



**Satellite Propulsion Spectral Signature
Detection and Analysis for Space Situational
Awareness using Small Telescopes**

DISSERTATION

Pamela L. Wheeler, Major, USAF
AFIT-ENY-DS-17-S-063

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SATELLITE PROPULSION SPECTRAL SIGNATURE DETECTION
AND ANALYSIS FOR SPACE SITUATIONAL AWARENESS
USING SMALL TELESCOPES

DISSERTATION

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Degree of Doctor of Philosophy

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Abstract

Safe satellite operations are of utmost importance in today's congested and contested space environment. Maintaining precise orbital maintenance places stringent performance requirements on current propulsion systems, which are often electric propulsion systems due to the savings offered in both spacecraft mass and launch costs. Electron temperature is a commonly used diagnostic to determine the performance of a Hall thruster, and recent work has correlated near infrared (NIR) spectral measurements of ionization lines of xenon and krypton to electron temperature measurements. In the research herein, appropriate line spectra ratios are identified for each propellant type when used with remote space-to-ground observations. Next NIR plume emissions were used to characterize a 600 Watt Hall thruster using either xenon or krypton propellant for a variety of observation angles and operating power levels. Laboratory tests were performed and reported on, and an end-to-end model was developed to predict the signal-to-noise ratio (SNR) of an on-orbit operating Hall thruster when viewed from a terrestrial telescope. For the model, a collision radiative model of the thruster plume and a precise atmospheric transmission model are combined with an optical telescope/camera model. Good agreement between the model's SNR prediction and several observed celestial star spectra was achieved. It was concluded that the operating power of a Hall thruster could be determined from observed spectral ratios, and that the measurements were constant across a wide range of viewing angles. It was also determined that small commercial telescopes would be incapable of achieving the desired SNR when observing low-Earth and geosynchronous satellite thruster firings, however the model could have utility in remote thruster performance measurements with observations from high-altitude aircraft or other space-borne platforms.

*One does not discover new lands without consenting
to lose sight of the shore for a very long time.*

-Andre Gide

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I especially owe the completion of this work to my husband and sons. Without their love and support I would not have been able to dedicate the time and energy I needed to complete this effort. Having a second child while working on my dissertation was challenging, but my husband was there every step of the way to make sure I never lost my focus. Our kids kept me focused on what was truly important... our family. Knowing that they would be there for me, succeed or fail, kept me from panicking and helped me to keep pushing through to the end without driving myself insane.

Pamela L. Wheeler

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List of Abbreviations

Abbreviation		Page
NSSS	National Security Space Strategy	1
DOD	Department of Defense	1
ASAT	anti-satellite	1
RPA	Retarding Potential Analyzer	3
US	United States	3
AFRL	Air Force Research Laboratory	3
S&T	science and technology	3
SSN	Space Surveillance Network	4
GEODSS	Ground-Based Electro-Optical Deep Space Surveillance	4
SNR	Signal-to-Noise Ratio	5
GEO	geosynchronous	5
SPASS	Space Propulsion Analysis Simulation System	6
AFIT	Air Force Institute of Technology	6
CRM	Collision Radiative Model	6
LEEDR	Laser Environmental Effects Definition and Reference	6
Isp	specific impulse	9
NASA	National Aeronautics and Space Administration	9
LEO	low-Earth orbit	10
MEO	medium-Earth orbit	10
PPT	Pulsed Plasma Thruster	12
EEPF	Electron Energy Probability Function	16

Abbreviation		Page
NIR	near Infrared	18
CCD	charge coupled device	18
TAL	Thruster with Anode Layer	24
SPT	stationary plasma thruster.....	24
LIF	laser-induced fluorescence	24
MSSS	Maui Space Surveillance Site.....	25
GUI	Graphical User Interface	28
WPAFB	Wright-Patterson Air Force Base	32
NOMADS	NOAA Operational Model Archive Distribution System	32
GADS	Global Aerosol Data Set	33
HV 5/7	Hufnagel-Valley 5/7	34
sccm	standard cubic centimeters per minute	44
PPU	Power Processing Unit	44
NIST	National Institute of Standards and Technology	55

SATELLITE PROPULSION SPECTRAL SIGNATURE DETECTION AND ANALYSIS FOR SPACE SITUATIONAL AWARENESS USING SMALL TELESCOPES

I. Introduction

The current space environment is congested, contested, and competitive. As of 2011, 60 nations had assets in space with a total of 1,100 active satellites on orbit, including commercial and academic platforms [1]. The number of satellites on orbit grew exponentially with 300 satellites launched in 2014, up from 197 satellites launched in 2013 [2, 3] and is continuing to hold that pace with 262 satellites launched in 2015 [4]. It is vital as the number of nations and assets in space continue to grow that all spacecraft on orbit maintain proper positioning. If the spectral signature of an operating thruster on orbit can be detected from ground-based observations, it might provide timely insight into the operational performance of the satellite's thruster while on orbit. This would provide insight into optimizing operation for orbit maintenance or maneuvers for the propulsion community while also aiding the Space Situational Awareness (SSA) community by providing characterization and performance of on-orbit propulsion systems.

1.1 Motivation

According to the 2011 National Security Space Strategy (NSSS), the Department of Defense (DOD) tracks over 22,000 objects in orbit that are large enough to be observable [1]. Past space events such as the 2007 Chinese anti-satellite (ASAT) test and the 2009 Cosmos-Iridium collision have shown how a single collision in space can

drastically escalate the danger of future collisions. The Chinese ASAT test alone led to a 20% increase in objects with over two thousand pieces of debris that were large enough to be tracked with a 37% increase in potential conjunctions between existing objects on orbit [5]. Two years later, the Iridium-Cosmos collision generated over 1,300 more pieces of orbital debris to be tracked [6]. As the objects in space continue to grow, properly functioning propulsion systems will be vital to keep on-orbit assets where intended. In Figure 1, taken from the 2011 NSSS, the dramatic increase in objects due to these two events can be seen.

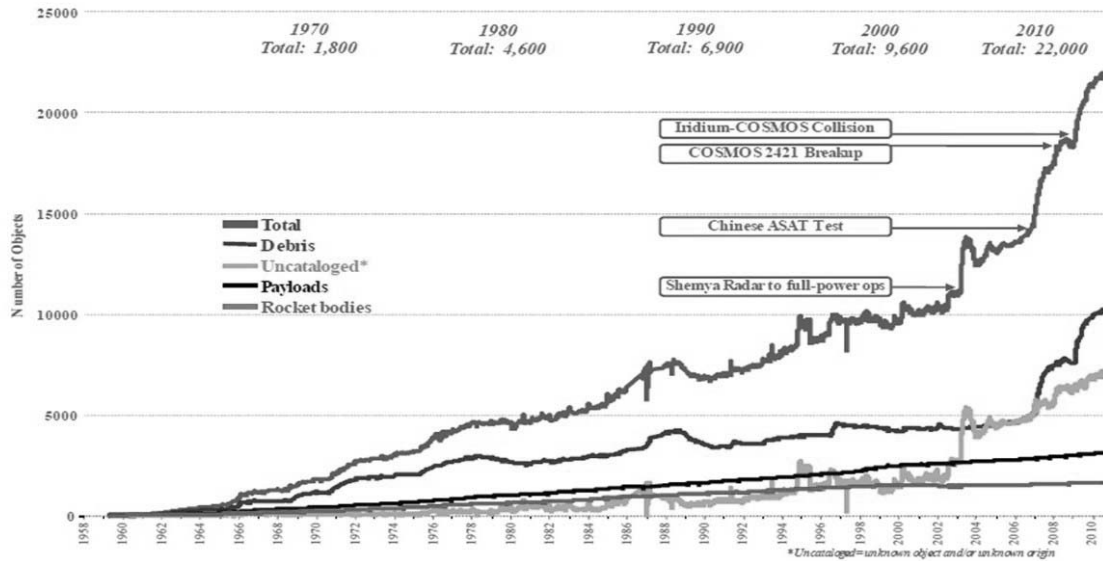


Figure 1. Number of space objects tracked by the U.S. per year [1].

In order to determine how a propulsion system is performing, first the type of propulsion system needs to be identified. Due to the desire for cost and mass savings, electric propulsion has become the preferred system for on orbit maneuvers. More satellites are employing electric propulsion for stationkeeping and operational knowledge of these systems can provide insight into whether it is performing correctly. Some electric propulsion systems, specifically electrostatic, can be character-

ized through the emission spectra of the system while in operation. Passive diagnostic tools such as a Retarding Potential Analyzer (RPA) or ExB probe (Wien filter) can provide characterization data on ion species distributions and abundances but are required to be directly in the plume [7]. While these instruments provide information in ground testing useful for the prediction of emission spectra, utilizing these instruments while a satellite is on orbit is not feasible. Instruments on board a satellite can provide information on operating voltage, operating current, and fuel tank pressure but acceptable parameters will be based on simulated conditions on the ground in vacuum chambers, not real-world conditions. Other measures such as orbit evolution or acceleration data using accelerometers can provide details on thruster operation; however, since electric propulsion is very low thrust, multiple orbits and long periods of time would be required to determine the orbit changes. To truly understand how a thruster is operating on orbit, actual performance data while the thruster is operating in space is needed. Spectral observations using ground-based telescopes can potentially provide instantaneous feedback on how a thruster is operating on orbit.

In order to keep a safe and stable space environment, the United States (US) Space Policy sets strengthening stability in space as a key goal with strengthening measures to mitigate orbital debris as a tenant of that goal [8]. To do this, it is necessary to invest in capabilities to “develop, maintain, and use SSA information...to detect, identify, and attribute actions in space that are contrary to responsible use [8: pg. 7]” as well as developing space collision warning measures. The current Air Force Research Laboratory (AFRL) Strategic Plan guides future activities in support of Air Force Science and Technology strategic goals. Of particular interest to this research is the third goal, “develop concepts and create new science and technology (S&T) options that address threats and maintain or increase capability, readiness, and availability at reduced cost [9].” By characterizing on-orbit satellite thruster firings using

ground-based sensors¹, this research directly supports the technical competencies of two AFRL directorates; space environmental impacts and mitigation in support of SSA for Space Vehicles (RV) and space and missile propulsion characterization for Aerospace Systems (RQ). In addition, it directly ties into the S&T goal outlined above by providing a method to gather data for SSA and propulsion technology analysis on orbit without complicated and expensive on-orbit sensors. Ground-based sensors also have the ability to gather information on multiple satellites of interest regardless of their orbital altitudes and positions. A current US Space Surveillance Network (SSN) sensor that focuses on tracking deep space objects is the Ground-Based Electro-Optical Deep Space Surveillance (GEODSS) system. There are currently only 3 operational GEODSS sites, which are located in Socorro, New Mexico, Maui, Hawaii, and Diego Garcia. These sites are tasked with tracking over 4,000 objects currently on orbit with only three, 1 meter telescopes at each location [10]. By utilizing smaller telescopes for plume detection and analysis, the burden placed on GEODSS for routine tracking could be accomplished through hundreds of small telescopes freeing the GEODSS system for more important taskings.

1.2 Research Questions, Tasks, and Scope

1.2.1 Research Questions.

The objective of this research is to determine the efficacy of using small telescopes to augment the current SSA architecture in the collection and analysis of Hall thruster signatures. This work focuses on addressing the needs of both the propulsion and SSA communities by seeking to provide a method to collect data for analyzing thruster

¹Ground-based sensors and observations refer to viewing on-orbit assets from Earth using Earth-based sensors. Other types of observations discussed include space-based meaning viewing on-orbit assets using sensors on orbiting satellites and ground-ground observations meaning both the sensor and asset are on the ground in a laboratory environment.

performance and characterizing on-orbit assets through ground-based observations. Research questions relating to this hypothesis are:

1. From observed signatures of operating Hall thrusters, can the propellant type, power level, and physical orientation be determined?
2. What is the signature of a Hall thruster when observed from the ground and can it be detected through the atmosphere using small telescopes? If so, how can we isolate this signature from the relative atmospheric noise?
3. How should an end-to-end model be constructed to capture predicted performance, Signal-to-Noise Ratio (SNR), for candidate sensors and locations?

1.2.2 Research Scope.

This topic opens the door to many paths in this area worth investigating. In order to meaningfully advance the research in this area, the scope will be limited to key areas of importance for the SSA and propulsion communities at AFRL. Electric propulsion is becoming the dominant choice for on-orbit station keeping and maneuvers and the diagnostics associated with Hall thrusters are of particular interest. In addition, the ability to characterize on-orbit assets using ground-based observations, specifically at geosynchronous (GEO) orbits, is of interest to the SSA community. The primary scope of this research will be to develop an end-to-end model to predict the observed spectral signatures of on-orbit thruster firings and provide system level specifications for successful detection of Hall thruster plumes using ground-based small telescopes.

1.2.3 Research Tasks.

In order to address the above research questions, tasks will be accomplished in three separate phases.

1. Hall thruster spectral modeling and experimental validation using xenon and krypton in the Space Propulsion Analysis Simulation System (SPASS) chamber at the Air Force Institute of Technology (AFIT) in conjunction with AFRL's Collision Radiative Model (CRM).
2. Atmospheric modeling using the AFIT Laser Environmental Effects Definition and Reference (LEEDR) to determine signature transmission through the atmosphere.
3. Verification of combined CRM/LEEDR model using small telescope observations of GEO thruster firings and/or star observations using the TeleTrak telescope system at AFIT.

1.3 Assumptions and Limitations

Several assumptions and limitations need to be made to successfully bound the research tasks outlined above.

1. Thrusters examined will be limited to Hall thrusters using xenon or krypton as a propellant. Xenon is currently the dominant propellant used for Hall thrusters; however, AFRL is looking into krypton as a viable alternative, and thus it will be investigated as well.
2. Calculations will be limited to satellites operating at LEO and GEO (this orbital regime is of particular interest to the SSA community).
3. Real-world celestial observations will be limited to the TeleTrak system located at AFIT.
4. It is assumed that results can be extrapolated to other locations and systems via the model.

5. Currently LEEDR has the capability to model the atmosphere from ground level to 100 km altitude. It is assumed that above 100 km altitude, atmospheric loss is negligible and will therefore be neglected in the model.

1.4 Research Methodology

The end-to-end model will be developed using Matlab as both LEEDR and the CRM models for krypton and xenon have been previously developed using Matlab. This will allow for simplicity in combining the results of both within the code developed for this problem. LEEDR is an AFIT developed tool that characterizes the atmosphere at a specific location providing profiles on temperature, turbulences, pressure, particulates, and transmission [11]. For purposes of this research, atmospheric transmission will be the profile of interest. CRM computes plasma radiation intensity emitted based on analysis performed by Karabadzhak and Chiu [12]. Electron temperature and densities are the variables input to develop the spectral profiles computed by this program. The spectral signatures estimated using the CRMs will be compared with experimentally collected spectra using 2 different Ocean Optics spectrometers [13, 14] and SpectraSuite software [15]. This same sensor and software will be used for any on-orbit measurements taken with the TeleTrak system. SpectraSuite is a Java-based software platform that connects to the spectrometer via a USB link and produces spectral profiles in one of three areas of interest: absorbance, reflectance, and emittance. Emittance measurements will be used for the purposes of this research.

1.5 Expected Contributions

Specific contributions to the existing body of knowledge in this topic area include:

1. Demonstrate that spectral signatures of Hall thrusters can be used to determine propellant type (krypton or xenon), operating power level, and thruster orientation with respect to the observer.
2. Demonstrate or refute that inexpensive small telescopes² can be used to augment the current SSA architecture for the detection and analysis of Hall thruster signatures.
3. Provide an end-to-end model to identify spectral signatures detectable through the atmosphere at varying elevations and the minimum optics necessary to detect these signatures.

1.6 Document Outline

This dissertation contains five chapters and three appendices. Chapter I covered the research motivation, scope, tasks, and methodology. Chapter II reviews relevant research in this topic area to determine which methods and advancements have already been investigated and relevant research that can be leveraged to meet the objectives of this research. Chapter III introduces the specific methodology and a framework for answering the research questions proposed in Chapter I. Chapter IV discusses the findings of this research effort to include experimental results and analysis. Chapter V presents a summary and conclusions of the research accomplished and discuss future work opportunities. Appendix A contains supplemental data and results that supported the experimental set-up and analysis in this research. Appendices B and C provide the Matlab scripts and functions developed for the end-to-end model and star data verification.

²Small telescopes encompass commercial off-the-shelf hardware with a 20" and smaller primary optic.

II. Literature Review

Background on this research effort starts with the reasoning and history that led to the propulsion choice selected for analysis. A brief overview on plasma diagnostics is offered followed by a more in-depth discussion on the hardware used for data collection. The various software packages used in this analysis are discussed. Finally, previous research on spectroscopy including laboratory measurements and ground-based space observations are examined. Calibration and measurement techniques to account for atmospheric effects will also be included in the spectroscopy section.

2.1 Propulsion Choice

Propulsion systems are designed to move a body utilizing Newton's 3rd law which states every action has an equal and opposite reaction. Rockets expel material forcefully in one direction in order to move in the opposite direction. This can be accomplished through a number of different mechanisms. Rocket propulsion can be classified in one of three main categories: chemical, electrical, and exotic/other. Chemical propulsion is the most widely thought of when thinking of rockets. This type of propulsion uses the energy produced from a chemical interaction of a propellant or propellants, liquid and/or solid, producing high heat and pressure accelerating the gases created forcefully through a nozzle. Electric propulsion uses an electrical source to accelerate a propellant and has a higher specific impulse (Isp) but much lower in thrust than chemical propulsion. Exotic/other propulsion includes new and controversial methods such as nuclear and solar sources of power [16]. These propulsion options are still in development with the National Aeronautics and Space Administration (NASA) focusing on a Nuclear Thermal Rocket using a fission reactor [17] and solar sails utilizing pressure from solar-borne photons [18]. If proven successful,

both of these technologies are being considered for interplanetary travel to deep space and future Mars missions.

Chemical propulsion is still the method of choice for space launch but electric propulsion is being used more frequently for on-orbit maneuvers such as orbit transfers and station keeping. This is largely due to the mass and cost savings that are possible when using an electric propulsion system over traditional chemical options [19–21]. Satellite propulsion systems are typically the largest subsystem and greatest contributor to overall mass. Traditional chemical propulsion systems onboard low-Earth orbit (LEO) and medium-Earth orbit (MEO) satellites make up 20-40% of spacecraft mass while GEO satellites can be over 50% [22]. Electrical propulsion allows for this mass percentage to be significantly reduced allowing for smaller launch vehicles and reduced launch costs, saving millions of dollars. In 2013, Aerojet published the image in Figure 2 highlighting the number of satellites on orbit utilizing electric propulsion [23].

The number of satellites on orbit with electric propulsion has continued to grow. Boeing has been working on an all electric propulsion satellite design to take full advantage of the mass savings possible [24]. Two of these satellites, the ABS 3A and the Eutelsat 115 West B, were launched in 2015. Conventional propulsion systems would have put the weight of each satellite at over 8,000 lbs at launch; however, each satellite weighed less than 5,000 lbs due to the significant savings in propellant mass offered by the electric propulsion systems on board. The reduced mass also allowed both communication satellites to be launched on the same vehicle reducing launch costs by half [25]. As electric propulsion becomes more prolific, these systems represent an increasing piece of the SSA puzzle. For these reasons, electric propulsion was chosen as the primary system of interest for characterization in this research.

Electric propulsion technologies can be placed in one of three categories [19, 20].

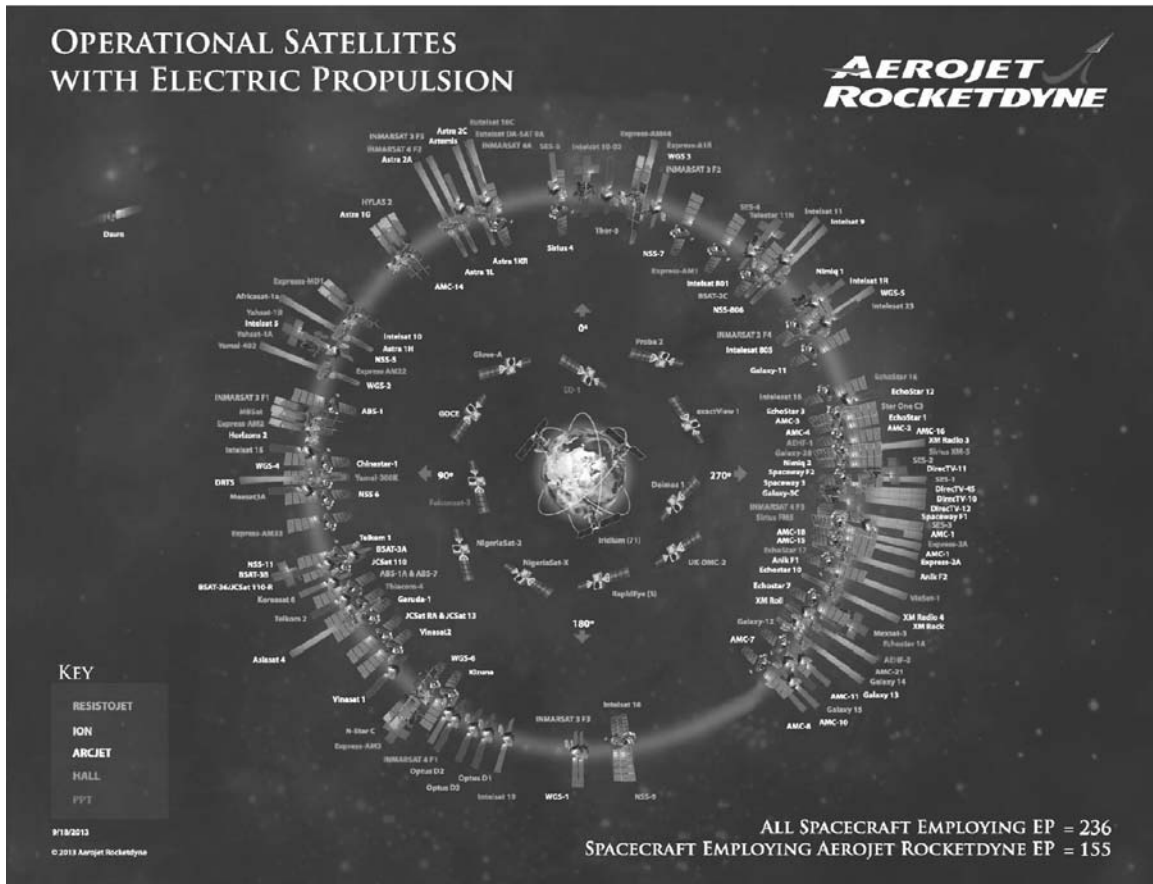


Figure 2. Satellites with electric propulsion as of 2008 [23].

1. Electrothermal
2. Electromagnetic
3. Electrostatic

Each of these systems is briefly explained next.

2.1.0.1 Electrothermal.

Electrothermal propulsion uses electricity to heat up a propellant. Examples of electrothermal thrusters are the arcjet and resistojets. Both of these technologies operate in a manner similar to traditional chemical thrusters with the gas propellant

being heated and then forced through a nozzle, accelerating as it expands, producing thrust. Resistojets heat up the propellant by passing it over an electric heater, while arcjets use an electric arc generated between an upstream cathode and downstream anode [26]. While there are a number of arcjets on orbit, they have a limited Isp at only 500-700 sec and are rapidly being replaced by other forms of electric propulsion that can produce higher Isp. Ground-based observations have been done on arcjets in orbit and this work will be discussed in detail in the spectral observations ground-to-space section in 2.4.1.2.

2.1.0.2 Electromagnetic.

Electromagnetic propulsion uses an electric field to ionize a propellant and the interaction of electric and magnetic fields on the charged particles to accelerate the ions and produce thrust. An example of an electromagnetic thruster is the Pulsed Plasma Thruster (PPT). The PPT differs not only in its method but also in the type of propellant used. PPT's typically use a solid Teflon propellant and operate in short bursts, or pulses, as opposed to longer time intervals. A capacitor applies a voltage across the propellant face causing it to ablate. The electromagnetic field then accelerates the ablated ionized Teflon away from the source to produce thrust. This results in a fraction of a second burst but can reach an Isp of 1500 sec [26]. While the PPT offers high Isp, the amount of thrust produced is relatively small and thus electromagnetic thrusters are a suitable choice for low thrust propulsion applications such as station keeping on small research satellites. Other electric propulsion technologies are capable of higher Isps and continuous thrust making them preferable over electromagnetic thrusters like the PPT.

2.1.0.3 Electrostatic.

Electrostatic thrusters use electricity to ionize and accelerate a propellant. An electrostatic thruster creates a constant electric field that extracts ions from a propellant. By applying that electric field in the direction of acceleration, the thruster can accelerate those ions due to the Coulomb force. Two widely used examples are Hall and ion thrusters. Hall thrusters generate an electric field perpendicular to a magnetic field generated by the thruster. A neutral gas is ionized in the static electric field and accelerated out of the device by the interaction of the electrically charged ions. Although Hall thrusters have a magnetic field, the acceleration of the ions is accomplished by the electric field. The magnetic field is in place to direct electron motion for ionization with the propellant, not for acceleration. Ion thrusters use grids to extract ions from a generated plasma and accelerate them through interaction with an electric field as well [19]. Although ion thrusters have a higher Isp, over 2000 sec as opposed to 1500-2000 sec, Hall thrusters are the most widely used electrostatic thrusters due to this and other benefits and are the electric propulsion devices in use on new satellites over the past several years. As described above, as the desire for higher efficiency and low mass propulsion options continue to be pursued, the use of Hall thrusters will continue to increase. There is a push for ion thruster development due to the higher Isps possible over Hall thrusters [25, 27], but the simple design and ability to provide higher thrust at a given power level keep Hall thrusters at the forefront of the industry [19].

Hall thrusters typically use heavy inert gases such as xenon and krypton due to the fact they are non-hazardous, easily stored at high densities, do not condense on spacecraft, have a higher utilization of propellant, and produce a high thrust relative to the input power. The reason it is called a Hall thruster is because of the “drift” effect caused by the crossed electric and magnetic fields. This causes the electrons to

propagate in a coil pattern as they come into contact with the crossed electric and magnetic fields. Physically, Hall thrusters consist of an anode within a channel, an inner and outer coil system that generates a radial magnetic field across the channel, and an external cathode. There are also two gas feeds for this system, one for the anode and a second for the cathode. The inert gas propellant is injected at the back of the channel via the anode gas feed and travels down the channel. Near the exit it comes into contact with the electrons trapped in the Hall current from the cathode gas feed which ionizes the propellant creating a plasma. This plasma is then accelerated out of the channel due to the applied electric field, shown in Figure 3 [19].

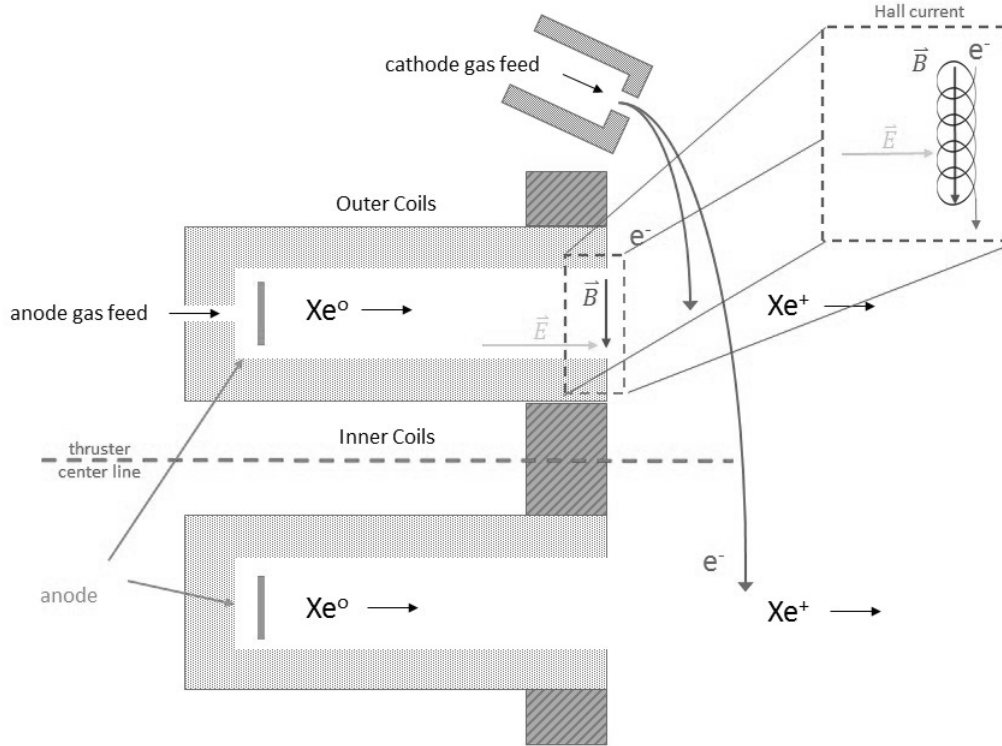


Figure 3. Hall thruster cross-section schematic (adapted from Goebel and Katz [17]).

Electrostatic thrusters, specifically the Hall thruster, will be the focus of the research herein.

2.2 Plasma Diagnostics

Plasma diagnostics is an analysis that uses observations and measurements of physical processes of a plasma to determine its state. A plasma generated by Hall thrusters consists of ions and neutral particles within a gas that are suspended in electromagnetic fields. Plasma diagnostics can be divided into 8 categories based on the physical process/property of the plasma that is being measured [28].

1. Magnetic measurements
2. Plasma particle flux measurements
3. Plasma refractive index
4. Electromagnetic emission from free electrons
5. Electromagnetic emission from bound electrons
6. Scattering of electromagnetic waves
7. Neutral atom diagnostics
8. Fast ions and fusion products

Electromagnetic emission from bound electrons (item number 5), measures spectral line emissions caused by the electron transitions between energy levels within a plasma. Temperatures, velocities, and densities can be determined for the ions and electrons in the plasma from measurements of spectral line emissions [28]. Analysis of the spectral line emissions can be done using invasive electrical measures using a probe inserted directly into the plume and measuring the voltage or through non-invasive optical measures by observing the photons emitted from the plume [29]. Emission spectroscopy has been used to measure line intensities of excited states within the

plasma. By selecting two lines from the emission spectrum, the ratio between the two is a direct function of the temperatures and densities of the plasma. At very low pressures, less than 1 Pa, the excitation levels of the plasma are mainly due to electron impacts with the ground state and are depopulated by spontaneous radiation. In Hall thrusters, there is a high ionization ratio and excitation can also occur from metastable and excited states [30].

