Development of a Ground-Based Aerial-Tracking Instrument for Open-Path Spectroscopy to Monitor Atmospheric Constituents

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1. Introduction

The term climate can be used to describe the physical conditions of our atmosphere at nearly any temporal or spatial scale. These conditions may be temperature, humidity, or composition, describing the state of matter and molecular concentrations. In general, the climate is a cause and effect of natural phenomenon affecting virtually every natural process in the biosphere. As stated by Henderson-Sellers and McGuffie, "Climate is both a forcing agent and a feature liable to be disturbed. It can fluctuate on relatively short timescales … or over much longer times" [1]. Earth's radiation budget (ERB) is the balance between incoming solar energy, and energy that radiates from Earth into space in the form of longwave energy and reflected shortwave energy. The ERB depends greatly on the composition of the atmosphere; gases, clouds, water vapor, and aerosols are all capable of absorbing and radiating electromagnetic energy [2]. The ERB is the driving factor in Earth's climate and the circulation of the atmosphere. However, many geologic factors influence the composition of the atmosphere including anthropogenic sources [3].

The greenhouse effect describes how the atmosphere influences the ERB to have an overall warming effect on the planet. This effect can be attributed to increases in concentrations of greenhouse gases in the atmosphere, including water vapor (H_20), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and tropospheric ozone (O_3). Much of the increase in the concentrations of the aforementioned constituents can be attributed to anthropogenic gas emissions. Since the dawn of the industrial era around 1750, atmospheric concentrations of CO_2 have seen an increase by 31 percent and methane by 151 percent. These increased levels have not been exceeded during the previous 420,000 years [3]. Many coalitions have been formed to investigate and promote action to mitigate global warming, notably the IPCC (Intergovernmental Panel on Climate Change), which was established "to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts" [4]. The IPCC proposes that global warming, if not mitigated, could lead to sea-level rise, increased frequency of extreme weather events, and other phenomenon which would have devastating impacts to human life and the global economy as well as irreversible effects on the biosphere [4].

This paper describes the continued development of a ground-based aerial-tracking instrument for open-path spectroscopy first conceptualized by P. Huang. The project background and motivation will be discussed followed by the methods and procedures used to construct and operate the instrument. The device was field tested by taking spectral measurements of the full moon on June 17, 2019. The results and procedure of this field test are discussed.

2. Project Background

One way to observe the composition of the atmosphere, and greenhouse gases which are of particular interest, is through the use of spectrometry. Spectroscopy refers to the use of instruments to measure light in a specific wavelength range. Spectrometers are able to collect photons of various energies and produce a spectrum, that is, a graph of energy intensity as a function of wavelength as seen in Figure 1.

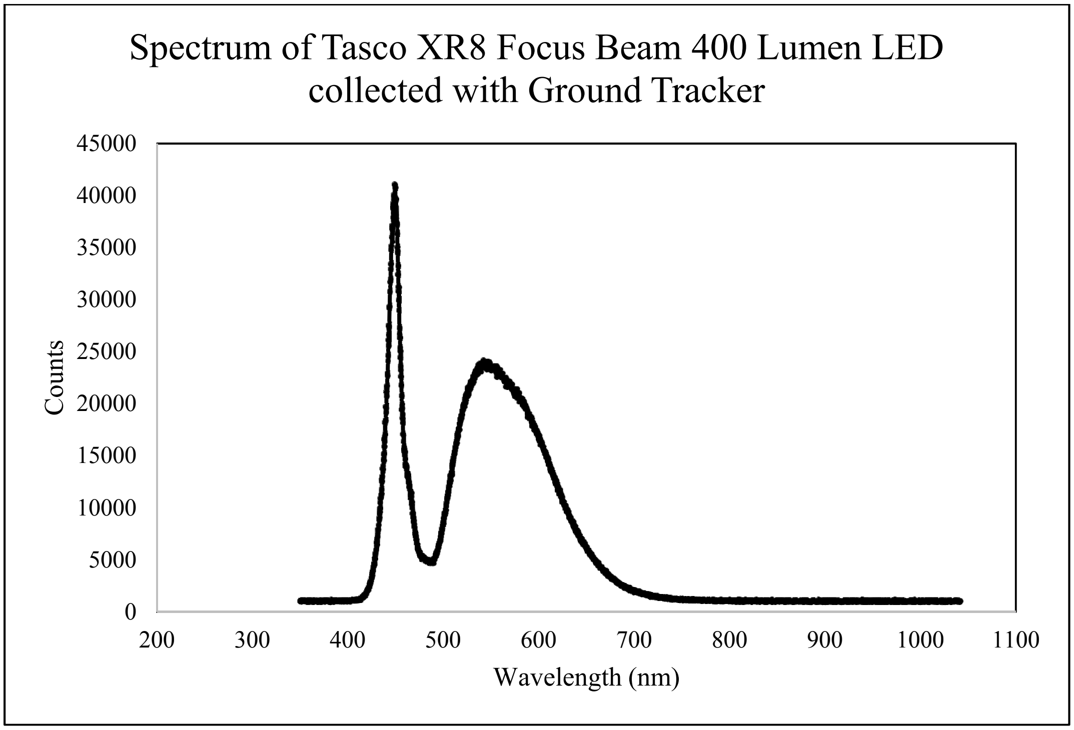

Figure 1. Spectrum of Tasco XR8 Focus Beam 400 Lumen LED light source collected by author at full focus. Spectra (y-axis) represents the intensity of light measured at a specific wavelength (x-axis). Spectral intensity is output from the spectrometer having 16-bit precision thus a range from 0 to 65,536.

Determining the greenhouse gas concentrations throughout the atmosphere is necessary for producing climate models which help scientists understand how the atmosphere evolves and assess how to mitigate climate change. Spectrum collected when atmospheric gases are present between the energy source and spectrometer can be analyzed to determine the concentrations of said gases along the optical path. Gases present will produce spectral lines in the waveform, which will appear as sharp troughs a specific wavelength. The path-integrated concentration of gases can be computed by noting the path length, absorptivity of the species of interest, and the presence of interfering species [5]. This technique is referred to as open-path monitoring, where the path is completely open to the atmosphere.

3. Project Motivation

Remote sensing satellites, such as NASA's OCO-2 (Orbiting Carbon Observatory), Aura MLS (Microwave Limb Sounder), and Japan's GOSAT (Greenhouse Gases Observing Satellite), use spectrometry to observe concentrations of greenhouse gases and temperature trends [6]. While these instruments can provide precise data that can be used to observe the atmosphere on a regional and global scale, these instruments do not have the capacity to observe the entire biosphere at a local scale with high temporal resolution. Observing the climate requires measurements that span the globe, including the vertical dimension since the climate is an extremely complex and time dependent system as noted by Vardavas and Taylor, "Many important processes, for example those involved in ozone depletion, are associated with transient dynamical phenomena and occur on local and diurnal scales, calling for high-resolution measurements in space and time…requiring measurements at the surface and external to the planet, ideally with global coverage that is comprehensive in angular as well as geographical space, and time." [3]. State-of-the-art satellites are also limited by orbital configurations and geophysical limitations such as cloud cover [7]. Terrestrial sensors are able to overcome these limitations as these sensors can be deployed anywhere and wait for suitable conditions to collect measurements. Additionally, these systems are able to monitor the same location over time, while a satellite can only pass over a specific location briefly. This is important when monitoring areas which produce high amounts of greenhouse gases, such as natural deposits, agricultural land, or large cities [8].

