Recommissioning REDDI: Reviving a Doppler Asymmetric Spatial Heterodyne Spectrometer for Observing Thermospheric Winds

Robert Kallio

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RECOMMISSIONING REDDI:

REVIVING A DOPPLER ASYMMETRIC SPATIAL HETERODYNE SPECTROMETER FOR OBSERVING THERMOSPHERIC WINDS

By

Robert Kallio
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By

Robert Kallio

This thesis was prepared under the direction of the candidate’s Thesis Committee Chair, Dr. Edwin Mierkiewicz, and has been approved by the members of the thesis committee. It was submitted to the Department of Physical Science and was accepted in partial fulfillment of the requirements of the Degree of Master of Science in Engineering Physics.

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Abstract

The REd-line DASH Demonstration Instrument (REDDI) was designed to prove that a Doppler Asymmetric Spatial Heterodyne (DASH) spectrometer could be used to accurately measure thermospheric winds by observing the Doppler shift of the 630nm emission of oxygen in the thermosphere. In 2015, we began a project to redesign the input optics of REDDI to repurpose the instrument from a demonstration unit to a long duration instrument. Integration of REDDI into the INSpIRe (Investigating Near-Space Interaction Regions) trailer at Embry-Riddle Aeronautical University (ERAU), Daytona Beach, began in 2016 with assembly of the new input optics in 2017. REDDI and INSpIRe will remain at ERAU until full loadout and instrument checkout is completed in late 2018, at which time it will be moved to a dark site. After recovering from a serious camera malfunction, full testing of REDDI commenced in January 2018. Thermospheric oxygen was first detected on 31 January, with first lateral winds being measured on 6 February. In total 20 nights of data were observed from 31 January to 6 March 2018. Thermospheric wind magnitudes ranging from 50 to 200 m/s were detected most nights despite a challenging observation location and constantly changing weather conditions.
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Chapter 1 – Introduction and Background

In the 1990’s a new type of spectrometer was developed by John Harlander and Fred Roesler at the University of Wisconsin – Madison [Harlander, 1991; Harlander et al, 1992]. The new spectrometer combined some of the best aspects of a Fabry-Perot Interferometer and a Michelson Interferometer. The fundamental design uses the interference of two beam paths, much the same as a Michelsen Interferometer, however the mirrors at the ends of the separate arms of the Michelsen are replaced with diffraction gratings. The result of such a change is a high resolution, high etendue, low cost, robust design that can fit into a relatively small package; it contains no moving parts and does not require scanning as the entire spectrum is acquired simultaneously. Further refinements of the design brought two major upgrades to the spectrometer. The first upgrade was the addition of field-widening prisms, which was discussed in Harlander’s Dissertation [Harlander, 1991]. The second upgrade was a result of optimizing the design to detect Doppler shifts, known as DASH or Doppler Asymmetric Spatial Heterodyne [Englert et al., 2006; Englert et al., 2007].

1.1 – The Instrument – REDDI

The REd-line DASH Demonstration Instrument, or REDDI, pictured in Figure 1.1, is the spectrometer that will be discussed throughout this Thesis. REDDI is a DASH spectrometer optimized to observe the 6300 Angstrom Oxygen-I forbidden line that is present in thermospheric airglow, most often seen as the red haze above the Earth in pictures taken from the International Space Station. The design consists of a monolithic glass spectrometer (INT), which includes an optically-bonded prism, beam-splitter, field-widening prism, diffraction grating (G), and spacers and heaters to ensure optimal alignment. In support of the monolith are a Cerium-Neon Hollow Cathode Lamp (CL) for simultaneous calibration, a liquid-cooled Princeton Instruments PIXIS 2048 CCD (CAM) that is binned to 4x4, the input optics (M1, M2, L1, BS, L2, L3), a narrowband filter (F), a Newport Optics rotation stage capable of rotating 360 degrees which was used to control the observation direction of the instrument, a blackout enclosure, an optical breadboard on which REDDI is assembled, and the electronics that control the instrument.

REDDI was constructed in 2010 and was tested periodically from 2010 to 2013, with moderate results largely due to poor weather during observation times. Part of this initial testing was to verify that the quality of the data received was at least equivalent to data taken from a Fabry-Perot Interferometer, and during at least one observing run the instrument was moved to a location where simultaneous observation with a Fabry-Perot could be performed. During this time the input optics for the instrument consisted of a pair of first surface fold mirrors. The primary mirror was set on the Newport optics.
rotation stage, and was fixed to observe the sky at an elevation of 35 degrees. An additional fixed auxiliary first surface mirror, that allowed the primary mirror to look at the zenith when the correct azimuth was selected, was located to the side of the primary mirror. The 35-degree elevation meant that the instrument was never observing the same patch of sky that Fabry-Perot was observing, due to the FPI’s input optics being set for the more typical 45-degree elevation. [Englert et al., 2010, Englert et al., 2012, and Harlander et al., 2010]

Figure 1.1: Layout of REDDI components (a) from a picture of the inside of REDDI’s blackout box, (b) from a schematic highlighting all the major components before upgrades were made to the input optics [Englert et al., 2010].

REDDI’s original purpose as a demonstration instrument proved successful and a follow-on instrument, MIGHTI (Michelson Interferometer for Global High-resolution Thermospheric Imaging), would go on to be approved for implementation on the Ionospheric Connection Explorer ICON satellite, which is set to launch later in 2018 [Harlander et al., 2017].

In 2016, the ERAU LENSES lab received REDDI as the second instrument of the INSpIRe (Investigating Near-Space Interaction Regions) project. At the time of its reception it was known that the input optics would need to be redesigned into a smaller planform due to the size and location of the observing dome under which REDDI would sit. A preliminary set of input optics had been designed by John Harlander, including ray traces, as seen in Figure 1.2 below, however no opto-mechanical engineering had been performed and it was not clear if such a design could be implemented in the space available. The observation requirements for REDDI included, at a minimum, observing
the 4 cardinal directions at an elevation of 45 degrees and the zenith, as seen in Figure 1.3 below.

Figure 1.2: REDDI’s proposed input optics design, courtesy of John Harlander.

The original design of REDDI, depicted in Figure 1.1, with the pair of mirrors acting as a periscope for observations would be maintained for the redesign. The basic idea for the upgrade was to move the mirrors, M1 and M2 farther apart and to fit relay lenses in between, as seen in Figure 1.2. The original turret (not pictured) that was used to rotate M1 and to position the zenith mirror was too large to fit in the observation dome and so had to be removed from the system and a replacement designed and built. The rest of the optics remain unchanged and are as described in Figure 1.1 and Englert et al. [2010].
Figure 1.3: REDDI’s new observation geometry.

Over the summer of 2016, I designed the opto-mechanical input and came up with a design that conformed to the Harlander’s optical design and included ample alignment considerations while attempting to keep costs low. In the Fall of 2016 the design was accepted and parts were manufactured and delivered in the winter of 2016-2017. Some initial testing was done throughout 2017, including parallel upgrades to the REDDI control software, that will be included in the final instrument used by REDDI when INSpIRe is moved to a remote site. Christina MacFarland and Margaret Gallant have been handling the software upgrades necessary for remote observations, while I did the installation of the instrument. In the Fall of 2017, as full-time observations with REDDI were beginning, a persistent error occurred that required removal and repair of the Princeton Instruments CCD. Observations commenced in 2018, after the CCD was returned and reintegrated.

1.2 – The Thermosphere

The thermosphere is one of the least understood regions of the atmosphere. The lower bound of the thermosphere is defined by a sudden rise in the temperature of the atmosphere that begins at approximately 85 to 100 km in altitude. In this region, temperatures quickly rise to approximately 1000 K. The true lower-bound altitude and maximum temperature of the thermosphere varies significantly depending on space weather conditions. During solar minimum the maximum temperature of the thermosphere may be as low as 500 to 600 K. The upper boundary of the atmosphere, typically is defined to be at 500 to 600 km. At this altitude, the molecules and atoms within the atmosphere typically have a mean free path that is so large that the atmosphere no longer acts as a fluid and this is what defines the upper boundary of the thermosphere. Molecules and atoms follow a variety of paths ranging from ballistic and orbital trajectories, to escape trajectories. This region is depicted in Figure 1.4, below. Furthermore, within the thermosphere, a transition occurs from molecular nitrogen, N₂, being the dominant species to atomic oxygen, O, at approximately 200 km altitude.
Figure 1.4: Regions of the Earth’s atmosphere, (a) showing the temperature divisions of the atmosphere, and (b) showing the ionized regions compared to the density of the neutral atmosphere [Harding, 2017; Picone et al., 2002; Bilitza and Reinisch, 2008].

The process by which atomic oxygen is created in the upper atmosphere and allowed to relax and emit a 630 nm photon is complicated and one possible path will be discussed here. Any oxygen atom that ends up in the \( \text{O}(^1\text{D}) \) state, has the potential to relax and emit a 630 nm photon, but the following description is believed to be one of the more common energy and charge paths to reach that state. The first step is to create ionized \( \text{O}_2^+ \) this is done either directly by solar photoionization or by a charge exchange reaction with another ion in the thermosphere. Solar radiation, particularly ultraviolet radiation, is so intense in the thermosphere, that it creates a large amount of ionized monatomic oxygen, \( \text{O}^+ \), which is one of the most common ions for the charge exchange reaction with \( \text{O}_2 \). Once you have \( \text{O}_2^+ \), dissociative recombination, a process by which an ionized molecule dissociates into two or more molecules or individual atoms upon recombination with an electron, creates the monatomic oxygen in various energy states, this can include the reaction below, which creates the excited oxygen that we need:

\[
\text{O}_2^+ + e^- \rightarrow \text{O}(^1\text{D}) + \text{O}(^3\text{P}) \quad (1.1)
\]

There are a multitude of possibilities for the right side of this reaction in (1.1) depending on energy distribution of the daughter atoms, this is just one possibility. The important
result is the creation of $O^{(1}D)$ atoms. This is the excited state needed to emit 630 nm photons when these atoms relax to the ground state, $O^{(3}P_2)$. That leaves the final reaction in the chain where the photon is emitted as:

$$O^{(1}D_2) \rightarrow O^{(3}P_2) + h\nu_{\lambda=630\ nm} \quad (1.2)$$

This reaction can occur, technically, anywhere in the atmosphere. However, because $O^{(1}D)$ requires, on average, 110 seconds to relax to its ground state, it is only in the thermosphere that excited oxygen is free from other collisions long enough for a significant portion of the oxygen to go through this process, thus allowing a visible 630 nm airglow. Above the thermosphere, the oxygen becomes too diffuse for the airglow to be visible. Below the thermosphere, the atmosphere becomes too thick for excited oxygen atoms to hang around long enough to relax to ground state without a kinetic interaction with another atom or molecule. Additionally, most of the airglow is emitted where conditions are best for the previously stated reactions and this occurs primarily between 200 and 300 km of altitude, in the middle of the thermosphere [Harding, 2017; Link and Cogger, 1988; Link and Cogger, 1989].

Understanding thermospheric oxygen is an important factor in developing a full model of the upper atmosphere. More than ever, the upper atmosphere is becoming an active region for human activity. Low altitude satellites are being designed to incorporate the possibility of air-breathing electric thrusters to counter the additional drag and allow for manipulation of their orbits. JAXA is currently running (launched on 23 December 2017) an experiment with a small, low-altitude, ion-thruster satellite that incorporates an oxygen sensor, the satellite is known as SLATS (Super Low Altitude Test Satellite) or Tsubame, which is Japanese for Swallow. The mission has a two-year design life, however it does not have air-breathing capability, so when it runs out of fuel, it will quickly re-enter the lower atmosphere and burn up. However, this satellite is an important proof of concept that low altitude satellites are viable and may lead to a greater number of such satellites in the next decade. Low altitude satellites also nearly guarantee mitigation of a Kessler syndrome event occurring and make end-of-life deorbiting a matter of just turning off the thruster [SLATS, 2017].

A greater understanding of thermospheric wind speeds and directions as well as interactions with the ionosphere is becoming increasingly important to the continued advancement of air-breathing ion engines. Just as a car engine needs a steady flow of fuel and air to operate, an air-breathing ion engine will require a constant flow of the atoms and ions it will use to propulse the satellite [Shabshelowitz, 2013]. Additionally, large swarms of CubeSats and other smaller satellites are being designed to operate in regions affected by the thermospheric conditions which have the potential to significantly shorten
the lifetime of such satellites. An example of this shortened life is the Humanity Star satellite that was launched into orbit on 21 January 2018 by New Zealand-based, Rocket Lab. Originally, Humanity Star was expected to orbit for nine months; the satellites orbit decayed much more quickly than expected and returned to Earth on 22 March 2018 [Blau, 2018]. Communications and navigation arrays, such as space-to-ground and over-the-horizon systems may also be affected by the oxygen in the thermosphere [Harding, 2017].
Chapter 2 – Optical Relay Tower Design Philosophy

The Optical Relay Tower was a necessary design change to REDDI’s input optics. Previous uses of REDDI involved placing the instrument outside allowing direct observations through the original input optics. The original design placed the primary mirror approximately where the bottom relay lens of the new design is located. This set of relay lenses was determined to be necessary due to the placement of REDDI within the INSpIRe remote observatory. The second issue with the original input optics that necessitated a complete redesign of the input was that the original design was too large to fit under the acrylic dome that had been designated for REDDI. In the original design the primary mirror was set at a fixed angle, and to observe the zenith, it had to look at another mirror located to the side. This set up was too wide and too tall to fit under the acrylic dome.

So, the design requirements for the new version of the input optics included: reducing the size of the primary observation turret, making the primary mirror articulable so that it would be able to observe at a standard angle of 45° and at the zenith without the use of relay mirror, and building a structure to support the relay lenses that would allow the precise alignment of the lenses in 5 degrees of freedom (translation of X, Y, and Z as well as rotation about X and Y).

The design of the Tower was completed using CATIA V5 3D CAD software. Upon final approval, parts were manufactured by the Physics Department Shop at the University of Wisconsin – Madison. Manufacture of all parts including black anodization was overseen by Doug Dummer. Engineering drawings for all the parts manufactured at the University of Wisconsin can be found in Appendix A.
Figure 2.1: (a) Optical Relay Tower Design showing all major components. (b) Relay Optics with provided ray traces and (c) without ray traces. Some hardware components are not included in the image to better show the structure of the Tower.

2.1 – Tower Structural Group

The Tower Structural Group parts include the T-slotted framing used as the main structure of the Optical Relay Tower; the Floor Mounting Brackets, which attach the tower to the Optical Breadboard; and the necessary hardware to connect and secure the individual pieces.
Figure 2.2: Tower Structure Group components. Some hardware components are not included in the image to better show the structure of the Tower.
2.1.1 – T-Slotted Framing

The T-Slotted Framing, also commonly known as 80/20, is a standard product available from McMaster-Carr. It consists of extruded aluminum rails with a slot on all four sides designed for a variety of attachment hardware, as well as a hole that runs the length of the rails. I chose this material for the structure of the Optical Relay Tower because the tensile strength exceeds that is required with a comfortable safety margin, it is easily cut to the lengths that were required, and the hole through the middle could be tapped for ¼”-20 mounting screws. In addition to the physical properties of the T-Slotted Framing, the material is relatively inexpensive and readily available.

The alternatives to using T-Slotted Framing included other similar metal extrusions available from other retailers or a completely custom-built structural design. Other retailers were found to either not have the necessary variety of support hardware and/or were more expensive. Designing a custom-built structural design for the tower would have resulted in a less functional tower that would be more labor intensive to produce and thus more expensive. In this regard, I found that it would not have been a wise use of grant funds to design a custom-built tower.

![T-Slotted Framing](image)

Figure 2.3: T-Slotted Framing used for the structure of the Optical Relay Tower.
2.1.2 – Floor Mounting Bracket

The Floor Mounting Brackets serve two purposes in the structure. The first purpose is simply to secure the tower to the Optical Breadboard, this ensures that the Optical Axis of the tower is fixed. The second purpose is to increase the footprint and thus the stability of the tower. They were chosen to be cut from a piece of 2”x4” aluminum angle, with a set of holes drilled in the appropriate locations to attach the Brackets to the Tower and to mount the Tower to the Optical Breadboard. The holes used to attach the Brackets to the Tower were located as high as possible to maximize moment arm of the Bracket.

During assembly of the Tower Group, the tower was found to be stable without the Floor Mount Brackets. However, the primary purpose of the Brackets, securing the tower and fixing the Optical Axis, more than justifies their manufacture.