Hall thrusters operate at temperatures well above room temperature, thus the Fermi-Dirac distribution does not apply and the plasma will take on a Maxwellian distribution [31]. The line ratio method has been widely used for determining plasma properties in Maxwellian distributions for rare gases [29, 30, 32–35]. Using the line ratio method, two emission lines are observed from an excited plasma and compared to the Electron Energy Probability Function (EEPF) from a model of electron energy dependencies and excitation cross sections. The inverse slope of the electron energy versus the EEPF gives the electron temperature. Using the model, the electron temperature is varied until the computed ratio of the selected emission lines matches the observed ratio of the emission lines. A reliable species population model must be used in conjunction with the line ratio method to provide accurate results for comparison [30, 35, 36].

Plasma diagnostics play a vital role in determining the operational efficiency of the Hall thruster. The electromagnetic emission from bound electrons will be the selected method for plasma measurements used in this research. In addition, the estimated line ratios will be computed using a reliable, tested CRM that incorporates an energy dependency and cross section model with a given electron temperature.

2.3 Hardware

2.3.1 Hall Thruster.

The Busek BHT-600W Hall thruster will be used in this research. It is currently advertised by Busek to produce 39 mN thrust with an input power of 600 W and a specific impulse of 1500 seconds [37]. AFIT currently owns and operates a Busek BHT-600W; however, this particular version is an older model and has been used by previous students. The published properties of this version are 42 mN thrust, 1650 second specific impulse, and 600 W input power. It is also “optimized for operating over a range of 300-600 W and produce 15-45 mN thrust with a specific impulse of 1100-1700 sec[onds]” [38].

The BHT-600W uses the BHC-1500 hollow cathode, also manufactured by Busek. This cathode has an abundant flight heritage and has successfully operated on two on-orbit satellites. The model used in this research effort is an externally mounted, porous tungsten emitter that is mounted to the back of the BHT-600W with a bracket supplied by Busek [39].

2.3.2 Sensors.

Sensors can be used to determine the plasma diagnostics of Hall thruster plumes. Three will be used in this research and are described below. The first two, the ExB and Faraday probes were not specifically used in this effort’s research collection, but data collected by other students using these devices was leveraged for analysis.

2.3.2.1 ExB Probe.

The ExB probe, also referred to as a Wein filter, uses the Lorentz force to separate ions based on their velocity. A particle’s acceleration is dependent on its charge so by filtering ions based on velocity, the ExB probe is able to give ion species distribution

information [40]. The ExB probe at AFIT was developed by Colorado State University and consists of an entrance collimator, permanent magnets, drift tube, and collector plate [41]. The set of permanent magnets generate electric and magnetic fields that separate the ion species in the plume. By varying this field, different ion species can be collected by colliding with the collector plate and generating a current [40, 41].

2.3.2.2 Faraday Probe.

A Faraday probe is another electrostatic probe used in plasma diagnostics. This probe has an exposed electrode that measures ion density distribution of a plasma. To be effective, a good electron temp and plasma potential measurement or estimate is essential and is typically used in conjunction with a Langmuir or emissive probe or the results from such probe experiments [40]. The Faraday probe at AFIT consists of a collector disk accessible through a 0.015-inch aperture in the center of the probe cap. Ions from the plasma enter through the aperture and strike the disk creating a voltage which is read across a resistor in order to measure the current of the plasma and can be used to calculate the current density as well [42].

2.3.2.3 Spectrometer.

The new measurements for this research will be done using two different Ocean Optics spectrometers, the HR4000 [13] and the QE65000 [14]. In simple terms, a spectrometer is a diagnostic tool used to measure the spectral content of a light source. It shows the relative intensity as a function of wavelength. The HR4000 has a wavelength range of 190-1100 nm although the range of interest will be on the near Infrared (NIR) wavelength range, approximately 700-900 nm, with an optical resolution of 1 nm. This spectrometer uses a Toshiba TCD1304AP charge coupled device (CCD) detector consisting of 3648 pixels with a pixel size of $8\text{ }\mu\text{m} \times 200$

μm for a total detector area of $29.18\text{ mm} \times 0.2\text{ mm}$ [43]. The HR4000 will be used for in-chamber measurements of the Hall thruster as a proof of concept with previous research. The results of data collection with the HR4000 will also be used to determine the necessity of a higher-end model for successful observations. These will be discussed in more detail in Chapter III.

The QE65000 is more sensitive than the HR4000 and has been configured specifically for analysis in the NIR. This spectrometer will be used for both lab measurements of the Hall thruster and observations using the AFIT TeleTrak system. The QE65000 has been configured with Ocean Optics H14 grating which limits the spectral range to 620-980 nm with a spectral resolution slightly less than 1 nm. This spectrometer uses a Hamamatsu S7031-1006 CCD detector consisting of 1024×58 active pixels each pixel being a $24.6\text{ }\mu\text{m}$ square making the total detector area $24.6 \times 1.4\text{ mm}$ [44].

The primary hardware utilized for this research will be the Ocean Optics spectrometers described above. The software packages used for in conjunction with the hardware above for analysis and data collection will be discussed next.

2.4 Software

Matlab will be the main software tool for developing the primary deliverable of this research. The original code developed will need to work seamlessly with two other codes, CRM & LEEDR. The CRM code developed at AFRL and the LEEDR program developed at AFIT have both undergone years of research and development and thus will be leveraged.

2.4.1 Collision Radiative Model.

A CRM is a tool used to estimate the population densities of ions in plasmas given various parameters to include electron temperature, plasma number densities, and ion speeds. The CRM developed by AFRL computes plasma radiation based on emission cross section analysis done by Yu-Hui Chiu [45] and a CRM developed by George Karabadzhak [12]. These models have been developed for a number of different plasmas to include helium [46] and argon [47, 48]. This research will focus on models developed for xenon as this is the propellant used in Hall thrusters currently on orbit. Previous models developed for xenon [49, 50] were not determined using emission cross-sections or taking metastable atoms into account. The latter was proven to be especially important in electric thrusters and NIR emissions [51]. Karabadzhak's CRM takes into account six main collisional processes that emit optical radiation shown below where asterisks signify excited species, q the charge state, and p ground and metastable states [12].

$$e^- + Xe(p) \rightarrow Xe^* + e^- \quad (2.1)$$

$$e^- + Xe(p) \rightarrow Xe^{q+*} + (q+1)e^- \quad (2.2)$$

$$e^- + Xe^+(p) \rightarrow Xe^{q+*} + qe^- \quad (2.3)$$

$$Xe^+ + Xe \rightarrow Xe^{+*} + Xe^* \quad (2.4)$$

$$Xe^{2+} + Xe \rightarrow Xe^{2+*} + Xe^* \quad (2.5)$$

$$Xe^{2+} + Xe \rightarrow Xe^{+*} + Xe^{+*} \quad (2.6)$$

A CRM is currently under development by AFRL for krypton. Krypton is currently being investigated as a cost-effective alternative for xenon. The measurements

taken in the SPASS lab at AFIT for this research will be used to further refine and update this model. Emission-excitation cross sections have already been taken into account for this model. The CRM for krypton is based on eight optical emission collisional processes listed below [52]:

$$e^- + Kr \rightarrow Kr^* + e^- \quad (2.7)$$

$$e^- + Kr \rightarrow Kr^{n+*} + (n+1)e^- \quad (2.8)$$

$$e^- + Kr^+ \rightarrow Kr^{n+*} + ne^- \quad (2.9)$$

$$e^- + Kr^m \rightarrow Kr^* + e^- \quad (2.10)$$

$$e^- + Kr^m \rightarrow Kr^{n+*} + (n+1)e^- \quad (2.11)$$

$$Kr^+ + Kr \rightarrow Kr^* + Kr^{+*} \quad (2.12)$$

$$Kr^{2+} + Kr \rightarrow Kr^* + Kr^{2+*} \quad (2.13)$$

$$Kr^{2+} + Kr \rightarrow Kr^{+*} + Kr^{+*} \quad (2.14)$$

2.4.2 SpectraSuite.

Spectral measurements will be taken using Ocean Optics SpectraSuite software. SpectraSuite is a Java-based platform that controls and collects data in real-time from the spectrometer via a USB interface. It provides graphical and numerical representations of collected spectra in three different modes: absorbance, reflectance, and emission. It allows the user to define integration time, number of scans to average, and boxcar width (averages multiple, adjacent points) [15]. This allows for a significant amount of variation to accurately collect spectra for dim and bright objects.

2.4.3 Laser Environmental Effects Definition and Reference.

LEEDR is an atmospheric radiative transfer model developed by the Center for Directed Energy at AFIT that covers a wide range of wavelengths from ultraviolet to radio frequency and altitudes from ground level to 100 km [11]. It is implemented using Matlab and is comparable to MODTRAN [53]; however, LEEDR allows for a wider spectral band and altitude range for analysis. LEEDR allows the user to select a location worldwide and defines the climatology based on season, time of day, and weather as desired. The user is also permitted to use a traditional atmospheric model or import their own, estimate aerosol levels, turbulence, humidity, and the number of layers to be used in calculations. Once the atmospheric inputs above are complete, the desired wavelength or range of wavelengths can be added as well as line of sight geometry from the transmitter to the receiver. LEEDR then uses that information to calculate radiative transfer and propagation effects for that wavelength(s) given the specified profile [11].

LEEDR is an extremely powerful tool and provides a number of outputs including path result values such as path extinction, visibility, and transmittance. The main output needed for this research is on the transmittance and path extinction values. Transmittance across a wavelength band can be determined and graphed using the “comparisons” tab in LEEDR [11]. Previous LEEDR editions were only designed to properly characterize the atmosphere up to 100 km [11], it was assumed that any atmospheric effects above that altitude will be negligible so as to extend the profile to satellite altitudes. Recently, Denton successfully demonstrated this approach in his AFIT MS thesis. He used LEEDR to estimate selected laser wavelengths propagation through the atmosphere from altitudes of 500 km [54]. New updates to LEEDR allow for characterization to unlimited altitudes so this assumption is no longer needed.

2.5 Spectroscopy

A general background in spectroscopy will be discussed as well as specifics in astronomical spectroscopy. Due to the goals of this research, both facets of spectroscopy will be tackled and deserve equal attention. Spectroscopy in general deals with the absorption, emission, and scattering of electromagnetic radiation. More specifically, electronic spectroscopy focuses on either absorption or emission transitions between electronic states of an atom [55]. Spectra of atoms or molecules act like a fingerprint and can be used to identify composition and electronic state.

Astronomical spectroscopy applies these principles to stellar objects such as the moon and stars. One of the differences between the two is that while color is obvious in ground observations, objects in the night sky typically all appear white. It is only with careful observation that you can make out a tinge of color. By making spectral observations of stellar objects, the colors have been shown to be indicative of temperature and historically have been used to determine stellar spectral classes [56]. At high resolutions, even more data is discernable from absorption and emission lines to include composition, species abundance, and species motion [57].

2.5.1 Spectral Observations.

Electronic propulsion spectra have been observed extensively in the laboratory as well as limited observations of satellite thruster firings on orbit. As stated above, a number of details can be determined through spectral analysis of thruster plumes to include electron temperatures, species composition, and species abundance.

2.5.1.1 Ground-to-Ground (Laboratory).

A large number of experiments have been conducted to determine the propulsion spectra of Hall thrusters in vacuum chambers. While xenon is the preferred pro-

pellant, experiments are now starting to become more frequent for krypton as well. The amount of xenon data far exceeds that of krypton, but what is available will be presented here. Experiments were performed with plasma diagnostic tools like the Faraday and ExB probe discussed above as well as a Langmuir probe and RPA. The results of an ExB probe can provide a spectral estimate of the propellant [7]. A comparison study was done at AFRL using xenon and krypton analyzed with an RPA to determine ion energies but did not use an ExB probe [58]. A study done at the University of Michigan did do a comparison of krypton and xenon using both an RPA and an ExB probe. This study was conducted to determine the efficiencies of each propellant and analyze any performance gap between the two [59].

Spectra have been determined using traditional emission spectroscopy with Hall thrusters using xenon, specifically the Thruster with Anode Layer (TAL). The vast majority of this analysis was done to verify and improve CRMs. Observations were done through a viewing port on the chamber to determine propellant signatures in the visible and NIR [12, 51]. Leray determined optical emission of a stationary plasma thruster (SPT) using traditional emission spectroscopy for both xenon and a xenon-helium combo for use in a CRM model they were developing. Prior to his CRM research, Karabadzhak used the same technique with a spectrometer to analyze the body erosion rate of a Hall thruster running xenon [60].

Interest in Hall thruster spectra led to an increased interest in laser-induced fluorescence (LIF) analysis. LIF uses a continuous-wave laser to excite atoms in the plasma. As the laser is tuned over a range of wavelengths it provides an excitation-line shape corresponding to the spectral line-shape of the plasma. The line-shapes indicate a spread in ion energy and can be used to calculate ion species velocities in the plume as well [61]. LIF has been used to determine exit plane velocity of xenon Hall thrusters [62, 63]. Exit plane ion velocities are important for characterizing Hall

thrusters for on-orbit performance and to provide valuable information on plume divergence and any spacecraft interactions that may occur within the plume. A study has also been conducted using LIF on Hall thrusters operating with krypton as a propellant [64].

For ground-based observations, spectrometers provide the most useful and easily performed optical diagnostic. While spectrometers have been used to characterize xenon electric thrusters in the laboratory, Hall thrusters have only been initially explored. Krypton has not been explored in terms of spectral observations using a spectrometer, and provides an area to be exploited for improvement in both CRMs and on-orbit detection. This will be the method for determining spectral signatures observable for both xenon and krypton by ground-based telescopes.

2.5.1.2 Ground-to-Space.

Ground-to-space observations are less explored and reported on in the literature. Optical observations of a system on orbit provide an additional diagnostic into how the thruster is performing. On-board instrumentation can provide data on thruster operation but an actual observation allows for confirmation of that information or identification of a problem in either the system itself or the sensor monitoring it. AFRL performed on-orbit optical observations of a 26-kilowatt arcjet using the Maui Space Surveillance Site (MSSS) [65]. A total of eight firings were observed using a spectrograph and CCD detector on a 1.6 m telescope located at MSSS. An on-board camera was also used to confirm plume emission and take images of the thruster in operation. Observations occurred when the satellite was in complete darkness, meaning that the spacecraft was not illuminated by the sun during pass times over MSSS. Exposures were taken both with and without obscuration of the plume and nozzle. The results of this experiment showed a higher degree of excitation in the

propellant, a smaller plume than observed in ground tests, and accurate detection of propellant spectra [65]. No other ground-to-space observation experiments are reported in the literature.

2.5.2 Measurements.

A number of measurements and approximations will be made during the course of this analysis. For this reason, two topics need to be addressed. Atmospheric effects will be taken into consideration both when taking data using TeleTrak as well as analysis done using LEEDR. In addition, calibration techniques for laboratory measurements using the Ocean Optics spectrometers are discussed.

2.5.2.1 Atmospheric Effects.

The composition of the atmosphere directly effects electromagnetic radiation as it passes through it. Scattering is of primary importance to this research. As light travels through Earth’s atmosphere it interacts with molecules in the air which causes photons to be both absorbed and emitted, sometimes in different directions than the original path. Rayleigh scattering is the primary concern here as it is dependent on wavelength. This type of scattering will give rise to atmospheric windows or areas where over 80% of the light transmitted is able to get through [66]. These windows will be used to determine what sets of identifiable wavelengths are detectable through the atmosphere for the propellants chosen.

Mie scattering is another process of concern, but unlike Rayleigh scattering is independent of wavelength and much more dependent on particle size [66]. This is the dominant factor in scattering through clouds in the atmosphere and will greatly impact the optical transmission of certain wavelengths. For this reason, all calculations using LEEDR and any observations done with TeleTrak will be done under “clear

sky” conditions. Clear sky still allows for atmospheric calculations and aerosols but assumes an absence of large scattering in the transmission path. The effects from scattering and the clear sky assumption will be represented in the LEEDR profile for this research. This assumption negates any estimation of cloud cover in the area and its effects. For real-world observations, this estimate may drastically change results if observations are made on days not considered “clear sky” conditions and would need to be addressed.

2.6 Summary

This chapter provided a brief summary of past research efforts and methods used in analysis of plasma plumes and spectral collection. Numerous experiments have been performed on Hall thrusters to determine plume properties; however, using spectral data for performance characterization has yet to be explored. Spectral changes based on viewing angle and operating power level of Hall thrusters has not been researched nor has spectral collection of on-orbit operation of Hall thrusters. Using previous research and methods outlined in this chapter, this research will expand the understanding of Hall thruster spectral output and how it can be used to determine operating performance. In addition, it will determine if observations can be made of Hall thrusters firing on-orbit using small telescopes.

III. Methodology

3.1 Overview

The flow chart in Figure 4 highlights the three aspects of this research. The ultimate goals of this research are to develop a model that will effectively estimate the expected spectral signature and optics needed to detect that signature from the ground and determine the characteristics of a Hall thruster from a detected spaceborne signature. This was done in three concurrent steps: model development, experimental validation, and real-world validation. Spectral measurements of a Busek 600W Hall thruster using both xenon and krypton was accomplished in the SPASS chamber at AFIT. These results were used to validate AFRL’s CRM code and the accuracy with which the code can estimate spectral signatures based on the ion and electron interactions within the plume. Real-world observations validated the overall code for optics determination and the atmospheric estimates produced by LEEDR. Both LEEDR and the CRM model will be discussed in greater detail in the next section.

3.2 Model Development

One of the overall goals of this research is to produce an end-to-end model that can be used in two ways. First it estimates the spectral signature at the ground and determine the optics needed given a Hall thruster’s performance specifications. Second, it determines the propellant and estimated performance specifications for a Hall thruster system from a collected spectral signature. The final product is a Graphical User Interface (GUI) developed in Matlab. In order to focus the first part of the research on the task of detecting and observing faint spectral signatures, two previously developed and proven models will be used. Utilizing the CRM and LEEDR

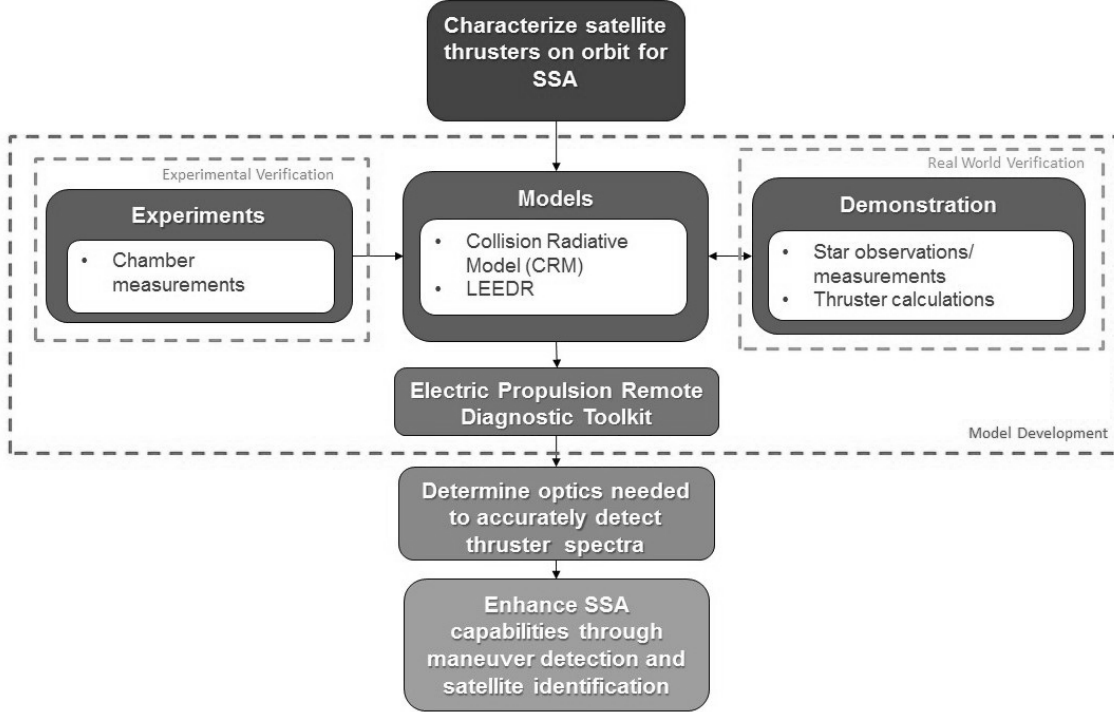


Figure 4. Research Flow Chart.

models, Hall thruster intensity estimates will be used to determine the minimum size optical system needed to detect a thruster signal. The second part of this model will also incorporate the CRM and LEEDR models to characterize the propulsion system that produced a given spectral signature. Given a detected signal, LEEDR can be used to estimate the original intensities of the spectral signature and the CRM code can be used to determine the electron temperature of the thruster which can then be used to determine the thrusters' operating power level.

3.2.1 Collision Radiative Model.

Two versions of the CRM will be used in this research, both developed by AFRL. The first is a Matlab routine developed by Scharfe [67]. This code takes a number of inputs associated with the plume and generates the plasma radiation intensity

emitted using a number of subroutines based on the collisional radiative model developed by Karabadzhak [12]. The input values include neutral number density (n_n), electron number density (n_e), electron temperature (T_e), singly charged ion density (n_{i1}), singly charged ion speed (v_{i1}), doubly charged ion speed (v_{i2}), and if metastables should be taken into account. As was discussed in Chapter II, metastables are extremely important to an accurate CRM. Metastables are transitions that last longer than normal ion transitions. The majority of transitions occur in microseconds whereas metastable transitions get “stuck” in lower levels for seconds rather than microseconds before they are able to transition to other levels. The CRM subroutines include previously determined data from Karabadzhak and Chiu [12, 45] on cross sections, transition energies, and relative lines for xenon in particular. Scharfe’s CRM was validated against published differential cross section data for xenon ions/neutral ion collisions [68, 69]. In this research, Scharfe’s CRM will be considered “truth” due to this validation.

Scharfe’s CRM has not been expanded to include krypton yet, but for observation purposes no krypton thrusters are currently on orbit and thus a xenon model is preferable. The research conducted on krypton will be used to strengthen and validate the second CRM code which can then be used to develop a krypton version of the first code. Scharfe’s CRM code generates the prominent wavelengths and estimated intensity per unit volume of each. It is important to note that this code is a simplified version of the AFRL CRM code. It treats the thruster as a point source as the fine detail of the plume in space would not be discernable from the ground.

As described in Chapter II, there are six main collisional processes in xenon and eight in krypton that are responsible for emitted optical radiation. These processes include neutral and singly charged ions; however, in the NIR region emissions are

due to neutral atomic collisions. For this reason, we can narrow down the responsible processes to only four of those equations, (2.1), (2.2), (2.7), and (2.8).

In order to use Scharfe's CRM for evaluation, the input values need to be determined based on laboratory data. Using an ExB and Faraday probe, ion species fractions and current density data can be collected from the plume. This information, along with assumptions on neutral and electron temperatures, can be used to calculate the data needed. The equations below will be used to calculate those values from the collected data [19].

$$nn = \frac{P_c * 133.32 \text{pascal/Torr}}{k * T_n} = 9.65 * 10^{24} * \left(\frac{P_c}{T_n} \right) \quad (3.1)$$

k is Boltzman's constant, P_c is chamber pressure (Torr), T_n is neutral temperature (K)

$$ne = \frac{j}{(q_e * v_e)} \quad (3.2)$$

j is current density ($\frac{A}{m^2}$), q_e is e^- charge (C), v_e is e^- velocity ($\frac{m}{s}$)

$$v = \sqrt{\frac{(2 * q * V)}{M}} \quad (3.3)$$

q is charge (C), V is voltage (V), and M is ion mass ($\frac{kg}{amu}$)

The second CRM code developed by Prince [70], is a reverse process of the CRM code described above. Prince's code is capable of determining electrical temperatures of both xenon and krypton given the measured intensities of a thruster's spectral lines. Using the same cross-section data for xenon in Scharfe's code and cross-section data for krypton, the CRM iterates through a user defined input range and given step size of electron temperatures to calculate the best fit temperature for the given

intensities. The spectral lines themselves are used to determine the type of propellant and thus the cross-section information that needs to be input into the model. Electron temperature can then be used to determine the power supplied and possibly the power limits of the thruster. Power losses can also be determined using electron temperature and thus thruster efficiencies can also be calculated.

3.2.2 LEEDR.

Another vital piece to the final model will be atmospheric effect estimates calculated by AFIT's LEEDR model. LEEDR was primarily developed for laser propagation through the atmosphere up to and from altitudes of 100 km. A recent update has allowed the program to be used beyond the 100 km limit originally proposed. The atmospheric profile used by LEEDR is a user defined input and includes parameters such as ground site, time of day, relative humidity, aerosol levels, number of atmospheric layers, wind, turbulence, clouds, precipitation, and laser type, or in this case signature geometry. The ground sites of primary interest in this research include Wright-Patterson Air Force Base (WPAFB) in Dayton, Ohio, Magdalena Ridge in Socorro, New Mexico and Maui, Hawaii. These three sites allow for sufficient atmospheric calculations to cover varying atmospheric conditions. In addition, all three sites are AFRL locations for observations and two, Maui and Socorro, have large telescopes that can potentially be used for real-world validation of the developed model and provide a future comparison for small telescope observations done at these locations.

The atmosphere modeled by LEEDR has several options available. Users can select from the U.S. 1976 Standard Atmosphere, ExPERT, Ocean, NOAA Operational Model Archive Distribution System (NOMADS), or their own atmosphere that must be input in Microsoft Excel. For this research, an ExPERT atmosphere was used. The

ExPERT atmosphere uses an average of historical conditions for the chosen location and allows for more parameters to be included such as time of day, season, and relative humidity, while the U.S. 1976 Standard Atmosphere uses a single international standard from 1976 [11, 71].

Next, aerosol levels present in the atmosphere are estimated. LEEDR again allows for a number of options including Global Aerosol Data Set (GADS), standard models, and a user defined aerosol set that must be input as an Excel data sheet. GADS defines aerosol constituent number densities based on a $5^\circ \times 5^\circ$ (555 km x 555 km) grid across the globe and if selected will use the aerosol data for the closest grid to the chosen site location. The standard aerosol option allows for the use of numerous standard models of pre-defined aerosol types to include desert, urban, maritime, and arctic to name a few and is based on global data. GADS was used due to the ability to generalize the aerosol estimates to the specified area of interest for observations rather than a generic estimate of that type of environment. This will allow for a more accurate estimate since it is based on the $5^\circ \times 5^\circ$ section of the grid that houses the ground site selected rather than an estimate based on that location's climate label, i.e. urban, desert, etc. In addition to the drop-down options, two methods of calculations can be used. There is a checkbox to use "Correlated K". By checking this, LEEDR uses Correlated K Distribution Band Modeling to perform atmospheric calculations which results in a band-averaged result as opposed to the line-by-line method. The line-by-line method has a longer computation time, but provides more accurate transmission calculations. For this research, the line-by-line method is preferred since specific spectral lines are targeted and the ratio of those lines is vital for analysis [11, 71].

Lastly, wind and turbulence must be estimated. This research focuses on spectral detection in the NIR where optical turbulence and wind effects on the signature will be negligible. For this reason, the default values of the standard Hufnagel-Valley 5/7 (HV

5/7) for turbulence and the climatological option for wind were used [11, 71]. LEEDR also allows for cloud and rain data to be input; however, clear skies correspond with most collection opportunities which give the best condition for NIR detection and thus will be assumed. The atmosphere input screen using the LEEDR GUI with options selected is shown in Figure 5.

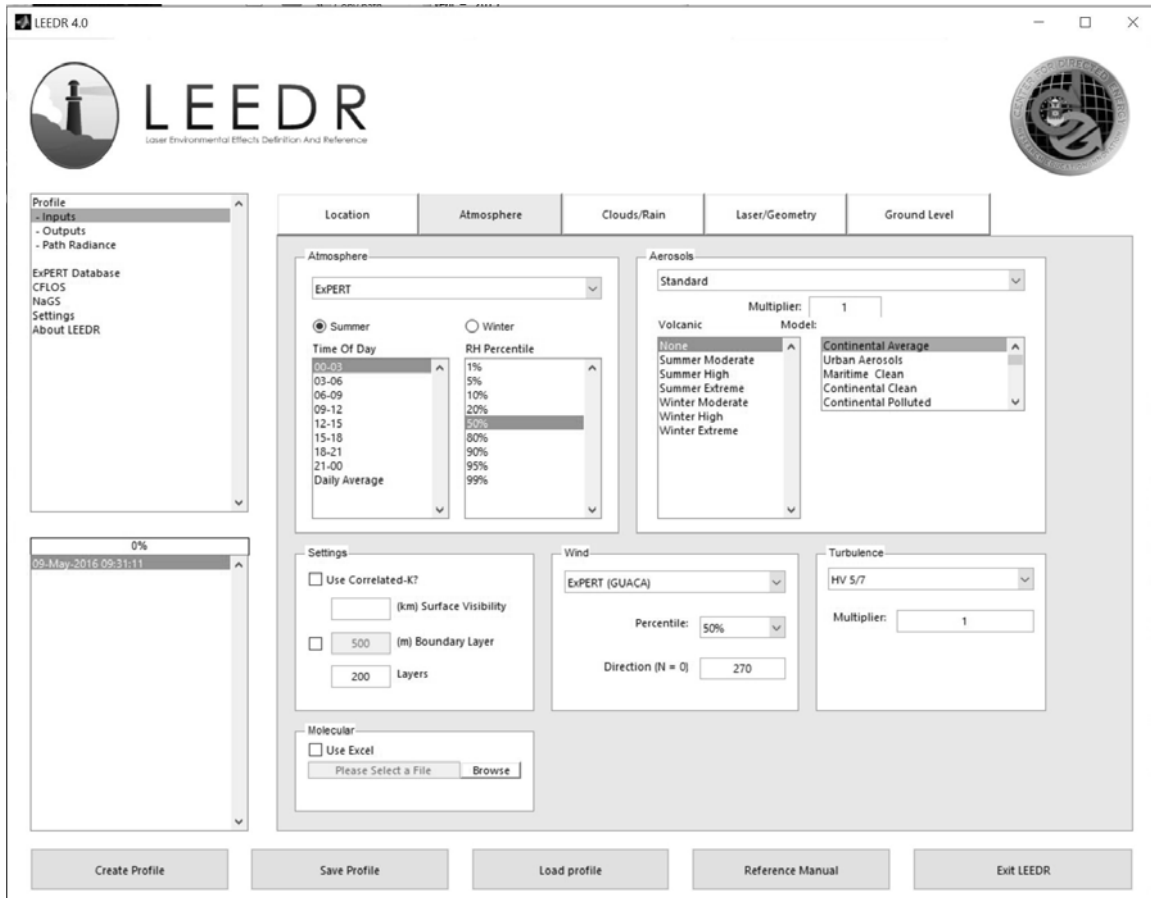


Figure 5. LEEDR input atmosphere tab showing all tunable atmospheric options.