Atmospheric observation systems which can be implemented at a local scale and in great quantity should be used in addition to the network of large satellites to have a complete picture of the state of our climate system. These sensors can offer important data about trends in greenhouse gas and aerosol concentrations at spatial and temporal resolutions not currently available to state-of-the-art atmospheric monitoring satellites. The proposed solution is a ground-based aerial tracking spectrometry system. This system should be able to take passive and active spectrometric measurements and be capable of automatically tracking an airborne light source to collect data throughout an atmospheric column. This system can be referred to as the Ground Tracker.

The Climate cube, (Fig 2) as proposed by Vardavas and Taylor [3] is a representation of how the climate can be viewed as existing in three domains: time, space, and human perception. Earth observing satellites and the Ground Tracker are instruments used for acquiring data and therefore fall into the personal observation slice of the climate cube. If networks of Ground Trackers are used, the regional and global spatial scale could be reached. Over time, daily data can be used to observe monthly and yearly trends.

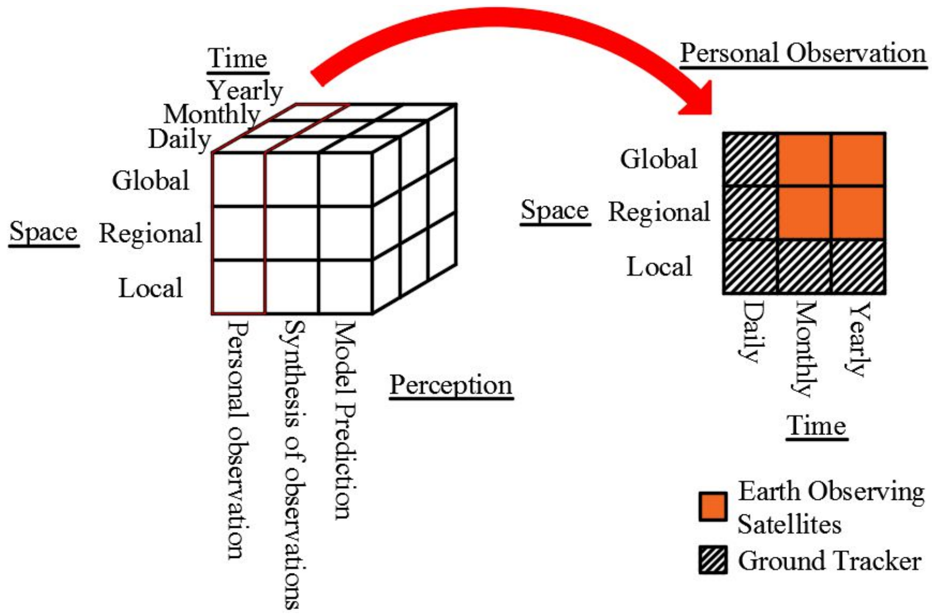

Figure 2. The Climate Cube (left) and Personal Observation slice (right) showing the scope of the Ground Tracker and Earth Observing Satellites. Figure created by author.

The design of a ground-based aerial-tracking spectroscopy system was comprised of two parts. The Ground Tracker which tracks an airborne light source and takes spectral measurements, and an Emitter package which will provide an active light source aligned with the spectrometer and communicate location data with the onboard computer on the Ground Tracker. This system is considered low-cost and highly mobile as this device is built using commercially available components. The system requires a one person crew to set up and take measurements. Additionally, the system will take advantage of already existing weather balloon infrastructure, which will greatly reduce the cost of sending an emitter through the troposphere and into the stratosphere. The Emitter package will eventually be miniaturized and integrated with the radiosonde instrument package that is the standard instrumentation on weather balloons. As the weather balloon rises through the atmosphere, the Ground Tracker follows the Emitter, taking continuous spectra. Spectra taken while the light source is active can be compared to reference spectra taken while the light is off to determine quantities of atmospheric constituents.

Twice a day, every day of the year, almost 900 weather balloons are simultaneously released from different locations across the globe [9]. These balloons are outfitted with a radiosonde instrument package that records temperature, relative humidity, and pressure relative to altitude. The National Oceanic and Atmospheric Administration (NOAA) releases over 180 weather balloons daily in the US and US territories. This existing weather balloon infrastructure could be inexpensively integrated with spectrometry based atmospheric constituent monitoring techniques to provide high resolution data on a global scale.

4. Methods and Procedures

This research focuses on the development of the Ground Tracker and Emitter that contain three major components. a) The **Optical System:** Optics, Light Path, Spectroscopy, which concerns how the device will capture light and use this stimulus to observe the atmosphere.
b) The **Mechanical System:** The design of the structure, including supporting/aligning the optics and stepper motors which will control the movement of the device. c) The **Development of Code:** The development of the LabVIEW Code which will enable the user to easily control the movement of the tracker as well as view and record data output from the spectrometer. Eventually, the LabVIEW code will be developed using LabVIEW VISION to analyze the camera images and track the emitter, the logic of this code will be discussed.

4a. Optical System: Optics, Light Path, and Spectroscopy

The spectroscopy system will be able to perform passive (solar radiation as a spectral source) and active (an artificial spectral source, i.e. a broadband light) observations using an Ocean Optics USB 4000 UV-Vis-NIR spectrometer. When spectra are collected using an active light source, the Beer-Lambert Law and position data from the emitter package can be used to compute concentrations of observed constituents along the optical path [8]. Spectra of atmospheric gases provided by the HITRAN [10] database will be used to identify absorption bands. The Optical system employs the use of a magnifying rifle scope to enhance the emitter signal, a spectrometer to take measurements, a camera to take images and track the movement of the emitter, and an actuating mirror to direct the light path between the camera and spectrometer. Thus, the Ground Tracker will have two-phase operation in relation to the position of the mirror. In Phase 1, when the mirror is open and light is directed to the spectrometer, spectral data is collected. In Phase 2, the mirror directs light to the camera, which will take an image and determine how far the Emitter has moved since the last cycle. The Ground Tracker Optical System is shown in Fig 3 and highlights the light path during Phases 1 and 2.

