alignment. The use of this
alignment utility in conjunction with the HEHSI Mark III instrument has made repeatable
alignment achievable. It also allows for quantifiable alignments and focusing which were
only done to visual inspection previous to this alignment utility.

The modifications to the HEHSI design resulting in the Mark III instrument allowed for
the acquisition of field measurements without loss of calibration. The addition of in-situ
adjustment made the instrument easier to calibrate and more robust in it’s ability to
achieve desired fringe spacings. Vignetting was reduced by the choice of optic mounts
that allowed for shorter beam path.

The HEHSI Mark III instrument allowed for a proof of concept instrument to evolve into
a prototype instrument that has successfully demonstrated user friendly interface, stability
in alignment throughout transport and acquisition of field data, and repeatability from its ability to have repeatable calibrations.

5.2 Future Development

Future development may include advances in hardware and software for the advancement of the instrument. Hardware advances may include rectangular mirrors and beamsplitters to compliment the rectangular CCD sensor, motorized actuators for mirrors and focus, lens corrected for wavelength range with longer focal distance, actuators with more precision, instrument mounted diffuse monochromatic light sources. Another hardware advance that should come in the future is a calibrated light source attached to the HEHSI housing that would be used in the field for multiple field calibrations. Software advances may include incorporating motor control into the alignment program for automated fine alignment, image processing to remove effects of lens aberration from the image, adaptive learning for faster motorized alignment, include instructions in software for directing the alignment based on image quality.

Rectangular optics to replace the current circular optics will allow for less vignetting. Larger rectangular optics with L/20 surfaces would be custom items and more expensive. A corrected lens with longer focal ratio would allow for higher spatial resolution as well as a way to maximize the available aperture size. Possibly a 100mm or even 200mm lens corrected for the wavelengths of interest will be available in the future.
APPENDIX A
DATA IMAGES
Appendix A contains images of data taken from the labview alignment utility. Each image contains 3 windows. The right window contains the image being received by the cameras CCD. The upper left window shows a 1D histogram of the image as the 2D image is summed over rows or columns in the direction of the fringes. The lower left window shows a Fourier transform of the 1D data in the histogram in the upper left window. The lower right window shows the spectral bands. These bands are useful when calibrated in determining the spectral content. These images do not show hyperspectral images, only one set of spectra is shown and it is for the average of the image. Hence this utility is utilized best when calibrating to flat fields where there is no spatial data.
Figure 49  HeNe at the Nyquist limit of a ROI that is 512 in the y direction.

The HeNe peak appears at band 256. Only 256 band are given with a 512 tall image with the fringes oriented with the x direction. As the fringes period becomes smaller than two pixels the HeNe peak becomes aliased and moves back to band 255 while its peak decreases. It continues to move backwards and shrink as it is further aliased.
Figure 50  Peaks in fluorescent light showing up in bands 92 (red) 104 (green) and 113 (blue).  Green peak at value of 11 DN.
Figure 51  Peaks in fluorescent light showing up in bands 45 (red) 49 (green) and 54 (blue).  Green peak at value of 28 DN.
Figure 52  Peaks in fluorescent light showing up in bands 140 (red) 154 (green) and 170 (blue). Red peak at value of 3 DN.
Figure 53  Fluorescent light past the Nyquist limit. No peaks show.
Figure 54  HeNe peak in band 43. Peak is 515 DN.
Figure 55  HeNe peak past Nyquist limit. Aliased.
Figure 56  ROI taken from image with rectangle selection tool in LabVIEW G code.