LEEDR also has a laser/geometry tab that allows for the user to define both the wavelength of interest and path geometry. The path geometry can be either a horizontal, slant, or refracted path. The refracted path option allows for path bending estimations and is typically used for laser estimations when aiming for a specific target. As we are collecting light coming off of a target as opposed to hitting

a target with a laser, path bending is not of importance for these estimations. The slant path is the vertical path observation option and will be used in simulations. In the LEEDR GUI, there are options for input that allow for the viewing angles from the ground to be altered. This is done by changing the distance to the target and altitude of the target as seen in Figure 6. Using simple trigonometry, the distance to the target can be calculated from a desired viewing angle and input into the GUI.

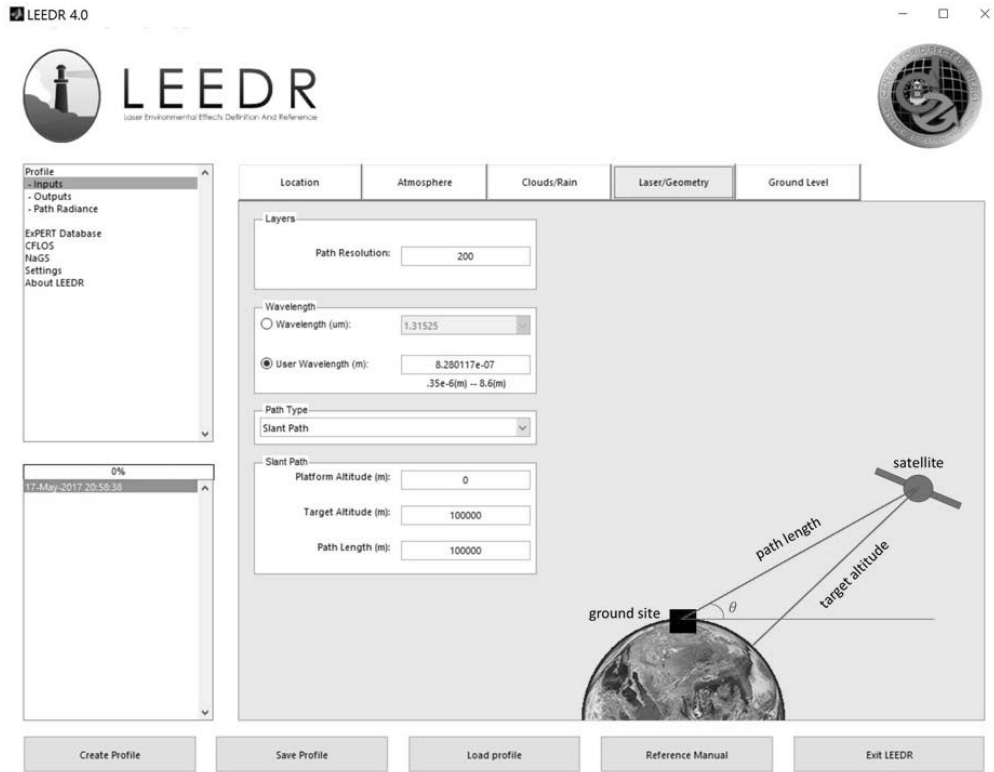


Figure 6. LEEDR input screen showing wavelength and geometry inputs. A small subimage shows the difference between the two inputs and how a viewing angle is computed with the inputs.

After the profile is loaded, the transmission of the selected wavelength is displayed in the outputs section along with path extinction, path specific attenuation, and surface and path visibility (see Figure 7). Of primary interest in this research is the transmittance values for the selected wavelengths in the NIR; however, under the comparisons tab, the user can define a range of wavelengths, molecular, and aerosol

levels and plot the transmittance for a specified wavelength band. The graph produced for the NIR, 700-900 nm, at the Zenith angle for a satellite over WPAFB is shown in Figure 8. This option has proven beneficial in estimating the blackbody curve detected when looking at a specific star. The estimated transmission curve can be used to verify the spectrometer output prior to running the intensity value of the blackbody curve at each wavelength through the LEEDR program.

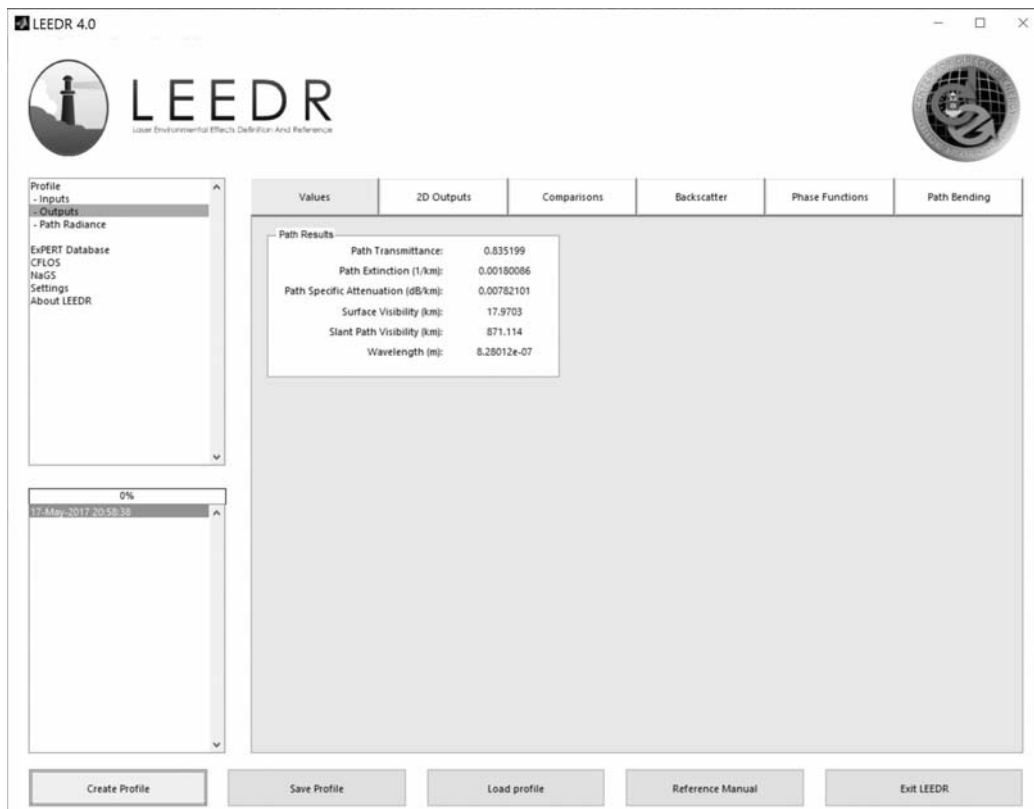


Figure 7. Default LEEDR output screen showing wavelength, attenuation, and transmission values.

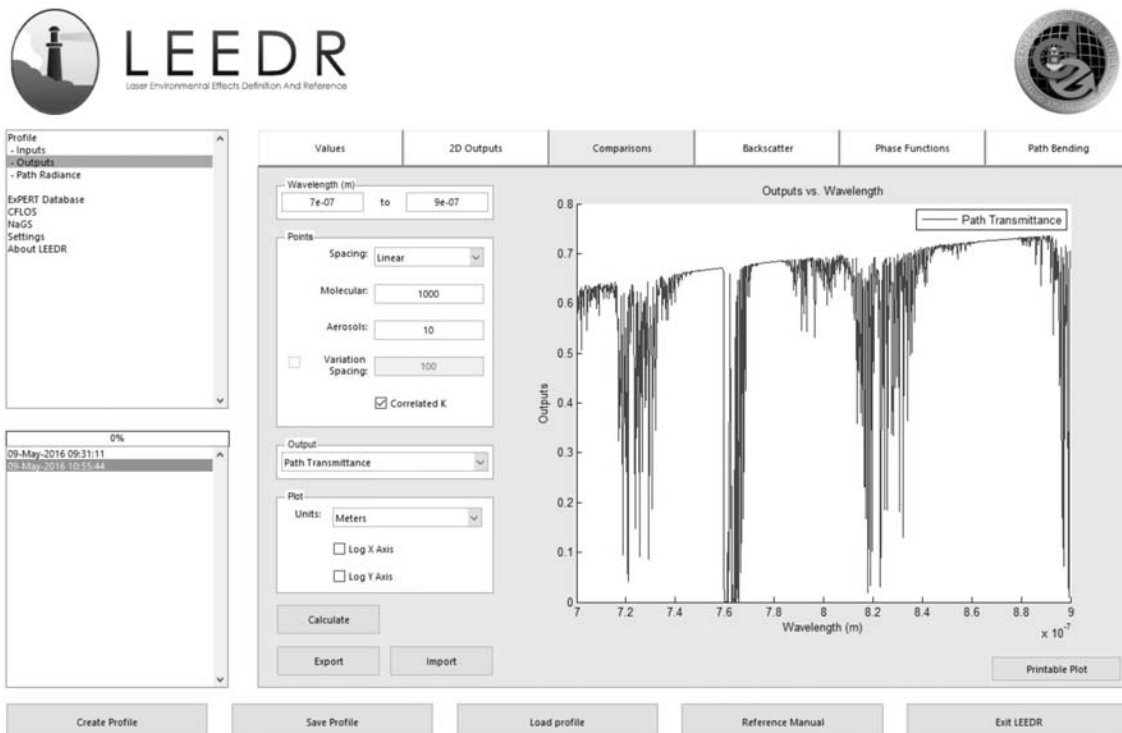


Figure 8. Graph showing zenith transmission in NIR as a function of wavelength using LEEDR Comparison Tab in Outputs.

To compute the atmospheric transmission at the selected wavelengths over the range of viewing angles for a satellite passing overhead would be tedious and time consuming to perform using the LEEDR GUI. For this reason, a Matlab script was developed to perform the geometry calculations needed to cover all elevation angles for the specified wavelengths of interest. In addition, the program has the capability to step through all wavelengths collected by a spectrometer and apply transmission values to get an estimated blackbody curve that would be detected on the ground.

3.2.3 Optics Estimations.

The optics code developed for use with the end-to-end model were based on calculations performed by Shultz on the TeleTrak team [72]. Schultz designed a spreadsheet in Excel that calculates specific properties of the telescopes located here at AFIT. In-

cluded in this worksheet are details on availability, SNR, and exposure time for various camera systems that can be used in conjunction with the telescope. The background sky was calculated using the visible magnitude of Vega and the dark sky magnitude from the night of collection. The equations that Shultz used were integrated into the estimates for the optics code developed here. The equation adapted from the Excel spreadsheet is provided (equations (2.4-2.6) along with the SNR equation used from Dereniak (equation (2.7)) [73].

$$\Phi_{Vega} = \frac{551}{10^{\frac{-(sunmag-vegmag)}{2.5}}} \quad (3.4)$$

sunmag is sun's magnitude, vegmag is Vega's magnitude

$$\Phi_{darksky} = \frac{\Phi_{Vega}}{(10^{\frac{-(vegmag-skymag)}{2.5}})} \quad (3.5)$$

skymag is the dark sky magnitude

$$photons_{backgroundsky} = n_{photons} * A_{CCD} * \Phi_{darksky} * QE * T * pixels \quad (3.6)$$

$n_{photons}$ is $\frac{\#photons}{\lambda}$, A_{CCD} is CCD area, QE is spectrometer quantum efficiency, T is atmospheric transmission, and pixels is the number of pixels on the CCD.

$$SNR = \frac{Signal * t_{int}}{\sqrt{(Signal + photons_{backgroundsky} + darknoise) * t_{int} + (readnoise^2)}} \quad (3.7)$$

3.3 Experimental Validation

Along with model development, this research included experiments in the SPASS chamber at AFIT to determine if power levels and viewing angle will affect the in-

tensity of the spectral signature and validate the CRM. Busek's 600W Hall thruster was viewed using both xenon and krypton. The test facility, equipment, set-up, and various test cases will be discussed.

3.3.1 Test Facility.

All testing was conducted at the SPASS Laboratory in the main vacuum chamber at AFIT. The chamber is 1.8 meters in diameter, 2.5 meters long, and able to maintain at least 10^{-6} Torr with thrusters running (10^{-8} Torr with no thrusters). It is pumped down using a two-stage process. An Oerlikon Leybold SP250 roughing pump is used for the initial evacuation down to approximately 50 milliTorr followed by 6 helium cooled cryopumps (four CVI Torr Master TM500 and two CVI Torr Master TM250) to reach the high vacuum level. It has seven ports outfitted with quartz viewing windows measuring roughly 21 cm in diameter to allow for the thruster to be visually monitored during operation. During thruster operation, the internal surfaces of the chamber can be eroded due to interaction with the highly energetic ionized particles in a process called sputtering. This material is then deposited back onto surfaces within the chamber including the viewing windows thus changing their transmission ability. Two options exist to combat this. First, the windows can be removed and polished periodically or second, the plume can be viewed from within the chamber. There are a number of additional ports on the chamber that allow for wiring and feedthroughs. In addition, the location of the viewing ports are either in front of or behind the location of the thruster within the chamber making a wide range of angle measurements difficult. For these reasons, the plume will be viewed from inside the chamber via a fiber optic using a feedthrough located on the bottom side at the back of the chamber (see Figure 9). By moving the optic inside the chamber, a larger

range of viewing angles are able to be collected, and the transmissivity of the quartz viewing windows will not affect the experimental results.

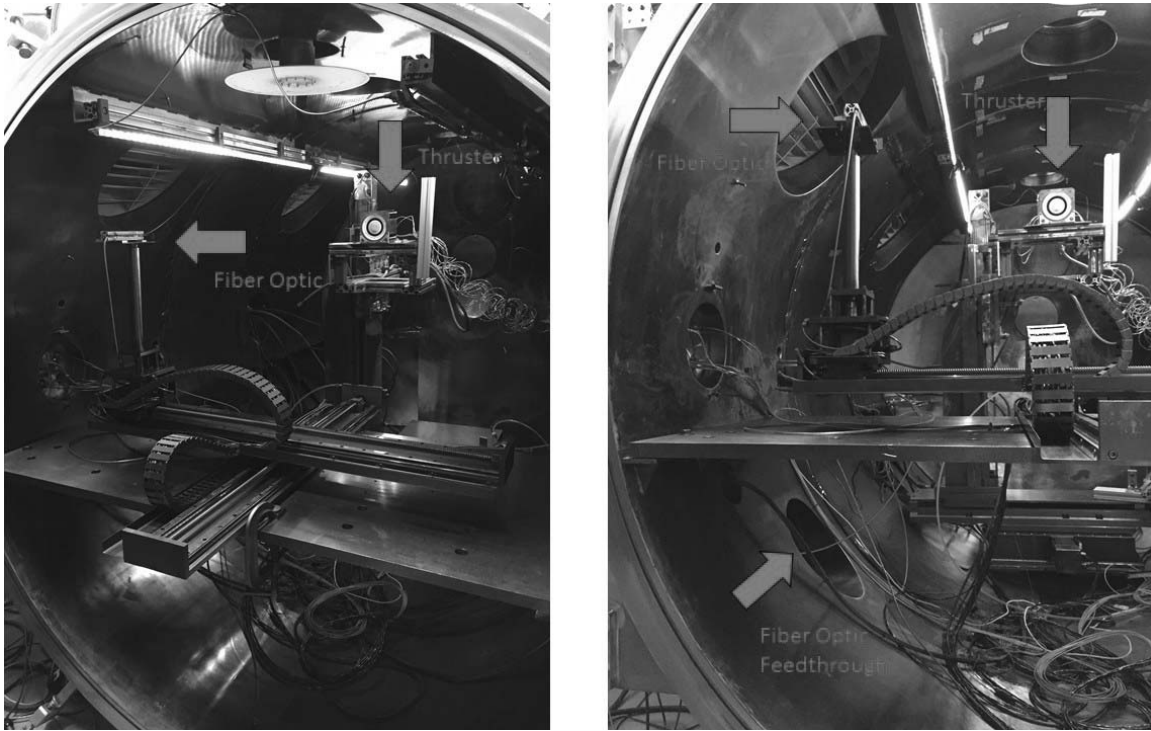


Figure 9. SPASS chamber set-up showing optical feedthrough, thruster, and optic fiber placement.

Due to the sputtering previously discussed, the lens used on the fiber optic cable is also susceptible to degradation. A glass microscope slide approximately 1 mm thick and glass cover slide approximately 0.2 mm thick were each placed over the collimating lens used with the fiber optic cable to protect it from sputtering degradation. A clean (never used in the chamber) microscope slide and cover slide were analyzed along with a microscope slide that was mounted within the chamber and exposed to the 600W Hall thruster in operation. The thruster was operated with a discharge voltage and current of 300 V and 1.4 A respectfully for a one hour interval. All three slides were analyzed for transmissive properties using a Vigilant Cary 5000 series spectrophotometer. For the NIR range of interest (700-900 nm), the difference in

transmission between the un-used slide and the slide used in the chamber was only 1% while the biggest change occurred around 350 nm with a 5% drop in transmission. The largest difference was seen between the 0.2 mm microscope cover slide and 1 mm microscope slide, both of which were untested in the chamber and analyzed clean. This resulted in a 91% transmission as opposed to 55% with the microscope slide. The results of this analysis led to the use of the 0.2mm glass slide for all chamber testing to protect the optical fiber.

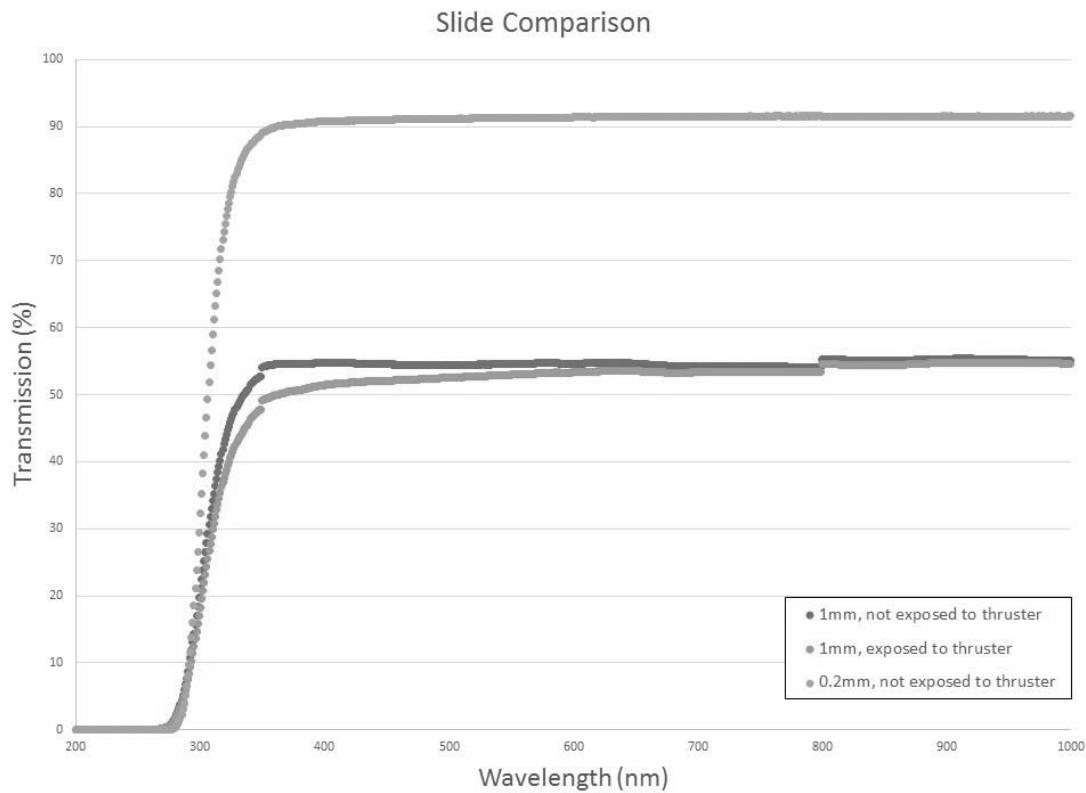


Figure 10. Slide comparison of clean slide, dirty slide (following test campaign in the chamber), and clean cover slide.

There are two movable stages located within the chamber, one for the thruster and the second for sensors. The thruster is mounted to a to a three-axis (x,y,z) stage that is controlled via a program called Nview HMI installed on a computer located outside the chamber. This allows for the stage to be moved while the chamber is

under vacuum. For the experiments performed in support of this research, the stage will be moved into proper positioning to line the plume up vertically with the optical fiber assembly prior to pumping down. The thruster stage will be left stationary for the duration of the experiments accomplished under vacuum.

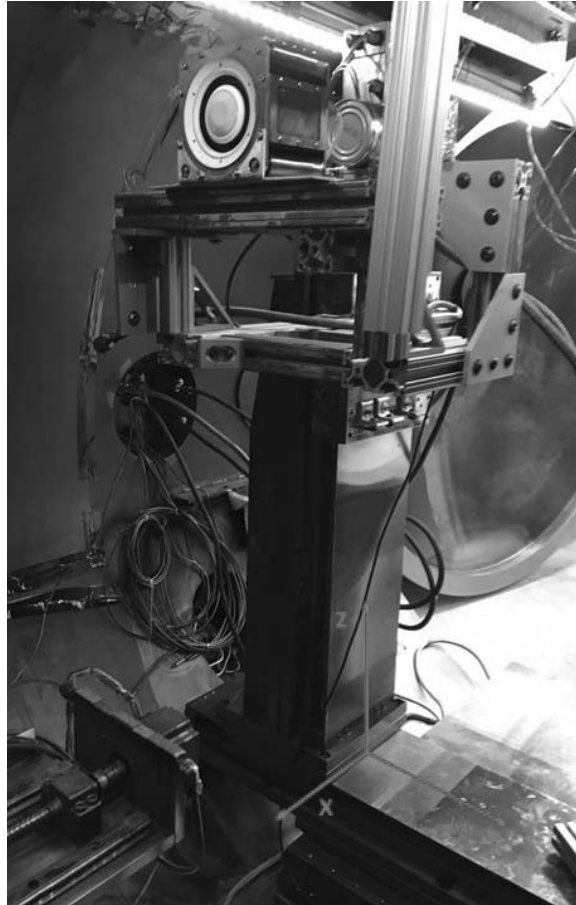


Figure 11. Three axis stage installed in SPASS chamber upon which the thruster is mounted showing axes of movement.

A second large x-y translation stage is located within the chamber and has a mounting plate with a rotation stage installed on it. This stage has a range of 100 cm in the radial and longitudinal axes and 180° for the rotation. All three axes are also controlled through a Labview program installed on an external computer just like the thrust stand allowing for the translation stage to be moved while the chamber is under vacuum and the thruster is in operation. Assuming thruster plume symmetry¹, this allows for the full range of viewing angles to be accomplished on a single run of the thruster at vacuum.



Figure 12. Translation stage installed in chamber upon which the fiber optic assembly is mounted showing axes of movement.

¹Thruster plume symmetry is assumed based on previous Faraday probe data [38], symmetrical thruster geometry, and proper cathode placement during testing.

The propellant is supplied through an MKS mass flow controller. The cathode line is capable of 10 standard cubic centimeters per minute (sccm) while the anode has the ability to reach 50 sccm. Power to the thruster was supplied through a Power Processing Unit (PPU) controlled via a Labview program. The user sets the discharge voltage, magnet and cathode currents. Actual values can be monitored in real time via the GUI, shown in Figure 13.

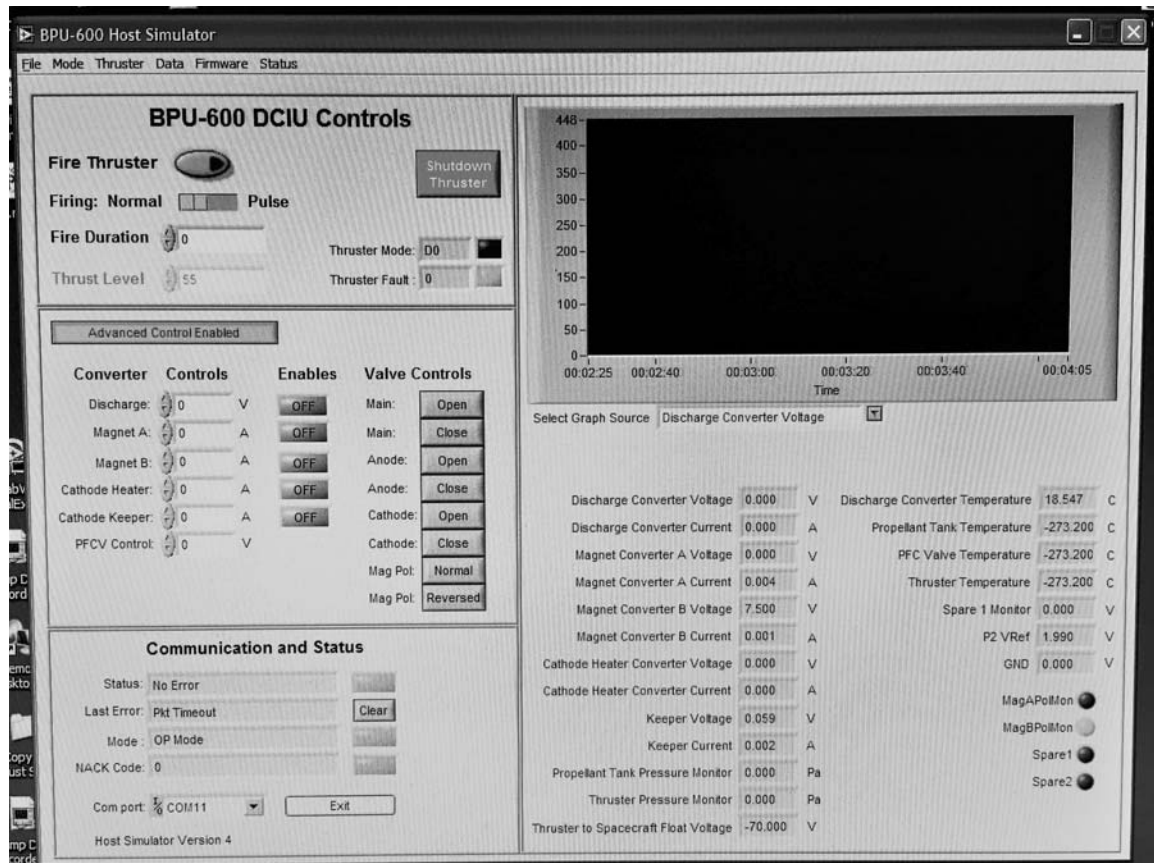


Figure 13. PPU program used to control the thruster while operating in the SPASS chamber.

3.3.2 Equipment.

Two spectrometers were used for this experiment. An Ocean Optics HR4000 and QE65000 spectrometer will both be used. The fiber optic will determine the spectrometer's slit size. In this case a 200 m fiber optic cable will be used with both spectrometers. The HR4000 has a 1200 mm⁻¹ grating with a range of 200-1100 nm and the QE65000 has a 600 mm grating with a 600-1000 nm range. In addition, both spectrometers will need to be calibrated for wavelength and intensity. A separate calibration was done for krypton and xenon using Orielle pen lamps. Each spectrometer was calibrated prior to testing with each pen lamp respectively. The coefficients were noted and updated prior to chamber testing with each propellant with any deviations being noted. In addition, a blackbody lamp with a known temperature was used for intensity calibration. Absolute intensity calibration is extremely difficult to accomplish and thus intensity counts will be used. Using the known black-body curve of the tungsten lamp and the relative intensity calculated by the spectrometer when viewing the lamp, the difference in intensity counts can be calculated. This will allow for a more accurate estimate of relative intensity of each line in relation to one another. The calibration results are in Appendix A.

3.3.3 Test Set-Up.

The optic assembly was rotated around the thruster in approximately 10 degree increments between 0 and 53 degrees. The fiber optic cable used is an Ocean Optics 200 μ m with a numerical aperture of .22 which equates to approximately a 25.4 degree field of view.

The fiber was positioned far enough away to capture the entire plume and will be protected by the 0.2 mm glass microscope cover slide which will allow transmission of the NIR wavelengths as well as protect the optics. The distance of the fiber from the

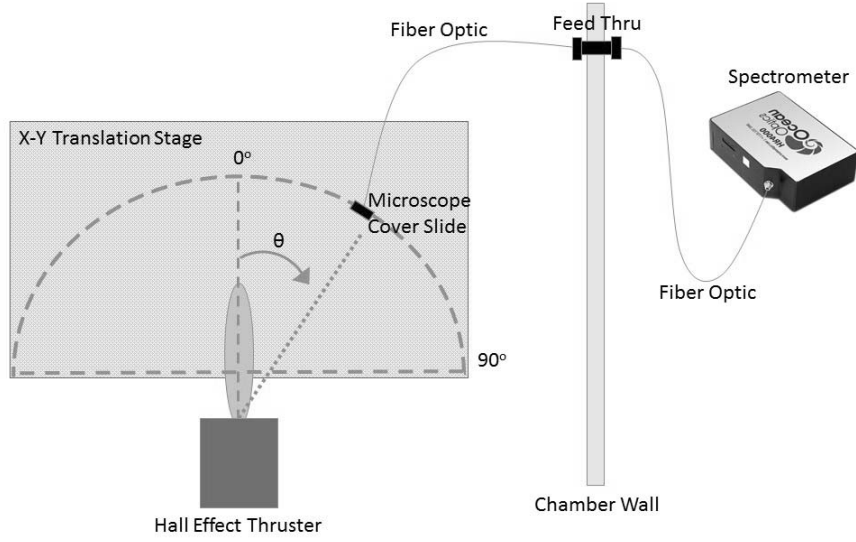


Figure 14. Top-down view of optical assembly set-up and planned range of movement of translation stage in SPASS chamber.

thruster was determined through two separate sets of calculations. First the plume size was estimated using a profile image of the 600 W Hall thruster in operation with xenon, shown in Figure 15. From that estimation, the minimum distance for the plume to be completely within the field of view (FOV) of the fiber was calculated for both the direct (0°) view and indirect (90°) view (see Figure 9). The FOV and minimum distance were calculated using the following equations where NA is the numerical aperture of the fiber, n is the index of refraction of the medium (1 for air), $\theta_{1/2max}$ is half the field of view angle, and $r_{thruster}$ is the radius of the thruster.

$$FOV = 2(\theta_{1/2max}) = 2n(\sin^{-1}(NA)) \quad (3.8)$$

$$d_{min} = \frac{r_{thruster}}{\tan(\theta_{1/2max})} \quad (3.9)$$

The results for the 600W thruster are shown in Table 1.

Table 1. Minimum distance for thruster plume to fill the entire FOV of the fiber

Minimum Distance (m)	
Direct (0°) FOV	Indirect (90°)
0.141	0.281

Second, an optics analysis was done to determine the minimum distance for the plume to fill the CCD of the spectrometer. The CCD of the Ocean Optics HR4000 spectrometer is a Toshiba TCD1304AP with a total area of 29184 x 200 μm and the QE65000 has a Hamamatsu S7031-1006 detector with an active area of 24.576 x 1.392 mm. For both detectors, the width of the plume will be maximized on the short end of the CCD. This means that in testing the plume must be captured in the lateral position to ensure the shorter section of the plume is focused on the shorter end of the CCD.