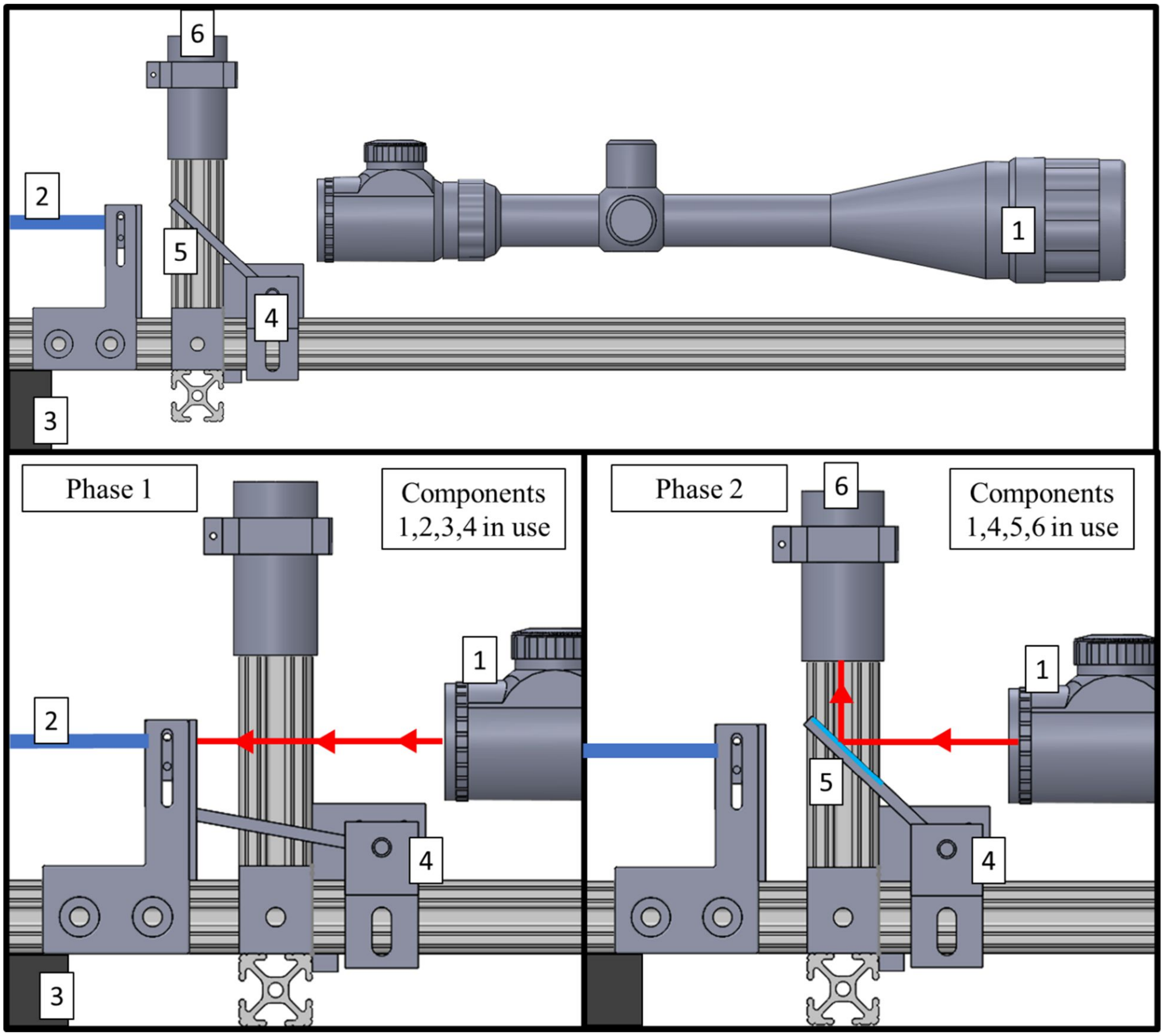

Figure 3. Ground Tracker Optical System including 1) Trinity Commander 10x40 50mm scope, 2) Fiber optic cable to spectrometer, 3) Ocean Optics USB 4000 spectrometer, 4) Nema 11 stepper motor with 100:1 gearbox, 5) 1" x 1" mirror for directing scope image to Microsoft Life Cam Video camera, 6) Microsoft Life Cam video camera . Figure created by author.

Spectrometers use an optical grating or prism to separate incoming light into its different wavelengths and measure the intensity at each wavelength. The Ocean Optics USB 4000 UV-Vis-NIR spectrometer will be used in our design. This spectrometer includes a built-in Toshiba TCD1304AP Linear CCD (Charged Coupled Device) which detects the amount of incoming light according to wavelength. In our setup, light passes through the rifle scope and fiber optic cable, entering the USB 4000 spectrometer at the Connector, a in Fig 4. The light then passes through several components that include: a filter, collimating mirror, grating, and focusing mirror before being cast onto the linear CCD. The linear CCD contains 3648 pixels which absorb different wavelengths of light, offering high wavelength resolution within the range of 350-1050 [nm]. Before measurements are taken, the spectrometer must be calibrated using a light source which produces 4-6 spectral lines of known wavelengths. Wavelength calibration coefficients can then be calculated and stored in an EEPROM on the spectrometer which will be later referenced in the LabVIEW code to assign a wavelength to each pixel on the CCD sensor.

The optical system assembly can be seen in Fig 5. The actuating mirror (4) is attached to the gearbox (ratio of 1:100) shaft of the Nema 11 stepper motor. The entire assembly must be aligned so that the aperture of the fiber optic cable is colinear with the rifle scope and coincident

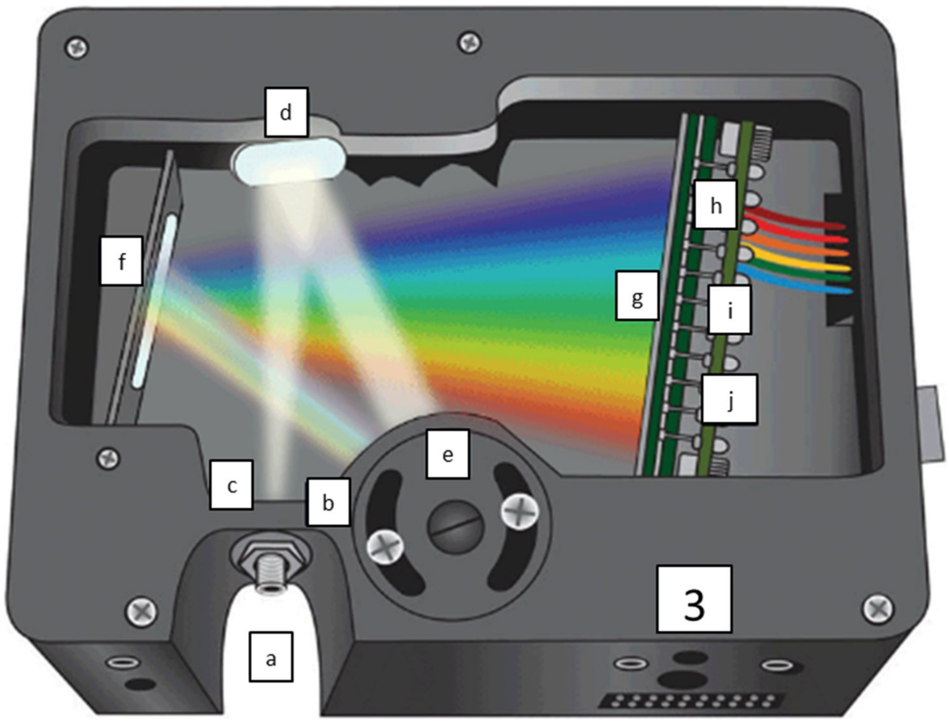

Figure 4. 3) USB Spectrometer internal light path. Figure created by manufacturer, Ocean Optics [11].

with the focal plane of the rifle scope. The video camera must be aligned so that the image is centered and in focus. Once the actuating mirror is calibrated to the correct angle for Phases 1 and 2, the mirror will oscillate precisely between these positions.