2.2 – Lens Group

The Lens Group consists of all the parts needed to mount a single lens in the Optical Relay Tower. The requirements for the lens mounting included the ability to translate the lens in three dimensions and to have a limited tip-tilt functionality in the lens. The following design provides the lens the ability to translate in the Z-direction (along the Optical Axis) for most of the height of the tower. Translation in the X- and Y-directions is limited by the size of the lens holder but amounts to nearly a half-inch in a single direction. However, it is advisable to keep the lens as close to the center of the Optical Relay Tower as possible, to minimize distortion of the beam and to keep the Optical Axis centered in the Tower. In this configuration, the lenses will most closely match the ray traces that were provided by Dr. John Harlander.

The parts of the Lens Group include, a Lens Mount Plate, four Vertical Mount Brackets, a Lens Holder, three Hold-down Clamps, and the necessary hardware to adequately secure the individual parts. Four such assemblies were required for the Optical Relay Tower, due to the distance between the Optical Breadboard and the Plexiglas observation Dome that would be used in order to perform observations in the INSpIRe remote observatory.
2.2.1 – Lens Mount Plate

The Lens Mount Plate is milled from ½” thick aluminum. As much material as possible was removed from the plate to reduce the weight of the structure. In order to accommodate the ability to make the lens tip and tilt, two key design choices were made. The first is that the length of plate section that fits between the legs of the Tower is 1/8” smaller than the distance between the legs. This gap allows the plate to sit at an angle of just under ±14.5°. The second design choice was to mount the plate on top of a set of dual screws, these will be further discussed in section 2.2.2. However, the plate needed to have a slot and a tapped hole drilled for each screw set. Then the limiting factor on the angle that these screws will allow is dependent on the length of the screws.
Figure 2.5: Lens Mount Plate seen isometrically from (a) above and (b) below.

In addition to the tip-tilt of the plate, the lens platform at the center of the plate is also a crucial design choice. The hole in the center is 3.5” in diameter while the lens holders that would be placed atop the platform would have an inner diameter of 75 mm (~2.95”) and an outer diameter of 100 mm (~3.93”). This allows the lens holder to translate up to 0.4” in any direction without obscuring the optical path and still providing the necessary contact area to clamp down on the lens. The recess of the lens is a necessary feature as the lens holders are just over 1” thick (26 mm) and the hold down clamps are required to reach above the lens holder to clamp down on them. The recess is 3/8” deep and alleviates this problem, without increasing the amount of wasted material that would occur if the plate was milled out of a thicker piece of stock aluminum, thus reducing costs.
2.2.2 – Vertical Mount Bracket

The Vertical Mount Brackets are used to set the height and tip-tilt of the Lens Mount Plates. They are cut and machined from 2”x2” aluminum angle. The vertical mounting hardware consists of two ¼”-20 round head screws and a back-plate that slides into the T-Slot of the Tower leg, the hole in the Bracket is unthreaded. By tightening these screws, the vertical position of Lens Mount Plate is locked into position. The tip-tilt hardware consists of a jacking screw and a locking screw. The locking screw is inserted into a slot in the Bracket and a tapped hole in the Lens Mount Plate. The slot allows the plate to remain tilted when the screw is tightened down locking that corner of the plate in position. Before, the corner is locked-down, it must first be jacked up to the angle necessary to for proper alignment (ideally this angle is 0°). The jacking screw is threaded into a hole in the Bracket, and rests in a corresponding slot in the Lens Mount Plate.

Figure 2.6: Vertical Mount Bracket and associated hardware for the Lens Mount Plate.

2.3 – Turret Group

The Turret Group includes all the parts necessary for the rotation and articulation of the primary mirror. The Turret is required to rotate the mirror through a minimum of 270°, allowing the mirror to observe in 4 orthogonal directions (0°, 90°, 180°, 270°), as well as to observe the zenith. In order to perform this action the Turret Group consists of two primary subgroups: the Stationary Turret and the Rotating Turret. Between the Stationary and Rotating Turrets, is the Newport Optics Rotation Stage that was repurposed from the original REDDI input optics. Finally, the primary mirror is mounted
at a 22.5° angle from the vertical, the purpose of which is to set the standard observation angle at 45° from the horizon.

Figure 2.7: Turret Group composing the Stationary Turret, Rotating Turret, Newport Optics Rotation Stage, and Primary Mirror.
2.3.1 – Stationary Turret

The Stationary Turret is composed of the Turret Base Plate, and the Race Assembly.

Figure 2.8: Stationary Turret including the Turret Base Plate, Race Posts, and the Race.

2.3.1.1 – Turret Base Plate

The Turret Base Plate serves as the coupler between the Turret Group and the Tower Structure. It is made from ½” thick aluminum and sits atop the Tower Structure, which it is secured to with ¼”-20 screws through the four corners of the Plate and into the four tapped holes in the ends of the T-Slotted Framing. Mounting holes for two sets of objects are drilled on the perimeter of the Plate. First, is the set of mounting holes for the Race Posts located midway along each edge. Second, is the set of mounting holes for the Newport Optics Rotation Stage. This second set of mounting holes are offset by 15° from the orthogonal due to the control box of the Newport Optics Rotation Stage, which protrudes on one side of the stage and would interfere with the Race Posts. The final feature of the Turret Base Plate is the chamfered edge on the bottom of the central opening of the Plate. This chamfer provides enough room that the first Lens Group can be positioned properly.
2.3.1.2 – Race

The Race is the part that allows the rotational motion of the Newport Optics Rotation Stage to be translated into a rotation about a relative X-axis that is fixed to the Rotating Turret. The idea for the Race came from 4-D rollercoasters that rotate the seats of the car by changing the distance between a parallel set of rails. The Race is not normally in contact with the Extension Rod located on the Hinged Section of the Rotating Turret. As the Rotating Turret moves beyond 285°, the Race catches the Extension Rod and begins to lift the Hinged Mirror Assembly off of the fixed Mirror Support Stands. Once, the Rotating Turret has hit 315°, the Primary Mirror has been lifted nearly vertical (less than 0.5° from vertical). Any movement of the rotation stage beyond 330° will result in the Primary Mirror getting stuck and being unable to return to 0° and will need to be manually reset. The Newport Optics Rotation Stage is not able to rotate beyond...
360°. To secure the Race there are 12 ¼”-20 tapped holes evenly placed around the circumference of the Race. Only 4 holes are necessary to be used at a time, the extras are there to allow for the repositioning of the Race if it is necessary for the reorientation of the Race due to local conditions.

Figure 2.10 – Race used to raise the primary mirror out of the way in order to allow zenith observations.

2.3.1.3 – Race Support Post

The Race Support Posts are designed to hold the Race at the position necessary to not interfere with normal operation, yet to still be able to lift the Primary Mirror out of the way for zenith observations. It is critical to the operation of the Turret, that these Posts are exactly 6.645” from their base to the center of the screw hole at the top of the Post. This distance is fixed based on the geometry of the Zenith rotation and the required position and angle of the Primary Mirror.
Figure 2.11 – Race Post used to secure the Race in the exact position necessary for Zenith observations.
2.3.2 – Rotating Turret

The Rotating Turret is composed of all the parts mounted to the top of the Newport Optics Rotation Stage. The Rotating Turret is further divided into two sections, the fixed-angle lower section and the hinged upper section.

Figure 2.12 – Rotating Turret used to position the Primary Mirror.

2.3.2.1 – Mirror Rotator Base Plate

The Mirror Rotator Base Plate connects all the parts of the Rotating Turret to the rotating section of the Newport Optics Rotation Stage. The four holes surrounding the central opening of the Plate are drilled to match a corresponding set of holes in the
Newport Optics Rotation Stage rotating section. Along two of the edges of the plate are a set of holes that mount the Mirror Support Stands. On another edge of the Plate, are three holes that position and mount the Hinge Plate. The corners of the Plate are rounded off sufficiently that they will not catch on the Rare Posts with plenty of room to spare.

Figure 2.13 – Mirror Rotator Base Plate used to attach the Rotating Turret to the Newport Optics Rotation Stage rotating section.

2.3.2.2 – Mirror Support Stand

The Mirror Support Stands are the two vertical pieces that set the angle that the Primary Mirror is normally sitting at. The rest is set at a 22.5° angle from the vertical. This results in an observation geometry of 45° from the horizon, which is a standard for Thermospheric observations and a change from the previous design of REDDI which made observations at 35° from the horizon and was one of the lacking points of the original deployments of REDDI.
2.3.2.3 – Hinge Plate

The Hinge Plate positions the Mirror Mount Plate at the proper height so that the Primary Mirror will be located in the required position. Between the hinge plate and the Mirror Mount Plate is a spring loaded hinge that allows the Mirror to rotate along the local X-axis allowing for Zenith observations.
2.3.2.4 – Mirror Mount Plate

The Mirror Mount Plate is the part that holds the Primary Mirror in its required position along the Optical Axis of REDDI while observing at the standard angle of 45° above the horizon and, due to the hinge at the bottom of the Plate, allows the Mirror to be raised out of the way for Zenith observations. Mirror Mounting is accomplished with a series of #4 screws positioned so that they wrap around the edges of the Primary Mirror and hold onto the Primary Mirror using washers between the heads of the screws and the Mirror surface. The Primary Mirror is a 4”x8” first-surface mirror.

The crucial piece that allows the hinged Mirror to be moved out of the way for Zenith observations is a 2” long ½” diameter stainless steel rod with a plastic sheath that brings the total diameter to 5/8”, which is screwed into the side of the Plate. The Rod must be secured using a lock washer, otherwise repeated rubbing between the Rod and the Race will unscrew the Rod. The Rod must also be screwed into the appropriate side of the Mirror Mount Plate. If the Rod is screwed into the left side of the plate, looking at the Mirror side of the Plate, then the Race should be set up to do Zenith observations in the 270° to 360° quadrant. If the Rod is screwed into the right side of the Plate, Zenith observations would have to occur in the 0° to 90° quadrant, this positioning was not tested and would need to be checked to find the appropriate orientation of the Race to make sure that the Rod does not go over the entire raised section of the Race, thus requiring a manual reset of the mirror position. It should be noted that the Newport Optics Rotation Stage defaults to 0° every time it is shut off or given a reset command. So, the Race should never be set up such that the Extension Rod would immediately move backwards onto the raised section of the Race during a reset.

Figure 2.16 – Mirror Mount Plate used to secure the Primary Mirror.
2.4 – Optical Alignment

The assembly of the optical relay tower and optical alignment of the lenses and mirrors of the new input optics was performed in March of 2017. Assembly of the tower extended to installing the lens mounts and the turret on the top of the tower. It did not include placement of the relay lenses in the tower, that was performed during optical alignment. It was necessary during the optical alignment of the relay lenses to remove lens L3, which can be seen in Figure 1.1, so that a cube beam splitter could be inserted at this point in the optical train. A standard helium-neon laser was used, with a pair of relay mirrors for leveling and orienting the beam. This laser is then aimed at the cube beam splitter and followed up the input optics.

It is important that the laser is perfectly centered on the optical axis to ensure perfect alignment of the input optics with the optical axis. Sets of cardstock circles were made that were sized to the different lenses and fixtures in the optical relay tower. These cardstock circles, with the hole left in the middle of them from the compass point used to define the circle, made for perfect pinpoint irises. The first two elements of the optical relay tower to be aligned were the relay mirror, M2, at the base of the tower, and the tower itself. The tower needed to be perfectly vertical and centered on the optical axis and M2 needed to be oriented such that it reflected the laser beam perfectly vertically up the relay tower. So, the tower is first made vertical using a spirit level, and then placed close to the final position with the optical axis going through the middle. Then, two of the lens mounts, the top one and the bottom one, before the lenses were installed, were leveled and a cardstock circle was centered on both lens mounts in the lens recess, seen in Figure 2.5(a). An additional cardstock circle was placed at the top of the tower on the hole in the mirror rotator base plate, seen in Figure 2.12 and 2.13. Finally, the beam was walked to center vertical by adjusting the mirror and moving the tower until the beam struck the center of all three cardstock circles, thus defining the optical axis of the tower. To ensure that the optical axis stayed in the center of the tower, the feet of the tower were locked down at this point.

The last part of optical alignment was centering the lenses of the tower on the optical axis. First, the lens mounts were roughly positioned at the assumed position in the tower during assembly of the tower, and the mounts were leveled using the vertical mount brackets and jacking screws. Next, the lenses final positions were determined. One at a time, starting from the bottom, the lenses were placed in the tower. The lens mounts placed at the appropriate vertical position, with exactly two focal lengths between each pair of lenses and were leveled using the jacking screws. Then, using a cardstock circle at the top, the position of the lens in the horizontal directions was determined by re-centering the laser on the card stock. Finally, a mirror was placed at the location of the cardstock circle to fold the beam back on itself to verify perfect alignment. This process
was repeated for each of the four relay lenses until all four were aligned on the optic axis at their exact positions. After each was individually aligned, they were locked down so that they wouldn’t be moved while adjusting the subsequent lenses. The last check of alignment was to observe the sky and verify that the optical tower was properly transmitting light through the input optics.
Chapter 3 – REDDI Data and Figure Set Tutorial

This Data Tutorial will break down the image processing and data handling of the REDDI data to utilize the full capabilities of the DASH interferometer at observing thermospheric winds.

The figures are broken up into two different types of figure sets, diagnostic and analytical. There are 7 figure sets in total, three diagnostic and four analytical. Two of the diagnostic figure sets are processed for each image. In order to save system memory, the previous figure sets are closed during the main loop of the Matlab program. If a single image needs to be checked the Matlab program can be set to end on the image of interest, as the last figure set is maintained. The third diagnostic figure set is the temperature and stability figure set. The analytical figure sets are divided into line center tracking and phase data tracking. These figures will be broken down in the following pages.

3.1 – Diagnostic Figure Sets

The diagnostic figures are used to quickly confirm the quality of the data and simultaneously the underlying data used to create these figures is stored for analysis.

![Figure 3.1: Figure set 1, image and spectral line diagnostics.](image-url)
Figure set 1 (FS1), is used for image and spectral line diagnostics. As seen above in Figure 3.1, FS1 displays a non-standard aspect ratio image of the data, the Hanning filtered data cuts, the negative order of the FFT spectrum taken from the data cuts, and two examples of how the data is being fit to find the line centers for the oxygen, 630.03 nm, and neon, 630.47 nm, lines, as well as, the notched section of the image.

The image in the first subfigure of the figure set 1 is a display of the working image. The image size will always fill this space despite the binning of the image and the colorbar is automatically scaled based off of the mean value of the data. These images are pseudo-bias subtracted, meaning a minimum value from a dark section of the image is subtracted from every pixel. A true bias subtraction is not taken, because the bias contains periodic noise, possibly 60 Hz noise, which is continuously changing. The images are not flatfielded either, a true flatfield of the spectrometer cannot be taken due to the design of REDDI. Flatfielding with an SHS can be done a few different ways, all of which require separate access to the individual arms of the spectrometer [Englert, Harlander, 2006]. As can be seen in Figure 1.1, REDDI is a sealed spectrometer. Additionally, REDDI is within a sealed pressure chamber and the individual arms are optically bonded to together with the field-widening prism and the Koester’s prism beam splitter.

Figure 3.2: Images taken by REDDI (a) 4x4 pixel binning, (b) 8x2 pixel binning, and (c) 8x1 pixel binning.

The full format of the Princeton Instruments PIXIS 2048 CCD that captures images for REDDI is 2048x2048 pixels. However, images taken by REDDI are binned in either 4x4
binning (512x512 pixels), 8x2 binning (256x1024 pixels), or 8x1 binning (256x2048 pixels). Henceforth in this text, a pixel will be the combined 4x4 pixel, 8x2 pixel, or 8x1 pixel as required by the image that is being processed. 4x4 binning was the standard binning used by REDDI in previous applications. As an experiment in testing the resolution of REDDI without greatly affecting the read noise and file size of REDDI, the binning was changed to 8x2 and then to 8x1 (more information on the results of this binning will follow in the later sections). Note: the spacing of the Fizzeau fringes visible in the images above does not change in physical space, they are merely being stretched based off of how the data is recorded by the CCD.

The second step in the data handling process is selecting and generating spectra. This is first done by breaking the image up into 18 different segments. These segments are in approximately the same location whether the image is 256 or 512 pixels tall. This is done by choosing the height of segment to be either 12 pixels or 25 pixels.