Table 2. Minimum distance for thruster plume to fill entire spectrometer CCD.

Minimum Distance (m)	
HR4000	0.176
QE65000	0.026

The maximum distance from all calculations done above is 0.281 m so that will be the true minimum to ensure all requirements are met. The planned length will be 0.47 m to ensure the entire plume will be captured and the fiber optic will be far enough away to minimize damage from sputtering. In addition, an Ocean Optics collimating lens will be used to focus the light into the fiber optic. It was determined after testing that the collimating lens did not have as wide a FOV as the fiber optic itself despite being advertised to. The FOV was found to be 8.29 degrees (full details are provided in Appendix A). After performing the optics calculations above for the

FOV estimates, the minimum distance was found to be .42 m which is within the original test set-up parameters and thus the results are still valid. The test set-up with dimensions is in Figure 15.

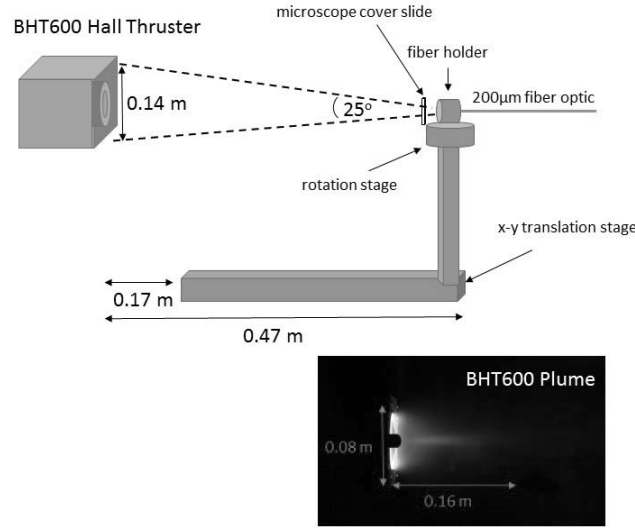


Figure 15. Side view of optical assembly set-up with dimentions in SPASS chamber.

3.3.4 Test Cases.

The 600W thruster was previously run at varying power levels and mass flow rates by Bui [38]. After the CRM is validated using test cases for xenon, Bui's data will be used to estimate spectral differences due to varying power levels and mass flow rates. The test cases accomplished in this previous research are summarized in Table 3.

Table 3. Power levels to be tested.

		Mass flow rate (mg/s)			
		2.079	2.325	2.600	2.875
Discharge Voltage (V)	400	X			
	350		X		
	300	X	X	X	
	275		X		X
	250			X	
	225			X	X
	200			X	X
	175	X	X	X	X
	150	X	X	X	X
	125	X	X	X	X
	100	X	X	X	X
	90	X	X	X	X
	80		X	X	

3.4 Real-World Validation

Validation of the model was accomplished through use of the TeleTrak system at AFIT. All observations will be made using a Meade 16" telescope. Tracking of any satellites observed will be done using a student developed Matlab-based satellite tracking code. The spectrometer assembly is based on a previous design accomplished by Sutliff [74]. He designed a spectrometer assembly for use with the Meade telescopes to collect the reflected light curve spectra of orbiting satellites. His work was referenced and used as a starting point for the optics design for this research. In his work, a diverging and converging lens design were compared. Ultimately, the converging lens design proved to be more advantageous of the two. It allowed for a shorter image chain thus reducing alignment issues in the divergent design as well as an increased FOV.

An Ocean Optics 74-ACR collimating lens was used to focus light into the fiber optic cable. This particular lens is adjustable and was advertised to increase the FOV of the fiber optic cable (25°) to 45° . In addition, it has an achromatic lens that corrects for any spherical or chromatic aberrations [75]. An optics analysis was done using the same fiber optic assembly as described above for the chamber measurements to determine the true FOV at different adjustments. Measurements were taken in the SPASS chamber. A xenon pen lamp was mounted on the thruster stand and the optical assembly was kept on the translation stage. The fiber optic was centered on the penlamp and then moved radially in either direction by 0.1 cm increments with an intensity measurment being collected at each point. The results showed that the lens has an approximate 11° FOV when the shaft was fully extended and 6° when not extended. A picture of each adjustment is shown in Figure 16.



Figure 16. Collimating lens showing two adjustable positions used for FOV calculations.

A 50:50 beam splitter was implemented by Sutliff to allow half the detected light to be directed to a webcam for accurate alignment into the spectrometer. The webcam was used to verify the satellite remained in the FOV of the spectrometer, albeit with a 50% loss due to the splitter. There is a drastic reduction in intensity of a Hall thruster versus sunlight reflected off of a satellite. This light reduction combined with this research's focus on detecting GEO satellites and star verification which remain stationary or move slowly over the course of an evening, the beam splitter was removed. This will allow all of the collected light to be focused directly onto the fiber optic for analysis, but will require another method to verify the telescope pointing.

The assembly used remained the same only the beam splitter optic was removed from its casing but the cube casing was still used in the assembly. This was done to allow a simple integration later if a beam splitter was deemed to be necessary. The collimating lens screws into a small removable plate located on one face of the cube. This side of the cube is then attached directly to the adaptor for the rear assembly of the telescope. This allows the lens to be placed exactly where the light would focus on the human eye observing through the optic.

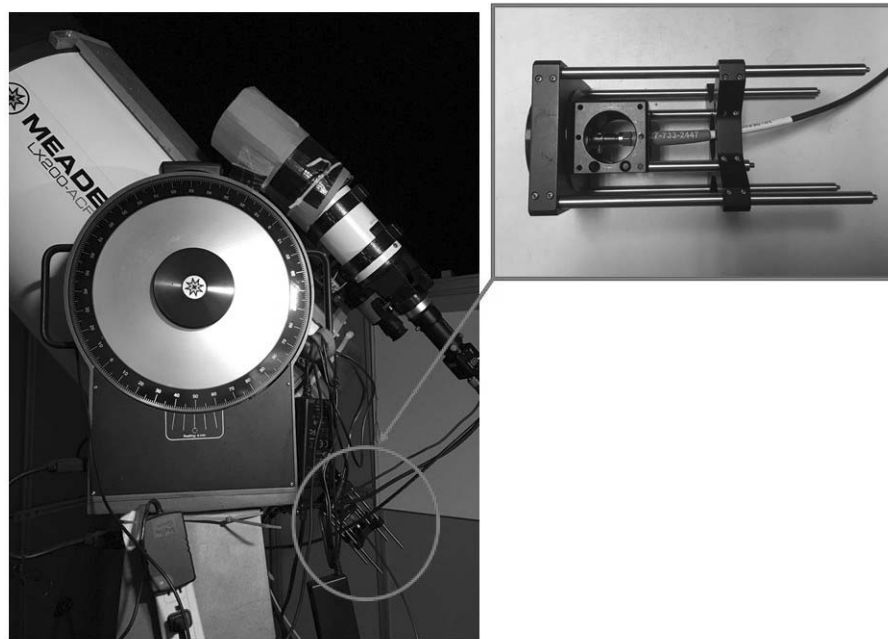


Figure 17. Optical assembly design for use with the Meade telescope showing a close-up as well as placement.

For purposes of verifying SNR estimates from the developed model, several stars emitting in the NIR were chosen as candidates for collection. While stars are much brighter than a Hall thruster emission, a stars intensity can be calculated and used as an appropriate verification of the developed program. Using the Morgan-Keenan classification system, stars with a stellar classification of K and M were considered. These stars have emission peaks in the NIR and tend to be orange or red giants

and supergiants. Observations were slated to occur in the spring of 2017 between March and May. Stellarium was used to estimate the stars overhead on evenings of collection during this time frame. Three stars were chosen as appropriate candidates, Betelgeuse, Arcturus, and Aldebaran. All three have peak wavelengths in the NIR spectrum and are in the K and M spectral classes.

Table 4. Characteristics of chosen stars for code validation and collection.

	constellation	magnitude	class	T(K)	peak λ (nm)	distance (ly)
Betelgeuse	Orion	0.5	M	3590	807	643
Arcturus	Bootes	-0.05	K	4286	676	371

3.5 Summary

This chapter started by discussing the overall flow and pieces of this research effort. Model development was discussed including the previously developed and proven models that will be integrated into the end-to-end model developed in this research. SpectraSuite software will produce both a table of data comparing radiometric parameters with respect to wavelength as well as a graph for each set of data taken. The integrated spectral irradiance at each angle will also show the location of the extinction point (angle where irradiance drops off to near zero). Lab data will be compared with simulated data from AFRL's CRM. The measured intensities in conjunction with corresponding wavelengths will be compared. The difference between the two spectrums will be calculated to determine how close the model results are to the measured data. Any deviations noted in the calibration will be taken into account. The lines used for validation will be chosen based on accuracy in determining electron temperature from their ratio as well as persistence in detection as defined by NIST. The spectrometers that are to be implemented for both experimental and real-world

validation were introduced and discussed. The chapter concluded with the optical design for the telescope and selected stars to be used for real-world observations and code validation.

IV. Results

This chapter will discuss the results of this research effort. The selection of spectral lines used for analysis and equipment choices for code validation will be discussed first, followed by experimental testing results and code development. Finally, real-world observations of select stars will be presented to verify the end-to-end model predicted SNR results.

4.1 Line Selection

As discussed previously, xenon is well documented on which lines are best used to determine the electron temperature of a Hall thruster plasma, namely the 823 and 828 nm lines. Krypton is not as well analyzed and thus all four pairing candidates from Prince will be evaluated [52]. The method used to determine the best line pairs for ground observations combined National Institute of Standards and Technology (NIST) data and LEEDR atmospheric transmission estimates. NIST data for the persistent lines of xenon and krypton were compared with the selected lines from the literature review results. Persistent lines are described by NIST as such: “the number of observable lines of the element is found to decrease with decreasing concentration until only the most ‘persistent’ or ‘sensitive’ lines remain. [...] a relatively small group of lines can be specified for each element that will include the [persistent] lines as observed over a wide range of experimental conditions [76]”. Persistent lines are used in this case because they will have the greatest probability of being detected by a staring telescope through the atmosphere.

LEEDR estimations for the atmosphere transmission values were accomplished for the entire range of 700-900 nm as well as at each of the six candidate lines for xenon and krypton. Ground-based observations using the small telescopes will be

conducted at Wright-Patterson AFB, Ohio. Other inputs to LEEDR include using the ExPERT atmosphere model for summer with observations between 0000-0300 in the Summer, 50 percentile relative humidity, GADS aerosols, climatological wind, and the HV 5/7 model for turbulence. The individual values were determined by running the wavelength values separately using the Laser/Geometry tab on the input screen while the overall transmission graph for wavelengths between 700 and 900 nm was developed using the Comparisons tab on the output screen. For the generation of the overall transmission graph the number of points used in molecular and aerosol transmission calculations could be input. The higher the number of points selected, the longer the calculation time. It was found that increasing the aerosols number above the auto populated 10 resulted in no discernable difference in the graph (Figure 18).

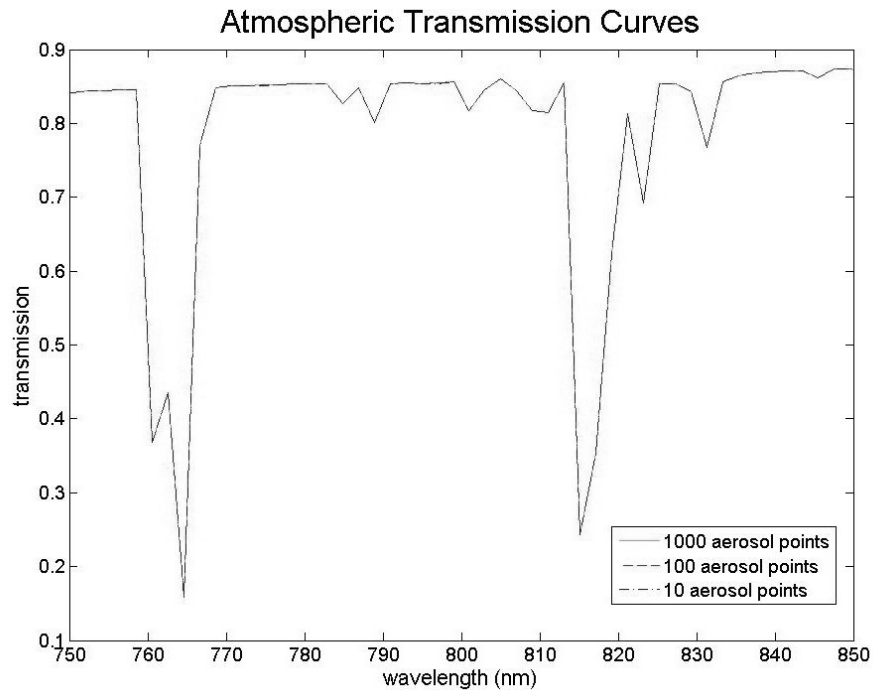


Figure 18. LEEDR transmission curves showing difference in aerosol point numbers used while molecular point number is kept constant.

The molecular points resulted in a drastic difference in the curve. The auto populated 10 was extremely deficient for accurate depiction of transmission in the atmosphere as was 100 points. Using 1000 points generated a curve in a high level of detail for atmospheric transmission. All three are shown in Figure 19 to illustrate the exponential difference between the three.

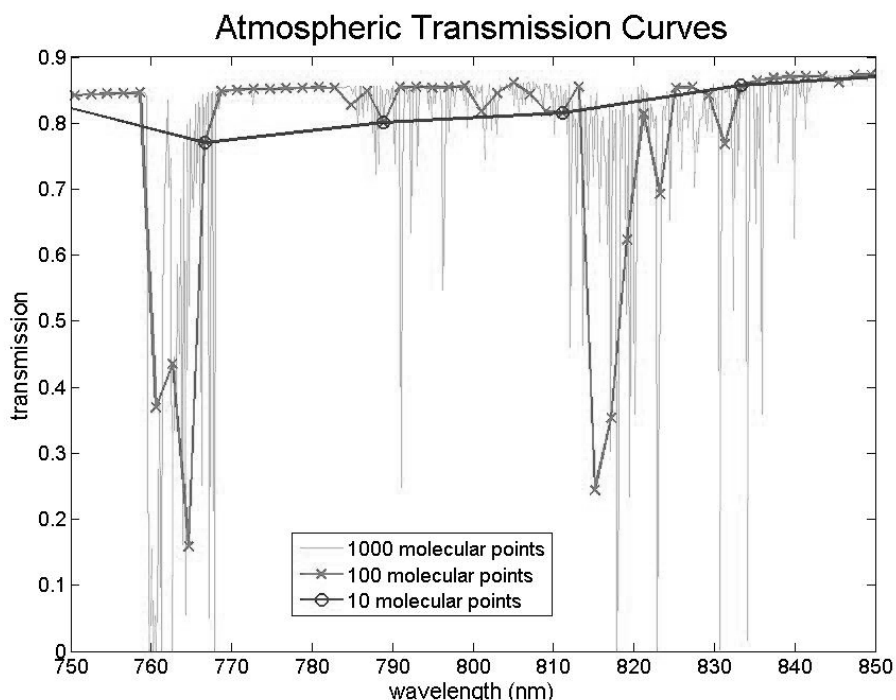


Figure 19. LEEDR transmission curves showing difference in molecular point numbers used while aerosol point number is kept constant.

The comparisons resulted in the selection of 10 for the aerosol points to be used and 10,000 for the molecular points to be used. This number for molecular points was chosen because it allows for a well estimated transmittance curve especially around defined water lines in the atmosphere discussed in Chapter II, specifically around the 760 and 820 nm lines. This research aims to determine the efficacy of estimating line ratios thus precise estimates of the transmittance values of these lines is vital. In addition, Figures 20 and 21 combine the resulting LEEDR transmission curve

with the line data available through NIST. From this analysis, we can pare down the lines to be considered for ground observations. For xenon, the 823 and 828 lines are classified as persistent lines and have transmission values through the atmosphere of around 70-80%.

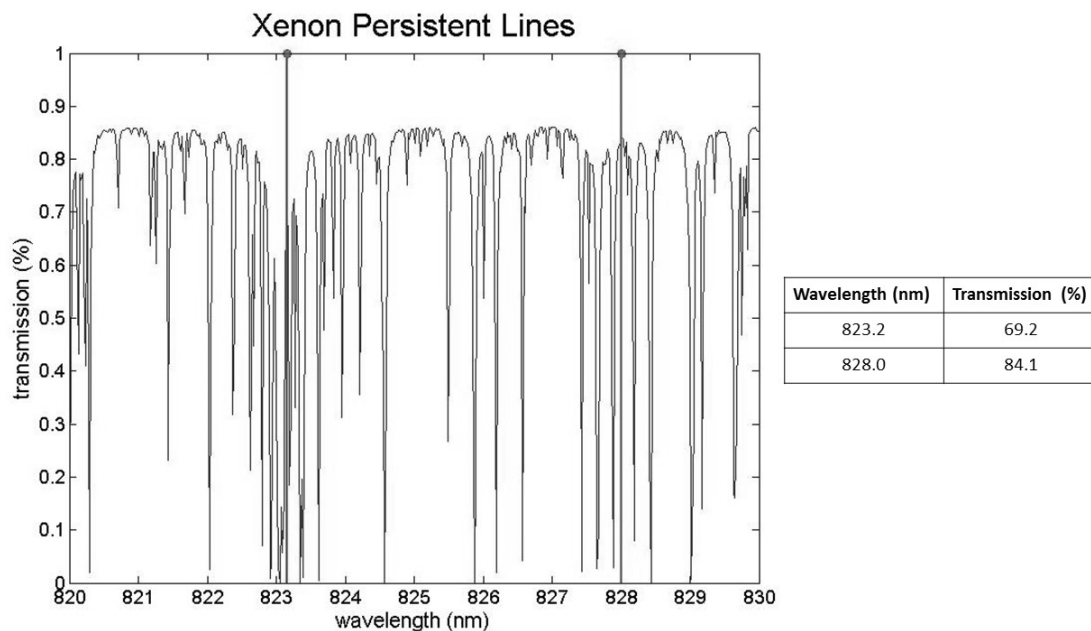


Figure 20. LEEDR transmission curves showing persistent lines from xenon NIST data and transmission values.

For krypton, only the 811/810 and 829/826 pairs were categorized as persistent lines by NIST. The 758/760 and 768/769 line pairs are both considered strong lines but not persistent meaning that these lines do not remain observable over all the conditions tested by NIST. In addition, there is a very strong water line in the atmosphere around 760 nm which resulted in the first pair, 758/760, to be discounted due to the low transmission of the 760 nm line in particular. The 768/769 pair had an acceptable transmission value calculated by LEEDR around 85%, however; due to the fact that these lines are not classified as persistent lines they will also be discounted for this

analysis. This leaves two potential krypton line pairs for ground-based observations, the 811/810 and 829/826 pairs.

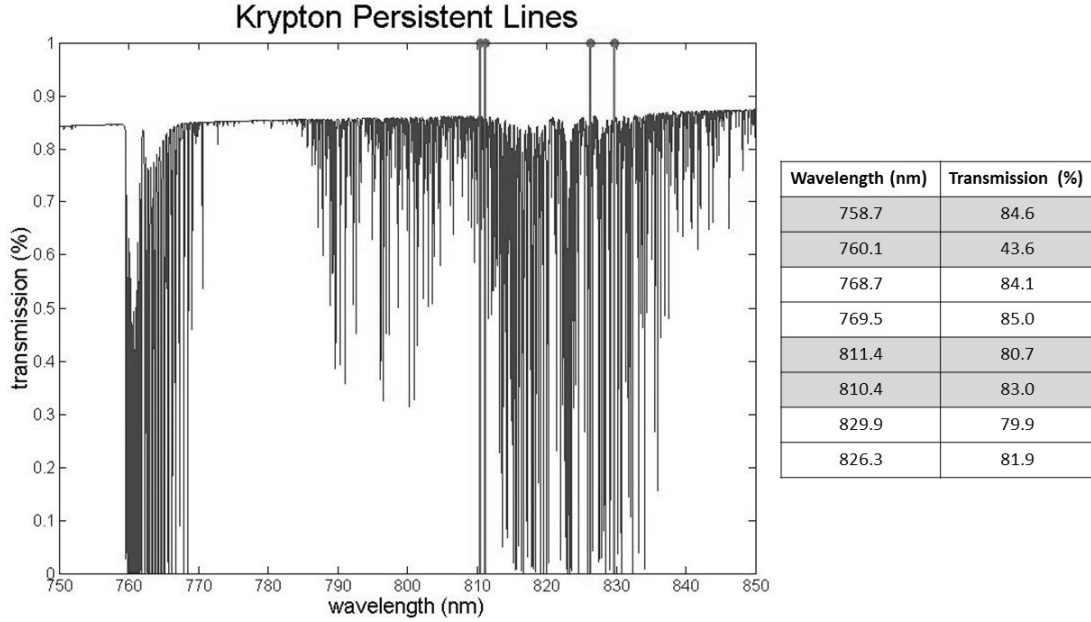


Figure 21. LEEDR transmission curves showing persistent lines from krypton NIST data and transmission values.

4.2 Experimental Results

The experiments run in the chamber served two purposes. The first is to observe and collect data on the spectral signature of the plume to validate the CRM code estimations to the observed data. The second purpose was to observe the spectral signature over a range of viewing angles around the plume to determine the effects, if any, on the observed spectra. Observations were made using the experimental set-up detailed in Chapter III for the BHT 600W running both xenon and krypton as a propellant. The xenon data was used to validate Scharfe's CRM code which estimated spectral line intensities of the plasma and the krypton data was used to

validate Prince's CRM code which estimated electron temperature of the plasma given observed spectral line intensities.

4.2.1 CRM Validation.

Bui's data from his ExB and Faraday probe measurements were used to estimate parameters for Scharfe's CRM code [67]. Calculated inputs were made using equations (3.1-3.3) outlined in Chapter III based on data collected 50 cm directly in front of the Hall thruster, 0° angle. Those calculations and values are shown in Table 5.

Table 5. Measured and calculated inputs for AFRL's xenon CRM code.

Measured Values		Calculated Values)	
$V_d=$	300V - discharge voltage	$nn=$	$3.22 * 10^{17}/m^3$
$V_c=$	11V - cathode voltage	$ne=$	$2.609 * 10^{13}/m^3$
$P_t=$	10^{-5} Torr - chamber pressure	$ni1=$	$2.233 * 10^{13}/m^3$
$T_n=$	300K - neutral temperature	$vi1=$	20987.74 m/s^2
$j=$	$8.2 \text{ A}/m^2$ - current density	$vi2=$	29681.15 m/s^2

The last input to the CRM code is electron temperature (T_e) which was not measured by Bui and thus needed to be estimated. In order to provide a sound estimate of the electron temperature of the plasma one can combine two parameters. The first is the ionization energy of xenon and the second is the keeper voltage of the cathode. The plume of a Hall thruster is primarily made up of Xe^{+1} ions and therefore the temperature of the plume must at least be that value. According to the CRC handbook, Xe^{+1} has an ionization energy of 12.13 eV [77]. The second parameter is the keeper voltage. The keeper is a part of the cathode that aides in igniting the cathode and maintaining the beam voltage should the discharge be momentarily interrupted [19]. For the experiments that were run in the chamber,

a keeper voltage of 8 V on average was maintained. By adding the two parameters together, a good estimate of the electron temperature of the plume can be made. In this case, $T_e \approx 20\text{eV}$. A good check of this approximation is by comparing it to the ionization energy of Xe^{+2} . While the majority of the plume, around 80-90%, is composed of Xe^{+1} ions, the rest of the plume is Xe^{+2} ions. While it comprises a small percentage of the overall plume, the temperature should be around the ionization energy of those ions. The ionization energy of Xe^{+2} is 20.975eV [77] verifying our approximation of 20eV.

Before taking measurements in the chamber, both spectrometers were calibrated using Orielle xenon and krypton pen lamps to verify the location of the detected wavelengths on the spectrometers' CCD. A second calibration was done to determine the sensitivity of the CCD in each spectrometer and allow for accurate representation of the line intensity measurements relative to one another. This calibration was to be accomplished using a tungsten lamp of a known temperature so that the resulting blackbody curve could be compared with the counts registered by the spectrometer. This would give an intensity per count correction factor for each pixel on the CCD. The lamps available at AFIT had grey body curves that tapered off too drastically in the region of interest, 800-830 nm, and did not provide a large enough signal to accurately calculate the correction factors. In troubleshooting this issue, it was discovered that the sun provided a large enough signal in this region to calibrate the spectrometers. It is important to note that a true calibration would be difficult using the sun due to transmission factors in the atmosphere but for the purposes of this calibration the relationship of the lines with one another is of more importance than an accurate intensity measurement. The sun's collected spectra and calculated blackbody curve can therefore be used as an accurate calibration of the sensitivity of the spectrometer CCDs. A Matlab function was developed to perform this calculation and output

the correction factors for the entire spectrum collected on each spectrometer and is located in Appendix B.

Spectral measurements were made using Ocean Optics SpectraSuite software. The optic fiber assembly was kept at the home position of the translation stage which is located at the top left with the optic pointing towards the chamber wall. This was done to protect the fiber assembly from bombardment of the ions in the plume. Once the chamber pressure was around 10^{-4} , the thruster was turned on and left to run for approximately an hour. This gave sufficient time for the thruster discharge to stabilize. The fiber was then positioned using the translation stage at the 0° position. Data was collected first with the HR4000 spectrometer and then the QE65000 spectrometer. Due to the fiber optic being fed through a port in the chamber, this was a simple unplugging of the fiber optic from one spectrometer and plugging into the other. After all data was collected with the thruster in operation, the thruster was turned off and the optical assembly was moved back to the home position so that a dark spectrum could be collected. The dark spectrum will provide the noise inherent in the spectrometer itself as well as any in the chamber environment that can be subtracted from the thruster signature to isolate the signal from the noise. By taking this step, the true spectral counts can be determined and a more accurate representation of the individual lines and thus the overall ratio can be calculated. The correction factors from the CCD sensitivity calibration were then applied and the resulting spectra and calculated CRM values are shown in Figures 22 and 23.

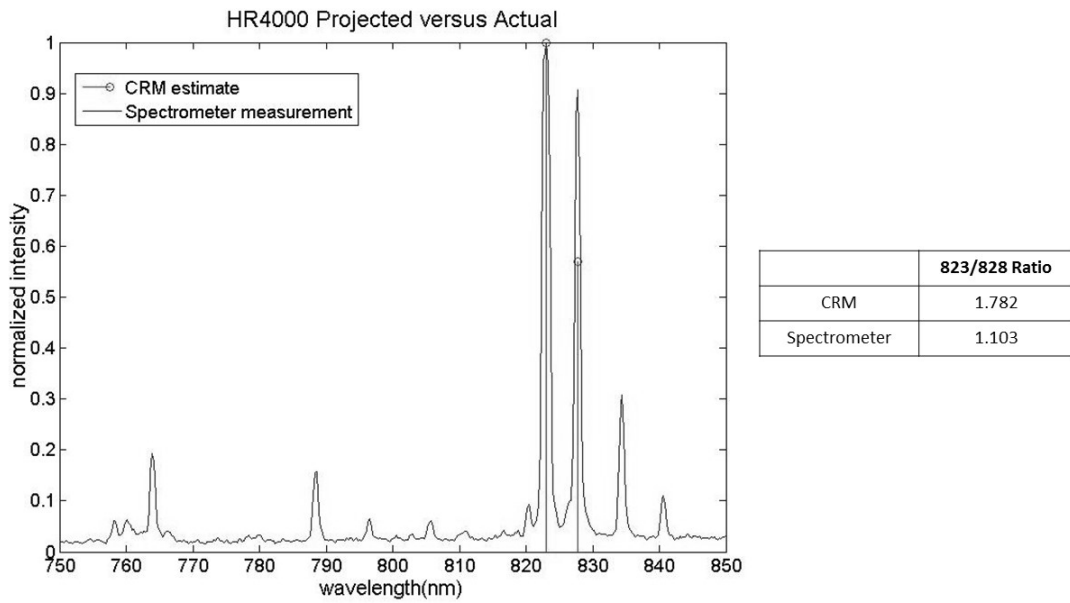


Figure 22. Visual comparison of spectrometer generated spectra and CRM line estimates highlighting approximate ratio values for HR4000 spectrometer.

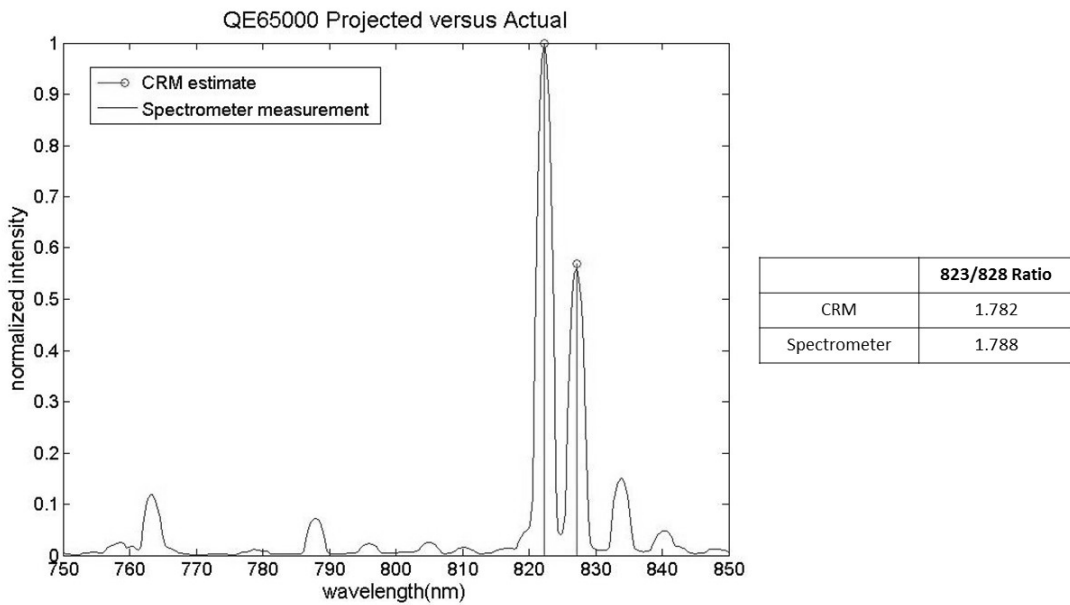


Figure 23. Visual comparison of spectrometer generated spectra and CRM line estimates highlighting approximate ratio values for QE65000 spectrometer.