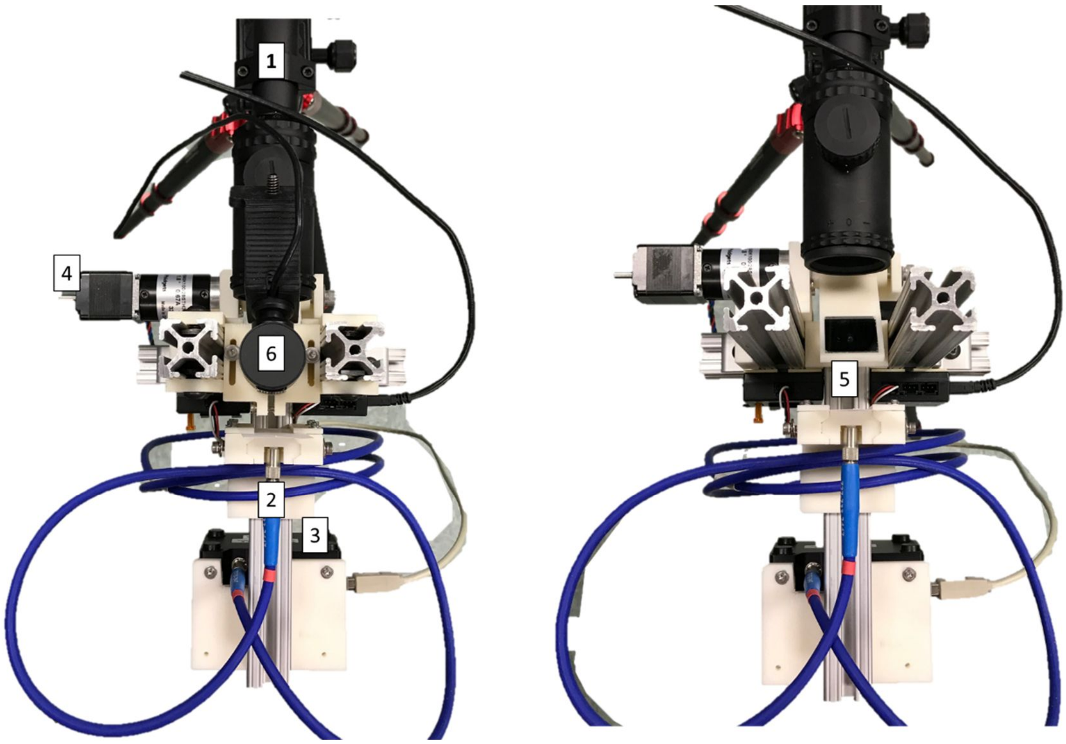

Figure 6. Optical System assembly shown. including 1) Trinity Commander 10x40 50mm scope, 2) Fiber optic cable to spectrometer, 3) Ocean Optics USB 4000 spectrometer, 4) Nema 11 stepper motor with 100:1 gearbox, 5) Actuating mirror shown by removing video camera 6) Microsoft Life Cam video camera. Figure created by author.

The alignment of the optical system is very important for acquiring data. If the fiber optic cable is misaligned, the maximum sensitivity of the instrument will be reduced, requiring greater integration times. The alignment procedure includes aligning the scope with the emitter creating a projected light through the ocular lens of the scope. Inserting a sheet of paper into the front slit on the front face of the fiber optic support, the scope image can be seen projected on the paper. The fiber optic support can then be aligned so that the scope image becomes a very small dot on the paper. When the diameter of this dot is minimized, the fiber optic support is located at the correct focal length from the scope, nominally 3.5 in [88.9mm]. The aperture of the fiber optic cable can then be aligned to this dot within the plane of focus. The fiber optic cable is a QP400-2-UV-VIS premium-grade patch cord by ocean optics. The fiber core diameter is 400 [μm] and the field of view is approximately 25°, enough to collect the entire scope image. Each time the Ground Tracker is deployed, ground truth data should be taken to properly calibrate the instrument. The Emitter Gimbal was outfitted with an LED Flashlight (Tasco XR8 Focus Beam 400 Lumen) to take ground truth data. Emittter Gimbal was placed on a tripod and the flashlight and optical system of the Ground Tracker were aligned collinearly, facing each-other. This could be verified by using the web-camera to align the crosshairs to the center of the flashlight.

For a field test of the Ground Tracker, moon spectra will be taken during a full moon. The following procedure outlines Once the optical system was aligned, the integration time of the spectrometer was adjusted so that the maximum observed value counted by the spectrometer is approximately 85% of the maximum possible output value. An integration time of 1s was used to produce an observed maximum value near 52,000 counts which is 79% of 65,536 counts and therefore offers a high SNR. The Moon spectrum captured by the Ground Tracker ranges from about 400 to 900 nm in the Visible spectrum. Each time the Ground Tracker is deployed, ground truth data should be taken to properly calibrate the instrument. The Emitter Gimbal was outfitted with an LED Flashlight (Tasco XR8 Focus Beam 400 Lumen) to take ground truth data. Emittter Gimbal was placed on a tripod and the flashlight and optical system of the Ground Tracker were aligned collinearly, facing each-other. This could be verified by using the web-camera to align the crosshairs to the center of the flashlight.

4b. Mechanical System

The Gound Tracker is composed of two rectangular shaped frames accommodating two high accuracy Nema 21 stepper motors with 1:77 gearboxes controlling the azimuth and elevation of the optical system as seen in Fig 6. The Optical System is supported by standard extruded aluminum beams known as 8020 T-Slots. These are lightweight members which can be easily reconfigured with bolts and nuts using friction connections.