![Image segment division of REDDI data done during processing.](image)

Figure 3.3: Image segment division of REDDI data done during processing.

The first 17 segments of the image are the data segments that are used for analysis of spectra. A space before segment 1 is not recorded due to blooming affects that commonly disrupt the data. Additionally, a space between segment 17 and the notched segment is not recorded. If a full width segment was taken below segment 17 it would partially overlap with the notched segment and the spectra could be contaminated with the artificial spectra generated by the notches. The notched segment is used only for checking
on quality of the image. Each of these segments are reduced by taking a median of the
column and the resulting vector is called a datacut as seen in the following figure.

Figure 3.4: Datacuts taken from an image from REDDI.

Visible is Figure 3.4, is the notched segment in purple and the dark section from the
upper left corner of every image. There is also some vignetting seen on the left side of the
image.

Next, the datacuts have a Hanning filter applied to them to reduce the noise in the
Fourier transform, in the form of ringing from the hard edge, of the datacuts and it is this
that is plotted in FS1. Below, is a figure showing the datacuts after they have had a
Hanning filter applied similar to how they appear in FS1 (the notched segment is not
present).

Figure 3.5: Datacuts as depicted in FS1, showing the datacuts after they have had a
Hanning filter applied for noise reduction.

The next step in the data reduction process is to take a discrete Fourier transform,
DFT, of the datacuts. The Matlab function that handles the Fourier transform, fft,
produces both a positive and a negative order to the DFT, with the positive order appearing in the first half of the data and the negative order appearing in the second half with zero being the first and the last value. This should produce a spectrum that is symmetric around the middle position of the DFT. Below is a figure showing both the full DFT and the half that is displayed in FS1. Note: DFT and FFT reference the same method of taking the Fourier transform on discrete data and are interchangeable in this document.

Figure 3.6: DFT of the datacuts, (a) full DFT performed by Matlab displaying the symmetry of the Fourier transform, (b) half of the DFT displayed in FS1.

It should be understandable that for images of different binning the possible number of values in the DFT is proportional to the number of columns in the data. So in a 4x4 binned image, there appears to be more spacing between the spectral lines we are interested in, visible in the above image near columns 1950 and 2000. The pre-filter to REDDI has a FWHM of 1.9 nm, this results in a cutoff of real data in the DFT between approximately 500 and 1550 for an 8x1 binned image, or 500 and 550 for an 8x2 image. The standard 4x4 binned image does not have an artificial cutoff.
From the negative order of the DFT, a section between columns 1920 and 2020 (900 and 1000 for 8x2 binning, 390 and 490 for 4x4 binning) is extracted to fit a double Gaussian. It is this double Gaussian that is used to find the line center of the oxygen and the neon lines in the spectrum, as well as the line width, and the line intensity. Only one fit is plotted, however all 17 data segments are processed in the background. In addition to a double Gaussian being fit for each of the 17 data segments of each image, a single Gaussian is fit to the notched segment using the same extracted section. The notched segment produces a number of pseudo-spectral lines with geometrically decreasing power. The pseudo-spectral line that appears between the oxygen and neon lines is the one that is picked for the Gaussian fit. Within the figure seen below, two other pseudo-spectral lines can be seen as bumps in the data at column 10 and 85. The oxygen and neon lines can also faintly be seen at columns 27 and 62.

![Graphs showing Gaussian fits for oxygen and neon lines, and a notched line fit.](image)

Figure 3.7: Gaussian fit data for the (a) oxygen and neon spectral lines observed by REDDI and (b) the notched segment pseudo-spectral line that appears in the same section.

The coefficients of the Gaussian fits above are stored for later processing in the analytical figures.

Figure set 2 (FS2), is used as a diagnostic for the phase data extracted from the image. Phase data is an alternative method of observing the Doppler shifts of these spectral lines and DASH spectrometers are optimized to use this method.
Figure 3.8: Figure set 2, phase information diagnostics.

FS2, seen in Figure 3.8, only shows data from segment 9, however all data segments are processed identically in the background. FS2 consists of a windowed DFT, a representative filtered DFT, two recovered phases, and the unwrapped phase data.

The first two subfigures of FS2, contain DFT data taken from the DFT of segment, this is the same DFT that is displayed in FS1. In the first subfigure, the positive order of the DFT between columns 1 and 120 is overplotted with a narrow Hanning filter set over both the neon and the oxygen spectral lines. The neon filter is color coded orange and the oxygen filter is color coded red, this color coding is maintained throughout FS2. The second subfigure displays the effect of combining the spectrum with the filters.
Figure 3.9: Spectrum filtering for the phase data, (a) overplot of the segment 9 spectrum, neon filter, and oxygen filter, (b) combined spectrum.

The second subfigure is just used as a representative of what is used to extract the phase data. The data handling of the phase data does not combine both spectral lines.

To recover the phase data, the spectrum is combined with the individual filter for the relevant spectral line creating a spectrum that only contains the relevant spectral line. Then, an inverse Fourier transform is applied to the data. The arctangent is then taken of the imaginary part over the real part of the inverse FFT. This procedure converts the data into a value between negative pi and pi. This results in an overwrapping of values when the arctangent transitions to from pi to negative pi.

Figure 3.10: Recovered phase data for the (a) filtered neon spectral line and (b) the filtered oxygen spectral line.
Due to the spectral lines not being perfect Dirac delta functions, there are some edge effects visible in the phase data, particularly in Figure 3.10 above, between 1950 and 2000 of the oxygen phase data.

In order for this information to be useful, the phase data has to be unwrapped. This is done by checking the data for values above approximately 2.5 and that the next value is less than the current value; these are called jumps. For each jump two pi are added to the data from that point forward. This is not a perfect method of unwrapping the phase, if there are edge effects visible in the jump range extra jumps may be included in the data.

![Unwrapped Phase](image.png)

Figure 3.11: Unwrapped phase data for all 17 data segments.

As can be seen in the unwrapped phase data in Figure 3.11, multiple parallel lines are drawn for both the oxygen and the neon data. These parallel lines are caused by extra jumps being detected. It can be seen in the upper right corner that the oxygen data has an extra jump visible on at least one of the 17 segments. A linear fit is used on the center segments of these lines to extract the most accurate version of the phase data, this is not plotted but is saved for analytical processing.

Figure set 3 (FS3), seen below in Figures 3.12 and 3.13, is the first full data set figure set and the only full data set diagnostic. FS3 consists of two subsets of figures, the first is the temperature logs from all four temperature sensors attached to REDDI; the second subset is the plotted coefficients for the line center and FWHM (full-width, half-maximum) of the selected notched segment Gaussian line from Figure 3.7.
Figure 3.12: Figure set 3, temperature and notched segment diagnostics.

The temperature sensors on REDDI were originally designed to maintain the temperature of the monolithic spectrometer at the core of REDDI using a PID control system and a set of heaters. Temperature sensor T0, T1, and T2 are attached to the monolith and directly control heaters on REDDI. T3 is placed in the blackout box separated from the monolith by about 6 inches. The resolution on these four sensors is 0.1°C. This temperature control has a distinct purpose in that the spectrometer is sensitive to temperature changes which lead to changes in the optical path difference. However, due to degradation in the connectors between the temperature sensors and the controllers, it was discovered that T0 was not accurately reporting the temperature of the monolith, nor was it consistently offset from any nominal value. T0 was regularly reporting thermodynamically impossible values. The target temperatures for the heaters were initially set at between 28°C and 30°C for each of the heaters. If the sensor connections were accurately reporting, the heaters would heat the monolith and reach equilibrium in about five hours, so there is significant thermal inertia in the monolith. However, as can be seen in Figure 3.13 below, unstable connections have been responsible for reporting temperatures as low as -150°C, it should be noted that the sensors are only connected to a heat source, not a thermoelectric cooling system such as the one in the CCD.
Figure 3.13: Figure set 3 reporting thermodynamically impossible data.

This false reporting would have created a major issue with the spectrometer if a solution to the situation was not found. Fortunately, REDDI is no longer taken outside to perform observations. REDDI is now located inside a temperature controlled environment, the INSpIRe (Investigating Near-Space Interaction Regions) trailer. INSpIRe is equipped with a fairly standard air conditioning and heating system. While, ordinarily this sort of temperature control would be far too sloppy in order to control the temperature of an instrument, the environmental controls are not directly controlling the temperature of REDDI. The thermal inertia of the monolith, the air inside REDDI’s blackout box, and the air inside the trailer all contribute to the thermal stability of the monolith as seen in Figure 3.14 below.

The standard procedure for thermally controlling REDDI using the environmental control system is to set the heater in INSpIRe to 22°C to 24°C (a temperature that was determined to be within the capability of the environmental controls without having to run continuously and was still in the standard positive control range). Then, to shutoff the heaters controlled by REDDI’s control software, the target temperatures for the sensors are set at 0°C (the lowest accepted value by the REDDI software), this guarantees that T1 and T2 do not turn on their heaters, as it has never been observed that T1 or T2 report inaccuracies nearly as large as T0, however small spikes of a few degrees have occurred while the monolith heaters were active. Additionally, T0 may have to be spoofed by
reseating connections so that the reported temperature is at least 10°C. Taking these steps will result in the best probability that the heaters on REDDI do not turn on and all temperature control will be done through thermal inertia and the environmental controls of the trailer.

Figure 3.14: Thermal control of REDDI using the INSpIRe trailer environmental controls.

A further check on the temperature stability on REDDI can be found by corroborating T1 and T2 with the track of the notched pattern line center. The variation is inversely proportional to the temperature shift as seen in Figures 3.13 and 3.15.

Figure 3.15: Notched segment line center and line width under thermal control by the INSpIRe trailer environmental controls.
Any shifts visible in the notched pattern line center are because of a change in the optical path difference of the system as a whole and cannot be narrowed down to just the interferometer.

The INSpIRe trailer is equipped with a full suite of self-reporting temperature and humidity sensors [Gallant et al., 2016]. Every night at local midnight (reported in UTC), a report is emailed to all members of the INSpIRe team. Below is an excerpt of that report for March 3rd, of interest is from 05:00 to 11:00 UTC which overlaps with the temperature plots in Figures 3.14 and 3.15 from midnight on.

Figure 3.16: Section of the INSpIRe daily report relevant to REDDI thermal control.

The current thermostat in INSpIRe is a fairly low quality analog device that cannot be controlled remotely. This will be upgraded prior to moving REDDI to its remote site so that the environmental controls can be managed without having to flip a physical switch.
3.2 – Analytical Figure Sets

The analytical figure sets contain all the data analysis of the images processed by the software. The first two figure sets use the double Gaussian coefficients that are fitted during figure set one processing and use the spectral line information. The last two figure sets use the phase information that is obtained during the figure set two processing. In both of these groups the first figure set displays the data in the imaging order regardless of directionality. Also, in both of these groups, the second set of figures displays the information by directionality; this results in a variable number of figures, from 2 to 6, that might make up figure sets 5 or 7, depending on the number of directions observed. The data that will be discussed in this tutorial is all from March 2nd, in which 3 directions were observed: Zenith, East, and West. As such, figure sets 5 and 7 will have 4 plots on them.

Figure set four (FS4), breaks down the double Gaussian line data produced by each individual segment of each image in the night’s data set. FS4 is roughly broken into three parts. The first part of FS4 is the column of 3 plots on the left, these plot the centers of the two individual Gaussians. The second part is the column of 3 plots on the right side, these plot the widths of the Gaussians as well as the background noise level of the Gaussians. The third part is the large plot on the bottom, this plots the amplitude of the Gaussians and is broken down by the neon line and the directionality of the oxygen line.

![Figure 3.17](image)

Figure 3.17: Figure set 4, line tracking data and line intensity data.
One of the primary purposes of figure set 4 is to have a quick look at the data set for instances of bad data. Bad data primarily is produced from one of two different effects. The first effect, which is seen in nearly every data set, is due to the current placement of the INSpIRe trailer. To the east of the trailer is a tennis court and the lights for those tennis courts are on almost every night, they are usually shut off sometime between 21:00 and 23:00. In Figure 3.18, the effects of the tennis court lights can be seen in the data up until 20:30 as spikes in the data. The second effect that degrades the data is due to clouds or fog. Figure 3.18 has a nearly pristine data set that does not have clouds or fog. Clouds appear in the data as random noise across all spectral elements and as a physical block of the oxygen signal. Fog largely does the same thing; however, it also scatters more stray light into the spectrometer adding even more noise, but due to parking lot lights dispersing through the fog, the neon calibration lamp signal can get dominated.

Figure 3.18: Spectral line center information from FS4, in pixels.

The subplots of the first group of FS4, Figure 3.17 and 3.18, plot out the oxygen Gaussian line center for all 17 segments (as the 17 overplotted lines), the neon Gaussian line center, and the subtraction of the two. If a temperature change is present, leading to thermal drifts in REDDI, this subtraction will remove that drift from the oxygen data.
The second group of plots from FS4, the Gaussian line widths for the oxygen and the neon spectral lines, as well as the background level noise constant that sits under the data. These line widths in some cases are even more sensitive to the effects of clouds or fog in the field of view. As can be seen in Figure 3.19, occasionally one segment will be consistently more variable than the rest, in this case it was segment 17. The background noise level is solved for as a constant added to the data to calibrate for the brightness of the overall image. It can be very clearly seen in Figure 3.19 that while the tennis court lights are on not only are the images looking east brighter, but those looking in other directions are also elevated.

Figure 3.19: Spectral line width and background levels.

In cases where the data set does not look to the east, the tennis court lights can still be seen in the data set as a general elevation in the background level.

The last group from FS4 is probably the most interesting, it consists of a single plot that displays the amplitudes of the double Gaussian. The Gaussian that represents the neon calibration spectral line are in orange, with asterisk markers, and are relatively constant through the night. The Gaussian representing the oxygen spectral line is separated by direction with the zenith in black with open circle markers, north in blue with square markers, south in red with plus as markers, west in cyan with diamond
markers, and east in magenta with crosses or x’s as markers. This color/marker scheme is maintained for all directionality plots on figure sets 4, 5 and 7 (Figures 3.17, 3.20, 3.21, 3.23, 3.25, and 3.27). It should be noted that no single data set (night of data), will contain all 5 directions observed due to the limitations of the REDDI control software.

Figure 3.20: Spectral line intensities with oxygen by direction of observation.

In Figure 3.20, we can see some interesting effects. The first we see is brightening in the east and neon data due to the tennis court lights. The second interesting effect is the brightening of all the oxygen lines due to the sunrise. The west predictably lags behind the east and the zenith as the sunrise times for the approximate ground track locations of the observed volumes is 06:37 in the east, 06:47 in the zenith, and 06:57 in the west. These times all are much later than the brightening times seen in Figure 3.20, but there are a multitude of effects happening here. One of which is that REDDI is observing at a 45° angle and so will be observing an earlier than predicted sunrise. Another would be that it is the astronomical twilight times, which can easily be an hour earlier, that would be the time that brightening in oxygen would be predicted to begin and that time lines up nicely with what is observed.

Figure set five (FS5), as seen in Figure 3.21 below, provides the first analysis of thermospheric winds and uses a standard Doppler approach to look for winds, by tracking the frequency shift, in pixel space, of the spectral line of thermospheric oxygen versus the neon calibration lamp. FS5 consists of a number of plots broken down by direction including a median line, and one additional plot that overlays the medians to track the winds. REDDI is not optimized for this sort of Doppler shift tracking. To see a shift of 100 m/s the line center of the oxygen line, a shift of 0.018 pixels is required. At this level of precision, the fitting algorithm Matlab uses may not be accurately reproducing the line center. However, this still works as a first order approximation of the wind and a confirmation of wind directions and magnitudes observed in the phase data.
Figure 3.21: Figure set five, line center tracking by direction and derived winds.

FS5 is broken down, as stated above, into a series of subplots by the direction of the observation. The number of these subplots is variable, depending on the number of directions observed. Within each directional subplot, the line center from each segment is tracked using a normalized value and over-plot on these is a median value that section. The median values are then converted to a wind speed in m/s and plotted in the last subplot of FS5. The color coding on the segment data follows Matlab’s standard automatically assigned color coding. The color coding on the median data follows the standard that was laid out in FS4, that being: black for zenith, blue for north, red for south, cyan for west, and magenta for east. Additionally, in the winds subplots, the markers are added back to the plots.