The HR4000 resulted in a 68% difference in the ratio while the QE65000 had a 0.6% difference. The QE65000 is clearly in better agreement with the CRM estimations but whether that difference is enough to be accurately detected needs to be explored. If a Hall thruster was operating on orbit, the operator would have insight into the voltages being applied as well as the corresponding experimental values from ground testing. In addition, the main driving factor of the CRM is the electron temperature which also drives the efficiency estimates. By calculating the difference in the ratio for 1 eV change while keeping all other factors constant, a reasonable estimate on typical ratio changes can be calculated. Table 6 shows the results over a 6 eV change.

Table 6. Ratio changes for a given Hall thruster at different T_e values.

T_e (eV)	823/828 Ratio
18	1.86
19	1.82
20	1.78
21	1.75
22	1.71
23	1.68

The average ratio change for 1 eV was 3%. The QE65000 was well within the sensitivity needed to detect a single eV change, however; the HR4000 did not demonstrate the sensitivity needed.

4.2.2 Hall Thruster Dependencies.

Now that the CRM code has been validated and the sensitivities needed to determine a small electron temperature change have been determined, the Hall thruster

dependencies need to be analyzed. First the viewing angle dependencies of the plume will be looked at using collected spectra. Only krypton data was collected for this analysis due to the cathode failing to relight after switching propellants¹. The power level and mass flow rate dependencies on the ratio will be calculated using Bui's data and Scharfe's CRM code.

4.2.2.1 Viewing Angle.

The fiber was rotated around the plume to the approximate r and z values calculated for 10° increments and then toggled in the θ value until the brightest spectra was detected. This ensured the plume was being viewed directly and was a necessity due to the limited accuracy of the translation stage controls. Table 7 shows the calculated values for r and z using simple trigonometry as well as the actual θ value to capture the plume.

Table 7. Translation stage values used for plume observations.

calculated θ (degrees)	r value(cm)	z value (cm)	actual θ (degrees)
0	0	0	0
10	8.2	0.7	10
20	16.1	2.8	18
30	23.5	6.1	27
40	30.2	10.3	35
50	36	15.2	43
60	40.7	20.4	53

¹The cathode used for this analysis was nearing the end of its useful life and the failure is believed to be due to reaching that limit. Three other back-up cathodes were wired and attempted; however, all three failed to light. These subsequent failures are likely due to contamination of the cathode caused by exposure to oxygen and humidity during extended storage. The cathodes are stored in a dry nitrogen purged environment when not in use but it is not completely sealed.

Due to physical limitations of the translation stage and diameter of the chamber, measurements above 60° were not able to be collected. The resulting spectra for the HR4000 and QE65000 spectrometers are shown in Figures 24 and 25.

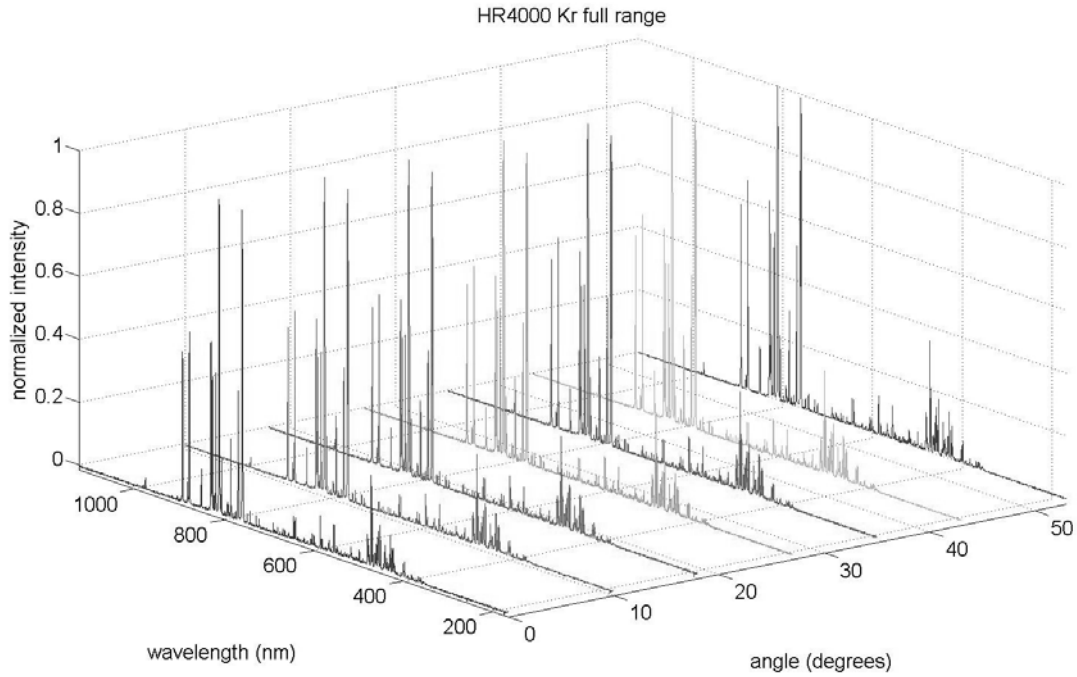


Figure 24. Visual comparison of spectrometer generated spectra of a Busek BHT-600W Hall thruster running on krypton propellant for varying viewing angles using the HR4000 spectrometer.

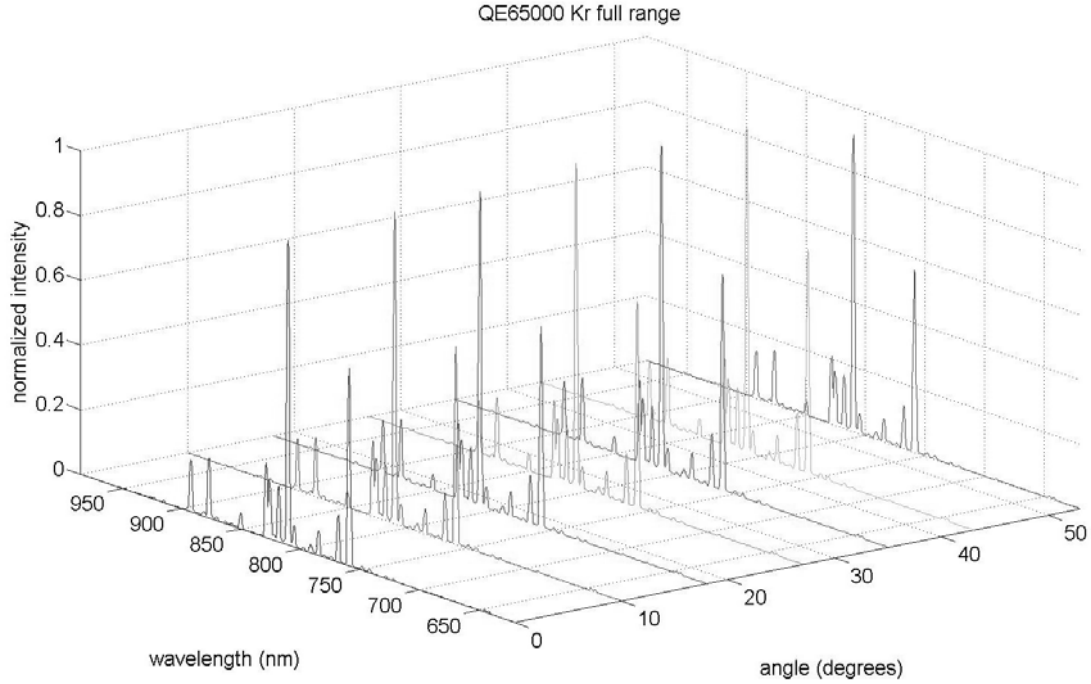


Figure 25. Visual comparison of spectrometer generated spectra of a Busek BHT-600W Hall thruster running on krypton propellant for varying viewing angles using the QE65000 spectrometer.

The viewing angles analyzed from 0° - 53° showed relatively little change in the overall spectra. In order to gain better insight, the standard deviation of each spectrometer across the viewing angles was calculated. The results provide more detail on the changes in spectral intensity for each spectrometer. The results are shown in Figures 26 and 27.

The HR4000, while still relatively stable across all viewing angles, showed a standard deviation 4 times as large as that measured by the QE65000. Even with the small discrepancy across spectrometers, the spectra were determined to have negligible dependence on viewing angle. This is largely due to the ionization occurring primarily in the channel of the Hall thruster as opposed to the ejected plume. For the range of angles tested, the channel is still visible and thus the ionization and the light emitted from those interactions is still detectable. A sudden drop off in inten-

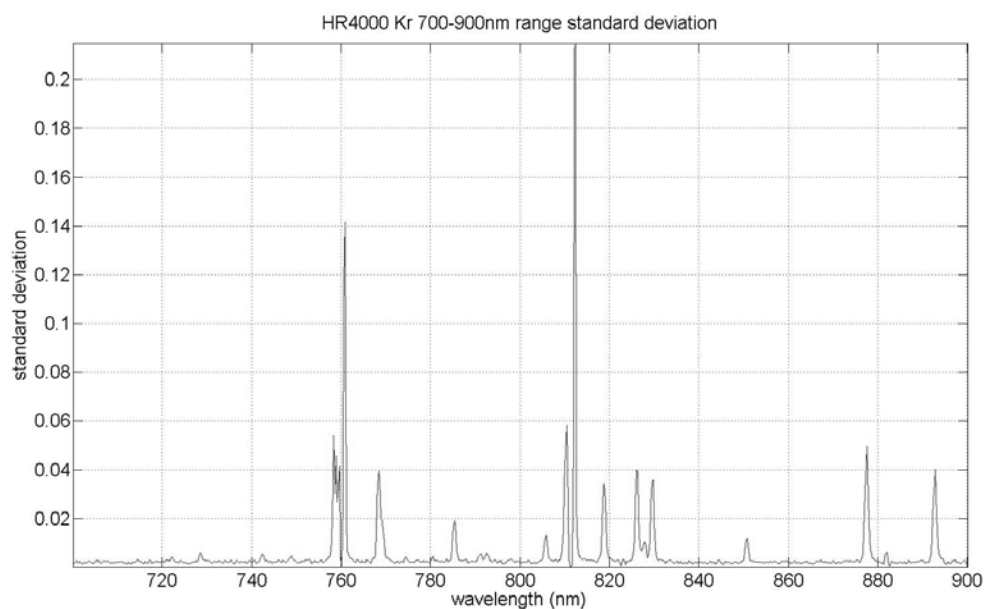


Figure 26. Visual comparison of the standard deviation across all viewing angles using the HR4000 spectrometer.

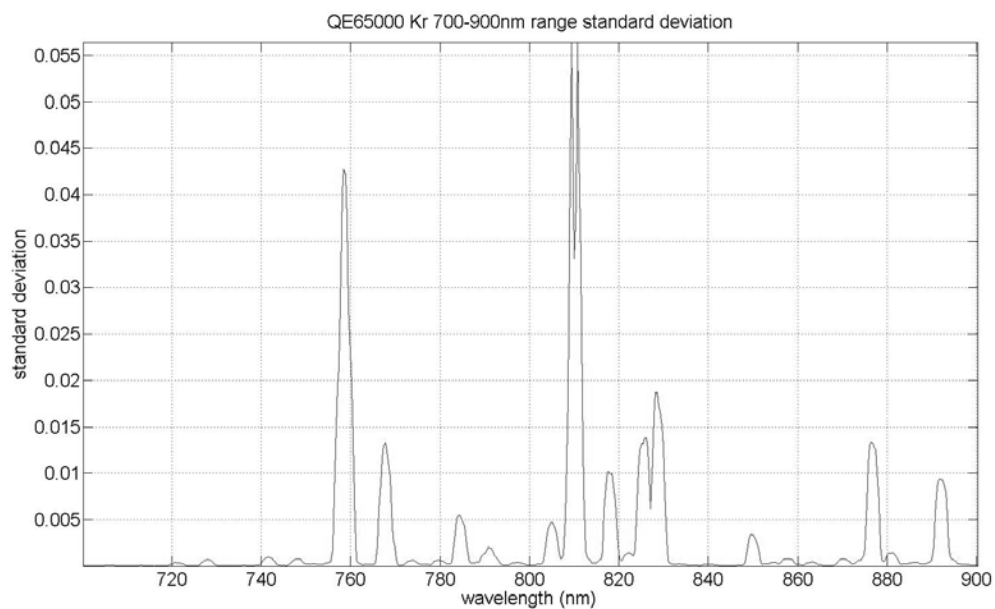


Figure 27. Visual comparison of the standard deviation across all viewing angles using the QE65000 spectrometer.

sity of the spectra would be expected as the channel is obscured by the outer walls of the thruster itself. This will present a challenge for ground-based observations if the attitude of the thruster is not known.

4.2.2.2 Operating Power Level.

Due to the failure of the cathode during the viewing angle measurements, the test campaign to observe spectra changes for varying operating power levels was not able to be completed. Bui did make a number of observations for varying power levels as well as mass flow rates that allowed for the spectral changes to be estimated using the CRM in lieu of running the test campaign as planned. A large amount of data was available from Bui's experiments using the ExB and Faraday probes. More variations in power levels and mass flow rates were evaluated with the Faraday probe and thus only the testing parameters that were available across both probes were used in this analysis. Data was collected at varying distances from the Hall thruster; however, these changes will not be evaluated in this effort. All data used had been collected at a probe distance of 40 cm from the Hall thruster.

Equations (3.1-3.3) from Chapter III were used in the CRM validation for power level. This time the electron temperature was estimated using a widely accepted rule of thumb for estimating this parameter. Electron temperature fluctuates depending on the voltages applied. In the CRM validation, it was estimated using known information on the keeper voltage observed during operation as well as the known ionization temperatures. If the keeper voltage is now known or an estimate is being made based on previously collected data, a better method to estimate electron temperature is provided by Haas' research. He found during his PhD research effort that the electron temperature varied as a function of $\frac{1}{10}$ the beam voltage [78]. Beam voltage can in turn be estimated as the discharge voltage minus the cathode

discharge voltage. The estimated line ratios are plotted as a function of operating power level and thrust for each of the mass flow rates. The resulting curves are shown in Figures 28 and 29.

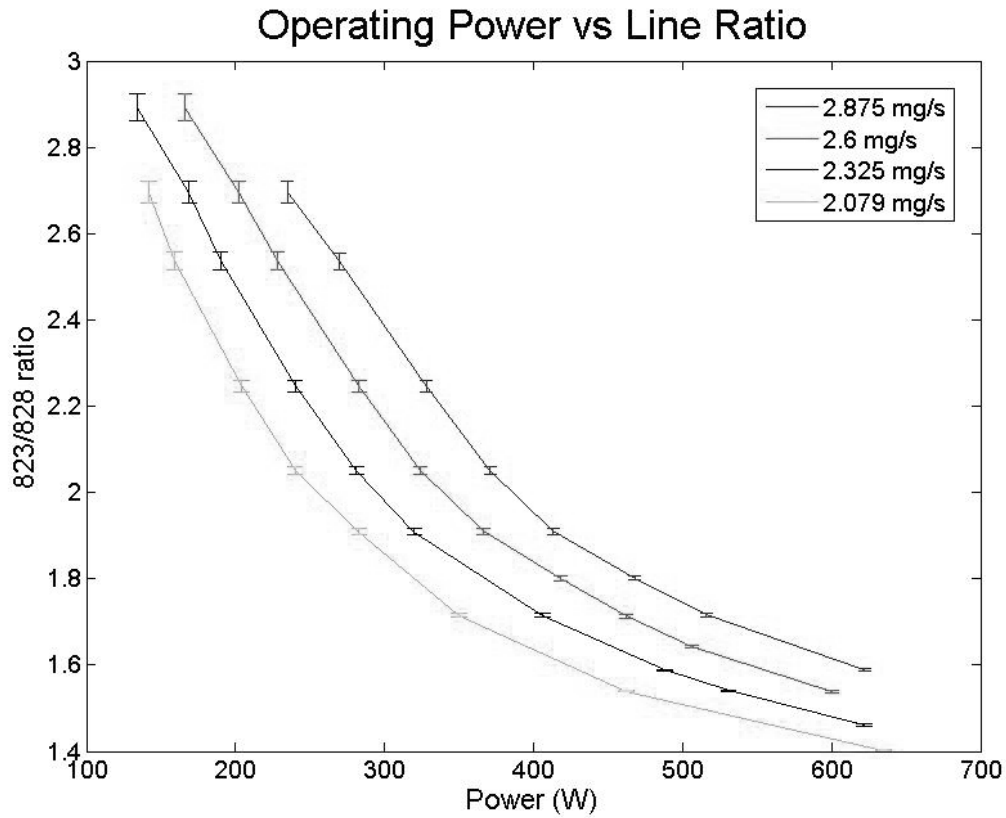


Figure 28. Xenon line ratio changes based on varying operating power levels and mass flow rates. [derived from data in [38, 78]]

The electron temperature estimates give a good representation of the curves and relative changes of the ratio values as a function of operating power level and mass flow rates. While the relative changes in ratio are accurate, it should be noted that the actual ratio values themselves are not exact and are based on thruster operation under ideal conditions.

Table 8. Operating power, line ratio, and mass flow rate data used for generation of Figure 28

Mass Flow	Power	823/828	Mass Flow	Power	823/828
Rate (mg/s)	(W)	Ratio	Rate (mg/s)	(W)	Ratio
2.875	622	1.590	2.079	635	1.403
	516	1.716		462	1.540
	468	1.802		350	1.715
	413	1.910		283	1.910
	371	2.051		240	2.052
	328	2.246		204	2.247
	270	2.535		159	2.536
	235	2.695		142	2.696
2.600	600	1.539	2.325	622	1.461
	506	1.644		531	1.540
	462	1.713		488	1.588
	418	1.800		406	1.715
	366	1.910		320	1.910
	324	2.052		281	2.051
	283	2.247		240	2.247
	228	2.536		190	2.536
	202	2.696		169	2.696
	166	2.892		134	2.892

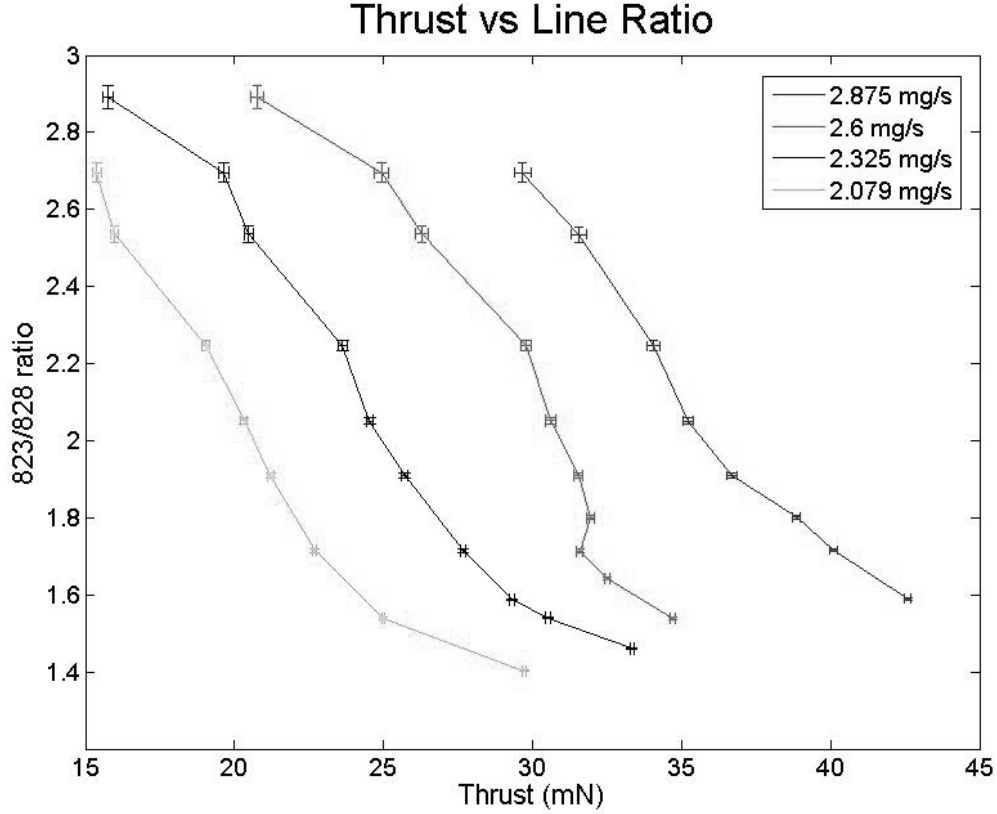


Figure 29. Xenon line ratio changes based on varying thrust and mass flow rates. [derived from data in [38, 78]]

4.2.3 Spectrometer Selection.

A secondary result of the data analysis performed was the selection of the preferred spectrometer for use with small telescope measurements. The HR4000 was shown to have a higher noise floor during chamber measurements even with the dark noise spectrum removed and a large deviation in relative intensity across viewing angles. Most importantly the HR4000 had a ratio difference when compared to the CRM outside the predicted deviation necessary to accurately detect ratio changes due to electron temperature differences (to within 1eV). For these reasons, the QE65000 is the more precise instrument and will be used for all observations.

4.3 LEEDR Analysis

An analysis was performed prior to conducting Real World Observations to determine the transmissivity of the lines of interest using WPAFB as the ground site. The results were compared to the three GEODSS sites discussed in Chapter II. This comparison was done to determine feasibility of using AFIT's small telescopes to detect Hall thruster spectra. The simulations were run using the LEEDR GUI with the following settings: Expert atmosphere (Summer season, 50 percentile humidity, viewing time of 0000-0300), GADS aerosols, climatological wind, and HV 5/7 turbulence models. A target altitude of 100 km was used assuming negligible transmissivity loss beyond that altitude as discussed previously. The results in Table 9 show that WPAFB, while having less transmission through the atmosphere for the wavelengths of interest, is only a 2-3% difference.

Table 9. LEEDR analysis comparing WPAFB transmission to three GEODSS sites.

	Wavelength (nm)	WPAFB trans (%)	Maui trans (%)	Socorro trans (%)	Diego Garcia trans (%)
xenon	823.2	65.6	70.9	82.1	58.5
	828.0	80.2	85.4	87.1	83.5
krypton	810.4	79.0	83.9	86.4	82.1
	811.3	76.9	81.6	85.9	77.4
	826.3	78.1	82.0	85.7	80.1
	829.8	76.1	80.9	85.7	75.7

The path attenuation for the lines of interest was also calculated and is provided in Figures 30 and 31.

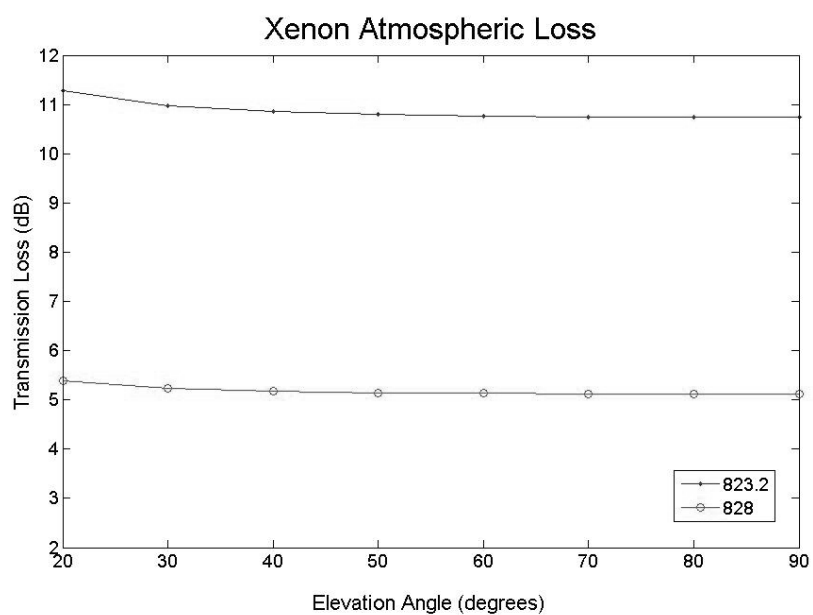


Figure 30. Path attenuation for a 650 km orbit for xenon lines of interest.

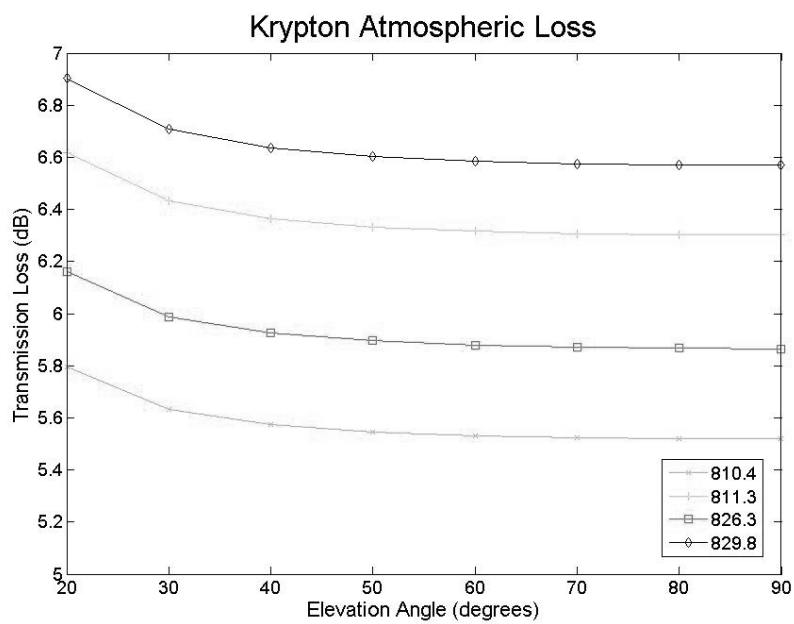


Figure 31. Path attenuation for a 650 km orbit for krypton lines of interest.

4.4 Code Development

The end-to-end model developed for this research effort combines two given functions, one with modifications, and one developed function. These are treated as subfunctions and combined to form one program developed through Matlab. Figure 32 shows the functions and how they feed into one another. The main program will be discussed first followed by the three other functions.

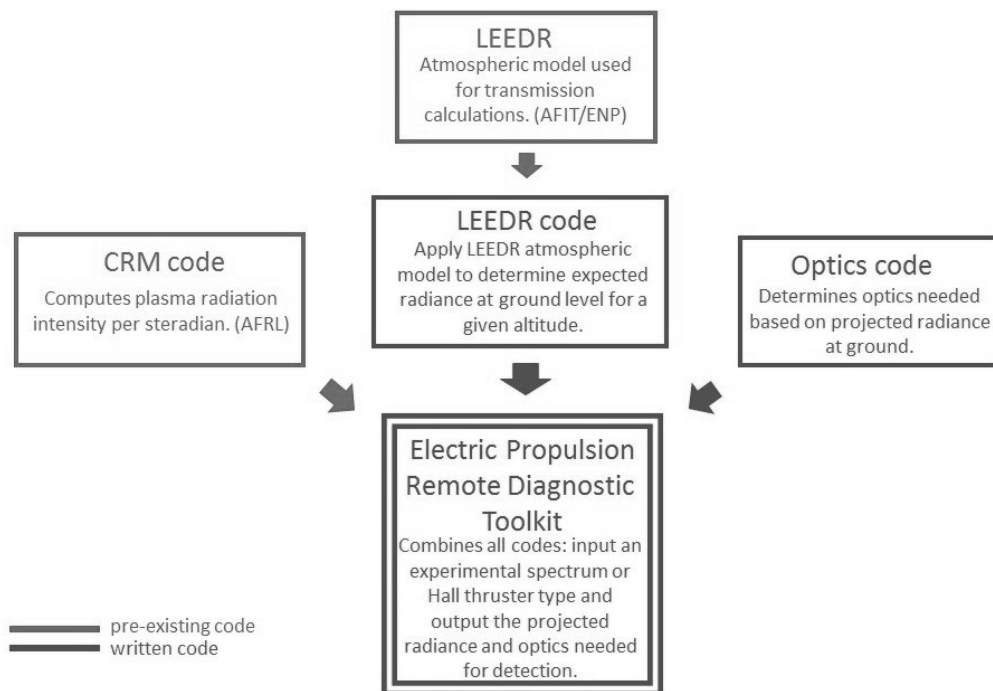


Figure 32. Development structure showing how individual functions feed into the main program and the developers of each.

The design of the model took into account the user may only need to change one parameter at a time. The user may want to run a test case for Wright-Patterson AFB using a set telescope and spectrometer and compare that to using the same equipment at Maui. To avoid taking unnecessary steps to reinput the same data,

the model was designed to allow for singular changes to be made to specific inputs and recalculated. The final format was a GUI developed using Matlab is shown in Figure 33. The set-up consists of three input panels for thruster operating parameters, ground site location, and data collection equipment. Underneath these three panels are three graphs. The far-left graph contains output directly from the CRM code and shows the expected intensity values for the given thruster's spectra. The far-right graph displays the output from the LEEDR portion of the code showing transmission values for the lines of interest across selected ground site viewing angles, 20° (low horizon) to 90° (zenith). The lines of interest are the two wavelengths used in the line ratio calculations. SNR values will be computed based on the individual lines selected. Finally, the center graph displays the SNR for integration times from 0.1 to 10 seconds in 0.1 second increments for the selected viewing angle from the adjacent button group. This version allows for data to be entered/changed as needed and recalculated without requiring the user to re-enter data or go through unnecessary steps.

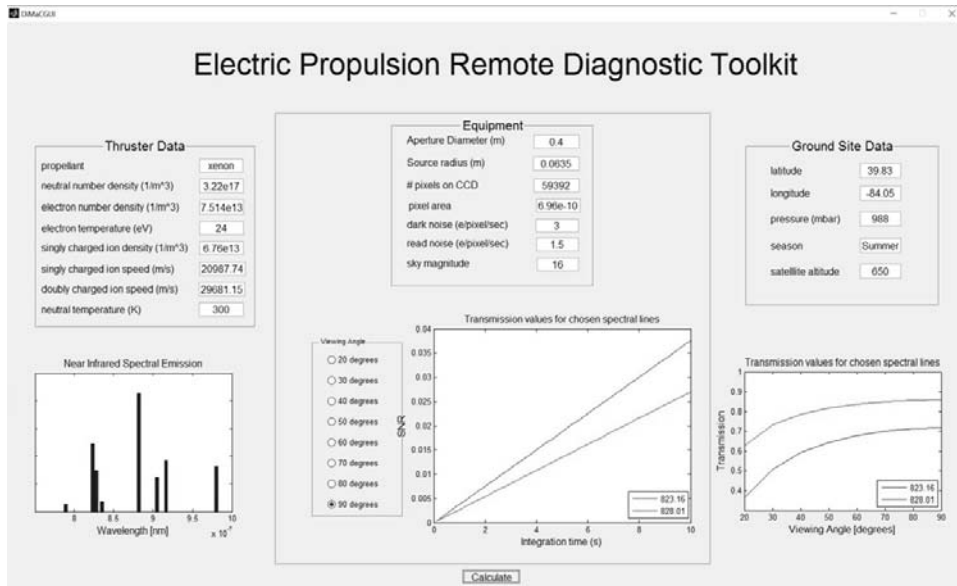
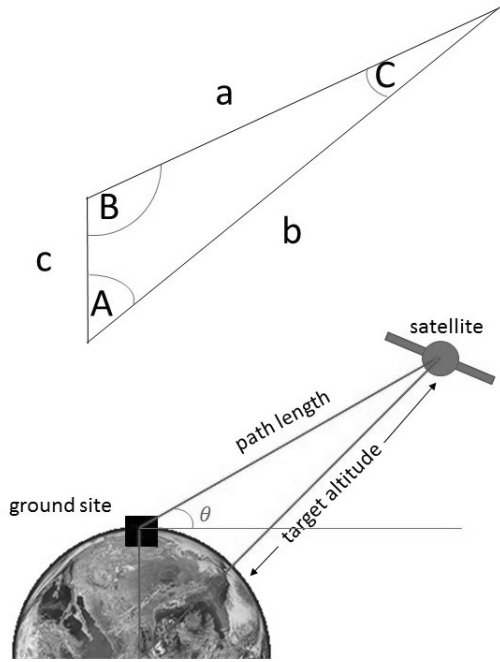


Figure 33. GUI for implementation of the developed program showing input controls and outputs.