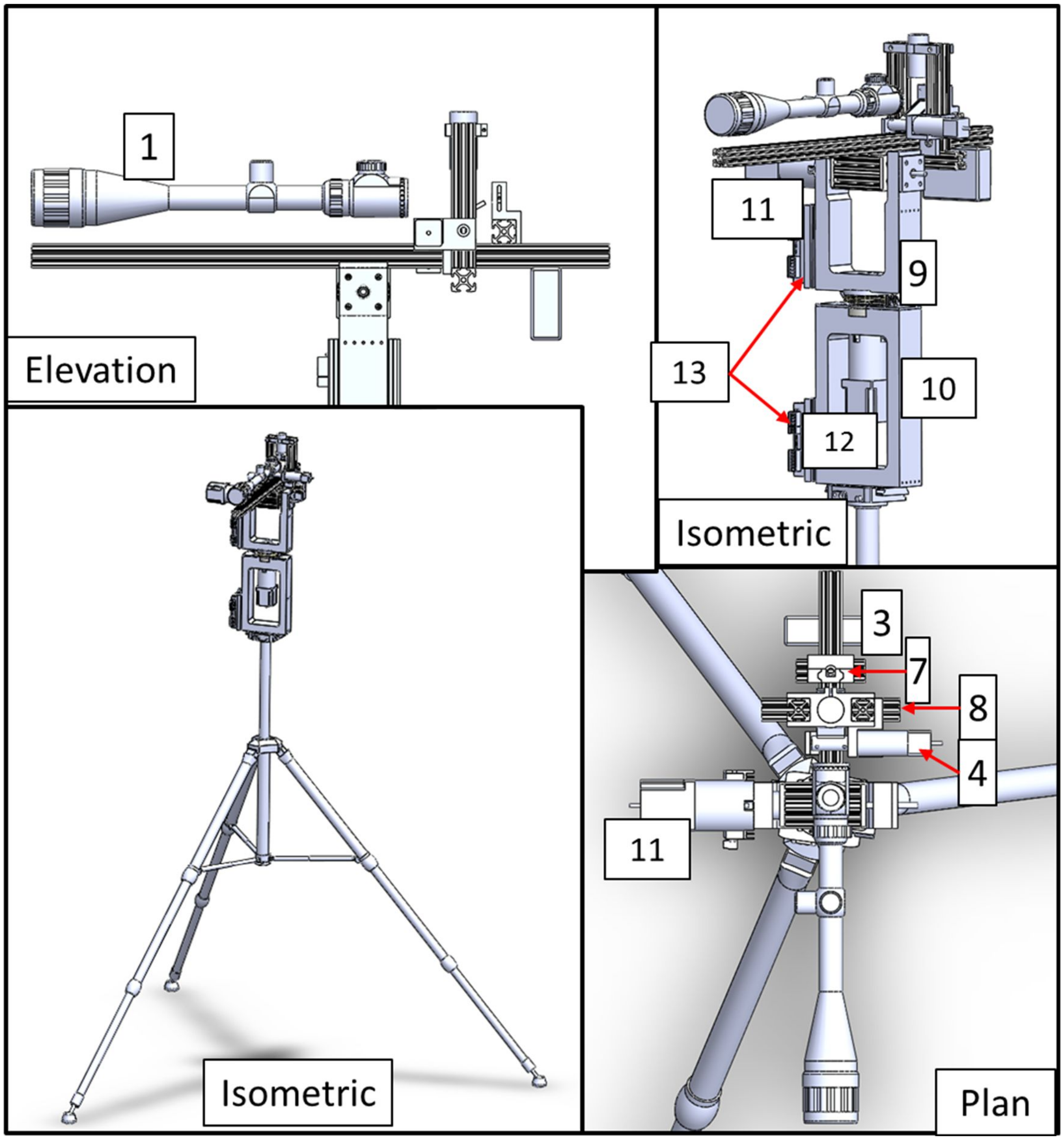

Figure 6. Ground Tracker model. 1) Trinity Commander 10-40 x 50mm scope. 3) Ocean Optics USB 4000 Spectrometer 4) Nema 11 with 1:100 gearbox for mirror control. 7) Fiber optic cable support 8) Frame for Microsoft Life Cam 9) Upper Frame 10) Lower Frame 11) Nema 21 with 1:77 gearbox for elevation control. 12) Nema 21 with 1:77 gearbox for azimuth control. 13) Stepper motor drivers. Model created in SolidWorks by author and P. Huang.

The ground-tracker mechanical system is still under development but is essentially identical in function, though much larger than the current Emitter Gimbal prototype seen in Fig 7. The Emitter Gimbal is responsible for aligning the light source to the Spectrometer based on location data provided by an onboard GPS and the known location of the Ground Tracker. While the first prototype will only be used for terrestrial measurements, a miniaturized version will be developed for use with weather balloons.

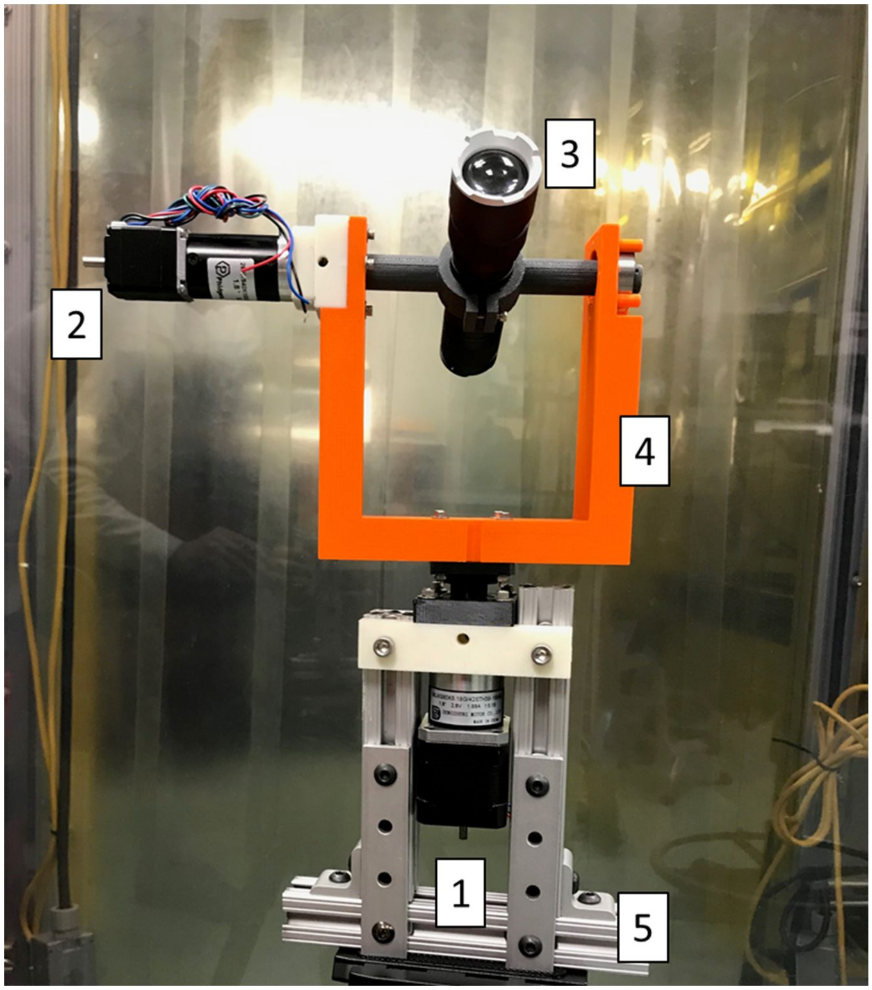

Figure 7. Emitter Gimbal Prototype for terrestrial measurements. 1) Nema 17 stepper motor 1:5.18 gear ratio responsible for azimuth control, 2) Nema 11 stepper motor 1:100 gear ratio responsible for elevation control, 3) Tasco XR8 Focus Beam 400 Lumen LED Flashlight, 4) 3D Printed U Frame, 5) 1" width 8020 T-slot. Designed and fabricated by author.