632nm red HeNe laser light in band 43.
Figure 57 Screen shot for ROI rectangle selection tool in G code. HeNe interference pattern is visible with vignetted edges.
Figure 58  Shows an off axis view of white light where the interference pattern exhibits hyperbolic traits.
Figure 59  Closeup of HeNe fringes. Peak is in band 10 with a secondary peak in band
Figure 60  Broadband light with fringes aligned to CCD. Central fringe in histogram shows 6320 DN. FT shows light in bands 30 through 51. (set1)
Figure 61  Broadband light not aligned to CCD. (set 1)
Figure 62  Broadband light not aligned to CCD.  (set1)
Figure 63  Broadband light not aligned to CCD. (set1)
Figure 64  Broadband light aligned to CCD.  (set 2)
Figure 65  Broadband light not aligned to CCD. (set 2)
Figure 66  Broadband light not aligned to CCD. (set 2)
Figure 67 Broadband light aligned to CCD. (set 3)
Figure 68  Broadband light not aligned to CCD.  Rotated about zero point. (set 3)
Figure 69  Broadband light not aligned to CCD. Rotated about zero point. (set 3)
Figure 70  Broadband light aligned to CCD. Histogram peak of central fringe showing 3100 DN and FT peak at band 62. (set 5)
Figure 71  Broadband light showing small modulation in upper window even though not aligned. This shows aliasing as the fringes have shifted past each other in the y direction because of the angle of rotation. Histogram peak at 2350 DN with no notable peak in FT bands.  (set 5)
Figure 72  Blue LED showing small modulation in upper window even though not aligned. Notice central fringe cannot be identified readily with crooked fringes. (set 6)
Figure 73  Blue LED showing large modulation in upper window while aligned.  (set 6)
Figure 74  Blue LED showing large modulation in upper window while aligned. (set 6)
Figure 75  Rotating around zero point with blue LED light. Looking at how the central fringe is not apparent with crooked fringes. (set 6)
Figure Rotating around zero point with blue LED light. Looking at how the central fringe is not apparent with crooked fringes. (set 7)
Figure 76  Rotating around zero point with blue LED light. (set 7)
Figure 77  Rotating around zero point with blue LED light. Looking at how the central fringe is not apparent with crooked fringes. (set 7)
Figure 78  Rotating around zero point with blue LED light. Looking at how the central fringe is not apparent with crooked fringes. (set 7)
Figure 79 Rotating around zero point with white light. Looking at how the central fringe is not apparent with crooked fringes. (set 8)
Figure 80  Rotating around zero point with white light.  (set 8)
Figure 81 Rotating around zero point with white light. Looking at how the central fringe is not apparent with crooked fringes. (set 8)
Figure 82  Rotating around zero point with white light. Looking at how the central fringe is not apparent with crooked fringes. (set 8)
APPENDIX B
PROGRAM CODE
MATLAB Code for Broadband Interference Pattern

```matlab
a = zeros(512,512);
for d = 1:size(a,2)
    for c = 1:size(a,1)
        shift = 256;
        scale=1;
        scx1=(scale*(d-.5-shift));
        scx2=(scale*(d-0.4-shift));
        scx3=(scale*(d-0.3-shift));
        scx4=(scale*(d-0.2-shift));
        scx5=(scale*(d-0.1-shift));
        scx6=(scale*(d-shift));
        scx7=(scale*(d+0.1-shift));
        scx8=(scale*(d+0.2-shift));
        scx9=(scale*(d+0.3-shift));
        scx10=(scale*(d+0.4-shift));
        scx11=(scale*(d+0.5-shift));
        sc1=sin(scx1)/scx1;
        sc2=sin(scx2)/scx2;
        sc3=sin(scx3)/scx3;
        sc4=sin(scx4)/scx4;
        sc5=sin(scx5)/scx5;
        sc6=sin(scx6)/scx6;
        sc7=sin(scx7)/scx7;
        sc8=sin(scx8)/scx8;
        sc9=sin(scx9)/scx9;
        sc10=sin(scx10)/scx10;
        sc11=sin(scx11)/scx11;
        sctotal=(sc1+sc2+sc3+sc4+sc5+sc6+sc7+sc8+sc9+sc10+sc11)/11;
        a(c,d)=sctotal;
    end
end
imwrite(mat2gray(a),'scale1.tif')```

MATLAB Code for Cosine Interference Patterns

```matlab
a = zeros(512,512);
for d = 1:size(a,2)
    for c = 1:size(a,1)
        a(c,d)=10*cos(8*(d-256));
        e(c,d)=10*cos(3*2*3.1415*(d-256));
        f(c,d)=5*cos(5*(d-256));
        g(c,d)=15*cos(12*(d-256));
        i(c,d)=15*cos(1*(d-256));
        j(c,d)=15*cos(2*(d-256));
        k(c,d)=15*cos(3*(d-256));
        l(c,d)=15*cos(4*(d-256));
    end
end
h=a+f+g+e;
imwrite(mat2gray(a),'suma.tif')
imwrite(mat2gray(e),'sume.tif')
imwrite(mat2gray(h),'sumh.tif')
imwrite(mat2gray(f),'sumf.tif')
imwrite(mat2gray(g),'sumg.tif')
imwrite(mat2gray(i),'sumi.tif')
imwrite(mat2gray(j),'sumj.tif')
imwrite(mat2gray(k),'sumk.tif')
imwrite(mat2gray(l),'suml.tif');
```


Krista Carver, Graphing Conic Sections. 

MULTIPLE APPLICATIONS FOR AIRBORNE HYPERSPECTRAL SENSORS*
J. Ellis, H. Davis, and M. Quinn.  HJW GeoSpatial, Inc., Oakland, California, U.S.A.


Aaron J. Wilson and J. Bruce Rafert, TIME INDEPENDENT FOURIER TRANSFORM HYPERSPECTRAL IMAGER, Michigan Technological University, Houghton, Michigan, USA.

http://www.csr.utexas.edu/projects/rs/hrs/classify.html

Oriel Instruments, BEAM SPLITTERS TECHNICAL DISCUSSION.  

Oriel Instruments, INCONEL BEAM SPLITTERS.  

James M. Ellis, Hattie H. Davis, and Michael B. Quinn, MULTIPLE APPLICATIONS FOR AIRBORNE HYPERSPECTRAL SENSORS.  HJW GeoSpatial, Inc., Oakland, California, U.S.A.  