The CRM code used in this GUI was discussed in Chapter III. It has not been modified and will not be discussed in detail here. The LEEDR code is adapted from a Matlab script provided by the Center for Directed Energy at AFIT. The provided script gave options to calculate transmission and path radiance values for both individual and bands of wavelengths. The calculations scripted for calculations involving bands of wavelengths and path radiance were removed. An additional section was added to calculate across a range of geometries designed to estimate different viewing angles from the selected ground site contained in Appendix B.

Inputs to this function are ground site details. The site latitude, longitude, and site pressure are needed as well as the season of the year and satellite altitude. As shown in Chapter III, Figure 6, the input values needed for LEEDR to calculate the transmission values for different viewing angles include the path length from the ground site to the target. This was accomplished through a series of trigonometric calculations that were scripted within the LEEDR code and can be seen in Appendix B. Using the viewing angle of the ground site, satellite altitude and Law of Sines as shown in Figure 34, the angles can be determined and in turn the path length. Each geometry configuration produced a transmission and attenuation value that was output in an array format for angles from 20° - 90° .



Law of Sines:

$$\frac{a}{\sin(A)} = \frac{b}{\sin(B)} = \frac{c}{\sin(C)}$$

$$A + B + C = 180^\circ$$

where:

b = radius of the Earth + satellite altitude

c = radius of the Earth

$B = 90^\circ + \text{viewing angle}$

Figure 34. Geometry calculations accomplished for LEEDR code to determine viewing angle inputs.

The final function is the optics code, developed largely in part based on a spreadsheet developed by Shultz on the TeleTrak team [72]. The SNR calculations in this function were adapted from this product and coded for use in this research. The optics code calculates the SNR based on outputs from the CRM and LEEDR code for integration times from 0.1-10 seconds. This function requires additional inputs relating to the equipment needed at the ground site for observations. The diameter of the telescope, approximate source radius, and estimated night sky magnitude are needed. In addition, sensor details including the pixel area, number of pixels, dark noise, read noise, and quantum efficiency of the spectrometer is required.

The wavelengths and intensity values calculated by the CRM code are first read in. The thruster is treated as a point source because its distance from the ground site is much much greater than the size of the source. The intensities are then converted into the number of photons reaching the ground detailed in Chapter III, section 3.2.3. This

result is the signal detected by the given spectrometer and telescope on the ground. The noise, dark current and read, are calculated for the entire CCD. Background noise will require a higher fidelity calculation adapted from Shultz's spreadsheet calculations and is based on the flux of Vega. Using equation (2.4-2.6), the sky magnitude is converted into a flux value and then using the same process detailed for the signal above, converted into total photons. The background noise is then multiplied by the transmission values calculated through the LEEDR code to estimate the total noise from the sky reaching the CCD at the ground site. The SNR is then calculated through a loop for each viewing angle and integration time using equation (2.7) and is output to a file.

4.5 Real World Observations

Due to limitations in viewing opportunities of satellite thruster firings on orbit, in addition to the chance that the signal would not be able to be detected, star observations were chosen as the best source to validate the developed code. The selected stars and their characteristics are detailed in Chapter III, Table 4. Observations were made on four separate days between 2100 and 2300 during clear night skies when the cloud cover was under 20%. The best observations, meaning strongest signals, were during periods of less than 5% cloud cover; however, the signals were successfully detected on the other nights as well.

A separate code was developed for the star analysis since the CRM code was not needed (Appendix C). The signal was calculated using the blackbody curve estimation and run through the developed LEEDR code to estimate the detected signal at the ground. Graphs were available for estimates on the telescope transmission curve and spectrometer's quantum and grating efficiency curves but not the equations. For use in the code to allow a more accurate blackbody estimate, the equations for the

telescope transmission and quantum efficiency curves were calculated using the three-point method to solve quadratic equations. The resulting estimates are provided in equations (4.1) and (4.2) (the ordinate value is the resulting fraction and the abscissa value is wavelength in nm).

Meade UHTC coating transmission curve:

$$Tel = -2.4 * 10^{-6}(x^2) + 2.64 * 10^{-3}(x) + 0.18 \quad (4.1)$$

QE65000 CCD quantum efficiency curve:

$$QE = -5.5 * 10^{-6}(x^2) + 7.15 * 10^{-3}(x) - 1.39 \quad (4.2)$$

The grating efficiency curve was not a parabolic curve as the transmission and quantum efficiency graphs were for the area of interest. For this reason, several points were chosen along the graph and then extrapolated using the interpolate function in Matlab. The resulting values were then applied to the blackbody curve. The installed grating according to Ocean Optics was the H14; however, upon inspection of the resulting spectrometer data from star observations, the curve appears to follow the H4 grating curve (see Figure 35). The H4 grating curve was assumed to be the correct grating installed and was used for this analysis.

Two stars were chosen for observations and analysis, Betelgeuse and Arcturus. The observed spectra were compared to an estimated spectral response calculated from atmospheric transmission values entwined with sensor response and the blackbody curve for that star. The spectral response estimate is only meant for use as a rough approximation of the spectral radiance curve shape for that star. LEEDR does have the capability to compute radiances, however, the only celestial blackbody programmed in the GUI is the sun. The sun is much hotter and spectrally whiter than

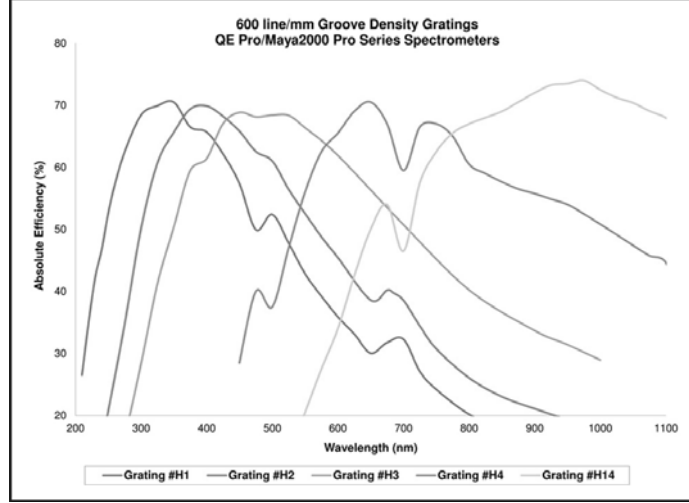


Figure 35. Ocean Optics grating efficiency curves available for the QE series spectrometers.

both Betelgeuse and Arcturus which peak in the NIR discrediting use of the LEEDR calculated radiance for comparison purposes. In addition, the estimated curve shows areas where the transmission drops to zero. This is impossible to replicate with the spectrometer as the spectrometer light curve response is averaged inhibiting it from reaching true zero.

Betelgeuse was the first star selected for analysis. This star was successfully viewed on 4 March and 12 April 2017. Using the time stamp from the data collected by SpectraSuite, the star's altitude was determined using Stellarium. On 4 March, three observations were made on Betelgeuse using an integration time of 10 seconds. Spectra was collected at 2207 with an altitude of 44° . Five observations were made on 12 April with an integration time of 30 seconds at 2145 at an altitude of 31° . Three separate noise spectra were taken for each integration time to determine the noise from the spectrometer, dark and read noise estimates. The data for both the signal and noise was averaged over all collections, the noise was subtracted from the signal, and the resulting estimate from each day was plotted with the estimated blackbody curve for that viewing angle (Figures 36 and 37).

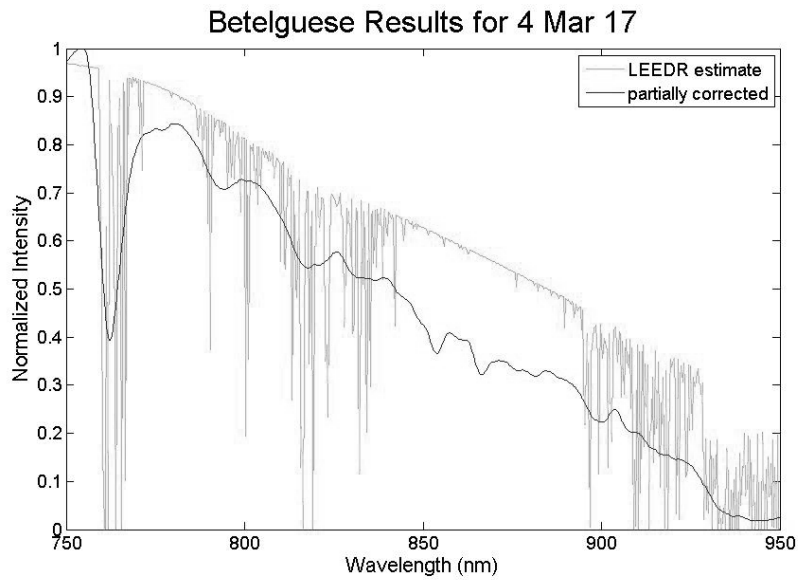


Figure 36. LEEDR atmospheric transmission coupled with sensor response and star effective temperature for Betelgeuse compared with actual observations made on 4 Mar 17.

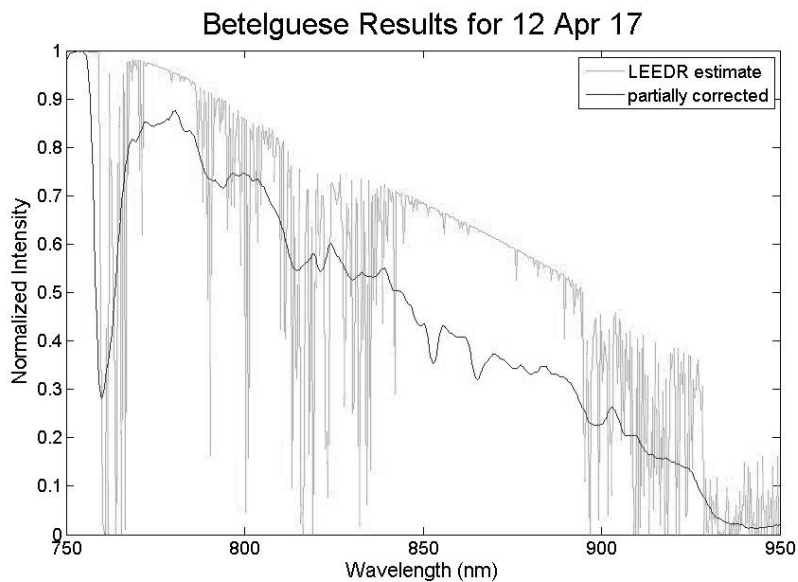


Figure 37. LEEDR atmospheric transmission coupled with sensor response and star effective temperature for Betelgeuse compared with actual observations made on 12 April 17.

There was good correlation between the estimated curve and the detected curve on the spectrometer. The next step was to determine if the calculated SNR was accurate. The main code developed determines the SNR for the individual lines needed for the ratio calculations. The wavelength to be evaluated for each star was selected using Wein's law which determined the peak wavelength of the blackbody spectrum. The read and dark noise parameters were taken directly from the spectrometer operators manual and the background sky magnitude was calculated using a limiting magnitude calculator available on cleardarksky.com [79] with weather information available online through wunderground.com. As stated above, observations were made on Betelgeuse on the evenings of 4 March and 12 April 2017. On those evenings, a dark sky spectrum was not obtained and thus the noise spectrum used for analysis is only from instrument noise (dark and read noise only).

Arcturus was viewed on the evenings of 31 May and 1 June 2017. A dark spectrum was obtained of the night sky on these two occasions. This was accomplished by moving slightly off the star until the response from the star was no longer measurable above the noise floor. The observations made on Arcturus were analyzed using both the dark spectrum obtained of the night sky as well as the dark spectrum of the isolated instrument noise. This comparison was made to validate the noise spectrum estimations of the code, namely what the dominant noise factor was. The resulting spectra for both observations are provided in Figures 38 and 39.

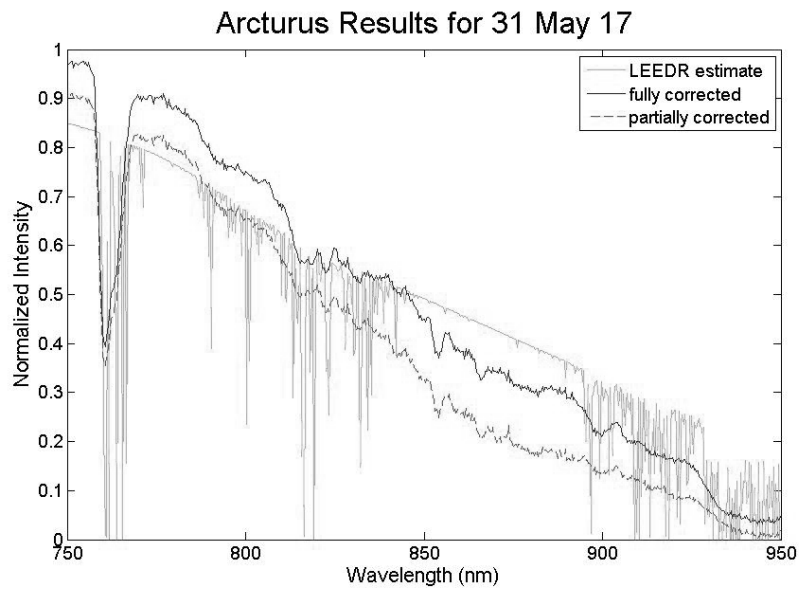


Figure 38. LEEDR atmospheric transmission coupled with sensor response and star effective temperature for Arcturus compared with actual observations made on 1 Jun 17.

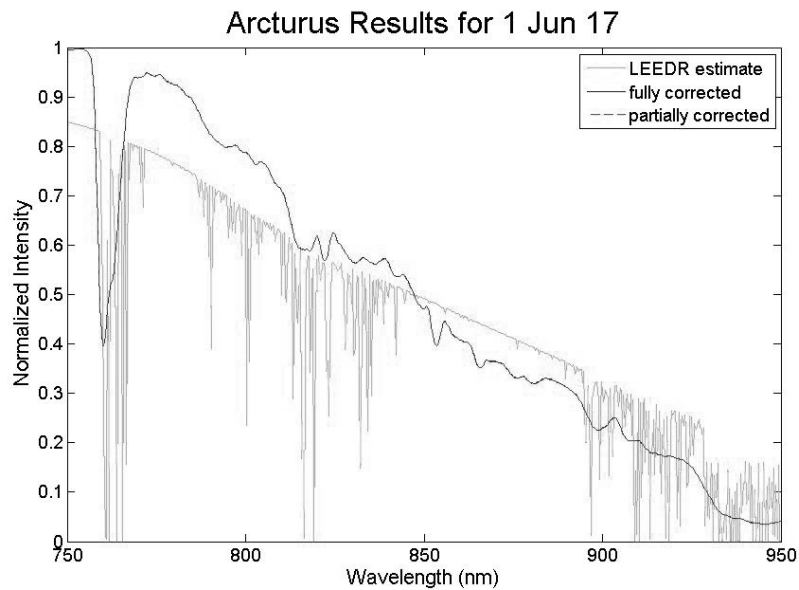


Figure 39. LEEDR atmospheric transmission coupled with sensor response and star effective temperature for Arcturus compared with actual observations made on 31 May 17.

The resulting SNR estimates and calculations are detailed in Table 8. For each observation, the date and time was used to determine the star’s relative azimuth and altitude in the night sky. This information was then used to determine the sky magnitude for that evening over the ground site location.

Table 10. Input parameters and SNR calculations compared to actual SNR of observations.

	observation	altitude	sky	calculated	observed
	date		magnitude	SNR	SNR
Betelgeuse	4 Mar 17	43°	19.29	2	6
Betelgeuse	12 Apr 17	31°	19.41	2	1.1
Arcturus	31 May 17	69°	20.21	14	17
Arcturus	1 Jun 17	65°	19.92	14	1.1

The second Betelgeuse and first Arcturus observations were difficult to center on during observations; however, the curve was still discernable. For further analysis, two lines were chosen (the xenon wavelength lines investigated for the CRM code) and the ratio was calculated for all four stars in the Table 8. The 823/828 ratio was calculated using the blackbody estimate and compared to the ratios of the observed values for both stars. The calculated ratio for Betelgeuse was 1.01 for the blackbody curve and observed to be 1.01 in both cases and for Arcturus the same held true. The calculated ratio using the blackbody curve was 0.99 and observed to be 0.99 for both cases. Even though the SNR was much different for each observation, the position and intensity of the lines relative to one another were still discernable and matched close to estimations.

4.6 Hall Thruster SNR Estimates

After accomplishing the star validations, the end-to-end model was run for different operating conditions of the BHT 600W using Bui’s lab data. The same sets of data that were used in the power level comparisons earlier are used here. The ground site and equipment remained the same for all cases run. The 16” telescope at AFIT and Ocean Optics QE65000 spectrometer were the equipment used in the scenario. Location was set at Wright-Patterson AFB in the summer and the orbital altitude for a LEO at 650 km. First, the discharge voltage was set at 225 V. This was chosen because it was the highest operating power where all four mass flow rates had a measurement at this voltage. The resulting SNR was below 1 for all mass flow rates tested. It varied from a maximum of 0.1 and a minimum of 0.025. Full details can be seen in Table 9.

Table 11. SNR estimates for a constant discharge voltage and varying mass flow rates.

mass flow rate (mg/s)	power (W)	SNR range (90°)	SNR range (20°)
2.875	516	0-0.1	0-0.05
2.600	462	0-0.075	0-0.04
2.325	406	0-0.06	0-0.03
2.079	350	0-0.045	0-0.025

The SNR was then analyzed for a constant mass flow rate with varying discharge voltages. It was found that higher operating power levels resulted in higher SNR, however; all were still below 1. In this case the SNR varied from a maximum of 0.13 at a discharge voltage of 275 V and zenith looking to a minimum of 0.003 for a discharge voltage of 90 V and an elevation angle of 20°. Full details are provided in Table 9.

Table 12. SNR estimates for a constant mass flow rate and varying discharge voltage.

discharge voltage (V)	power (W)	SNR range (90°)	SNR range (20°)
275	622	0-0.13	0-0.07
225	516	0-0.1	0-0.05
200	468	0-0.08	0-0.04
175	413	0-0.06	0-0.03
150	371	0-0.05	0-0.025
125	328	0-0.04	0-0.02
100	270	0-0.02	0-0.01
90	235	0-0.01	0-0.005

4.7 Summary

This chapter presented the results of the experimental analysis, code development, and real-world observations for verification purposes. The estimated dependency of spectral lines on viewing angles and thruster operating power levels was discussed. The code outputs for star observations were analyzed and compared with real-world observations. Finally, estimates of the feasibility of signal detection for Hall thruster firings at LEO were completed. The implications and conclusions of these results will be discussed in Chapter IV.

V. Conclusions

The research work discussed sought to answer three main questions; whether observed spectral signatures of Hall thrusters could be used to identify operating details of the thruster system, if small ground-based telescopes could be used to detect the signatures, and how to construct an end-to-end model to predict SNR. A model was developed that utilized both a CRM code developed by AFRL and AFIT's LEEDR atmospheric model. The findings support the use of Hall thruster spectral signatures for operating performance validation on orbit, although observations and collection of the signatures will be difficult using small ground-based sensors. The conclusions of both research questions are discussed in detail followed by recommendations for future work.

5.1 Hall Thruster Spectra

The first main question posed asked whether propellant, power level, and orientation could be determined from observed spectral signatures. This was accomplished through the first research task outlined in Chapter I. Analysis narrowed down the spectral ratios to the 823/828 nm pair for xenon and the 811/810 and 829/826 nm pairs for krypton. The QE65000 was shown to be the preferred spectrometer. over the HR4000 This discussion will focus on results from the QE65000 spectrometer only. As demonstrated during the vacuum chamber experiments, the viewing angle did not have an effect on the spectral signatures. The intensity of the krypton and xenon NIR emission lines were observed to have minimal deviation, 0.056 in a normalized spectrum, for the 700-900 nm range for viewing angles of 0° - 53° . The greatest deviation occurred at the 811/810 nm ratio for krypton, which was 2%.

Between 80 and 90% of the Hall thruster’s plume is composed of Xe^{+1} or Kr^{+1} ions. It can be inferred that 80-90% of optical emissions also occur from the generation of Xe^{+1} or Kr^{+1} ions which are generated through the processes outlined in equations (2.1), (2.2), (2.7), and (2.8). The collisional processes shown in the previous four equations occur from the interaction of the propellant and free electrons which primarily takes place directly in front of and within the channel of the Hall thruster where electrons are ejected from the cathode. Only a small part of interactions with neutral Xe and electrons occur in the plume. This creates a concentrated “plasma torus” around the exit plane of the thruster. The reason for the intensity remaining the same throughout the range of viewing angles tested is because the area of the plasma torus that is detected by the Hall thruster remains relatively constant. As you move around the thruster, the intensity remains the same until the actual Hall thruster itself starts to obscure the view of the plasma ball at which point the intensity drops significantly where the thruster spectra can no longer be detected and characterized. This point is referred to as the extinction point¹.

The results of the viewing angle experiments have good and bad implications. The negative implication is that viewing angle will not be a measurable parameter from the spectra alone except potentially at the “extinction points”. If the plume is not visible during one segment of its pass but becomes visible for another, this can indicate that the thruster is pointed in the direction of the orbit or away from the Earth (outside the $\pm 50^\circ$ viewing cone from nadir/zenith), the latter meaning the satellite is moving to a lower altitude orbit or correcting in that direction. This would only be discernable, however; if it could be confirmed that the thruster was operating for the entirety of the pass. The positive implication is that the thruster would be observable for a wide range of viewing angles where the Hall thruster was positioned

¹The extinction point refers to a spectral measurement viewing angle where the emissions from the plume are no longer visible by the optic due to the physical casing of the thruster body.

to fire towards the nadir direction, typical of an orbit raising maneuver. The Hall thruster firing would then be observable for the entirety of a pass. The previous examples are for LEO satellites. For GEO satellites, the findings indicate that as long as the thruster is positioned so that the plume is towards the Earth it would be observable. The long duration of GEO thrusting using Hall thrusters also allows for long integration times, necessary for desired SNR measurements. It can be concluded that attitude cannot be uniquely accessed from spectral intensity measurements.

The CRM code was also validated prior to running simulations to discern power level variances in spectra. Using xenon propellant and looking directly down the throat of the thruster, 0° viewing angle, spectra was collected and compared with the CRM output. It was found that the difference in ratios for the 823/828 nm lines was only 0.005 or 0.3% of the expected ratio. In order to discern a 1eV temperature difference of the plume, the ratio difference had to be at least within 0.03 or 2% of the expected ratio. This finding demonstrated the use of the CRM for accurate approximations of the spectral signature intensities of a Hall thruster plume.

Power level differences were calculated using the CRM code and observed ion density using Bui's probe measurements of the same thruster, same chamber, running xenon. Four different mass flow rates were observed for 8-10 power levels of the Hall thruster. The power levels tested showed measured electron temperature jumps ranging from 1eV at low power levels to 4eV changes at higher power levels. All four propellant mass flow rates produced similar curves with ratios that decreased as operating power was increased. As mass flow rate was increased, the curves shifted right on the graph, meaning that the spectral ratios occurred at higher power levels. For instance, as seen in Figure 28 in Chapter IV, a ratio of 2.7 for the 823/828 lines was obtained at power levels of 142, 169, 202, and 235 W as the mass flow rate was increased. As the power level was increased to its maximum output of around 600

W, the ratios increased with mass flow rates of 1.40, 1.46, 1.54, and 1.58 respectfully. As mass flow rate is increased, a larger number of ions and electrons are available for ionization which means the ratios would also increase as the line intensities are stronger. It is important to note that the power levels that are possible also depend on the mass flow rate. The slope of the lines suggest an exponential relationship where the minimum power level is fixed depending on the mass flow rate of the system.

For thruster system characterization, the question would be determining what curve to use and thus what power levels and ratios would occur. If the thruster is operating at low or maximum power levels it would be easier to identify what the mass flow rate is due to the limits of the thruster. The intermediate power levels would be more difficult to discern and there would most likely be multiple possible non-unique scenarios for operating condition if the mass flow rate is unknown (or uncertain). There is utility however, since the mass flow rate is fixed prior to launch for most satellites and is not tunable once on orbit. If the mass flow rate is known, the multiple scenario possibility is avoided.

5.2 Modeling

5.2.1 Atmospheric Modeling.

The second main question addressed whether the spectral signature will be observable from the ground, and whether the signature is detectable above the atmospheric noise. Tasks 2 and 3 can be addressed together. First the LEEDR model was successfully implemented with the developed model to estimate signature transmission through the atmosphere at viewing angles from 20° - 90° from the horizon. The developed code was validated using star data obtained on four separate nights when the forecast had low sky cover, 20% or less. It was found that the collected data showed good agreement with the expected star data calculated using the code. There was

some discrepancy in the intensity values along the curve. The star data for all observations showed lower intensities along the curve than the calculated blackbody curve. The background sky noise was important when correcting for this. Spectra that were corrected only for spectrometer noise (read and dark noise), showed a greater intensity difference than the spectra corrected for background sky and spectrometer noise. However, there was still a notable difference in the shape of the curve. The spectrometer generated curve dropped off more rapidly on either side of the maximum intensity wavelength. The maximum intensity wavelength was also shifted with the spectrometer reading. The peak efficiency of the QE65000 occurs at 1000nm for the current grating installed and the grating efficiency curve was taken into account. In addition, the telescope transmission and spectrometer quantum efficiency curve were also taken into account. There are a number of other parts within the system that can affect the response curve along the optical chain to include the optical fiber and collimating lens. While the efficiency and transmission curves used did correct the curve (see Figures 40-43), for better agreement the modeling of all system transmission curves would need to be completed and included in the model.

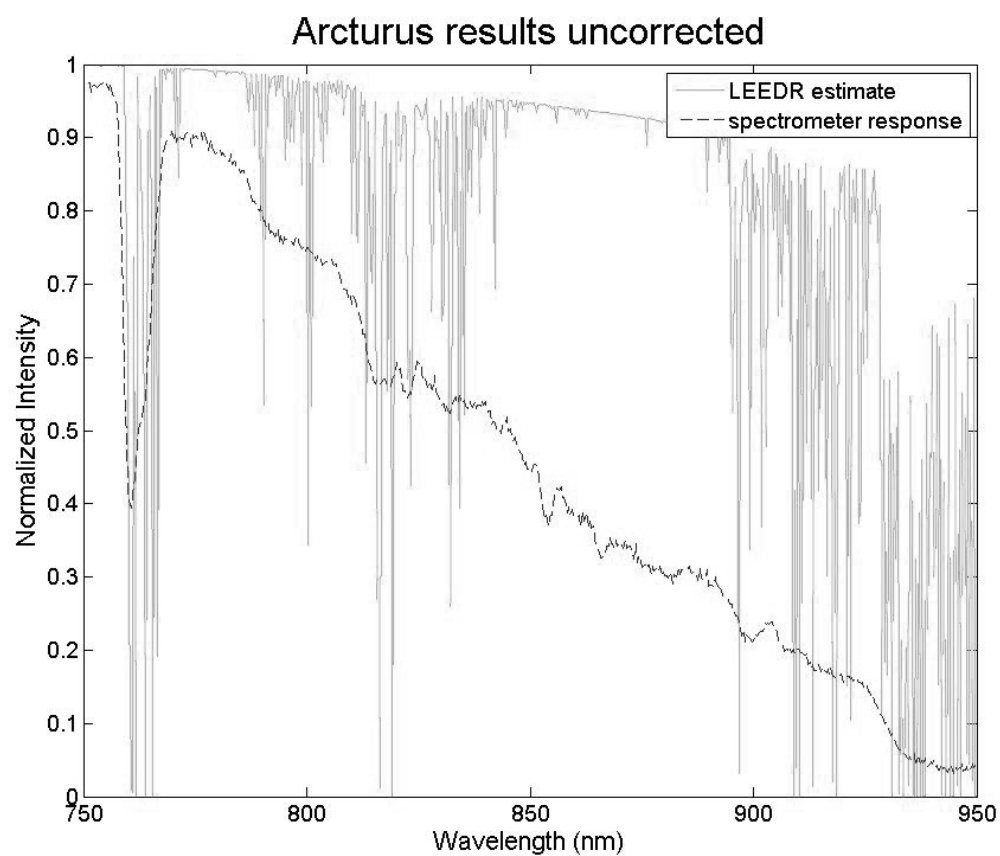


Figure 40. LEEDR atmospheric transmission coupled with star effective temperature for Arcturus corrected for atmospheric transmission compared with actual observations made on 31 May 17.