4c. Development of Code

Code for acquiring data from the spectrometer and controlling instruments such as the camera, mirror motor, and spectrometer were written in LabVIEW (National Instruments [13]) a graphical programming software. In LabVIEW, programs are known has Virtual Instruments (VI's). Sub VI's are blocks of code with inputs and outputs that can be nested within other VI's to perform certain tasks. National Instruments publishes several sub VI's that are compatible with commercially available devices, such as the Microsoft web camera and the Ocean Optics USB 4000 spectrometer. Phidgets Inc. produced the sub VI's for controlling the stepper motors. These sub VI's are the building blocks for the code used by the Ground Tracker. Each sub VI has a number of inputs and outputs which may take the form of strings, numbers, or Boolean logic. These sub VI's can be wired together including other logic gates, inputs, local variables, and loops to accomplish the process of controlling the device and taking and recording data. The logic is built on a virtual interactive schematic known as the block diagram. The front panel, which acts as the user interface while the program is running is seen in Fig 8. The Ground Tracker LabVIEW code includes controls and displays for the spectrometer, motor, and video camera.

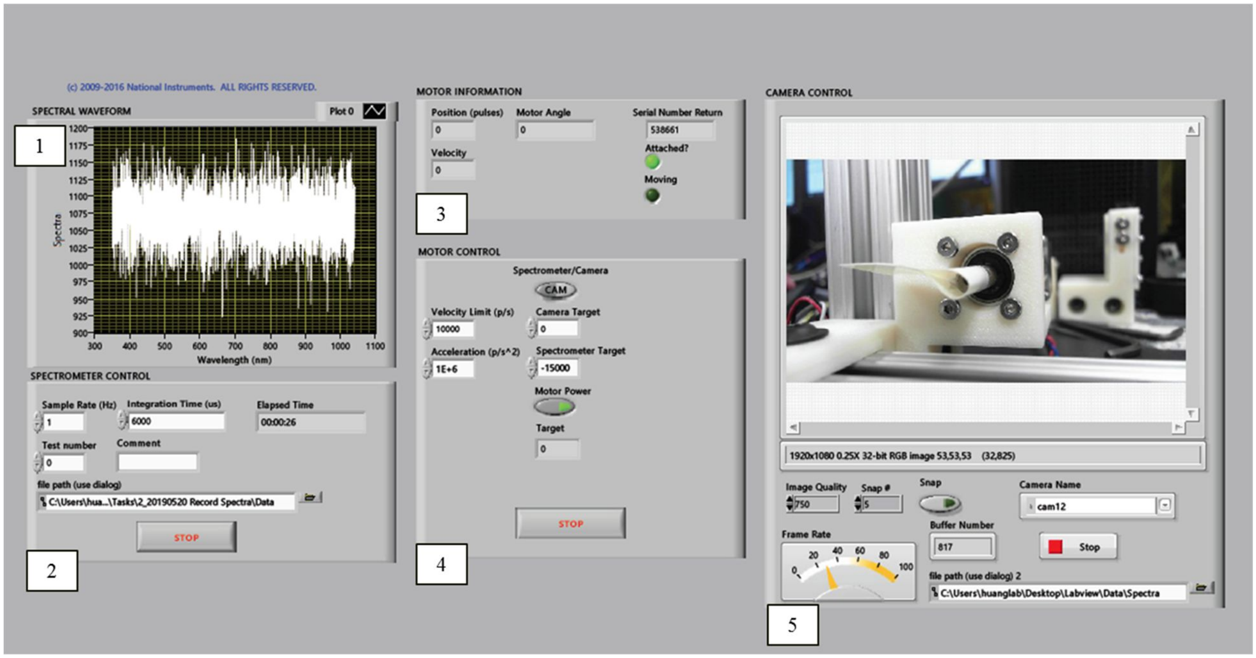

Figure 8: Ground Tracker LabVIEW code front panel. Each panel (labeled 1-5) is responsible for controlling and/displaying data for a specific device. 1) The Spectral Waveform with the spectra taken by the spectrometer in wavelength [nm] x-axis and spectra y-axis Note: Spectra is output as 16 bit value from spectrometer 2) The Spectrometer control allows for the control of the sample rate [Hz] and integration time [µs]. The display also includes the elapsed time from the beginning of the experiment and includes a number entry for the test number. A comment string is available to append information to the file name, as well as the file path input. 3) The Motor Information displays information about the stepper motor including absolute position of the motor (starting at 0 each time the program restarts), velocity, motor angle, serial number return from VISA device, and indicators if the motor is attached or moving. 4) The Motor Control includes inputs to specify motor velocity, acceleration, power to the motor and control the absolute position for Phase 1: spectral reading and Phase 2: camera, and switch between the two phases. 5) Camera Control displays the Microsoft LifeCam image and allows the user to take snapshots and save the snapshots to a designated file path.

The front panel also includes initialization data for the motor and spectrometer, which includes entry for GPS coordinates of the measurement. A complete description of the Ground Tracker Code block diagram can be found in the Appendix.

LabVIEW Vision is a graphical programming software that enables image acquisition and analysis. Images can be searched to located objects based on criteria such as shape or color. Once images of the emitter light are taken, this shape and color data can be used to locate the same light in other images. Our Vision code will be programmed to locate the position of the emitter within the scope by color relative to a set datum, this position will be used to send pulses to the stepper motors to realign the scope. A graphical description of this logic can be seen in Fig 9. This process will take place during time step two and Phase 2, when the mirror directs the scope image to the Microsoft Life Cam video camera.

Time Step	1	2	3
Data Collected	(X,Y,Z) Data Collected From Tracker and Emitter. Phase 1: Specral Data Collected	Phase 2: Image acquired	-
Calculations/ Action	Optical Path (L) Calculated – Distance between Emitter and Tracker	Displacement from Scope Origin observed, using scope magnification factor and L, actual displacement is calculated	Differentiation in Azimuth (φ) and Elevation (θ) calculated, converted to pulses and sent to steppers

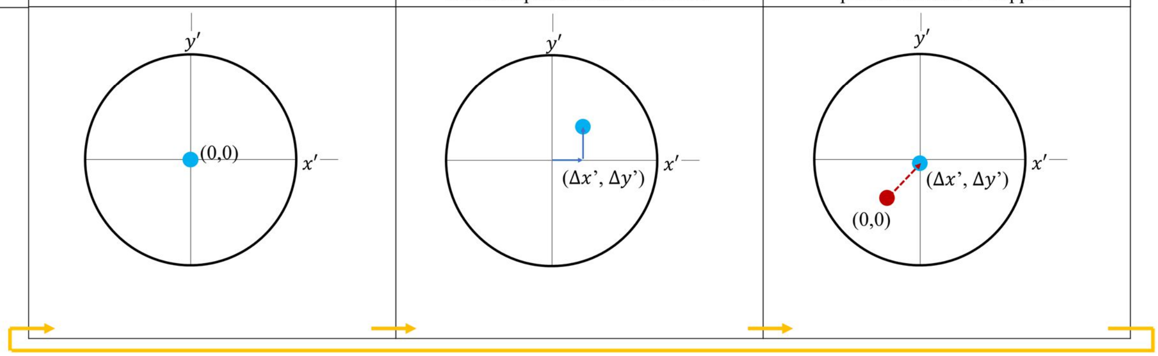

Figure 9: Logic for aerial-tracking code.