The normalization process for the segment data is a multistep process, the first thing that occurs is the pixel position of the oxygen line center is subtracted from the pixel position for the neon line center, for each segment. Next, if zenith observations were taken, a median value of all the zenith differences is taken to establish a zero point for the data set. If zenith observations are not performed, all the oxygen-neon differences are taken by first taking a median value by direction, then averaging all the directions together to establish a zero point for the data set. This zero-point, regardless of method used, is then subtracted from segment data producing a normalized value, with offsets
from zero being the result of thermospheric winds. Once the data is normalized, observed winds are then derived from the segment data as the medians that are taken.

Figure 3.22: Line center shift tracking by direction in pixels.

To produce the medians over-plotted on the directional plots, a moving median of the segment data is first taken of the 3 local values to smooth out the more rampant effects observed. Then a median is taken for each image (the plotted columns), to produce the wind data point. In addition, west and south data is inverted.

Figure 3.23: Thermospheric winds derived from the direction plots of the line centers, east and west winds are horizontal, zenith winds are vertical.
To convert the wind data that is over-plot on the segment data in pixel space, to the velocity data that appears in the last subplot of FS5 is a 3-step process, as seen in the following equations and described below:

\[ m_{pix} = \frac{\lambda_{Ne I} - \lambda_{O I}}{\Delta pix} \]  \( \text{[nm/pix]} \)  \( \text{(3.1)} \)

First, is to find the pixel pitch, \( m_{pix} \), in wavelength space, using the normalization zero point. Where, \( \lambda_{Ne I} \) is the wavelength of the neon line, 630.47893 nm, \( \lambda_{O I} \) is the wavelength of the oxygen line, 630.0304 nm, and \( \Delta pix \) is the average pixel distance between the oxygen and neon line centers. The pixel pitch of REDDI is nominally \( m_{pix} = 0.01 \text{ nm/pix} \). This is results in a spectral resolution of \( R \approx 63,000 \).

\[ \frac{dv}{dL} = \frac{c * m_{pix}}{\lambda_{O I}} \]  \( \text{[m/s/pix]} \)  \( \text{(3.2)} \)

Next, the pixel pitch is converted to an axial velocity conversion factor, \( \frac{dv}{dL} \), using the Doppler equation. Where, \( c \) is the speed of light, \( m_{pix} \) is found in equation (3.1), and \( \lambda_{O I} \) is the wavelength of the oxygen line.

\[ v_{con} = \frac{dv}{dL} * \sec(\theta) \]  \( \text{[m/s/pix]} \)  \( \text{(3.3)} \)

Next, for the non-zenith values, they are multiplied by the secant of 45 degrees (this step is not done for zenith observations), under the assumption that winds are moving horizontally with only minor verticality in the winds. Where, \( v_{con} \) is the horizontal wind velocity conversion factor, \( \frac{dv}{dL} \) is the axial wind velocity, and \( \theta \) is the observation angle of 45°. This conversion factor is then multiplied by the pixel separation of every pair of oxygen and neon lines in the data to calculate all the winds using this method. Due to inverting the west and south data, any time the east and west data, or north and south data, overlaps, it can be inferred that the wind being observed was moving nearly directly from east to west, or north to south (or vice versa). Additionally, it is assumed that the minimum instrumental error using this method is 100 m/s and all error bars are scaled to that value using the standard deviation of all 17 data segments wind speeds.

Figure set six (FS6), as seen in Figure 3.24, plots the linear fit data from the unwrapped phase portion of FS2 (see Figure 3.11). Once a linear fit is found for the data, the midpoint value of the fit is extracted and plotted in the first two subplots of FS6. Finally, the difference between the midpoint phase for oxygen and neon is plotted in the last subplot. This subtraction removes any kind of temperature curve as well as the spread broadening, due to variation from one segment to the next.
Figure 3.24: Figure set 6, phase fit data for neon, oxygen, and their difference.

Figure set seven (FS7), as seen in Figure 3.25, is the final analysis of the data set and contains the most accurate measurement of any thermospheric winds observed. The organization of FS7 is identical to the organization of FS5; the difference between the two figure sets is in the manner in which the data being plotted is obtained and handled. FS5 uses a Gaussian fit to a spectral line seen in the FFT of the fringe data. FS7 uses a Linear fit to the unwrapped phase data of the isolated spectral line.
Figure 3.25: Figure set 7, phase midpoint tracking by direction and derived winds.

The first step, just as in FS5, of the data analysis of FS7 is to normalize the phase data about zero so that we can see Doppler shifts in the phase due to thermospheric winds. First, the differenced phase data from FS6 have either the median value of the zenith phase differences, if there is zenith data, or the averaged median value of all the phase differences, if there is not any zenith data, subtracted from all the phase data. This normalizes all the data around a zero point.

In order to find the medians that are over-plot on the directional plots, the same process is used as in FS5. A moving median of the 3 local values of segment data is taken to smooth out the more rampant effects observed, then a median of all the individual segments produces the wind data point for the given image.
Finally, the median wind values are converted to wind speeds in meters per second and these are over-plot on the last subfigure to show the winds observed. The beauty of the DASH interferometer is that by doing the previous data reductions and analysis, we can find the wind speeds directly if we know the design parameters: wavelength (or wavenumber) and the optical path difference. Also, the observation angle is important for converting axial wind speeds into horizontal wind speeds by multiplying by the secant of the observation angle. The equation for this conversion, from Englert et. al. [2010], is:

\[
\frac{dv}{d\Phi(L)} = \frac{\lambda_{O1} * c}{2\pi * L} \quad \text{[m/s]} \left(\text{rad}^{-1}\right)
\]

(3.4)

Where \( \frac{dv}{d\Phi(L)} \) is the velocity conversion factor dependent on the optical path difference of REDDI, \( \lambda_{O1} \) is the wavelength of the oxygen line, 630.0304 nm, \( c \) is the speed of light, and \( L \) is the chosen optical path difference of REDDI. In REDDI, the nominal optical path difference at the center of the spectrometer is 3.08 cm. To convert this axial velocity conversion factor into a horizontal conversion factor the secant of the observation angle is multiplied by the result of equation (3.4) producing the following equation:
\[ v_{\text{con}} = \frac{dv}{d\Phi(L)} \times \sec(\theta) \quad \left[ \frac{m/s}{\text{rad}} \right] \] (3.5)

This is the horizontal conversion factor in which all the phase difference data is multiplied to produce the horizontal wind velocities such as those recorded in Figure 3.27, below. Where, \( v_{\text{con}} \) is the velocity conversion factor for horizontal winds, \( \frac{dv}{d\Phi(L)} \) is the axial wind conversion found in equation (3.4), and \( \theta \) is the observation angle. Error bars are determined based on an assumed minimum instrumental error of 30 m/s using this method and all error bars are scaled based on standard deviation of all 17 data segments wind speeds. Calculating the spectral resolution of REDDI using this method is not a straightforward calculation, however a conservative estimate is double the standard spectral resolution, or \( R \approx 120,000 \).

Figure 3.27: Thermospheric winds derived from the direction plots of the phase shifts, east and west winds are horizontal, zenith winds are vertical.

REDDI was designed for the observation of the 630.0304 nm emission line of oxygen, so that value is used in the conversion to velocity. The midpoint optical path difference of REDDI is 3.08 cm, so this value is used for the optical path difference value. Lastly, the west and south values are inverted to more readily observe region-wide winds, for example, in Figure 3.27, several sections of the data, the east and west data nearly overlap between -100 m/s and -150 m/s. These parts of the data appear to show winds that proceed from the east and propagate to the west.
Chapter 4 – Data Collection and Analysis

Observations with REDDI at ERAU to date have fallen into 3 different phases. The first phase of observation were the initial testing through removal for repair of the CCD; these observations will generally not be discussed except for a few anecdotes. The second phase of observation consisted of post-repair return to operation checkout and testing. Finally, the third phase of observation consisted of bulk data acquisition. These three phases are detailed in Table 4.1 with phase 1 color-coded orange, phase 2 is blue, and phase three is yellow, green, and red.

Table 4.1: Datasets by date, name, number of images, directions observed, and binning.

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<thead>
<tr>
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<th>Name</th>
<th># images</th>
<th>Directions observed</th>
<th>Binning</th>
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<td>29</td>
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<td>19</td>
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Currently, REDDI is on standby pending implementation of the $2^{nd}$ generation software that will allow for remote observation and relocation of REDDI to a dark site.

4.1 – First Phase Observations

First phase observations included: setting up REDDI directly under the main siderostat in the INSpIRe trailer, some initial testing of REDDI with a neon capillary tube calibration lamp, initial testing using early versions of $2^{nd}$ generation REDDI software, and some initial thermal testing of REDDI. Throughout this first phase of observations, the CCD increasingly had communications errors with the REDDI software and the control computer. These errors ultimately resulted in the complete failure of communication between the CCD and the computer. At this point, it became necessary to remove the CCD from the spectrometer to be sent back to Princeton Instruments for repairs. This was the first time since the original assembly of REDDI, that a major component of the spectrometer had been disassembled. Also, during first phase observations the optical relay tower was assembled and aligned. Upon the return of the CCD and the reassembly of the spectrometer, phase 2 testing began immediately.

4.2 – Second Phase Observations

The second phase of observations consisted of alignment observation checks, thermal stability testing, and initial on-sky observations. Because the Princeton Instruments CCD had never previously been removed from the system, realignment of the CCD with the original focal plane of the instrument was the first question to be answered.

Figure 4.1: CCD illumination pattern of a neon calibration lamp before and after repair of the CCD, a) 03 Oct 2017, and b) 18 January 2018.
As can be seen in Figure 4.1, the alignment changes of the CCD are minor compared to the previous positioning of the CCD. There is nearly no rotational difference between the two as can be seen from the vertical lines of the fringes in both the before and after. The translation of the CCD, both in left/right and up/down, appears unchanged, experiencing the same vignetting as before and the notched section of the diffraction grating is positioned nearly identically as before. As a test of this, I normalized the second image to the first using the ratio of their median values, then subtracted the two from each other, resulting in Figure 4.2.

Two things pop out in this image: the first being that all the values are centered on zero and the second is the beats that pop out in the image. This second point shows that the alignment of the two images is nearly identical, especially that there is no rotational beating occurring. The horizontal beating that is occurring is due to the temperature differences of the spectrometer resulting in the same observed calibration lamp having a different number of fringes across the image. This results in a pattern of constructive and destructive interference between the two sets of fringes.

4.2.1 – Thermal Testing

As soon as it was determined that the CCD was adequately aligned, thermal testing was performed. Thermal testing was required because the electronics that performed thermal control of REDDI were not adequately reporting the temperature; at times they were reporting thermodynamically impossible temperatures. If the thermal controllers were working properly, they would produce the most accurate data. However, this system has proven to not be robust or even repeatably incorrect. So, the plan was to
figure out if there was a way to control the temperature of REDDI close enough. REDDI’s thermal control was originally designed to be performed while exposed to the elements. However, REDDI now resides in the INSpIRe trailer, which is outfitted with a commercial air conditioner and heater.

![Temperature data for the evening of (a) 18 January 2018, using original thermal control regime, and (b) 31 January 2018, using new thermal control regime.](image)

In order to use the commercial air conditioner and heater to perform the thermal control of REDDI, a regime that I refer to as environmental control, a few things need to occur. First, the temperature of the thermostat needs to be set to a temperature that it will have positive control throughout the majority of the observation period, i.e. if it is cold outside, the heater needs to be on at a temperature that is maintainable throughout the night. Next, the heaters on REDDI need to be shut off, this is done by setting their temperatures to 0℃; the heaters on REDDI will only turn on if the corresponding sensor reads a temperature below this setting. Finally, occasionally, T0 will need to be reset in order to ensure that it reads at least 10℃. T0 has the worst connection of the four temperature sensors in REDDI. In order to reset the temperature while REDDI is here locally, it is sufficient to check the electrical connections of T0. However, prior to moving to a remote site, this connection will have to be fixed in order to report correctly, or the REDDI 2nd generation software will have to allow for negative temperatures.
4.3 – Third Phase Observations

On 31 January 2018, phase 2 observations were concluded and phase 3 observations began. In Tables 4.1 and 4.2, the datasets that are color coded yellow consist of zenith-only observations, green and red datasets observe multiple directions. Green datasets have a high proportion of the data being usable and red datasets have a low proportion of the data being usable for analysis.

Table 4.2: Datasets by date, name, and factors of quality.

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Appendix E contains the analytical figure sets for all the green color-coded datasets in Table 4.2. The following analysis will contain excerpts and examples from those datasets as well as the occasional counter example from the poorer quality datasets.

Initially, all observations were performed using the same 4x4 binning that previous observations with REDDI had used. This limits the resolution in the x-axis in which the fringes run. In order to increase the x-axis resolution without greatly increasing read noise, binning was converted to 8x2 binning, and then to 8x1 binning. The effect of
doing so was two-fold: first, the fringes are smoothed by increasing the number of pixels per fringe; second, this results in a region in the FFT in which the pre-filter does not allow any light through that could create fringes at that wavelength.

Smoothing the fringes, by increasing the number of pixels per fringe, is not the result of any physical change in the system, merely as a result of how the CCD is read. The photons from the spectrometer still fall on the same subpixels, it is merely how those subpixels are grouped together and read out that is modified. These smoothed out fringes create a more consistent pattern for the Fourier Transform to match. This means that, theoretically, higher fringe frequencies could be pulled out of the image.

In reality, this does not occur. The pre-filter in the spectrometer has a narrow band-pass with a FWHM of 1.9nm and a center at 630.64nm [Englert et al, 2010]. The following table shows some of the theoretical limits of the spectrometer using actual data to find the Littrow wavelength, the pre-filter parameters, and the windowing values determined by the x-axis resolution.

Table 4.3: Wavelength to Fringe relationship for several important values to REDDI, calculated values are in yellow.

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<td>Min 8x1</td>
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<td>-1024</td>
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Starting at the top of Table 4.3, we have the wavelength of the oxygen, 630.0304 nm, and neon lines, 630.47893 nm, we are observing as well as their corresponding number of fringes as determined by a pair of coefficients taken from 31 January 2018 data. The number of fringes shifts with every observation depending, primarily on the temperature of REDDI. Using these four numbers, a linear relationship between these values was assumed using the small angle approximation resulting in a slope of \( m = -85.4957 \) and a y-intercept of \( b = 53958.95 \), with fringes being the y-value and wavelength being the x-value. This results in finding the Littrow wavelength, which is by
definition, the wavelength at which 0 fringes would be observed, of 631.1304 nm, for this example. Ideally, the pre-filter would have zero transmittance occur as close as possible to the Littrow wavelength. Additionally, two other neon lines are near the wavelength range of the pre-filter, 629.37447 nm and 631.36855 nm. These are both far enough away from the maximum transmittance of the filter that they do not contribute to the fringe pattern. Using the values from Englert et al, 2010, for the fringes for the oxygen line, 80, and the neon line 42, this results in a design Littrow wavelength of 630.9747 nm. This value is different because REDDI was designed to be actively heated. The data used to generate Table 4.3 is from data that was passively heated using the environmental controls of the INSPIRe trailer, which is on average 6°C colder than actively heating REDDI. It is this temperature difference which is responsible for the change in the number of fringes observed at each wavelength and results in the shift of the Littrow wavelength.

The next 4 values are based on the filter information given in Englert et al. [2010], based on transmittance levels, then those wavelengths are converted into the number of fringes that would be observed across the CCD at that wavelength. Negative numbers of fringes are normal, and are the result of choosing wavelengths on either side of the Littrow wavelength. Both the oxygen and neon lines, as well as the majority of the filter band-pass occurs within what is assumed to be the positive fringe region.

The last 6 values from Table 4.3, represent theoretical resolution limits of the CCD under the three different binning cases used to perform observations. This is assuming a maximum resolution of fringe peaks and valleys alternating every column. This means that the current set up of REDDI could, hypothetically, with a filter change, observe anything between 619.1532 nm and 643.1076 nm. These, are not practically possible, however, they are only technically possible. Also, if values in one of these outer regions is chosen, but a lower binning is used for imaging, the image will not return accurate fringes, resulting in a doubly heterodyned image, confusing the results, and probably looking something like Figure 4.2.