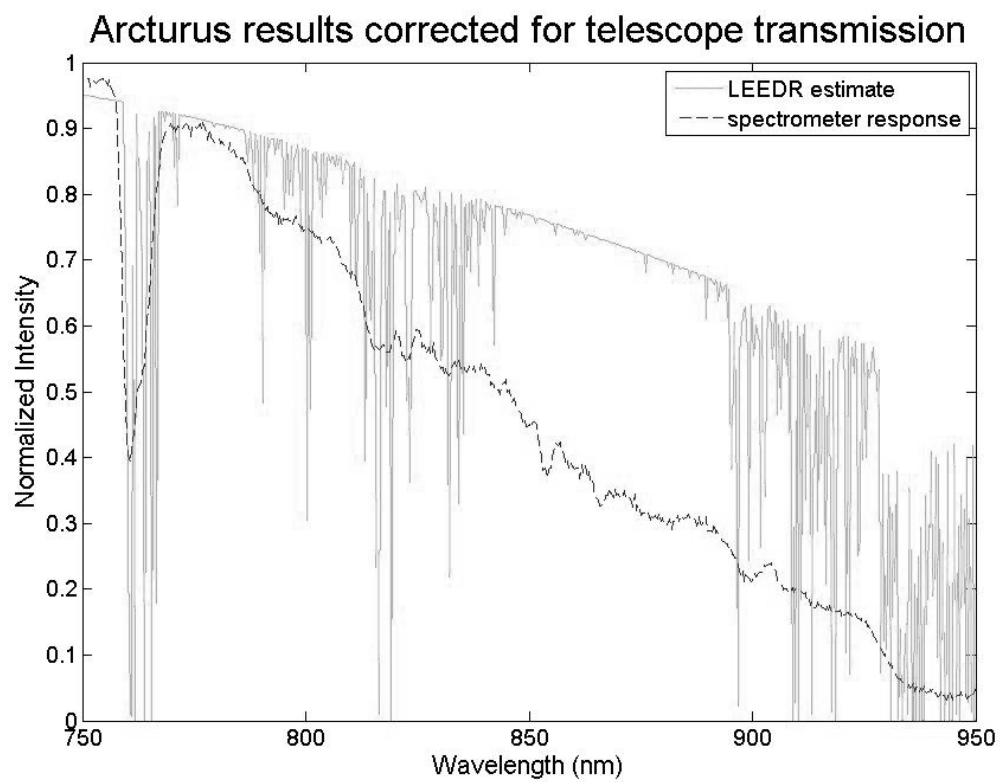


Figure 41. LEEDR atmospheric transmission coupled with star effective temperature for Arcturus corrected for atmospheric and telescope transmission compared with actual observations made on 31 May 17.

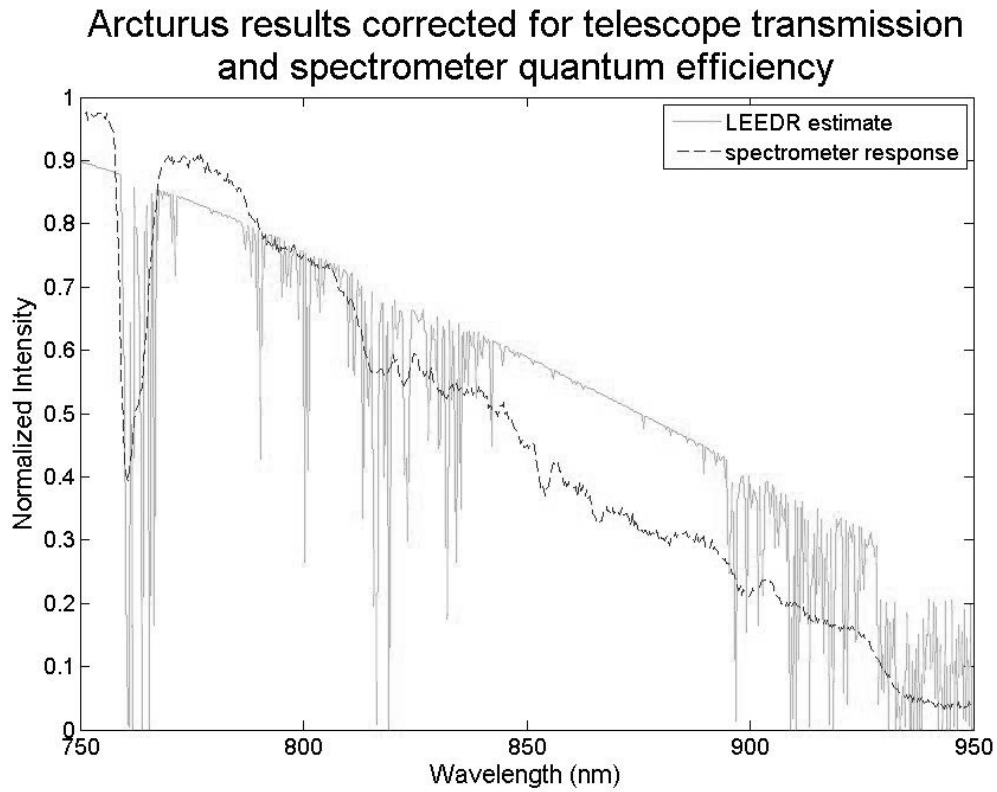


Figure 42. LEEDR atmospheric transmission coupled with star effective temperature for Arcturus corrected for atmospheric, telescope transmission, and spectrometer quantum efficiency compared with actual observations made on 31 May 17.

Arcturus results corrected for telescope transmission,
spectrometer quantum efficiency and grating efficiency

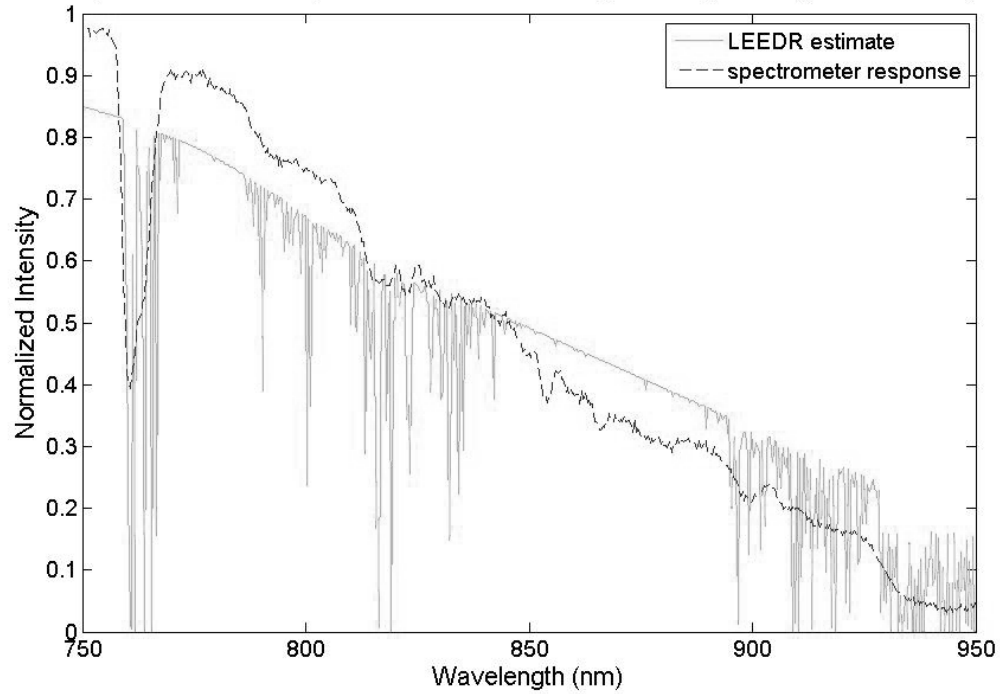


Figure 43. LEEDR atmospheric transmission coupled with star effective temperature for Arcturus corrected for atmospheric, telescope transmission, spectrometer quantum and grating efficiency compared with actual observations made on 31 May 17.

To assess feasibility of the detectability of the spectra, a $\text{SNR} \geq 1$ was assumed to be needed. The SNR results however, were varied. The SNR ratio was much less than anticipated on some nights and much greater on others. On evenings where the cloud cover was less than 7% and the relative humidity was low, the observed SNR were better than the calculated SNR. On evenings where the cloud cover was at 20% and relative humidity was high, the SNR observed was only slightly above one and barely detectable. On these evenings, the star's spectral signal was much harder to acquire. Also during these observations, data acquisition was paused for passing clouds. During this time, the signal was often completely lost until the cloud passed through the telescope's FOV. While the signal was still usable and showed agreement with expected ratio values and curve properties to the clear sky observations, the moisture in the air played a significant role in calculations. The developed code is currently not designed to allow for specific weather calculations and assumes clear sky conditions. It should be noted that LEEDR does allow for more specific weather inputs to include cloud conditions and relative humidity; however, those options were not implemented in the first generation of the code. It can be concluded that the calculated results from the code are a conservative estimate for true clear sky conditions meaning low relative humidity and sky cover, and that it is necessary to include specific weather conditions of cloud/relative humidity to obtain more accurate predictions.

5.2.2 Hall Thruster SNR.

After the code was demonstrated using observed stars, the Hall thruster SNR was calculated for a LEO satellite at 650 km observed from a 16" telescope at Wright-Patterson AFB, OH. The calculated SNR was found to be 0.1 for the ideal condition, nadir viewing, for a 10 second integration time. Further analysis indicated that

in order to successfully collect spectra from a Hall thruster on orbit, integration time must be at least 300 seconds or 5 minutes. For a LEO satellite, 5 minutes often will cover the entirety of a single pass. An extremely accurate pointing system would be needed on the telescope to keep it within the FOV of the system for its entire orbit. This estimate assumes that the satellite will pass through zenith. For satellites not passing through zenith the integration time required may be longer than a single satellite pass. Another assumption made here is that the thruster is oriented within the 50° viewing angle (line of sight) throughout the pass. The results therefore indicate that it will not be possible to successfully collect on LEO satellites with Hall thruster using small (16" and below) telescopes.

A 10 second integration time, however, is possible for a 5 m telescope such as the one at the MSSS in Hawaii. Hall thruster signatures could be successfully observed and collected on using larger telescopes but the constraint is now availability of the larger telescope sensors for observations. The workload of our SSN sensors would be increased rather than decreased in this case. The results discussed are for LEO satellites. For GEO satellites using small telescopes, the integration time needed would be on the order of hours for a good SNR and thus impractical for a single evening collection. It can be concluded that Hall thruster firings on both LEO and GEO satellites will not produce the SNR needed when using small telescopes.

5.3 Future Work

SNR and required optics for satellites equipped with Hall thrusters on LEO orbits can still be estimated for observations with larger telescopes. The current code is a good conservative estimate for clear nights with low humidity and cloud cover. LEEDR also allows for higher fidelity weather inputs. The code could be expanded to include inputs on relative humidity and cloud cover to provide a more accurate

estimate. The LEEDR and optics portion of the code developed herein could also be implemented for use in determining hardware requirements for use on light curve estimations for satellites, another active area of research for SSA.

As for the propulsion experiments accomplished in the vacuum chamber, more needs to be done here as well. The viewing angle experiments need to be accomplished for viewing angles beyond 53° in order to find the exact measurement extinction point of the plume. Further analysis on how this is related to the specific hardware geometry, as well as the installed geometry on the satellite is needed. The power level changes were estimated using the CRM code but not validated with actual spectral measurements in the chamber, but only calculated based on recorded data by Bui [38]. It would be useful to accomplish experiments running the thruster at the operating power levels estimated and comparing the results obtained directly from the spectrometer. In addition, acquiring electron temperature measurements for the same conditions using a probe of the plume would be beneficial in validating the electron temperature estimates.

According to Ocean Optics, the instrument response function is nearly impossible to determine due to a variety of factors. In this research the estimated blackbody curve was corrected for telescope transmission, spectrometer quantum efficiency, and grating efficiency curves. These calculations improved the correlation between the spectrometer results and estimated signal; however, other factors can be considered to further improve the correlation. The path attenuation and transmission efficiency of the fiber optic cable and efficiency of the complete optics set-up could all be taken into consideration and factored into the estimate.

Ultimately, the analysis and tools developed herein may be better suited to the use of high altitude (> 60 km) or on-orbit sensors. The logical progression would be to determine how spectra can be successfully obtained using high altitude airborne or

space-based sensors. This would lessen or negate the atmospheric estimation problems but introduce new challenges that need to be addressed. For airborne sensors, the need for accurate tracking would still be needed especially now that the sensor is located on a moving platform. For space-based observations, the spectrometer would need to be mounted on a separate satellite in order to view the plume. This would require a diagnostic satellite to be designed, built, and launched as well as precise sensor pointing to the target satellite to collect spectra, a technical, but not insurmountable challenge.

Appendix A. Supplemental Data and Additional Analyses

This appendix contains additional calculations and analysis accomplished in support of this research. It details the collimating lens analysis following the viewing angle measurements in the chamber to determine true FOV. Next the calibration method and results for the spectrometers is discussed. Finally, celestial observations of Dubne, Aldebaran, and Kocab and the resulting analysis is provided.

1.1 Collimating Lens Analysis

The original optics set-up for thruster data collection in the SPASS chamber was calculated using the published data on the collimating lens used for observations. During the viewing angle collections, the intensity of the plume dropped off very rapidly if the optic was not centered on the plume. For this reason, the optic was moved in the x and y direction on the translation stage to the approximate value for the desired viewing angle and then corrected with the rotational stage until the maximum intensity was observed. Upon completion of testing using the Hall thruster an additional test campaign was run to determine the true FOV of the collimating lens.

An Orielle xenon pen lamp was mounted above the 600W on the thruster stand perpendicular to the strut as seen in Figure 44. This physical set up was chosen to allow the light to radiate in all directions so that the FOV calculations would be entirely due to the collimating lens and not a physical aspect of the set-up. The fiber optic was mounted on the x-y translation stage and adjusted so that the direct line of sight from the collimating lens lined up with the center of the xenon pen lamp. This position was noted as the 0 degree angle. The translation stage was kept fixed in the longitudinal and rotational axes (reference Figure 12) with the distance between the pen lamp and collimating lens remaining fixed at 72.39 cm (28.5 inches) and the angle

fixed at 0 degrees. The collimating lens and fiber optic assembly was moved along the radial axis in both the negative and positive directions until the signal was no longer discernable above the spectrometer noise. This was done for both the fully extended and unextended positions of the adjustable collimating lens. Only the xenon lines of interest, 823 and 828 nm, were recorded and analyzed.

The results from this analysis provided distances in cm that could then be converted into angle approximations using trigonometry calculations. The raw results are shown in Figures 45-47 with distance along the radial axis from the center position. The analysis determined that the fully extended collimating lens provided a FOV of 10.26 degrees and the unextended position provided a FOV of 6.32 degrees.

The collimating lens' original position used in the data collection was half way between the fully extended and unextended position for this research. The FOV can be estimated to be 8.29 degrees. This would require a minimum distance of 42 cm from the thruster to ensure the entire plume is on the CCD. The set-up used for testing used a distance of 47 cm from the thruster and thus the optics set-up should still be effective in capturing the entire plume for analysis.

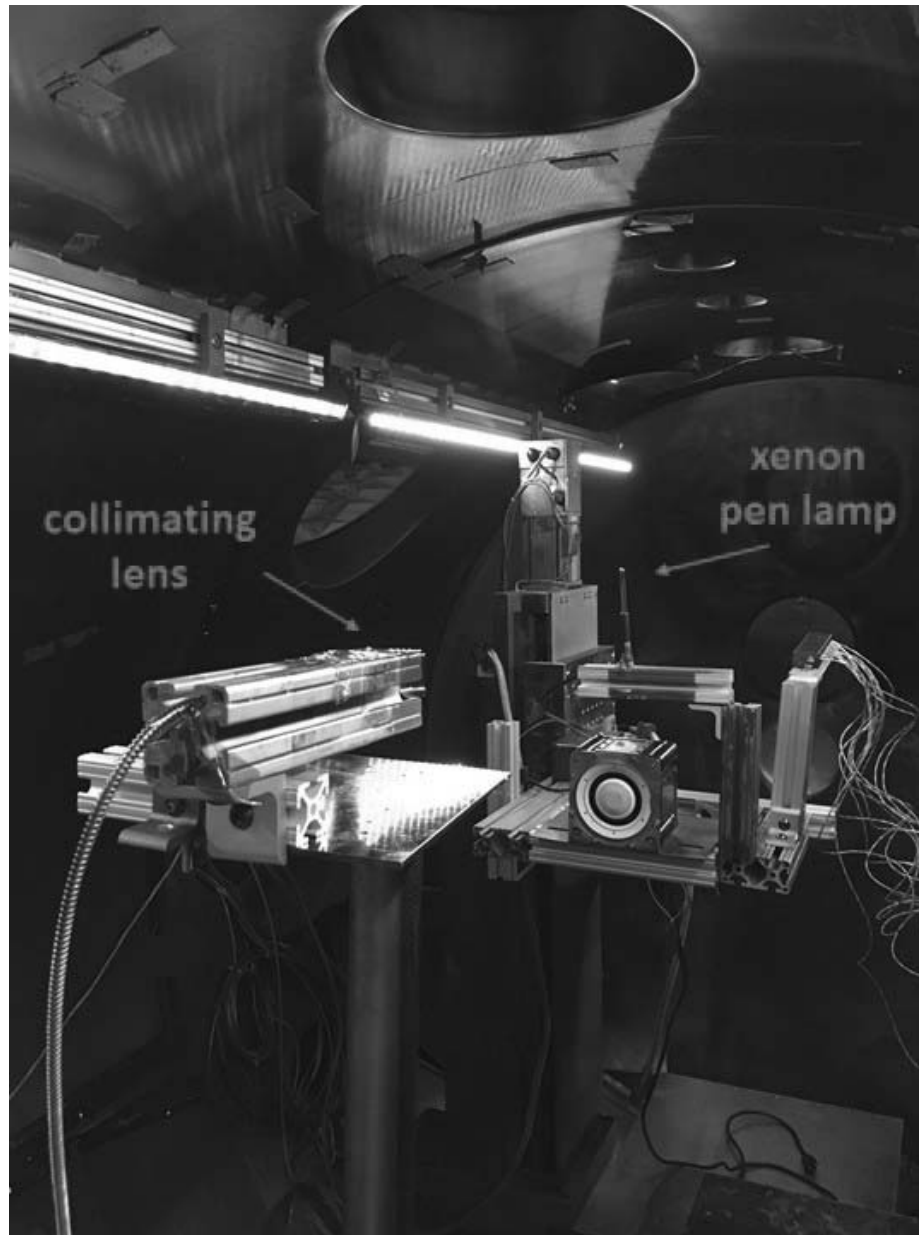


Figure 44. Experimental set-up in SPASS chamber for collimating lens FOV tests showing positioning of Orielle xenon pen lamp.

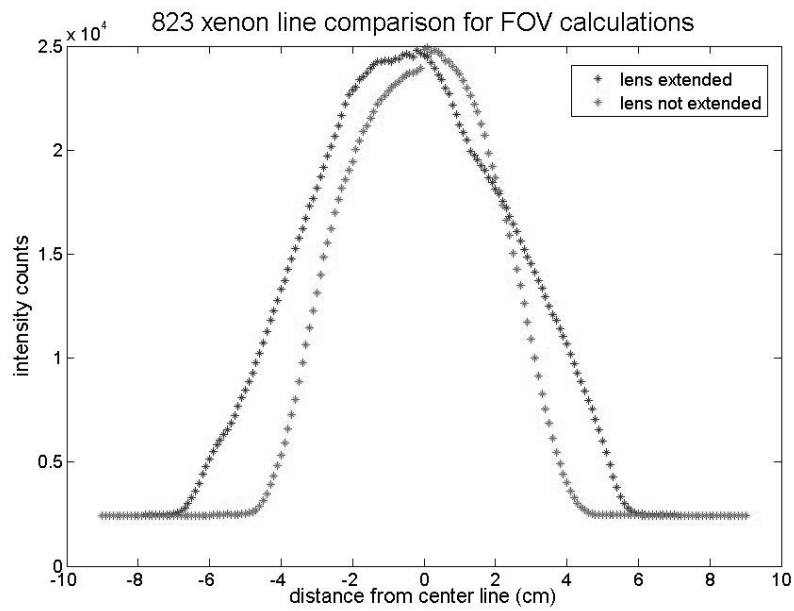


Figure 45. 828 line results for collimating lens experiment showing FOV for extended and not extended lens shaft.

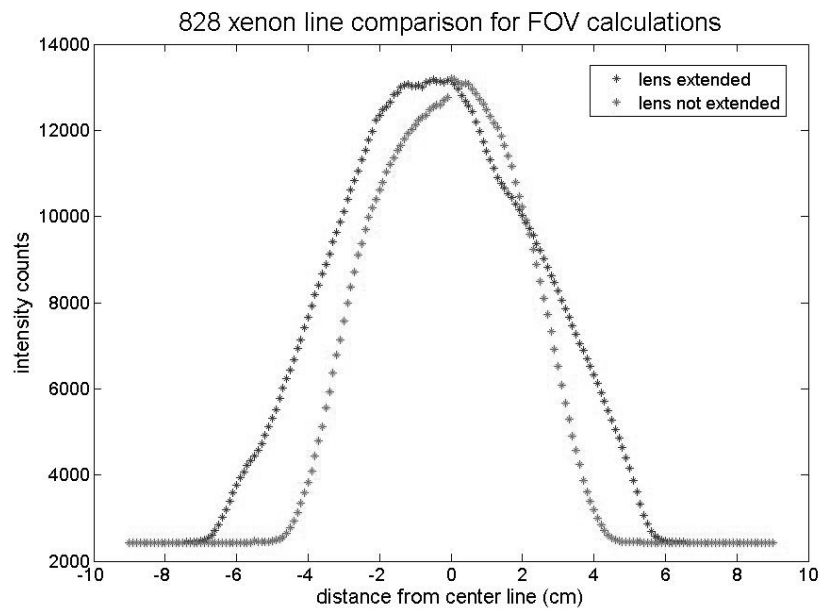


Figure 46. 823 line results for collimating lens experiment showing FOV for extended and not extended lens shaft.

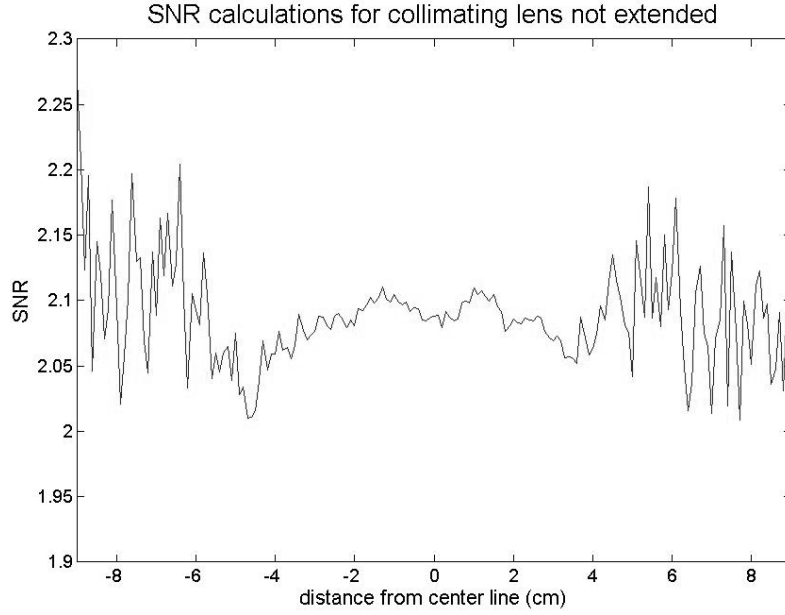


Figure 47. 823/828 line ratio SNR results for collimating lens experiment showing FOV for not extended lens shaft.

1.2 Spectrometer Calibration

Prior to use the spectrometers were calibrated using the recommended HG-1 calibration source. This source is a mercury argon calibration source that produces wavelengths in the UV, Vis, and NIR making it ideal for consistent calibration between the HR4000 with a range of 200-1100 nm and the QE65000 with a range of 600-1000 nm [80]. The fiber optic is attached directly to the calibration source as seen in Figure 48.

Calibration was accomplished with SpectraSuite software using a 50 μm fiber optic for both spectrometers. Peaks within the NIR were selected and the pixel numbers were recorded. A linear regression analysis using the regress function in Matlab which calculates a multiple linear regression using least squares. The inputs to this function are the true wavelength as the dependent variable and the pixel number, pixel number squared, and pixel number cubed as the independent variables for the calculation.



Figure 48. HG-1 Calibration Source from Ocean Optics used in HR4000 and QE65000 spectrometer calibrations.

Regress then returns the intercept value, first, second, and third coefficients. These values are then updated on the spectrometer using the USB Programmer. After updating the values, the wavelength peaks updated locations were verified using the calibration source.

Next, the spectrometers were calibrated using Orielle xenon and krypton pen lamps. Peak locations for the lines of interest were noted and any deviations from the expected values were documented for use in the analysis with the CRM. The spectrometer peak location deviations would allow for an accurate peak to peak comparison between the CRM data and spectrometer results. Those values are provided in Table 13.

Table 13. Measured wavelengths vs expected wavelengths for xenon and krypton lines of interest using the HR4000 and QE65000 spectrometers.

		HR4000	QE65000
Expected λ (nm)		Measured λ (nm)	Measured λ (nm)
xenon	823.16	823.08	822.99
	828.01	827.78	827.86
krypton	810.44	NA	NA
	811.29	NA	NA
	826.32	826.30	826.12
	829.81	829.76	829.60

It was found that neither the HR4000 or QE65000 were able to differentiate between the 810.44 and 811.29 nm lines. The difference between these two lines is 0.85 nm and neither spectrometer was sensitive enough to detect that small of a difference. The analysis performed in this research still proceeded to analyze the 810 and 811 nm lines for krypton as the transmission values made them good candidates for detection although a more sensitive spectrometer would be needed.

1.3 Additional Star Observations and Analysis

Additional star spectra were collected during nights of observations. The processed data agreed with the Betelgeuse and Arcturus results reported on in Chapter IV. The additional star collects included Dubhe and Kochab. Specific characteristics of these stars are reported in Table 14.

Table 14. Characteristics of additional stars for observation collection.

	constellation	magnitude	class	T(K)	peak λ (nm)	distance (ly)
Dubhe	Ursa Major	1.79	K	4500	644	123
Kochab	Ursa Minor	2.08	K	4030	719	130

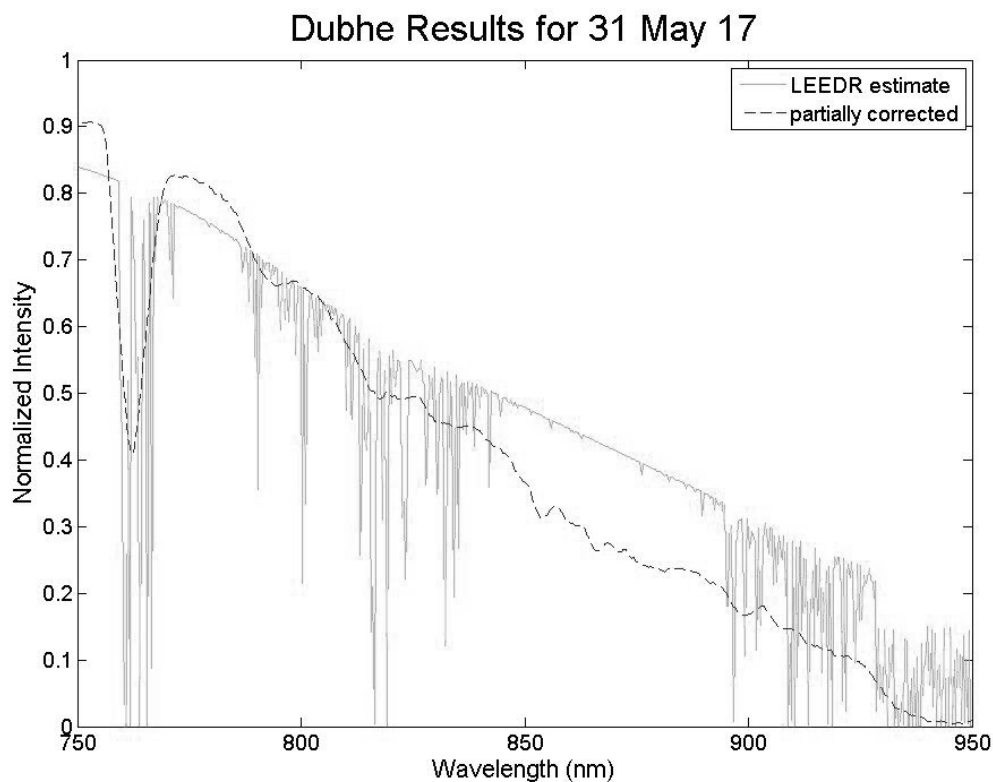


Figure 49. LEEDR calculated observable spectra for Dubhe compared with actual observations made on 4 March 17.

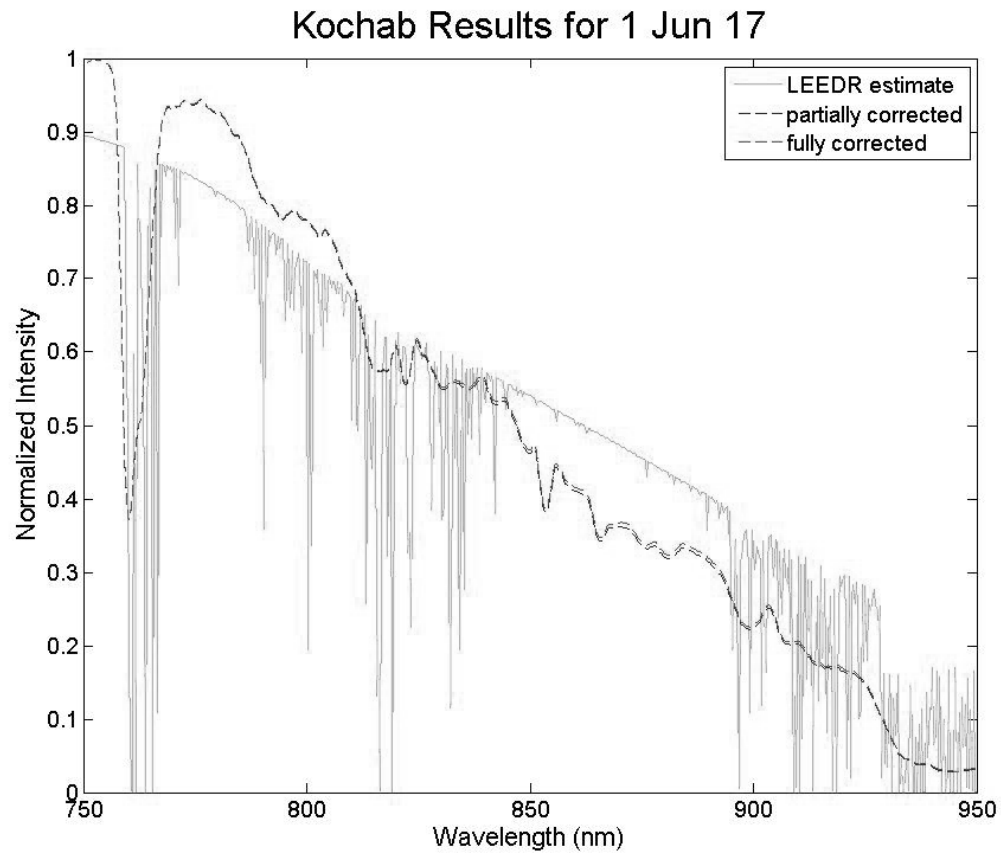


Figure 50. LEEDR calculated observable spectra for Kochab compared with actual observations made on 1 Jun 17.

Appendix B. Developed MATLAB Functions and Scripts for GUI

This appendix includes all MATLAB code function and scripts developed during this research. The functions and scripts are described briefly in the following paragraphs and the actual code is provided in the following pages in the same order as the descriptions.