5. Results and Discussion

To test the operation of the Ground Tracker, spectrum was taken of the full moon on June 17, 2019. Several steps were taken to ensure the success of the experiment and accuracy and repeatability of the data. 1) The spectrometer mount was aligned so that the aperture of the fiber optic cable is coincident with the focal point of light projected from the rifle scope. 2) Ground Truth data was recorded using a light source with known spectrum and intensity, distance to the source and integration time of the spectrometer were recorded. 3) Acquiring the moon in the scope using the camera, then lowering the mirror and taking spectra, adjusting the integration time of the spectrometer so that the maximum values output were near 85% of maximum, this is a manufacturer specification to increase signal to noise ratio.

The spectrum in Fig 10 shows the spectrum collected of the Tasco XR8 LED flashlight at a distance of 25 ft [7.62m] measured from the flashlight lens to the objective lens

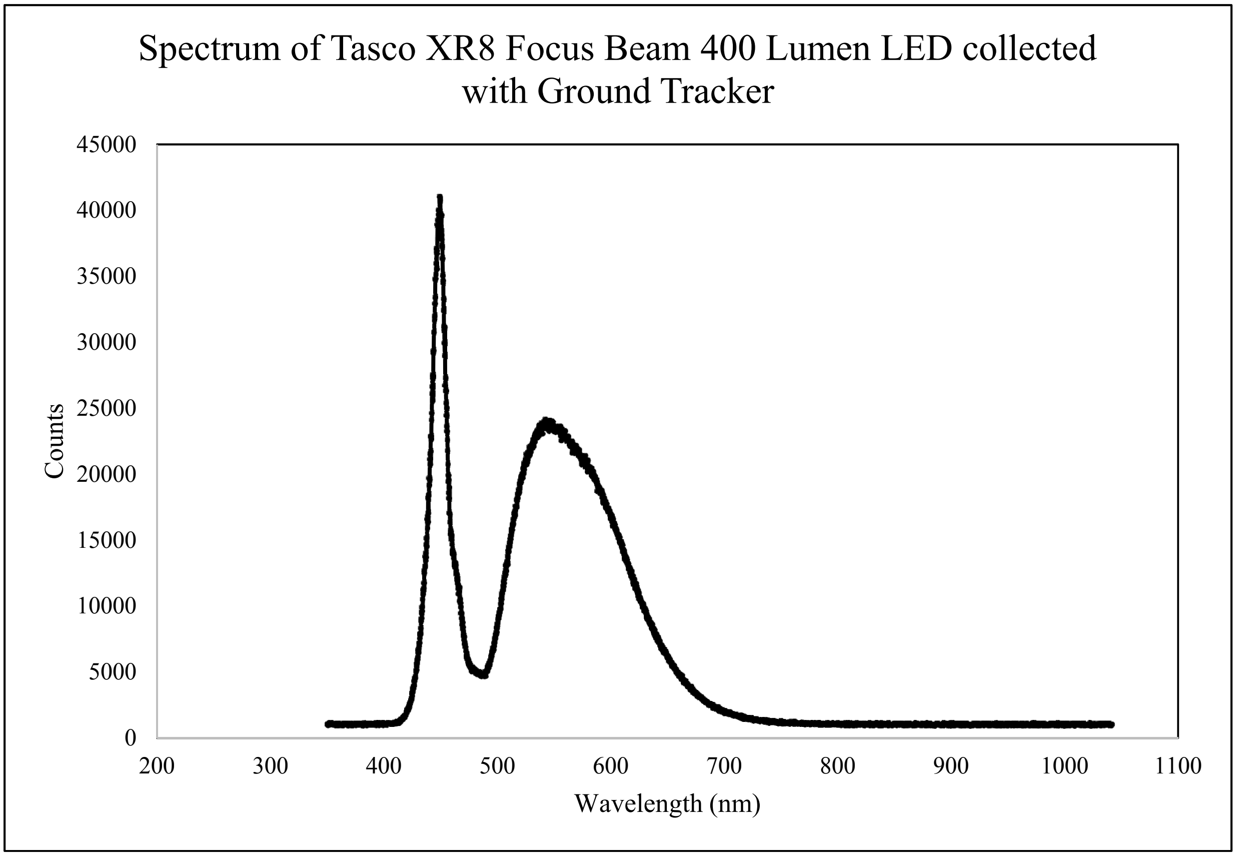

Figure 10: Spectrum of Tasco XR8 Focus Beam 400 Lumen LED at full focus at a distance of 25ft from the Objective lens of Rifle scope. Scope zoom set to 40x. Integration time 6000 µs taken with Ground Tracker for ground truth data on June 17, 2019.

The optical system was then aligned to the moon using the camera. A snapshot of the moon can be seen in Fig 11. The scope has a focal length of 3.5 in [8.89 mm] and an Ocular lens diameter of 1.5 in [4.06 mm]. Thus the angle of converging light is 24.2°. Since the fiber optic cable has a field of view of 25°, the entire scope image is captured by the fiber optic cable.

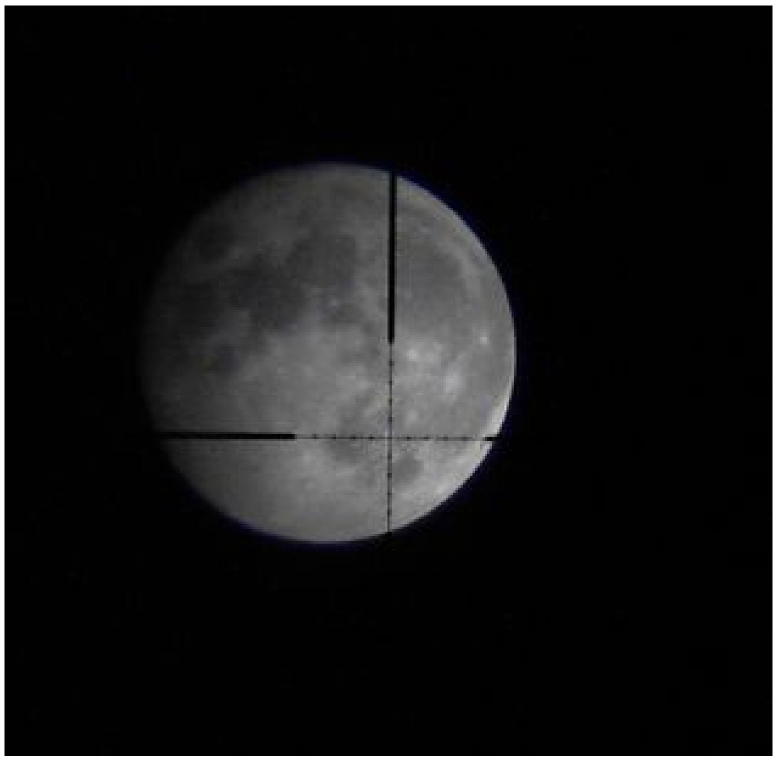

Figure 11: Snapshot of Moon June 17, 2019 using Ground Tracker.