4.3.1 – Observation Directions

Predominantly 4 different sets of directions were used for observations: Z, EWZ, NSZ, and NESW. Z consists of zenith-only observations, used primarily to check the stability of the spectrometer. EWZ observations alternate between east, west, and zenith; these are to look for winds that pass, to some degree, from the east to the west, known as zonal winds, and the zenith sets the baseline for the zero-wind level. NSZ is similar to the EWZ, however the north, south, zenith directions are observed, with north-south winds being known as meridional winds. NESW observations were to the 4 cardinal directions without zenith observations. The REDDI version 1 control software was only capable of observing in 4 directions. Because of that, I chose to limit the EWZ and NSZ cases to not include a 4th direction to increase the number of observations in the opposing directions. Table 4.1 has a complete breakdown of all observation sets by direction.
4.3.2 – Cloud Signatures

Clouds are not an unusual sight in the Florida sky, even when clear skies are forecast. It is common to see very thin, wispy, Cirrus clouds at high altitude seemingly form out of thin air. As such, during the observations that were taken, nearly every dataset shows some interference from clouds. Some, of this interference can be quite severe. The images with clouds in them tend to look like the image has been smoothed out, significantly brightened, and not uniformly illuminated as can be seen in the comparison below.

![Cloud Images](image_url)

Figure 4.4: Comparison images of (a) clouds being in the field of view and (b) having clear skies from 2 February 2018 dataset.

In Figure 4.4, the image with clouds is more than twice as bright as the image without clouds. These two images were taken 15 minutes apart looking at the zenith at around 4AM. The differences between the two images are subtle, however it can be clearly seen that despite the first image being brighter, the fringes do not appear more defined. The fringes are much smoother and the overall image is less evenly illuminated. If the brightening had been due solely to oxygen, the oxygen fringes would have become extremely well-defined.

The differences between images with clouds versus those without clouds can be difficult to determine visually, especially if cloud noise is due to thin high-level clouds. It is much better, and less time-consuming, to analyze the full dataset and see the signatures of clouds in the dataset at the end, instead of looking at each individual image. The most direct figure set for determining the presence of clouds in the field of view is figure set 6. Figure set 6 plots the phase data for the oxygen and neon lines and displays them separately and as a subtraction of the two. In Figure 4.5 we can see figure set 6 for the dataset from 23 February 2018. Additionally, the effect of these clouds is translated to the wind data and can be seen in Figure 4.6 as elongated error bars.

Clouds tend to make all the data harder to read and may be so thin that they would not be reported on a standard weather report. The cloud signature, the random spikes in the data from 2100 to 0100, visible in Figure 4.5 can clearly be seen in sub-figures (b)
and (c). In sub-figure (a), we see the neon line phase data. The neon data is relatively smooth, except for the interference of the tennis court lights in the first hour and a half of the night, which will be further discussed in the following section, the neon data does not show any interference. This is largely due to the strength of the neon line and that it is an internally located calibration lamp. The oxygen line is generally a much weaker line than the neon line, more will be discussed about that later. In sub-figure (b), it can be clearly seen that clouds are in the field of view for the first half of the dataset, and very quickly after 0100 the clouds clear out. After 0100, the oxygen phase data continues to be random, however it is all a similar magnitude and doesn’t spike outside the normal oxygen region. Finally, in sub-figure (c), the data from (a) and (b) is subtracted and normalized, this cleans up the temperature curve and the spatial separation. Additionally, cloud signatures can be seen in figure sets 4, 5, and 7, in Appendix E under the 23 February 2018 dataset or any other dataset in which clouds are present. However, I have found that clouds are most readily seen in figure set 6.

Figure 4.5: Figure set 6 for 23 February 2018 showing clouds for the first half of the observing session and clear skies for the second half of the observing session.
Finally, in Figure 4.6, when we compare the observed winds to the subfigures (b) and (c) in Figure 4.5, we can see a correlation between the clouds and randomness in the wind speeds. The zenith wind velocity is probably the most obvious correlation as before the clouds clear out we see vertical winds up to 200 m/s, which is almost certainly not real. After the clouds clear out, the vertical wind velocities hover near 0 m/s, which is the assumption for using zenith observations to calibrate against. Further discussion on winds will follow in a later section.

When the INSpIRE trailer is moved to the dark site, clouds should be a less prevalent phenomenon, so it is important that clouds can be recognized just by looking at the data. There is also the possibility that an all-sky camera will be installed in the INSpIRE trailer prior to moving to the dark site. If that is the case, then, checking for clouds can be done by directly checking images from the all-sky camera, assuming it is sensitive enough to detect those clouds. A potential student project could be to take such an all-sky imager, map out the observing locations of REDDI and attempt to do cloud logging and notifications for any clouds that are seen while REDDI is operating.

4.3.3 – Tennis Court Light Signatures

The second major source of interference in the datasets is due entirely to the temporary location of the INSpIRE trailer and should not be an issue at a dark site. The INSpIRE trailer is currently surrounded by parking lots and athletic facilities.
Figure 4.7: Satellite image of the current location of the INSpIRe trailer, red boxes indicate large tennis court/lacrosse field lights, blue boxes indicate parking lot lights, yellow triangles indicate REDDI observation directions.

One of the tennis court lights, immediately to the right of the INSpIRe trailer in Figure 4.7, lies nearly due east of REDDI’s observation dome. In addition to the large halogen tennis court and lacrosse field lights, which shut off at about 10 PM, there are also the smaller sodium parking lot lights that are on throughout the night. This results in a lot of noise in the data, particularly in the beginning of evening. In Figure 4.5, we can quite clearly see a series of spikes in the neon data visible in every third image (those looking east). Also, in the oxygen data, these spikes are negative.

In Figure 4.8, we see a comparison of two images taken from the 4 March 2018 dataset. The first image looks to the west and the second image to the east, almost directly at the tennis court light identified above. The image observing the east is nearly three times as bright as the one looking west. The east looking image also has a significantly larger number of hot spots in the image, most likely due to water spots and dirt on the observation dome refracting light.
Figure 4.8: Comparison of REDDI images taken while tennis court lights are on looking (a) to the west and (b) to the east on 4 March 2018.

Interference from the tennis court lights can be seen throughout the dataset, as seen as spikes in Figure 4.5. Figure sets 4, 5, 6, and 7 all have indicators of when the tennis court lights are turned on, to see evidence of this look through Appendix E. However, the one figure that most completely diagnoses the tennis court lights being on is the FFT background plot from figure set 4, seen in Figure 4.9 below.

The FFT background plot is generated from the constant coefficient that is calculated when trying to fit the double gaussian to the oxygen and neon lines. This constant value measures the background noise across the spectrum in which the oxygen and neon lines appear. In Figure 4.9 below, we can very clearly see the effects of the tennis court lights being on for a night that only the zenith was observed and a night that the east, west, and zenith are observed. In both cases, we can clearly see that when the tennis court lights are turned off, the background levels drop. In the EWZ case, we can also see, while the tennis court lights are on, the background level spikes every time the east is observed.
4.3.4 – Moonlight Scattering

Occasionally, the Moon will be observed by REDDI. Only two nights during the third phase observations did I observe to the south when the Moon was nearly full, thus being up during my observation. Those two nights were 3 March and 5 March 2018.

For the most part the 3 March 2018 observations, which followed the NSZ observation pattern, were not greatly affected by the additional scattered light from the Moon. During the night of the 3–4 March, the Moon passed due south of Daytona Beach at approximately 2:30AM (it should be noted that REDDI does not log time based on Daylight Savings, this accounts for the one-hour discrepancy between the figures and the stated time that the Moon passed due south) and was at an altitude of 59.1°. Combining this with the knowledge that the field of view of REDDI is 9° and it observes at an elevation of 45°, the Moon passed within 10° of direct observation. This resulted in enough light scattered into REDDI to increase the background levels of the FFT but not to cause any serious issues with REDDI’s imaging. The FFT background can be seen below in Figure 4.10(a). Additionally, in Appendix E, interference from the Moon can be seen in figure sets 4, 5, 6, and 7 for the 3 March 2018 dataset.

The night of 5–6 March, the Moon passed due south of Daytona Beach at 4:10AM at an altitude of 50.1°. Observations during this night followed the NSZ observation pattern, meaning we did observe in the direction of Moon. This resulted in the Moon passing within only 1° of REDDI’s field of view. Light scattering from the Moon at this
point is so bright that nearly the entire CCD on REDDI was saturated during 2 different 5-minute exposures, seen below in Figure 4.11. Those two images were removed from the 5 March 2018 dataset for two reasons. First, that the PIXIS camera outputs a 16-bit unsigned value for its data, and is not properly handled by the REDDI software which stores it as a 32-bit two’s complement signed value. This results in a negative flip in values at saturation, which should be fixed with the next version of REDDI’s software. This could potentially be fixed in my MATLAB code; however, it is a rare problem and is an indicator of problematic data. Second, the data has no useful information in it and results in shifts of zero points in the data. This means it is more useful to just remove the images from the dataset.

![FFT Background](image)

Figure 4.10: Moonlight scattering increasing the background levels of the FFT.

The gap in the dataset, due to removal of the two moon saturated images, can be plainly observed in Figure 4.10(b), above, as the gap between the two peaks between 2:30 and 3:00. The full effect of the moon saturated images can be seen in the 5 March 2018 dataset in Appendix E. The actual images that are saturated by the Moon in Figure 2.11, below. In Figure 4.11(a), the Moon appears to be on the direct azimuth of observation, resulting in a nearly vertical gradient of the image. Figure 4.11(b) appears to show that the Moon has moved, which makes sense as these two images were exposed 15 minutes 45 seconds apart, and the gradient is now at an angle. These images are so over-saturated that the Neon calibration lamp cannot be distinguished.
4.3.5 – Line Intensities

The relative brightness of the oxygen and the neon line in the FFT is a measure of how much energy is being pumped into the upper atmosphere. That energy can come from the lower atmosphere, the ionosphere, the magnetosphere, or from solar activity. The amplitude coefficients for the double Gaussian used to fit the data, see Figure 4.12, are extracted, and a median is taken of all 17 segments for each image. This creates two separate line intensity data points per image, one for the neon calibration lamp and one for the appropriate direction of the observed oxygen.

In Figure 4.13, three different line intensity plots have been selected to highlight different commonly observed features in the line intensity plots. In Figure 4.13 (a) and the first half of (b), the oxygen lines show a large variation in signal strength and don’t follow the standard background oxygen emission curve that can be seen in the second half of Figure 4.13 (b) and throughout (c). The moon observations that are so clear in Figure 4.10, are not present at all in the line intensity data seen in Figure 4.13 (c), showing that only a small amount of the moonlight, as expected, contributes to the signal strength of the oxygen and neon lines. However, the gap in the data is visible from a couple of missing data points both in the neon and in the south data.
Figure 4.13: Selected line intensity plots showing different common features.

Both the night of 15 February and the night of 24 February, (corresponding to Figure 4.13 (a) and (b)) were nearly cloud free, so the variation in the brightness is not due to cloud interference. Some of the brightness at the beginning of the night is due to the tennis court lights but, those lights shut off within the first two hours of observations on each of these nights. The tennis court lights also primarily interfere only with the neon line as there is a spectral line from the tennis court lights that is close to the same wavelength as neon.

The background level oxygen emission is nearly perfectly displayed in Figure 4.13 (c), as a low-level background emission that brightens extremely quickly just before sunrise. In Figure 4.13 (b), the rapid dimming just after sunset can also be seen. This dimming would be visible in Figure 4.13 (c) if observations had been started earlier in the evening.
The solar flux data for the third phase observation period is contained in appendix C and shows that throughout the observation period the sun was largely quiescent, with only a handful of flares and a F 10.7 value that stays between 67 and 79, throughout. There is a surge of activity between 4 February and 17 February. During this time, most of the solar flares occur and the F 10.7 value raises from around 70 to the upper 70’s. The data seen in Figure 4.13 (a) occurs during the tail end of this period and may be affected by that activity.

The planetary and mid-latitude geomagnetic Kp-indices for the third phase observations are contained in appendix D. These indices are a decent measure of the geomagnetic activity of the Earth and thus can be used to help account for some of what is observed in the line intensity plots. The solar wind typically arrives at the Earth 2 to 4 days after activity is observed on the sun, this is corroborated in a comparison of the solar flux data and the Kp-indices. Throughout the observation period, the Kp-indices are generally between 0 and 2, meaning minimal disturbances in the Earth’s magnetic field. Geomagnetic activity is elevated between 15 February and 19 February, with the Kp-indices going as high as a 5 during this period and consistently being around a 3, indicating moderate activity. It seems probable that this activity is causing the excitation of thermospheric oxygen in Figure 4.13 (a). However, geomagnetic activity is not the cause of the thermospheric excitation seen in the first half of Figure 4.13 (b), as the Kp-indices during this period were between 0 and 2. The Kp-indices for Figure 4.13 (c) were between 1 and 2.

![Line Intensities](image)

Figure 4.14: Line intensity plots for an evening when the neon calibration lamp was turned off.

Finally, as a test of the system and the software, one night of observations, the neon calibration lamp was intentional not turned on, as seen in Figure 4.14. The rapid dimming and rapid brightening of the oxygen during evening and morning twilight is clearly visible in the zenith curve. Additionally, the neon being detected here is not from the neon calibration lamp, it is just background light of the correct wavelength to be detected by REDDI. This background includes the tennis court lights that is clearly visible in the first 2 hours of the data.
4.3.6 – Wind Observations

Wind speeds are calculated using two methods. The first method is the traditional method of measuring the line center of the two Gaussians from the oxygen and neon lines, seen in Figure 4.12, then to calculate the Doppler shifts between the two. This method is unreliable because the fit of the Gaussian is not sensitive enough reproduce the line center with the precision required. Minimum errors are assumed to be 100 m/s using this method. The second method is much more precise because it comes directly from the phase data and the physical geometry of the DASH spectrometer at the core of REDDI. It is this method that will be further analyzed to determine wind speeds that are observed by REDDI. Minimum errors are assumed to be 30 m/s using this method with atmospheric errors increasing that. With proper thermal control of REDDI, this method can reduce wind speed errors to only a few meters per second.

In Figures 4.15, 4.16, and 4.17, we see three representative data sets that show some of the highest quality wind data taken during this observation campaign. These figures consist of the FS6, the phase fit data, and the extracted phase wind data from FS7. Together, these two figure sets do a good job of displaying which data is reliable and which data should not be trusted. Within each of these figures, regions that have lower quality data, whether it be from tennis court lights or from clouds, are shaded out with a blue box. More of the data from the campaign can be seen in Appendix E.
Figure 4.15: Phase fit data and phase winds for 6 February 2018. Shaded region contains interference with the tennis court lights.
Figure 4.16: Phase fit data and phase winds for 15 February 2018. Shaded region contains interference with the tennis court lights.

In both Figure 4.15 and 4.16, we see that the only real source of interference in the data is the tennis court lights. Additionally, both data sets contained zenith observation data, in which the vertical wind speed is measured and appears to be within approximately ±75 m/s throughout, and oftentimes dropping to near 0 m/s. A vertical wind speed of ±75 m/s is more than double what would be expected to be seen on an average night; 10-30 m/s vertical winds would be in line with what has previously been observed at a mid-latitude location during low geomagnetic activity. These vertical winds are affected by many upper atmospheric effects including gravity waves, tidal harmonics,
and geomagnetic storms. At times, vertical wind speeds up to 150 m/s have been observed, so a 75 m/s wind is not outside the realm of possibilities [Harding, 2017].

In data sets in which zenith observations are performed, such as Figures 4.15 and 4.16, the average of all the zenith observations is used to determine the 0 m/s wind speed. In data sets that do not contain zenith observations, such as Figure 4.17, all the data is taken together and averaged to determine the 0 m/s wind speed. This second method is obviously less reliable than the first, especially if there is a consistent prevailing wind.

Figure 4.17: Phase fit data and phase winds for 16 February 2018. Shaded region contains interference with the tennis court lights on the left and clouds on the right.
Horizontal winds, plotted in Figures 4.15, 4.16, and 4.17, are initially measured axially, at the 45° angle of observation, and are converted to horizontal winds by assuming a 0 m/s vertical wind speed on average, and then multiplying by the secant of 45°. Additionally, the west and south data is inverted, this serves the purpose that if there is a prevailing wind that travels from the east field of view to the west field of view, zonal wind, this single wind will overlap in the data. The same is true for a wind traveling north to south, meridional winds. Therefore, in many cases the winds observed appear overlapped and may be indicative of laminar flow.