LampCal

Lamp Cal is a MATLAB script file that was created to calculate correction factors for the CCD sensitivity of the spectrometer. A spectrometer measurement file of the calibration source is input and compared to the blackbody curve of that source. The two are compared and an output file of the correction factors for each wavelength is generated.

DiMaCGUI

DiMaCGUI is the file that generates the Electric Propulsion Remote Diagnostic Toolkit GUI. It calls upon the CRM, LEEDR, and optics files and performs the calculations necessary to produce the SNR output graph. Inputs needed from the user to run this GUI include thruster data, ground site information, and equipment specifications. The thruster data needed is the propellant type, neutral number density, electron number density, electron temperature, singly charged ion density, singly and doubly charged ion speed, and neutral temperature. Ground site information includes latitude and longitude, atmospheric pressure at the site, season, and altitude of the target satellite. The equipment specifications needed cover the telescope and the spectrometer. The telescope aperture diameter, source radius, and sky magnitude is required. For the spectrometer, the number of pixels on the CCD, area of a single pixel, dark and read noise are needed.

LEEDRapp

The LEEDRapp function adapted from a script provided by Brannon Elmore in the Center for Directed Energy at AFIT to use as a guide in development. The LEEDRapp function requires site inputs to include site latitude, longitude, atmospheric pressure at the site, season when observations are made, wavelength(s) of interest, and satellite (target) altitude. The file runs the LEEDR GUI to calculate atmospheric properties and effects of those selections and outputs the generated profiles along with the transmission and attenuation values along the path and viewing angles analyzed.

Optics

The Optics function calculates expected SNR values for the wavelengths of interest. Inputs necessary are wavelengths of interest, intensity values of the wavelengths at the source, transmission values through the atmosphere at the ground site, telescope diameter, satellite (target) altitude, number of pixels on the spectrometer CCD, area of a single CCD pixel, dark and read noise of the spectrometer, source radius, and sky magnitude on the night of observations. The file will then calculate the estimated signal at the ground and total noise encountered from the background sky and the inherent spectrometer sources of noise. The SNR will then be calculated for each wavelength and viewing angle's selected. The function will output the SNR ratios for each viewing angle as a separate variable as well as the integration times used in calculations.

```
function LampCal(Filename,Fileout,Temp)
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%  
% Spectrometer Calibration %
```

```
% Maj Pam Wheeler %  
% 10 Jan 17 %
```

```
%Function reads in an excel file of spectrometer readings from a  
%calibration source and outputs the correction factor for each wavelength
```

```
%%%% ENSURE YOUR LAMP FILE IS IN THE SAME FOLDER AS THIS FILE! %%%%
```

```
%INPUTS
```

```
%Filename = file name of lamp data  
%Fileout = file name for output of correction values  
%Temp = temperature of the lamp in Kelvins
```

```
%OUTPUT
```

```
%values in output file name given in inputs
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%Using a calibration source and resulting blackbody curve
```

```
%read in spectrometer files
```

```
Spec=xlsread(Filename);
```

```
%define constants
```

```
c=3*10^8; %speed of light in m/s  
k=1.38*10^-23; %Boltzmann's constant in joules/K  
h=6.6*10^-34; %Planck's constant in joule-sec  
Tl=Temp; %calibration source temperature in K
```

```
%define blackbody function
```

```
B=@(x,T) (2*h*(c^2))./((x.^5).*(exp((h*c)./(x.*k*T))-1))*0.0001; %in W/m^3-sr
```

```
%read in values from file
```

```
wave=Spec(:,1); %wavelengths in nm  
count=Spec(:,4); %intensity counts (signal-background)
```

```
%calculate expected blackbody values for wavelengths measured
```

```
Blamp=B(wave*10^-9,Tl);
```

```
%Determine correction factor
```

```
C=Blamp./count;
```

```
%output data to an Excel file
```

```
out=[wave,C];
```

```
xlswrite(Fileout,out);
```

```
end
```

```
function varargout = DiMaCGUI(varargin)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
                    % DiMaCGUI %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

                    % Maj Pam Wheeler %
                    % 24 May 17 %

%DIMACGUI M-file for DiMaCGUI.fig

%DIMACGUI creates the Electric Propulsion Remote Diagnostic Toolkit GUI

%%%%% ENSURE ALL FILES NEEDED ARE IN THE SAME FOLDER AS THIS FILE! %%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Last Modified by GUIDE v2.5 16-Jun-2017 10:48:00
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Begin initialization code
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                  'gui_Singleton',   gui_Singleton, ...
                  'gui_OpeningFcn', @DiMaCGUI_OpeningFcn, ...
                  'gui_OutputFcn',  @DiMaCGUI_OutputFcn, ...
                  'gui_LayoutFcn',  [], ...
                  'gui_Callback',    []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code

% --- Executes just before DiMaCGUI is made visible.
function DiMaCGUI_OpeningFcn(hObject, eventdata, handles, varargin)
handles.output = hObject;
guidata(hObject, handles);
%positions the GUI in the center of the screen
movegui('center');

% --- Outputs from this function are returned to the command line.
function varargout = DiMaCGUI_OutputFcn(hObject, eventdata, handles)
varargout{1} = handles.output;

% --- Executes during object creation, after setting all properties.
function axes1_CreateFcn(hObject, eventdata, handles)
```

```
% --- Create and callback all edit blocks in GUI.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Values from Thruster Data block.  This block of values are the inputs to
% the CRM code.

% nn is neutral number density (1/m^3)
function nn_Callback(hObject, eventdata, handles)
function nn_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% ne is electron number density (1/m^3)
function ne_Callback(hObject, eventdata, handles)
function ne_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% Te is electron temperature (eV)
function Te_Callback(hObject, eventdata, handles)
function Te_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% propellant is string value of propellant element name (ex. 'Xenon')
function propellant_Callback(hObject, eventdata, handles)
function propellant_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% nil is the singly charged ion density (1/m^3)
function nil_Callback(hObject, eventdata, handles)
function nil_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% vil is the singly charged ion velocity (m/s)
function vil_Callback(hObject, eventdata, handles)
function vil_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUicontrolBackgroundColor'))
```

```
    set(hObject,'BackgroundColor','white');
end

% vi2 is the doubly charged ion velocity (m/s)
function vi2_Callback(hObject, eventdata, handles)
function vi2_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUiControlBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% Tn is neutral temperature (K)
function Tn_Callback(hObject, eventdata, handles)
function Tn_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUiControlBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Site location values from Grond Site Data block.  This block of values
% are the inputs to the LEEDRapp code.

% lat is site latitude
function lat_Callback(hObject, eventdata, handles)
function lat_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUiControlBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% lon is site longitude
function lon_Callback(hObject, eventdata, handles)
function lon_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUiControlBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% sitepress is the site atmospheric pressure (mbar)
function sitepres_Callback(hObject, eventdata, handles)
function sitepres_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUiControlBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% season is a string value of the season in which observations are made
% (ex. 'Summer')
function season_Callback(hObject, eventdata, handles)
function season_CreateFcn(hObject, eventdata, handles)
```

```
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% satalt is the satellites altitude (km)
function satalt_Callback(hObject, eventdata, handles)
function satalt_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Spectrometer and telescope details from Equipment block.  This block of
% values are the inputs to the optics code.

% D is telescope diameter (m)
function D_Callback(hObject, eventdata, handles)
function D_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% R is source radius (m)
function R_Callback(hObject, eventdata, handles)
function R_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% pixels is number of pixels on spectrometer CCD
function pixels_Callback(hObject, eventdata, handles)
function pixels_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% dc is dark current noise (RMS)
function dc_Callback(hObject, eventdata, handles)
function dc_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% readnoise is read noise (RMS)
function readnoise_Callback(hObject, eventdata, handles)
```

```
function readnoise_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% skymag is the sky magnitude of the background sky on the night of
% observations
function skymag_Callback(hObject, eventdata, handles)
function skymag_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% --- Executes on button press in radiobutton1.
function radiobutton1_Callback(hObject, eventdata, handles)
function radiobutton2_Callback(hObject, eventdata, handles)

% apix is the area of a pixel (m^2)
function apix_Callback(hObject, eventdata, handles)
function apix_CreateFcn(hObject, eventdata, handles)
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% --- Executes on button press in calculate.
function calculate_Callback(hObject, eventdata, handles)

%now that we have all our inputs we need to do some converting

%read in values to variable names below
%all values are input as string values from the user so convert values to
%numbers where needed

nn = str2num(get(handles.nn,'String'));
nn = str2num(get(handles.nn,'String'));
ne = str2num(get(handles.ne,'String'));
Te = str2num(get(handles.Te,'String'));
Tn = str2num(get(handles.Tn,'String'));
nil = str2num(get(handles.nil,'String'));
vil = str2num(get(handles.vil,'String'));
vi2 = str2num(get(handles.vi2,'String'));
lat = str2num(get(handles.lat,'String'));
lon = str2num(get(handles.lon,'String'));
season = get(handles.season,'String');
satalt = str2num(get(handles.satalt,'String'))*10^3;
sitepres = str2num(get(handles.sitepres,'String'));
D = str2num(get(handles.D,'String'));
```

```

readnoise = str2num(get(handles.readnoise,'String'));
dc = str2num(get(handles.dc,'String'));
pixels = str2num(get(handles.pixels,'String'));
A_pixel = str2num(get(handles.apix,'String'));
skymag = str2num(get(handles.skymag,'String'));
source_R = str2num(get(handles.R,'String'));

%calculate wavelengths and intensities using CRM code
[ wavelengths J ] = calculate_spectra(nn, ne, Te, nil, vi1, vi2, Tn, 1);

%run LEEDR for transmission values of the lines
%CRM code rounds the wavelengths which does make a difference in LEEDR so
%reassign wavelengths from CRM without rounding
wavelengths=[7.8874e-07;8.231635e-7;8.280117e-7;8.34724e-7;8.819411e-7;9.04545e-7;9.16265
e-7;9.7997e-7];
for l = 1:length(wavelengths)
[outProfs, transmission, attenuation, Deg] = LEEDRapp(lat,lon, season, wavelengths(l),
satalt, sitepres);
A(l,:)=attenuation;
T(l,:)=transmission;
end
%transpose the transmission matrix, now each column represents a wavelength
trans=T';
%now to run the optics code
[SNR20,SNR30,SNR40,SNR50,SNR60,SNR70,SNR80,SNR90,t]=optics(J,D,T,satalt,wavelengths,
pixels,A_pixel,dc,readnoise,skymag,source_R);

%now to populate the graphs
%call the first graph on the bottom left of the GUI
axes(handles.axes1);
%plot the wavelengths and intensities from the CRM code
bar(wavelengths,J);
xlabel('Wavelength [nm'],'FontSize',12)
ylabel('Intensity per unit volume [W/m^3'],'FontSize',12)
title('Near Infrared Spectral Emission','FontSize',12)
%call the middle graph on the center bottom of the GUI
axes(handles.axes3);
%plot the transmission values vs viewing angles for the lines of interest
plot(Deg,trans(:,2));
hold on
plot(Deg,trans(:,3),'r');
hold off
xlabel('Viewing Angle [degrees]','FontSize',12)
ylabel('Transmission','FontSize',12);
legend('823.16','828.01','Location','southeast');
title('Transmission values for chosen spectral lines','FontSize',12)

% run through callback to see what button has been selected in Viewing
% Angle button group and plot appropriate SNR vs integration time
choice = get(handles.Buttons,'SelectedObject')
view = get(choice,'String')

```

```
axes(handles.axes4);
if (view=='20 degrees')
    plot(t,SNR20(1,:), 'b');
    hold on
    plot(t,SNR20(2,:), 'r');
    hold off
elseif(view=='30 degrees')
    plot(t,SNR30(1,:), 'b');
    hold on
    plot(t,SNR30(2,:), 'r');
    hold off
elseif(view=='40 degrees')
    plot(t,SNR40(1,:), 'b');
    hold on
    plot(t,SNR40(2,:), 'r');
    hold off
elseif(view=='50 degrees')
    plot(t,SNR50(1,:), 'b');
    hold on
    plot(t,SNR50(2,:), 'r');
    hold off
elseif(view=='60 degrees')
    plot(t,SNR60(1,:), 'b');
    hold on
    plot(t,SNR60(2,:), 'r');
    hold off
elseif(view=='70 degrees')
    plot(t,SNR70(1,:), 'b');
    hold on
    plot(t,SNR70(2,:), 'r');
    hold off
elseif(view=='80 degrees')
    plot(t,SNR80(1,:), 'b');
    hold on
    plot(t,SNR80(2,:), 'r');
    hold off
elseif(view=='90 degrees')
    plot(t,SNR90(1,:), 'b');
    hold on
    plot(t,SNR90(2,:), 'r');
    hold off
end
xlabel('Integration time (s)', 'FontSize', 12)
ylabel('SNR', 'FontSize', 12);
legend('823.16', '828.01', 'Location', 'southeast');
title('Transmission values for chosen spectral lines', 'FontSize', 12)
guidata(hObject, handles);
```

```
function [outProfs, transmission, attenuation, Deg] = LEEDRapp(lat, lon,...  
    season, wavelength, satalt, sitepres)
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%  
    % LEEDR Transmission Analysis %
```

```
    % Maj Pam Wheeler %  
    % 1 Feb 17 %
```

```
%Function is given a location, season, wavelength, and satellite altitude  
%and calculates the path length and transmission values.
```

```
% Code was adapted into a function from runLEEDR_c script recieved from  
% Brannon Elmore in the Center for Directed Energy LEEDR team at AFIT
```

```
%%%% ENSURE ALL FILES NEEDED ARE IN THE SAME FOLDER AS THIS FILE! %%%%
```

```
% INPUTS
```

```
%lat = location latitude  
%lon = location longitude  
%season = string value can be set to Summer or Winter  
%wavelength = wavelength in meters  
%satalt = satellite altitude in meters  
%sitepres = pressure at ground location
```

```
% OUTPUTS
```

```
%outProfs = generated profiles during LEEDR run  
%transmission = transmission values  
%attenuation = path attenuation values (dB/m)  
%Deg = viewing angles evaluated (degrees)
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%%%% ENSURE YOU OPEN LEEDR FIRST BEFORE RUNNING THIS SCRIPT %%%%
```

```
%initialize LEEDR to get access to subfunctions  
rl = RunLEEDR(pwd);
```

```
format long;
```

```
%upload a default profile (first parameter lets LEEDR know you are  
%providing an entire profile, second returns a default profile, third is  
%the name you assign the profile)  
rl.upload('profile', RunLEEDR.getDefaultProfile(), 'WPAFB');  
rl.load('WPAFB'); %load profile
```

```
%set the atmosphere to Expert for this profile  
    %Expert atmosphere is based on correlated, probabilistic surface  
    %climatology specific to your location and gives a more realistic  
    %profile (Ensure site you choose is an Expert site, Expert will use
```

```
%data for whatever site is "closest" to your lat/long selection)
rl.prof.inputs.setAtmosphere(Atmosphere.expert);

%set the season and location
rl.prof.inputs.setSeason(season);
rl.prof.inputs.setLatitude(lat);
rl.prof.inputs.setLongitude(lon);

%set wavelength of interest
wavelengthOfInterest = wavelength;
rl.prof.inputs.setWavelength(wavelengthOfInterest);

% GROUND LEVEL INPUTS
%rl.prof.inputs.setUserTemperature(sitetemp);
rl.prof.inputs.setUserPressure(sitepres);
%rl.prof.inputs.setUserDewpoint(sitedp);
%rl.prof.inputs.setUserRelativeHumidity(siteRH);

%run ghe atmosphere
rl.runAtmosphere();

%now that we have an atmosphere, we need to set up our geometry to get a
%transmission profile
%first calculate ranges of interest based on satellite altitude
%call in earth radius
earthRadius = rl.prof.inputs.getEarthRadius(); %in meters
Deg=[20 30 40 50 60 70 80]; %viewing angles to be evaluated
N=90.*ones(1,7);
B=(N+Deg).*pi/180;
c=earthRadius;
b=earthRadius+satalt;
C=asin((c.*sin(B))./b);
p=pi.*ones(1,7);
A=p-B-C;
a=(b.*sin(A))./sin(B); %corrected path length for veiwing angles
rangesOfInterest = [a satalt];
platformAlt = 0; % meters
targetAlt = satalt; % meters
Deg=[Deg 90]; %correct degree output to include 90 degree value

% Set the type of refraction to use. We want to get transmission to the
% target, so we'll use the corrected path model.
rl.prof.inputs.bending.setPathType(globals.Bending.PATH_TYPE_CORRECTED);
%preallocated transmission array
transmission = zeros(size(rangesOfInterest));
attenuation = zeros(size(rangesOfInterest));
%Preallocate some space for the profiles that are calculated. We'll want to
%extract the corrected elevation angles out of them if use use Path
%Refraction so that we can give appropriate inputs to Path Radiance.
outProfs = cell(size(targetAlt));
```

```
for z = 1:length(rangesOfInterest)
    range = rangesOfInterest(z);
    % Calculate the elevation angle from platform to target for the
    % given engagement range.
    downRange = Slant2Down(range, platformAlt, targetAlt, earthRadius);
    [~, ~, el] = EarthAlt(linspace(0, 1, 200), platformAlt,...
        targetAlt, downRange, earthRadius);
    el = el * (180 / pi);
    % The last input of 200 is simply the number of segments to
    % calculate for the path. This almost never needs changed unless
    % you're path is hundreds of kilometers long.
    %rl.prof.inputs.pathInputs = path.Refracted(platformAlt, targetAlt,
    %range, el, azimuth, 200);

    % If you'd rather use a simpler geometry, just uncomment this next
    % line and you'll get a Slant Path calculation instead. Comment out
    % the "path.Refracted..." line above if you're going to use Slant
    % Path.
    rl.prof.inputs.pathInputs = path.Slant(platformAlt, targetAlt,...
        range, 200);

    % Our geometry is set, let's get our transmission value we're
    % after. If you're using a single wavelength, the following line of
    % code is appropriate. Uncomment it if you want to use are using a
    % single wavelength.
    [outProfs{z}, transmission(z)] = rl.runGeometry();
    attenuation(z)=outProfs{z}.outputs.getPathSpecificAttenuation;
    % Otherwise use the following for multiple wavelengths.
    %[outProfs{z}, transmission(z,:)] = rl.runGeometry();
end
```

```
function [SNR20,SNR30,SNR40,SNR50,SNR60,SNR70,SNR80,SNR90,t]=optics(J,D,T,satalt,
wavelengths,pixels,A_pixel,dc,readnoise,skymag,source_R);
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
% Optics %
```

```
% Maj Pam Wheeler %
```

```
% 19 May 17 %
```

```
%Optics calculations function that given details on the spectrometer,
%thruster details, sky estimates, orbit and atmospheric details calculates
%the SNR for a range of integration times over varying viewing angles. The
%integration times are hard coded to calculate between 0.1 and 10 seconds
%in 0.1 increments but can be altered in the code where indicated.
```

```
%%%% ENSURE ALL FILES NEEDED ARE IN THE SAME FOLDER AS THIS FILE! %%%%
```

```
% INPUTS
```

```
% J = intensity per unit volume (W/m^3)
% D = telescope diameter (m)
% T = transmission values
% satalt = satellite altitude (m)
% wavelengths = wavelengths of interest (m)
% pixels = number of pixels on spectrometer CCD
% A_pixel = area of a single pixel (m^2)
% dc = dark current noise (RMS per pixel)
% readnoise = read noise (RMS per pixel)
% skymag = estimated sky magnitude
% source_R = radius of the source (m)
```

```
% OUTPUTS
```

```
% SNR20 = signal-to-noise ratio for wavelengths at 20 degree viewing angle
% SNR30 = signal-to-noise ratio for wavelengths at 30 degree viewing angle
% SNR40 = signal-to-noise ratio for wavelengths at 40 degree viewing angle
% SNR50 = signal-to-noise ratio for wavelengths at 50 degree viewing angle
% SNR60 = signal-to-noise ratio for wavelengths at 60 degree viewing angle
% SNR70 = signal-to-noise ratio for wavelengths at 70 degree viewing angle
% SNR80 = signal-to-noise ratio for wavelengths at 80 degree viewing angle
% SNR90 = signal-to-noise ratio for wavelengths at 90 degree viewing angle
% t = array of integration times used in calculations for SNR (sec)
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%define constants
```

```
c=3*10^8; %speed of light in m/s
h=6.6*10^-34; %Planck's constant in J/s
sunmag=-26.74; %visible magnitude of the sun on Earth
vegmag=0.03; %visible magnitude of vega on Earth
scopearea=(pi*(D/2)^2); %area of the telescope
d=satalt; %distance of light source to the optic is the satellite altitude
```

```
A_CCD=A_pixel*pixels; %area of the spectrometer CCD
A_scope=pi*((D/2)^2); %area of the telescope

%define wavelengths you need
I=[J(2);J(3)]; %read in 823 and 828 intensity from CRM
wavelengths=[wavelengths(2);wavelengths(3)]; %read in wavelengths
T=[T(2,:);T(3,:)]; %read in transmission values for 823 and 828 lines

%calculate the Quantum Efficiency (QE) value of the spectrometer
y=@(x) -5.5e-6.*x.^2+7.15e-3.*x-1.39;
QE=y(wavelengths/10^-9);

%calculate the number of photons in our signal
%because we are a point source can treat J as the flux at the ground
%loop to calculate total number of photons in the signal at the ground
for n=1:length(wavelengths)
    S=I(n)*A_scope*(pi*source_R)/(d^2);
    numphotons=wavelengths(n)/(c*h);
    photonsCCD=numphotons*S;
    PS(n,:)=photonsCCD*QE(n);
end
%calculate signal reaching the ground
Sig=zeros(length(wavelengths),length(T)); %preallocate size of Signal
for n=1:length(wavelengths)
    Sig(n,:)=PS(n).*T(n,:);
end

%calculate the noise in the spectrometer
%dark current noise
DN=dc*pixels;
%readout noise
RN=readnoise*pixels;
%sky background noise
Vega=551/(10^(-(sunmag-vegmag)/2.5)); %flux of Vega
GrVega=Vega.*T; %flux of Vega at the ground
sky=GrVega./(10^(-(vegmag-skymag)/2.5)); %flux of sky at the ground
%preallocate size of photons generated by the sky
phgensky=zeros(length(wavelengths),length(T));
%loop to calculate number of photons generated by the sky for each
%wavelength per pixel
for n=1:length(wavelengths)
    numphotons=wavelengths(n)/(c*h);
    photonsAper=numphotons*A_CCD*sky(n,:);
    phgensky(n,:)=photonsAper*QE(n);
end
skyback=phgensky.*T*pixels; %calculate total background sky noise

%make dark current and read current a vector for easier math
DN=ones(1,length(T))*DN;
RNS=ones(1,length(T))*(RN^2);
```

```
%calculate SNR
%allocate for wavelength and viewing angle choices in loop
%preallocate arrays for SNR outputs
SNR20=zeros(2,100);
SNR30=zeros(2,100);
SNR40=zeros(2,100);
SNR50=zeros(2,100);
SNR60=zeros(2,100);
SNR70=zeros(2,100);
SNR80=zeros(2,100);
SNR90=zeros(2,100);
%loop to calculate SNR given values above for each wavelength and
%integration time and populate each array allocated above
for n=1:length(wavelengths);
    count=1;
    for t=[.1:.1:10] %integration time loop, can be altered
        SNR=(Sig(n,:)*t)./sqrt(Sig(n,:)*t+skyback(n,:)*t+DN*t+(RNS));
        SNR20(n,count)=SNR(1);
        SNR30(n,count)=SNR(2);
        SNR40(n,count)=SNR(3);
        SNR50(n,count)=SNR(4);
        SNR60(n,count)=SNR(5);
        SNR70(n,count)=SNR(6);
        SNR80(n,count)=SNR(7);
        SNR90(n,count)=SNR(8);
        count=count+1;
    end
end
%create integration time array for output based on loop, can be altered
t=[.1:.1:10];
```

Appendix C. Star Analysis MATLAB Script

The Electric Propulsion Remote Diagnostic Toolkit was developed specifically for use with Hall thruster spectra estimates from the CRM model. In order to estimate the star spectral signature, the blackbody of that star needed to be calculated instead of using the CRM code. In order to do this a separate script was written to read in the observed star data collected using SpectraSuite and compare that to the estimated blackbody signature of that star. The same LEEDR code and part of the optics estimation code, namely the spectrometer QE and Meade telescope transmission curve calculations, were combined to produce a graph of the output. A second script was also written for specific wavelengths to calculate the SNR and 823/828 line ratio for the blackbody estimate to use in comparisons with the observed star data. Both scripts were written in MATLAB and are provided in this appendix.

%%%

% Star Estimates %

% Maj Pam Wheeler %

% 15 May 17 %

%Script was developed to estimate the blackbody curve of a given star
%corrected for the spectrometer CCD sensitivity and atmospheric
%transmission.

%%%

%define constants

c=3*10^8; %speed of light in m/s

k=1.38*10^-23; %Boltzmann's constant in joules/K

h=6.6*10^-34; %Planck's constant in joule-sec

%editable parameters for star data

T=3590; %star temperature in K

Star=xlsread('StarCalcs.xlsx'); %files from SpectraSuite

startrans=xlsread('startrans.xlsx'); %transmission values from LEEDR

%LEEDR takes a while to run for a blackbody curve across all wavelengths
%(15 min), to save time you can comment out the LEEDR function below and
%use the startrans input above to read in values from running the LEEDRapp
%seperately. This is useful if you have more than one star collect that
%you want to analyze.

%define blackbody function

B=@(x,T) (2*h*(c^2))./((x.^5).*(exp((h*c)./(x.*k*T))-1)); %in W/m^3-sr

%read in values from file

wave=Star(:,1); %wavelengths in nm

%Betelguese

%raw star data, in this case from two nights

count1=Star(:,5);

count2=Star(:,13);

%dark data

dark10=Star(:,50);

dark30=Star(:,54);

%corrected signal

Be1=count1-dark10;

Be2=count2-dark30;

%normalized corrected signal

Be1f=Be1./max(Be1);

Be2f=Be2./max(Be2);

%Calculate black body curve

BStar1=B(wave*10^-9,T1);

%correct blackbody curve for atmospheric transmission

%using Stellarium, check date and time of observation (from SpectraSuite

```
%file to get the altitude of the star at that time and use the appropriate
%LEEDR calculations (column one in LEEDRapp is 20 degrees, two is 30
%degrees, etc.
[outProfs, transmission, attenuation, Deg] = LEEDRapp(39.83, -84.05, 'Summer', wave,
100000, 988);
BStar1=BStar.*startrans(:,7);%using saved file

%Telescope transmission curve
T_trans=@(x) -2.4e-6.*x.^2+2.64e-3.*x+.18;
Tel=T_trans(wave);

%QE equation
y=@(x) -5.5e-6.*x.^2+7.15e-3.*x-1.39;
QE=y(wave);

%Calculate final signal taking equipment transmission and sensitivity into
%account
BStarfin1=BStar1.*Tel.*QE;
%normalize results
BStarF1=BStarfin1./max(BStarfin1);

%plot results
figure;
plot(wave,BStarF1,'g');
hold on;
plot(wave,Belf,'b--');
plot(wave,Be2f,'r--');
hold off
legend('LEEDR estimate','dark from background sky','dark from spectrometer');
title('Arcturus Results for 31 May 17')
ylabel('Normalized Intensity')
xlabel('Wavelength (nm)')
```

%%%

% Star SNR & Line Estimates %

% Maj Pam Wheeler %

% 15 May 17 %

%Script was developed to estimate the specific line emissions for a star
%using the blackbody curve, corrected for the spectrometer CCD sensitivity
%and atmospheric transmission. In addition, the SNR for a specific line is
%also calculated.

%%%

%read in files

Star=xlsread('StarCalcs.xlsx');

%specify the wavelength to be evaluated

wave=823e-9;

%define constants

c=3*10^8; %speed of light in m/s

k=1.38*10^-23; %Boltzmann's constant in joules/K

h=6.6*10^-34; %Planck's constant in joule-sec

sunmag=-26.74; %visible magnitude of the sun on Earth

vegmag=0.03; %visible magnitude of vega on Earth

%adaptable parameters

%star values

Tl=4286; %source temperature in K

d=3.5e17; %distance to star

source_R=17.89e9; %radius of star

%telescope specifications

D=0.4; %telescope diameter

scopearea=(pi*((D/2)^2)-((0.127^2)/2)); %area of the telescope

%spectrometer specifications

pixels=59392; %number of pixels on CCD

dc=3; %dark current noise of spectrometer

readnoise=1.5; %read noise of spectrometer

skymag=19; %sky magnitude of observation

A_CCD=(6.96e-10)*pixels; %area of the CCD

%define blackbody function

B=@(x,T) (2*h*(c^2))./((x.^5).*(exp((h*c)./(x.*k*T))-1)); %in W/m^3-sr

%calculate transmission

[outProfs, transmission, attenuation, Deg] = LEEDRapp(39.83, -84.05,...
'Summer', wave, 100000, 988);

%Calculate black body curve

BStar=B(wave,Tl);

```
%Telescope transmission curve
T_trans=@(x) -2.4e-6.*x.^2+2.64e-3.*x+.18;
Tel=T_trans(wave);

%QE equation
y=@(x) -5.5e-6.*x.^2+7.15e-3.*x-1.39;
QE=y(wave/10^-9);

%calculate the number of photons in our signal
S=BStar*Tel.*scopearea*(pi*source_R)/(d^2);
numphotons=wave./(c*h);
photonsCCD=numphotons.*S;
PS=photonsCCD.*QE;
%calculate signal reaching the ground
%using Stellarium, check date and time of observation (from SpectraSuite
%file to get the altitude of the star at that time and use the appropriate
%LEEDR calculations (column one in LEEDRapp is 20 degrees, two is 30
%degrees, etc.
Sig=PS.*transmission(3);

%calculate the noise in the spectrometer
%dark current noise
DN=dc*pixels;
%readout noise
RN=readnoise*pixels;
%sky background noise
Vega=551/(10^(-(sunmag-vegmag)/2.5)); %flux of Vega
GrVega=Vega.*transmission(3); %flux of Vega at the ground
sky=GrVega./(10^(-(vegmag-skymag)/2.5)); %flux of sky at the ground
phgensky=zeros(1,length(wave)); %preallocate size of photons generated by the sky
for n=1:length(wave)
    numphotons=(wave)/(c*h);
    photonsAper=numphotons*scopearea.*sky(n);
    phgensky(n)=photonsAper*QE;
end
%using Stellarium, check date and time of observation (from SpectraSuite
%file to get the altitude of the star at that time and use the appropriate
%LEEDR calculations (column one in LEEDRapp is 20 degrees, two is 30
%degrees, etc.
skyback=phgensky'*transmission(3);
N=Sig+skyback+DN+RN^2;
%calculate SNR given integration time used in collection
t=10; %integration time in seconds
SNR=(Sig*t)/sqrt(Sig*t+skyback*t+DN*t+RN^2)
```

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