Horizontal winds measured in Figure 4.15 have a magnitude up to 150 m/s and are generally traveling from the east to the west. These winds are not perfectly congruent throughout the night, so it is possible that the wind was shifting north and south throughout the night. Horizontal winds measured in Figure 4.16 are weaker than those measured in 4.15, as this data set was observing north and south, this is to be expected, if a prevailing east to west wind is assumed. The measured horizontal wind ranges up to a magnitude of approximately 100 m/s. The vertical wind throughout most of the night is observed to be less than 50 m/s; this is much more consistent with the expected vertical wind velocities than in Figure 4.15. Horizontal winds measured in Figure 4.17 are in both the east-west and north-south directions, as such no zenith observations were performed, and nothing can be learned about the vertical wind velocities. While a significant portion of this dataset has clouds within the field of view, the portions with clear skies show a very interesting trend in which the north-south wind speed is nearly 0 m/s and the east-west shows a wind coming from the east and smoothly increasing in velocity from 0 m/s to 150 m/s over the course of 2 hours. These winds are consistent with other studies done at similar latitudes [Makela et al., 2012; Emmert et al., 2006].

Finally, in the rest of the data that can be observed in Appendix E winds up to 200 m/s can be observed at times. In most of these data sets, though, clouds are visible in the data, decreasing the quality of the data. While clouds are present in the field of view, false winds appear in the data, as they do in Figure 4.17 with velocities that often exceed 400 m/s and show no east-west or north-south correlation, as expected. Determining when to exclude data due to interference from clouds, lights, the moon, or whatever other source of interference is crucial to understanding what was observed.
Chapter 5 – Conclusions

REDDI arrived at ERAU in 2016 with the intent to integrate it into the INSpIRe trailer as a permanent instrument to be upgraded for remote observations using an acrylic dome observation port. In this thesis, I described the work that was done to upgrade the input optics of REDDI so that it can utilize the new mode of observing. Previously, REDDI had to be taken outdoors to make observations. To use the observation dome, the primary mirror needed an optical relay tower to be designed and constructed including the need for limited 6 degree-of-freedom controls over each of the relay lenses for alignment and focusing.

Two other issues needed to be corrected during the upgrade process. First, the observation geometry need to be corrected to better conform to the standards of which other observations were performed, namely the observation elevation needed to be corrected from 35° to 45°. The second upgrade was more difficult to accomplish; the observation turret needed to be decreased in size so that it would fit in the observation dome. The problem was that previously, the observation turret used a second mirror to observe the zenith. Both upgrades were accomplished simultaneously by developing a mechanism that would hold the primary mirror at a 45° angle and directly in-line with the optic axis in 3 quadrants of observation, and in the 4th quadrant it automatically moves the mirror off the optic axis allowing direct observation of the zenith. Additionally, this upgrade was performed without adding any new electromechanical actuators to the system.

These upgrades worked exactly as intended resulting in a system that allowed REDDI to be utilized throughout the data gathering phases discussed in this thesis. REDDI’s control software upgrades continue as of the writing of this thesis and are expected to be complete prior to the moving of the INSpIRe trailer to its remote site, those upgrades are being performed by a separate group of students.

Secondly, I determined that the thermal controls of the REDDI control software were irregularly heating the monolithic spectrometer at the heart of REDDI. This irregular heating made the analysis less accurate and made tracking the spectral lines for oxygen and neon significantly harder to track over the course of a dataset, meaning one night of data. I was then able to determine that there was a way to control the temperature of REDDI using the environmental controls of the INSpIRe trailer. This method of thermal control was sufficient to adequately limit the thermal drift of REDDI so that data could be consistently analyzed.

Thirdly, I developed a Matlab program that would allow for relatively fast analysis of the data from REDDI. This program was used to analyze all the data taken during the observation phases of this thesis. During the process of analyzing that data,
three main sources of interference were identified in the data: local tennis court lights and parking lot lights, clouds, and rarely the Moon. Crucially, the program presents the data in a manner that is easily understandable and presents both the oxygen and neon line intensities and the wind data clearly.

Finally, 20 nights of data between 31 Jan and 6 Mar 2018 were taken to observe thermospheric oxygen. Within the line intensity data, evidence of energy being added into the thermosphere, can be seen in the line intensity plots. Vertical winds were commonly observed to gust as high as 75 m/s but were commonly much smaller, often approaching 0 m/s. The horizontal winds observed were typically 100–150 m/s, however they have been observed to be up to 200 m/s. Winds have also been observed to travel from the east field-of-view to the west field-of-view and from the north to the south.
Chapter 6 – Continuing Work and Recommendations

Throughout the body of this thesis, I have occasionally referenced the ongoing work on the INSpIRe trailer. This work includes but is not limited to necessary upgrades to REDDI that will allow REDDI to be used from a remote site. The plan for the INSpIRe trailer is that within a few months the INSpIRe trailer will be moved to a dark site and operated remotely. For this to occur, the REDDI software will need to be upgraded so that it can be operated remotely and any hardware that is manually operated will need to be upgraded and integrated into the REDDI control software. Other upgrades will need to be made to the REDDI software to make it more functional as well. Some of these upgrades are rather simple fixes to the software, such as refining the auto-scaling function displaying images. Other upgrades will be more complex, most notably being able to access REDDI via a secure internet connection.

At a bare minimum, the software upgrades will need to include controls for the calibration lamp, the camera cooler, and the power to the REDDI heater controllers. All other upgrades fall into one of two categories, either quality of life or non-essential functionality upgrades. Many of these lower level upgrades have already been included in the next version of the REDDI control software and will be utilized on the next observation run of REDDI.

Some necessary hardware upgrades to REDDI include installing controllable power supplies or outlets for the calibration lamp, camera cooler, and the REDDI heater controllers. Additionally, a non-necessary upgrade to REDDI should be to repair the heater connectors that connect to the heater controllers to allow for active thermal control of REDDI as the spectrometer was designed.

Continuing work on the INSpIRe trailer includes getting the dual Fabry-Perot spectrometers online. However, two upgrades to the INSpIRe trailer have been discussed to increase the functionality of the trailer at a remote site. The first upgrade is a higher quality thermostat that can be controlled remotely and will do a more complete job of maintaining the trailer at a fixed temperature. The second upgrade would be an all-sky camera capable of seeing clouds at night.

Once INSpIRe is up and running at its remote site, a more complete data set should be developed from multiple observation runs. This data can be combined with data from the MIGHTI instrument, which is a cousin instrument to REDDI, on the ICON satellite. Additionally, REDDI could potentially be integrated into the network of NATION (North American Thermosphere Ionosphere Observation Network) instruments that has been developed [Makela et al., 2015].

Finally, the data from REDDI should be compared to the most up-to-date upper atmospheric models available and should include interactions with the ionosphere.
Several atmospheric models have been developed including the Horizontal Wind Model (HWM07 or HWM14), which has gone through several updates, the Disturbance Wind Model (DWM07), and the Global Ionosphere Thermosphere Model (GITM) [Drob et al., 2015; Emmert et al., 2008; Ridley et al., 2006].
Bibliography


Spectroscopy (DASH) and Fabry-Perot Interferometer (FPI) Instruments,” Journal of Atmospheric and Solar-Terrestrial Physics 86 (2012).


Appendix A - Drawing Package

The documents on the following pages comprise the drawing package for the parts that were manufactured for the relay optics support tower. The designs were approved and manufactured by the Physical Sciences Department at the University of Wisconsin at Madison during the summer and fall of 2016. The scale of the following drawings is set at 1:2 for an A3 sized sheet of paper.

The following table details the quantities of the parts that were manufactured for the relay optics support tower.

Table A.1: Manufactured quantities of parts for the relay optics support tower.

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<tr>
<td>9</td>
<td>Floor Mounting Bracket</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
<td>Vertical Mounting Bracket</td>
<td>16</td>
</tr>
<tr>
<td>11</td>
<td>T-slotted Framing – 8” cut</td>
<td>8</td>
</tr>
<tr>
<td>11</td>
<td>T-slotted Framing – 56” cut</td>
<td>4</td>
</tr>
</tbody>
</table>

In addition to the custom parts manufactured from these designs by the University of Wisconsin, most of the assembly and support hardware was purchased from McMaster-Carr Supply Company and Thorlabs.
NOTE: RAISED SECTION OF THE RACE SPANS 70°
WITH THE FLAT SECTION AT THE TOP OF THE
RACE SPANNING 10°
DIMENSION TOLERANCE

DECIMAL:

.50 ± .03
1.50 ± .005

MATERIAL: 6061 ALUMINUM

ANGLE AR:

2.00" x 4.00" ANGLE

± 0.5°

EMORY-RIDDLE AERONAUTICAL UNIVERSITY
DAYTONA BEACH, FLORIDA

SIZE: A3
SCALE: 1:2
PROJECT: LENSES/REDDI v.2.0
DATE: 8/2/2016

DRAWN BY: ROBERT A. KALLIO

DRAWING TITLE: FLOOR MOUNT BRACKET

SHEET: 9
MATERIAL: 1" SQUARE 80/20 ALUMINUM STOCK RAILING  
PROVIDED FROM McMASTER-CARR  

CUTS: 8X - LENGTH "A" - 8 INCHES  
4X - LENGTH "A" - 56 INCHES  
HOLE "B" - 1/4-20 UNC  \( \pm 0.75 \)

DIMENSION TOLERANCE

DECIMAL:  
\( .XX \pm 0.03 \)  
\( .XXX \pm 0.005 \)

ANGULAR:  
\( \pm 0.5^\circ \)
Appendix B – Sample Data Processing Code

%% REDDI dataset batch processing program

% This program is designed to batch process REDDI data taken using the
% original REDDI control software. The next version of the control
% software has a different header format for the FITS files and so this
% program will need to be adapted for that header before it is used to
% process that data.
%
% In order to properly use this program, the data to be analyzed needs
% to be saved in a folder located in the same directory as the program.
% Individual data folders should contain sequentially timed FITS files
% from REDDI, it is preferable that each observing run be saved to an
% individual folder.
%
% This program is capable of analyzing FITS files from REDDI that are
% binned at 4x4, 8x2, and 8x1. It is also capable of automatically
% sorting data by direction of observation for the analysis. It is
% assumed that any observation taken at greater than 300 degrees is a
% Zenith observation, any observation less than 45 degrees is assumed
% to be a South observation, West, North, and East observations are
% subsequently between, 45 and 135, 135 and 225, and 225 and 300
% degrees, respectively.
%
% Finally, if only a portion of a dataset (folder) is to be analyzed,
% the main for loop indexing values should be changed appropriately.
% This loop typically starts at "3"; all folders start with two hidden
% files that should not be changed or interacted with by the program.
% The loop, when performing a full dataset analysis should end at "s"
% which is determined as the length of the filelist in the dataset.
%
% Author: Bert Kallio, ERAU Physical Sciences Dept.

% clearing commands to prepare the workspace
clc
clear
close all

% folder to look in for data, MUST only have fits files in it
look = '16Feb NESW';

% logs filenames in the folder
filelist = dir(look);

% move to the folder of the active data
cd(look)

% gather file and folder information
fileNames = {filelist.name}';
s = size(fileNames,1);

% check image size for the folder
info = fitsinfo(fileNames{3});
ImSize = info.Image.Size;
% set up vectors for external for loop
T0 = zeros(s-2,1);
T1 = zeros(s-2,1);
T2 = zeros(s-2,1);
T3 = zeros(s-2,1);
direction = zeros(s-2,1);
mincut = zeros(s-2,1);

% size of gauss fit window; match to datagauss variable
x = 1:101;

% log image times as standard datetime format
dt = datetime({filelist.date});
% log image times as standard datenum format for errorbar plots
dtn = {filelist.datenum};
dtn = [dtn{1:end}];

% set up Linear Fit Ranges and windowing
if ImSize(2) == 512 % For 4x4
    xLFit = 1:ImSize(2)-101;
    Lwind = [50, 460, 255]; % [start, end, mid]
elseif ImSize(2) == 1024 % For 8x2
    xLFit = 1:ImSize(2)-203;
    Lwind = [100, 920, 511];
elseif ImSize(2) == 2048 % For 8x1
    xLFit = 1:ImSize(2)-407;
    Lwind = [200, 1840, 1023];
else % default if previous cases don't match
    xLFit = 1:ImSize(2)-103;
    Lwind = [50, 460, 255];
end

% set up matrices for internal loop
datacut = zeros(17,ImSize(2)-2);
datafft = zeros(17,ImSize(2)-2);
absfft = zeros(17,ImSize(2)-2);
datacuth = zeros(17,ImSize(2)-2);
datagauss = zeros(17,101);
coeffs = zeros(17,7,s-2);
bcoeffs = zeros(s-2,3);
fmax = zeros(17,2);
fpos = zeros(17,2);
NeWavnumLFit = zeros(17,s-2);
OxWavnumLFit = zeros(17,s-2);

% set up hanning filters to isolate single lines
han10 = hann(10);
datafringeNe  = zeros(17,ImSize(2)-2);
datafringeOx  = zeros(17,ImSize(2)-2);

% get screen size for full screen figures
screen = get(0, 'Screensize');

% set up directional indices
dz=1;
ds=1;
dw=1;
dn=1;
de=1;
% set up directional coefficient logs
dzenith = zeros(1,17);
dnorth = zeros(1,17);
dsouth = zeros(1,17);
deast = zeros(1,17);
dwest = zeros(1,17);
% set up directional unwrapped phase logs
Zuphase = zeros(1,17);
Nuphase = zeros(1,17);
Suphase = zeros(1,17);
Euphase = zeros(1,17);
Wuphase = zeros(1,17);
% set up directional intensity logs
NeInt = zeros(s-2,1);
OxNInt = zeros(1);
OxSInt = zeros(1);
OxEInt = zeros(1);
OxWInt = zeros(1);
OxZInt = zeros(1);
% set up directional datetime logs
Xz = datetime(zeros(1,6));
Xn = datetime(zeros(1,6));
Xs = datetime(zeros(1,6));
Xe = datetime(zeros(1,6));
Xw = datetime(zeros(1,6));
% set up directional datenum logs
Xzn = zeros(1);
Xnn = zeros(1);
Xsn = zeros(1);
Xen = zeros(1);
Xwn = zeros(1);
for b = 3:s
    n = b-2;
    % move to working image and store data
    info = fitsinfo(fileNames(b));
data = fitsread(fileNames(b),'Image');
    % psuedo dark subtract
    mincut(n) = min(min(abs(data(5:25,5:25))));
data = data - mincut(n);
    % store current file name
    current = char(num2str(n),fileNames(b));
current = cat(2,current(1,:),current(2,:));
    % retrieve temp sensor data and direction
    metad = cell2mat(fitsread(fileNames(b),'binarytable'));
    T0(n) = metad(4);
    T1(n) = metad(5);
    T2(n) = metad(6);
    T3(n) = metad(7);
direction(n) = metad(12);
% set up phase data matrices that need to be reset for each round
% Hanning filters for phase line isolation
filt = zeros(17,ImSize(2)-2);
filt2 = zeros(17,ImSize(2)-2);
% pi-limited phase data
phaseNe = zeros(17,ImSize(2)-2);
phaseOx = zeros(17,ImSize(2)-2);
% unwrapped phase data
uphaseNe = zeros(17,ImSize(2)-2);
uphaseOx = zeros(17,ImSize(2)-2);
% pi jump logs
jumpsNe = zeros(17,ImSize(2)-2);
jumpsOx = zeros(17,ImSize(2)-2);

% segmental shift through the data to find the line centers
r = 18; % number of segments to work through, 18 = last before notch
for a = 2:r % 2 = skip 1st section w/ bloom effects
    k = a-1; % index shift
    % segment bracketing
    if ImSize(1) == 256 % for 8x binned images
        l = a*12;
        m = l-11;
    elseif ImSize(1) == 512 % for 4x binned images
        l = a*25;
        m = l-24;
    else
        l = a*25;
        m = l-24;
    end

    % move to working data segment, store median of all columns
    datacut(k,:) = median(data(m:l,2:ImSize(2)-1),1);

    % set up Hanning window multipliers for data
    shann = size(datacut);
    hanned = hann(shann(2));
    % apply Hann window
    datacuth(k,:) = datacut(k,:) .* hanned';
    % perform FFT, abs removes imaginaries for standard Doppler
    datafft(k,:) = fft(datacuth(k,:));
    absfft(k,:) = abs(datafft(k,:));
    % set up section to fit double Guassian
    datagauss(k,:) = absfft(k,ImSize(2)-120:ImSize(2)-20);

    % find start points for double Gaussian coefficients
    [ngauss, npos] = max(datagauss(k,55:75)); % neon line
    [ogauss, opos] = max(datagauss(k,15:35)); % oxygen line
    bckgrnd = median(datagauss(k,1:30));

    % Double Gaussian equation for simultaneously fitting both lines
    gaussEqn = 'a*exp(-(x-b)/c)^2 + d*exp(-(x-e)/f)^2 + g';

    % initial guess for amplitude, center, width
    % (a, b, c, d, e, f, g in gaussEqn)
startPoints = [ogauss-bckgrnd opos+14 1.4 ... 
   n gauss npos+54 1.4 bckgrnd];  
% fit the double Gaussian  
fl = fit(x', datagauss(k,:)', gaussEqn, 'Start', startPoints);  

% log every coefficient for every line  
coeffs(k,1:7,n) = coeffvalues(f1);  

% phase unwrapping  
% set up phase retrieval  
datafringeNe(k,:) = ifft(filt(k,:).*datafft(k,:));  
datafringeOx(k,:) = ifft(filt2(k,:).*datafft(k,:));  

% convert inverse fourier data to phase data  
phaseNe(k,:) = atan2(imag(datafringeNe(k,:)), ... 
   real(datafringeNe(k,:)));  
phaseOx(k,:) = atan2(imag(datafringeOx(k,:)), ... 
   real(datafringeOx(k,:)));  

% sets up the region where jumps are looked for near +pi  
% determines the width of the jump range  
NeJumpRange = phaseNe(k,ImSize(2)/2 + 1) - ... 
   phaseNe(k,ImSize(2)/2);  
OxJumpRange = phaseOx(k,ImSize(2)/2 + 1) - ... 
   phaseOx(k,ImSize(2)/2);  

% checks that the jump range is not negative  
if NeJumpRange < 0  
    NeJumpRange = phaseNe(k,ImSize(2)/2) - ... 
    phaseNe(k,ImSize(2)/2-1);  
end  
if OxJumpRange < 0  
    OxJumpRange = phaseOx(k,ImSize(2)/2) - ... 
    phaseOx(k,ImSize(2)/2-1);  
end  

% sets the jump range relative to +pi  
NeJumpRange = pi - 1.25*NeJumpRange;  
OxJumpRange = pi - 1.25*OxJumpRange;  

% find jumps in phase  
for d = 2:ImSize(2)-2  
    % check to see if the previous value is less than current
\[ \text{deltaNe} = \text{phaseNe}(k,d) - \text{phaseNe}(k,d-1); \]
\[ \text{deltaOx} = \text{phaseOx}(k,d) - \text{phaseOx}(k,d-1); \]
\[
\text{if } \text{phaseNe}(k,d-1) > \text{NeJumpRange} \&\& \text{deltaNe} < 0
\]
\[
\% \text{ add a 1 for every jump between positive pi and negative pi}
\]
\[
\text{jumpsNe}(k,d) = 1;
\]
\[
\text{end}
\]
\[
\text{if } \text{phaseOx}(k,d-1) > \text{OxJumpRange} \&\& \text{deltaOx} < 0
\]
\[
\% \text{ add a 1 for every jump between positive pi and negative pi}
\]
\[
\text{jumpsOx}(k,d) = 1;
\]
\[
\text{end}
\]
\[
\% \text{ unwrap the phase by removing the 2-pi jumps}
\]
\[
\text{uphaseNe}(k,d) = \text{phaseNe}(k,d) + 2\pi \text{sum(jumpsNe}(k,:));
\]
\[
\text{uphaseOx}(k,d) = \text{phaseOx}(k,d) + 2\pi \text{sum(jumpsOx}(k,:));
\]
\[
\text{end}
\]
\[
\% \text{ reset the first value of the unwrapped phase}
\]
\[
\text{uphaseNe}(k,1) = \text{phaseNe}(k,1);
\]
\[
\text{uphaseOx}(k,1) = \text{phaseOx}(k,1);
\]
\[
\% \text{ linear fit the center of the unwrapped phase to avoid edges}
\]
\[
[\text{w1},v1] = \text{polyfit}(xLFit,\text{uphaseNe}(k,Lwind(1):Lwind(2)),1);
\]
\[
[\text{w2},v2] = \text{polyfit}(xLFit,\text{uphaseOx}(k,Lwind(1):Lwind(2)),1);
\]
\[
\% \text{ log the midphase value}
\]
\[
\text{NeWavnumLFit}(k,n) = w1(1)\text{Lwind}(3);
\]
\[
\text{OxWavnumLFit}(k,n) = w2(1)\text{Lwind}(3);
\]
\[
\text{end}
\]
\[
\% \text{ logs the neon intensity values}
\]
\[
\text{NeInt}(n,1) = \text{median(coeffs(:,4,n))};
\]
\[
\% \text{ log the line and phase data by direction and bump directional indices}
\]
\[
\text{if } \text{direction}(n) > 300 \quad \% \text{Zenith}
\]
\[
\% \text{ log distance between line centers}
\]
\[
\text{dzenith}(dz,:) = \text{coeffs(:,5,n)} - \text{coeffs(:,2,n)};
\]
\[
\% \text{ log difference between mid-phase values}
\]
\[
\text{Zuphase}(dz,:) = \text{OxWavnumLFit(:,n)} - \text{NeWavnumLFit(:,n)};
\]
\[
\% \text{ log oxygen line intensity by direction}
\]
\[
\text{OxZInt}(dz,1) = \text{median(coeffs(:,1,n))};
\]
\[
\text{Xz}(dz,1) = \text{dt}(b);
\]
\[
\text{Xzn}(dz) = \text{dtn}(b);
\]
\[
\text{dz} = \text{dz}+1;
\]
\[
\text{elseif } \text{direction}(n) <= 135 \&\& \text{direction}(n) > 45 \quad \% \text{West}
\]
\[
\text{dwest}(dw,:) = \text{coeffs(:,5,n)} - \text{coeffs(:,2,n)};
\]
\[
\text{Wuphase}(dw,:) = \text{OxWavnumLFit(:,n)} - \text{NeWavnumLFit(:,n)};
\]
\[
\text{OxWInt}(dw,1) = \text{median(coeffs(:,1,n))};
\]
\[
\text{Xw}(dw,1) = \text{dt}(b);
\]
\[
\text{Xwn}(dw) = \text{dtn}(b);
\]
\[
\text{dw} = \text{dw}+1;
\]
\[
\text{elseif } \text{direction}(n) <= 45 \quad \% \text{South}
\]
\[
\text{dsouth}(ds,:) = \text{coeffs(:,5,n)} - \text{coeffs(:,2,n)};
\]
\[
\text{Suphase}(ds,:) = \text{OxWavnumLFit(:,n)} - \text{NeWavnumLFit(:,n)};
\]
\[
\text{OxSInt}(ds,1) = \text{median(coeffs(:,1,n))};
\]
\[
\text{Xs}(ds,1) = \text{dt}(b);
\]
\[
\text{ds} = \text{ds}+1;
\]
Xsn(ds) = dtn(b);
ds = ds+1;
elseif direction(n) <= 225 && direction(n) > 135 %North
dnorth(dn,:) = coeffs(:,5,n) - coeffs(:,2,n);
Nuphase(dn,:) = OxWavnumLFit(:,n) - NeWavnumLFit(:,n);
OxNInt(dn,1) = median(coeffs(:,1,n));
Xn(dn,1) = dt(b);
Xnn(dn) = dtn(b);
dn = dn+1;
else %East (default)
deast(de,:) = coeffs(:,5,n) - coeffs(:,2,n);
Euphase(de,:) = OxWavnumLFit(:,n) - NeWavnumLFit(:,n);
OxEInt(de,1) = median(coeffs(:,1,n));
Xe(de,1) = dt(b);
Xen(de) = dtn(b);
de = de+1;
end
% Notched segment bracketing
if ImSize(1) == 256 % for 8x binned images
  NSeg = [235,247]; % upper and lower segment limits
elseif ImSize(1) == 512 % for 4x binned images
  NSeg = [464,494]; % upper and lower segment limits
else % default
  NSeg = [464,494]; % upper and lower segment limits
end
% find line centers of notched section of the diffraction grating
% store median of each column in notched segment
blazecut = median(data(NSeg(1):NSeg(2),2:ImSize(2)-1),1);
% set up and apply Hanning filter
shann2 = size(blazecut);
hanned2 = hann(shann2(2));
blazecuth = blazecut .* hanned2';
% take FFT of notched segment
blazefft = abs(fft(blazecuth));
% store values for Gaussian
blazegauss = blazefft(ImSize(2)-120:ImSize(2)-20);
% find start points for Gaussian
[mblaze, bpos] = max(blazegauss(35:65));
% notched segment Gaussian
blazeEqn = 'a*exp(-(x-b)/c)^2';
% initial guess for amplitude, center, width (a, b, c in blazeEqn)
BstartPoints = [mblaze bpos+34 1.2];
% fit the Gaussian
b1 = fit(x',blazegauss',blazeEqn,'Start', BstartPoints);
% log coefficients
bcoeffs(n,1:3) = coeffvalues(b1);
data_ave = median(median(datacut)); % help with y-axis scaling
% close previous diagnostic figures to reduce RAM requirements
close all
xlabel('relative pos (pix)')
ylabel('power (arb units)')
title('FFT Spectrum/Line Filter')
legend([p1 p2 p3], 'FFT', 'Neon Filter', 'Oxygen Filter')
clearvars p1 p2 p3
box on

subplot(4,2,2)
plot((1:ImSize(2)-2),filt(9,:).*absfft(9,:)...+
    +filt2(9,:).*absfft(9,:), 'b')
ylim([0,fmax(9,1)*1.3])
xlim([0,125])
xlabel('relative pos (pix)')
title('Filtered Combined Spectrum')
box on

subplot(4,1,2)
plot(phaseNe(9,:),'-b', 'Color',[1,0.4,0])
xlim([0,ImSize(2)-1])
ylabel('Phase (rad)')
title('Recovered Ne Phase')
box on

subplot(4,1,3)
plot(phaseOx(9,:),'-r', 'Color',[1,0.4,0])
xlim([0,ImSize(2)-1])
ylabel('Phase (rad)')
title('Recovered Ox Phase')
box on

subplot(4,1,4)
hold on
p1 = plot((1:ImSize(2)-2),uphaseNe(:,1), 'Color', [1,0.4,0]);
p2 = plot((1:ImSize(2)-2),uphaseOx(:,1), 'r');
hold off
xlim([0,ImSize(2)-1])
ylim([0,625])
xlabel('pixel')
ylabel('Phase (rad)')
title('Unwrapped Phase')
legend([p1(1) p2(1)], 'Neon', 'Oxygen', 'Location', 'northwest')
clearvars p1 p2
box on
end

cd ..

% squeeze out plotted coefficients

OxyCen = squeeze(coeffs(:,2,:));
OxyWide = abs(2*sqrt(2*log(2))*sqrt(squeeze(coeffs(:,3,:))));
NeCen = squeeze(coeffs(:,5,:));
NeWide = abs(2*sqrt(2*log(2))*sqrt(squeeze(coeffs(:,6,:))));
bckgrnds = squeeze(coeffs(:,7,:));

% trace directions observed and set up directional plots
% trace used to determine number of plots on FS5 and 7 and what to use
for a zero-point in the wind speeds.

```matlab
tr = 0; % resets the trace
if dz > 1 % zenith
    zen_ave = median(median(dzenith)); % saves the zero points
    zuph_ave = median(median(Zuphase));
    tr = tr + 16;
end
if dn > 1 % north
    n_ave = median(median(dnorth));
    nuph_ave = median(median(Nuphase));
    tr = tr + 1;
end
if ds > 1 % south
    s_ave = median(median(dsouth));
    suph_ave = median(median(Suphase));
    tr = tr + 2;
end
if dw > 1 % west
    w_ave = median(median(dwest));
    wuph_ave = median(median(Wuphase));
    tr = tr + 4;
end
if de > 1 % east
    e_ave = median(median(deast));
    euph_ave = median(median(Euphase));
    tr = tr + 8;
end

% zen_ave and zuph_ave are used to normalize the data by setting a zero pt. In cases, that no zenith data is taken an alternative is generated, using averages from all the other directions.

% dlm is used to determine the number of subplots on FS5 and 7.

switch tr
    case 0 %null
    case 16 %Z
        dlm = 1;
    case 1 %N
        zen_ave = n_ave;
        zuph_ave = nuph_ave;
        dlm = 1;
    case 2 %S
        zen_ave = s_ave;
        zuph_ave = suph_ave;
        dlm = 1;
    case 4 %W
        zen_ave = w_ave;
        zuph_ave = wuph_ave;
        dlm = 1;
    case 8 %E
        zen_ave = e_ave;
        zuph_ave = euph_ave;
        dlm = 1;
    case 15 %NSWE
        zen_ave = (n_ave + s_ave + w_ave + e_ave)/4;
        zuph_ave = (nuph_ave + suph_ave + wuph_ave + euph_ave)/4;
```
```
dlm = 4;
case 3 %NS
    zen_ave = (n_ave + s_ave)/2;
    zuph_ave = (nuph_ave + suph_ave)/2;
    dlm = 2;
case 5 %NW
    zen_ave = (n_ave + w_ave)/2;
    zuph_ave = (nuph_ave + wuph_ave)/2;
    dlm = 2;
case 9 %NE
    zen_ave = (n_ave + e_ave)/2;
    zuph_ave = (nuph_ave + euph_ave)/2;
    dlm = 2;
case 6 %SW
    zen_ave = (s_ave + w_ave)/2;
    zuph_ave = (suph_ave + wuph_ave)/2;
    dlm = 2;
case 10 %SE
    zen_ave = (s_ave + e_ave)/2;
    zuph_ave = (suph_ave + euph_ave)/2;
    dlm = 2;
case 12 %WE
    zen_ave = (e_ave + w_ave)/2;
    zuph_ave = (wuph_ave + euph_ave)/2;
    dlm = 2;
case 7 %NSW
    zen_ave = (n_ave + s_ave + w_ave)/3;
    zuph_ave = (nuph_ave + suph_ave + wuph_ave)/3;
    dlm = 3;
case 11 %NSE
    zen_ave = (n_ave + s_ave + e_ave)/3;
    zuph_ave = (nuph_ave + suph_ave + euph_ave)/3;
    dlm = 3;
case 13 %NWE
    zen_ave = (n_ave + w_ave + e_ave)/3;
    zuph_ave = (nuph_ave + wuph_ave + euph_ave)/3;
    dlm = 3;
case 14 %SWE
    zen_ave = (s_ave + w_ave + e_ave)/3;
    zuph_ave = (suph_ave + wuph_ave + euph_ave)/3;
    dlm = 3;
case 17 %ZN
    dlm = 2;
case 18 %ZS
    dlm = 2;
case 19 %ZNS
    dlm = 3;
case 20 %ZW
    dlm = 2;
case 21 %ZNW
    dlm = 3;
case 22 %ZSW
    dlm = 3;
case 23 %NZ
    dlm = 4;
case 24 %ZE
    dlm = 2;
```
case 25 %ZNE
dlm = 3;
case 26 %ZSE
dlm = 3;
case 27 %ZNSE
dlm = 4;
case 28 %ZEW
dlm = 3;
case 29 %ZNEW
dlm = 4;
case 30 %ZSEW
dlm = 4;
case 31 %ZNSEW
dlm = 5;
end
dlm = dlm + 1; % adds an extra subplot to FS5 and 7 for winds

% normalizes about a zero point
adeast = deast - zen_ave;
adwest = (dwest - zen_ave)*-1; % flips zonal wind direction
adnorth = dnorth - zen_ave;
adsouth = (dsouth - zen_ave)*-1; % flips meridional wind direction
adzenith = dzenith - zen_ave;

% smoothes wind measurements
mzen = median(movmedian(adzenith,3),2);
meast = median(movmedian(adeast,3),2);
mwest = median(movmedian(adwest,3),2);
msouth = median(movmedian(adsouth,3),2);
mnorth = median(movmedian(adnorth,3),2);

% sets errorbar lengths for Doppler winds
errsZ = std(adzenith,1,2);
errsE = std(adeast,1,2);
errsW = std(adwest,1,2);
errsN = std(adnorth,1,2);
errsS = std(adsouth,1,2);
% normalizes errorbars to 100 m/s minimum wind
errsZ = 50*errsZ/min(errsZ);
errsE = 50*errsE/min(errsE);
errsW = 50*errsW/min(errsW);
errsN = 50*errsN/min(errsN);
errsS = 50*errsS/min(errsS);

% velocity conversions
% observation angle
theta = 45;
% pixel pitch, wavelength range, line center average distance
mpix = (630.47893 - 630.0304)/zen_ave; % [nm/pix]
c, pixel pitch, wavelength, dVdL = 299792458*mpix/630.0304; % [(m/s)/pix]
% observation angle correction
vconL = dVdL * secd(theta);
% wavelength, c, Lopt
dVdPhi = 630.0304*(10^-9)*299792458/(2*pi*3.08*(10^-2)); % observation angle
vconv = dVdPhi * secd(theta);
% normalizes phase data about a zero point
aEuphase = Euphase - zuph_ave;
aWuphase = (Wuphase - zuph_ave)*-1;  % flips zonal wind direction
aNuphase = Nuphase - zuph_ave;
aSuphase = (Suphase - zuph_ave)*-1;  % flips meridional wind direction
aZuphase = Zuphase - zuph_ave;

% smoothes wind measurements
mZuph = median(movmedian(aZuphase,3),2);
mEuph = median(movmedian(aEuphase,3),2);
mWuph = median(movmedian(aWuphase,3),2);
mNuph = median(movmedian(aNuphase,3),2);
mSuph = median(movmedian(aSuphase,3),2);

% sets error bar lengths for phase winds
errZ = std(aZuphase,1,2);
errE = std(aEuphase,1,2);
errW = std(aWuphase,1,2);
errS = std(aSuphase,1,2);
errN = std(aNuphase,1,2);

% normalizes errorbars to 30 m/s minimum wind
errZ = 15*errZ/min(errZ);
erE = 15*errE/min(errE);
erW = 15*errW/min(errW);
erS = 15*errS/min(errS);
erN = 15*errN/min(errN);

% % FS3: Plot temp sensor data
figure('Name', 'Temp plots', 'Position', screen)
% T0
subplot(3,2,2)
plot(dt(3:end),T0)
title('T0')
xlim([dt(3),dt(end)])
ylabel('Temp (C)')
box on
% T1
subplot(3,2,1)
plot(dt(3:end),T1)
title('T1')
xlim([dt(3),dt(end)])
ylabel('Temp (C)')
box on
% T2
subplot(3,2,3)
plot(dt(3:end),T2)
title('T2')
xlim([dt(3),dt(end)])
ylabel('Temp (C)')
box on
% T3
subplot(3,2,4)
plot(dt(3:end),T3)
title('T3 (ambient)')
xlim([dt(3),dt(end)])
ylabel('Temp (C)')
box on

% % plot line center and width for etched gaussian
% Notched pattern line center
subplot(3,2,5)
plot(dt(3:end),bcoeffs(:,2))
title('Notched Pattern Line Center')
xlim([dt(3),dt(end)])
ylabel('rel pos (pix)')
box on
% Notched pattern line width
subplot(3,2,6)
plot(dt(3:end),2*sqrt(2*log(2))*sqrt(bcoeffs(:,3)))
title('Notched Pattern Line Width')
xlim([dt(3),dt(end)])
ylabel('FWHM (pix)')
box on

% % FS4: Plot coefficients from all of the double Gaussians
figure('Name', 'Line Tracking', 'Position', screen)
% Oxygen line center
subplot(4,2,1)
plot(dt(3:end),OxyCen)
title('Oxygen Line Center')
xlim([dt(3),dt(end)])
ylim([median(median(OxyCen)) - 2, median(median(OxyCen)) + 2])
ylabel('rel pos (pix)')
box on
% Oxygen line width
subplot(4,2,2)
plot(dt(3:end),OxyWide)
title('Oxygen Line Width')
xlim([dt(3),dt(end)])
ylim([median(median(OxyWide)) - 1, median(median(OxyWide)) + 1])
ylabel('FWHM (pix)')
box on
% Neon line center
subplot(4,2,3)
plot(dt(3:end),NeCen)
title('Neon Line Center')
xlim([dt(3),dt(end)])
ylim([mean(mean(NeCen)) - 1, mean(mean(NeCen)) + 1])
ylabel('rel pos (pix)')
box on
% Neon line wicth
subplot(4,2,4)
plot(dt(3:end),NeWide)
title('Ne Line Width')
xlim([dt(3),dt(end)])
ylim([median(median(NeWide)) - 0.5, median(median(NeWide)) + 0.5])
ylabel('FWHM (pix)')
box on
% Neon - Oxygen line center
subplot(4,2,5)
plot(dt(3:end), (NeCen - OxyCen))
title('Ne - Ox Center')
xlim([dt(3),dt(end)])
ylim([median(median(NeCen - OxyCen)) -1, median(median(NeCen - OxyCen)) +1])
ylabel('line center diff')

box on

% FFT background

subplot(4,2,6)
plot(dt(3:end), bckgrnds)
title('FFT Background')
xlim([dt(3),dt(end)])
ylim([0,2000])
ylabel('power (arb units)')

box on

% Line intensity by species and oxygen by direction

subplot(4,1,4)
hold on
% allows overplotting

p = 1;

p1(p) = plot(dt(3:end), NeInt, '*-', 'Color', [1,0.4,0], ... 'DisplayName', 'Neon');

if dz > 1
    % zenith oxygen
    p = p+1;
    p1(p) = plot(Xz, OxZInt, 'ko-', 'DisplayName', 'Zenith');
end

if dn > 1
    % north oxygen
    p = p+1;
    p1(p) = plot(Xn, OxNInt, 'bs-', 'DisplayName', 'North');
end

if ds > 1
    % south oxygen
    p = p+1;
    p1(p) = plot(Xs, OxSInt, 'r+', 'DisplayName', 'South');
end

if dw > 1
    % west oxygen
    p = p+1;
    p1(p) = plot(Xw, OxWInt, 'cd-', 'DisplayName', 'West');
end

if de > 1
    % east oxygen
    p = p+1;
    p1(p) = plot(Xe, OxEInt, 'mx-', 'DisplayName', 'East');
end
legend(p1, 'Location', 'eastoutside')
clearvars p1 p

hold off

title('Line Intensities')
ylabel('power (arb units)')
xlim([dt(3),dt(end)])
box on

% % FS5: Plot directionality matrices

figure('Name', 'Directional Line Tracking', 'Position', screen)

dlp = 1;

if dz > 1
    % zenith variation from nominal center pixel
    subplot(dlm,1,dlp)
    plot(Xz,adzenith', 'o:', Xz,mzen,'k')
    title('Zenith Line Variation')
xlim([dt(3), dt(end)])
ylim([floor(min(mzen)), ceil(max(mzen))])
ylabel('center shift (pix)')
box on
dlp = dlp + 1;
end
if dn > 1  % north variation from nominal center pixel
    subplot(dlm,1,dlp)
    plot(Xn, adnorth', 'o:', Xn, mnorth, 'b')
    title('North Line Variation')
    xlim([dt(3), dt(end)])
    ylim([floor(min(mnorth)), ceil(max(mnorth))])
    ylabel('center shift (pix)')
    box on
dlp = dlp + 1;
end
if ds > 1  % south variation from nominal center pixel
    subplot(dlm,1,dlp)
    plot(Xs, adsouth', 'o:', Xs, msouth, 'r')
    title('South Line Variation')
    xlim([dt(3), dt(end)])
    ylim([floor(min(msouth)), ceil(max(msouth))])
    ylabel('center shift (pix)')
    box on
dlp = dlp + 1;
end
if dw > 1  % west variation from nominal center pixel
    subplot(dlm,1,dlp)
    plot(Xw, adwest', 'o:', Xw, mwest, 'c')
    title('West Line Variation')
    xlim([dt(3), dt(end)])
    ylim([floor(min(mwest)), ceil(max(mwest))])
    ylabel('center shift (pix)')
    box on
dlp = dlp + 1;
end
if de > 1  % east variation from nominal center pixel
    subplot(dlm,1,dlp)
    plot(Xe, adeast', 'o:', Xe, meast, 'm')
    title('East Line Variation')
    xlim([dt(3), dt(end)])
    ylim([floor(min(meast)), ceil(max(meast))])
    ylabel('center shift (pix)')
    box on
dlp = dlp + 1;
end

subplot(dlm,1,dlm)  % errorbar overplotting with wind speeds
hold on
p = 0;  % index labels for plots
if dz > 1  % zenith winds
    p = p+1;
    p1(p) = errorbar(Xzn, mzen*dVdL, errsZ, 'ko-', 'DisplayName', 'Zenith');
end
if dn > 1  % north winds
    p = p+1;

pl(p) = errorbar(Xnn,mnorth*vconL,errsN,'bs-', 'DisplayName', 'North');
end
if ds > 1  % south winds
    p = p+1;
    pl(p) = errorbar(Xsn,msouth*vconL,errsS,'r+-', 'DisplayName', 'South');
end
if dw > 1  % west winds
    p = p+1;
    pl(p) = errorbar(Xwn,mwest*vconL,errsW,'cd-', 'DisplayName', 'West');
end
if de > 1  % east winds
    p = p+1;
    pl(p) = errorbar(Xen,meast*vconL,errsE,'mx-', 'DisplayName', 'East');
end
plot(dtn(3:end),zeros(n,length(dt)-2),'k')  % sets a zero line
hold off
legend(pl, 'Location', 'west')
clearvars pl p
title('Line Winds')
datetick('x',1)  % sets x-axis format
xlim([dtn(3),dtn(end)])
ylim([-400,400])
ylabel('velocity (m/s)')
box on

% % FS6: Plot phase data

figure('Name', 'Phase Tracking','Position',screen);

subplot(3,1,1)  % Neon phase data
plot(dt(3:end),NeWavnumLFit)
title('Fit Ne Fringe Freq by Phase')
xlim([dt(3),dt(end)])
ylim([median(median(NeWavnumLFit))-2,median(median(NeWavnumLFit))+2])
ylabel('center phase (rad)')
box on

subplot(3,1,2)  % Oxygen phase data
plot(dt(3:end),OxWavnumLFit)
title('Fit Ox Fringe Freq by Phase')
xlim([dt(3),dt(end)])
ylim([median(median(OxWavnumLFit))-2,median(median(OxWavnumLFit))+2])
ylabel('center phase (rad)')
box on

subplot(3,1,3)  % Oxygen - Neon phase difference
plot(dt(3:end),(OxWavnumLFit - NeWavnumLFit)-median(median ...
    (OxWavnumLFit - NeWavnumLFit)))
title('Fit Diff Fringe Freq by Phase')
xlim([dt(3),dt(end)])
ylim([-2,2])
ylabel('phase shift (rad)')
FS7: Plot phase data by direction

figure('Name', 'Directional Phase Tracking', 'Position', screen);

dlt = 1; % index the subplot number
if dz > 1 % zenith phase data
    subplot(dlm,1,dlt)
    plot(Xz,aZuphase', 'o:', Xz,mZuph, 'k')
    title('Zenith Phase Variation')
    xlim([dt(3), dt(end)])
    ylim([2*floor(min(mZuph)), 2*ceil(max(mZuph))])
    ylabel('center phase (rad)')
    box on
    dlt = dlt + 1;
end

if dn > 1 % north phase data
    subplot(dlm,1,dlt)
    plot(Xn,aNuphase', 'o:', Xn,mNuph, 'b')
    title('North Phase Variation')
    xlim([dt(3), dt(end)])
    ylim([2*floor(min(mNuph)), 2*ceil(max(mNuph))])
    ylabel('center phase (rad)')
    box on
    dlt = dlt + 1;
end

if ds > 1 % south phase data
    subplot(dlm,1,dlt)
    plot(Xs,aSuphase', 'o:', Xs,mSuph, 'r')
    title('South Phase Variation')
    xlim([dt(3), dt(end)])
    ylim([2*floor(min(mSuph)), 2*ceil(max(mSuph))])
    ylabel('center phase (rad)')
    box on
    dlt = dlt + 1;
end

if dw > 1 % west phase data
    subplot(dlm,1,dlt)
    plot(Xw,aWuphase', 'o:', Xw,mWuph, 'c')
    title('West Phase Variation')
    xlim([dt(3), dt(end)])
    ylim([2*floor(min(mWuph)), 2*ceil(max(mWuph))])
    ylabel('center phase (rad)')
    box on
    dlt = dlt + 1;
end

if de > 1 % east phase data
    subplot(dlm,1,dlt)
    plot(Xe,aEuphase', 'o:', Xe,mEuph, 'm')
    title('East Phase Variation')
    xlim([dt(3), dt(end)])
    ylim([2*floor(min(mEuph)), 2*ceil(max(mEuph))])
    ylabel('center phase (rad.)')
    box on
    dlt = dlt + 1;
end

subplot(dlm,1,dlm) % errorbar overplotting with wind speeds
hold on
p = 0; % index labels for plots
if dz >1 % zenith winds
    p = p+1;
    p1(p) = errorbar(Xzn,mZuph*dVdPhi,errZ,'ko-', 'DisplayName', 'Zenith');
end
if dn >1 % north winds
    p = p+1;
    p1(p) = errorbar(Xnn,mNuph*vconv,errN,'bs-', 'DisplayName', 'North');
end
if ds >1 % south winds
    p = p+1;
    p1(p) = errorbar(Xsn,mSuph*vconv,errS,'r+-', 'DisplayName', 'South');
end
if dw >1 % west winds
    p = p+1;
    p1(p) = errorbar(Xwn,mWuph*vconv,errW,'cd-', 'DisplayName', 'West');
end
if de >1 % east winds
    p = p+1;
    p1(p) = errorbar(Xen,mEuph*vconv,errE,'mx-', 'DisplayName', 'East');
end
plot(dtn(3:end),zeros(n,length(dtn)-2),'k') % sets a zero line
hold off
legend(p1, 'Location', 'west')
clearvars pl p
title('Phase Winds')
datetick('x',1) % sets x-axis format
xlim([dtn(3),dtn(end)])
ylim([-400,400])
ylabel('velocity (m/s)')
box on
Appendix C – Solar Flux Data

The following table contains the solar flux data archived at the Space Weather Prediction Center from the beginning of 2018 until March 18th, 2018. This time period covers all observations performed during the discussion of this Thesis. The archive can be accessed at ftp://ftp.swpc.noaa.gov/pub/indices/old_indices/.

Table C: Daily Solar Flux Data

:Product: Daily Solar Data          quar_DSD.txt
:Issued: 2025 UT 18 Mar 2018

#
# Prepared by the U.S. Dept. of Commerce, NOAA, Space Weather Prediction Center
# Please send comments and suggestions to SWPC.Webmaster@noaa.gov
#
# Quarterly Daily Solar Data
#
# Sunspot        Stanford GOES15
# Radio  SESC  Area       Solar  X-Ray       Flares  Flares
# Flux  Sunspot 10E-6 New  Mean  Bkgd  X-Ray Optical
# Date 10.7cm Number Hemis. Regions Field  Flux  C  M  X  S  1  2
#
#---------------------------------------------------------------------------
#
2018 01 01  69  0  0  0  -999  A3.5  0  0  0  0  0  0
2018 01 02  70  0  0  0  -999  A3.2  0  0  0  0  0  0
2018 01 03  71  0  0  0  -999  A3.1  0  0  0  0  0  0
2018 01 04  70  13 20  1  -999  A3.1  0  0  0  0  0  0

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Appendix D – Geomagnetic Activity Data

The following table contains the geomagnetic activity data of the 3-hour Kp index and the 24 hour A index archived for two physical locations, Fredericksburg and College, as well as an estimated Planetary index by the Space Weather Prediction Center for 2018 through March 18th, 2018. This time period covers all observations performed during the discussion of this Thesis. The data is recorded in UTC, to convert to local time, subtract 5 hours from the recorded time. The archive can be accessed at ftp://ftp.swpc.noaa.gov/pub/indices/old_indices/.

Table D.1: Daily Geomagnetic Activity Data

:Product: Daily Geomagnetic Data   quar_DGD.txt
:Iissued: 1830 UT 18 Mar 2018

#
# Prepared by the U.S. Dept. of Commerce, NOAA, Space Weather Prediction Center
# Please send comment and suggestions to SWPC.Webmaster@noaa.gov
#
#
# Current Quarter Daily Geomagnetic Data
#
#
# Middle Latitude     High Latitude     Estimated
# - Fredericksburg ---- College ---- --- Planetary ---
# Date     A  K-indices     A  K-indices     A  K-indices
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Appendix E – Data Figure Sets

Within this appendix are FS4 – FS7, listed by date, for all high-quality datasets taken during the third observation phase of this thesis.

6 Feb 2018
24 Feb 2018
27 Feb 2018