Several absorption lines can be observed in the spectrum shown in Fig 12.

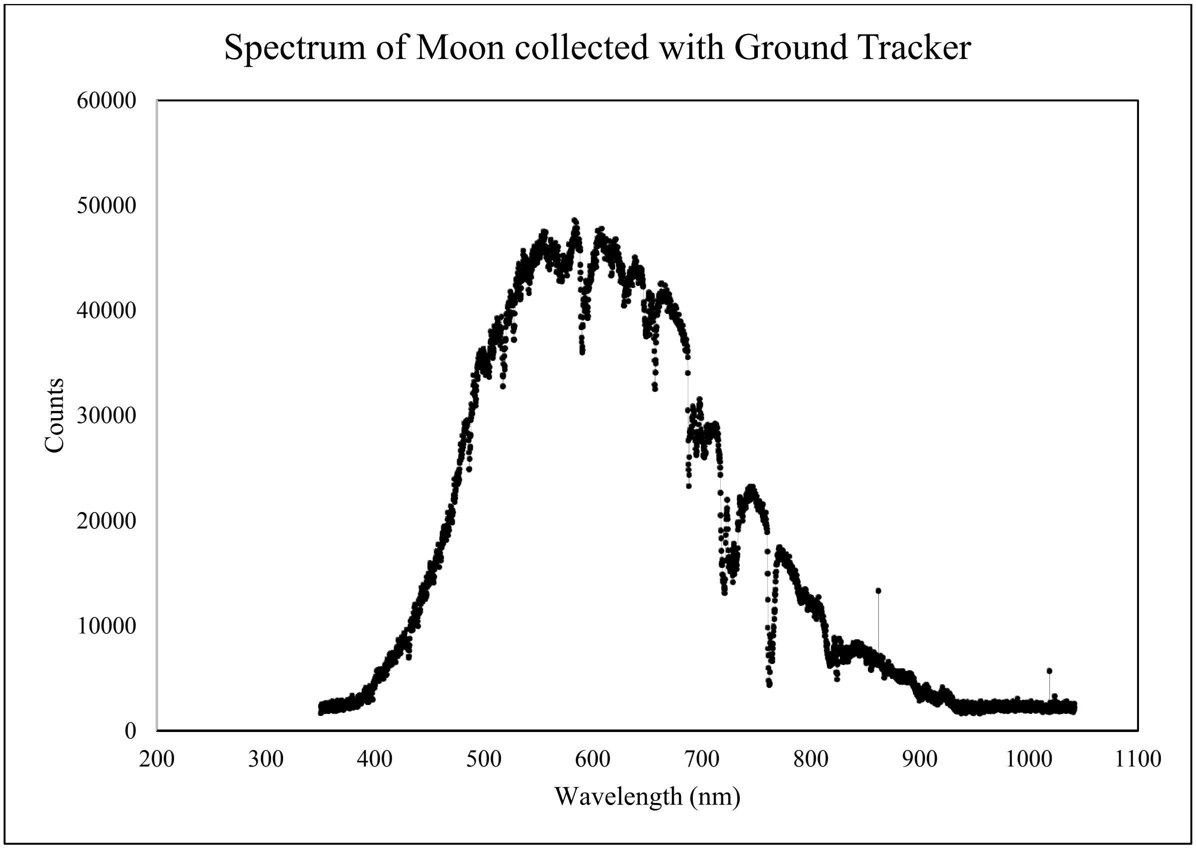

Figure 12: Moon Spectrum at Geographical Location: 36.0425875, -94.1663302 (Engineering Research Center, University of Arkansas) on June 17, 2019 at 11:117 PM CST. Integration Time 1 s.

6. Conclusion

A ground-based aerial-tracking instrument, known as the Ground Tracker, designed to provide spectral data to quantify greenhouse gases is under development. The Ground Tracker includes an Optical System including a high power rifle scope, video camera, and spectrometer used to locate an active light source from the Emitter, and collect spectral data by utilizing an actuating mirror. The implementation of this instrument could be made low cost by utilizing existing weather balloon infrastructure to allow the Emitter to be placed into the lower stratosphere. The recovery of the emitter will be possible by tracking the GPS coordinates. Weather balloon instrument packages contain shipping instructions and postage for those packages that go beyond GPS range or are lost. The Ground Tracker and Emitter Gimbal, while not ready for implementation, demonstrate the feasibility of a spectroscopy system that could provide important data for climate observation and modeling at temporal and spatial resolutions not currently available to state-of-the-art satellites. Going forward, the moving frame for the Ground

Tracker should be completed. Additional hardware will be required on the Ground Tracker including a power supply, small onboard computer, and radio communication to the Emitter.

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Appendix

Section 1: LabVIEW Code

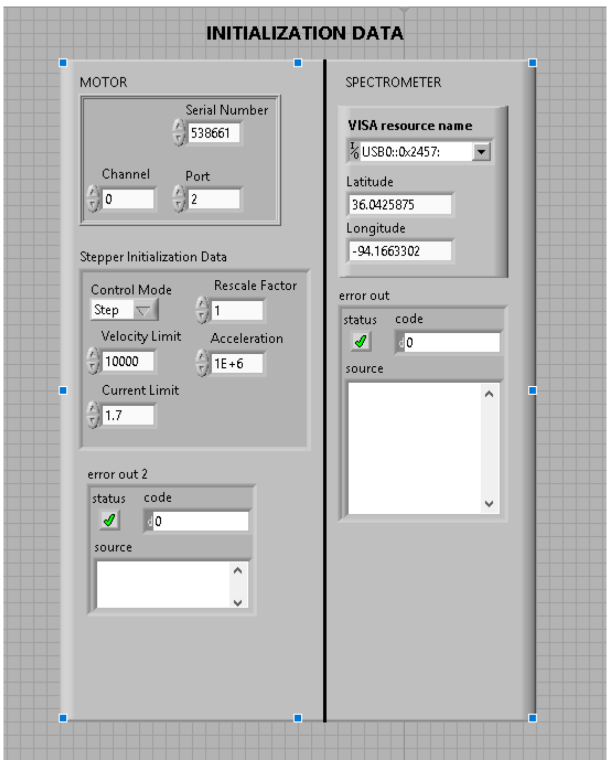

Figure A1: Front Panel initialization data for motor and spectrometer.

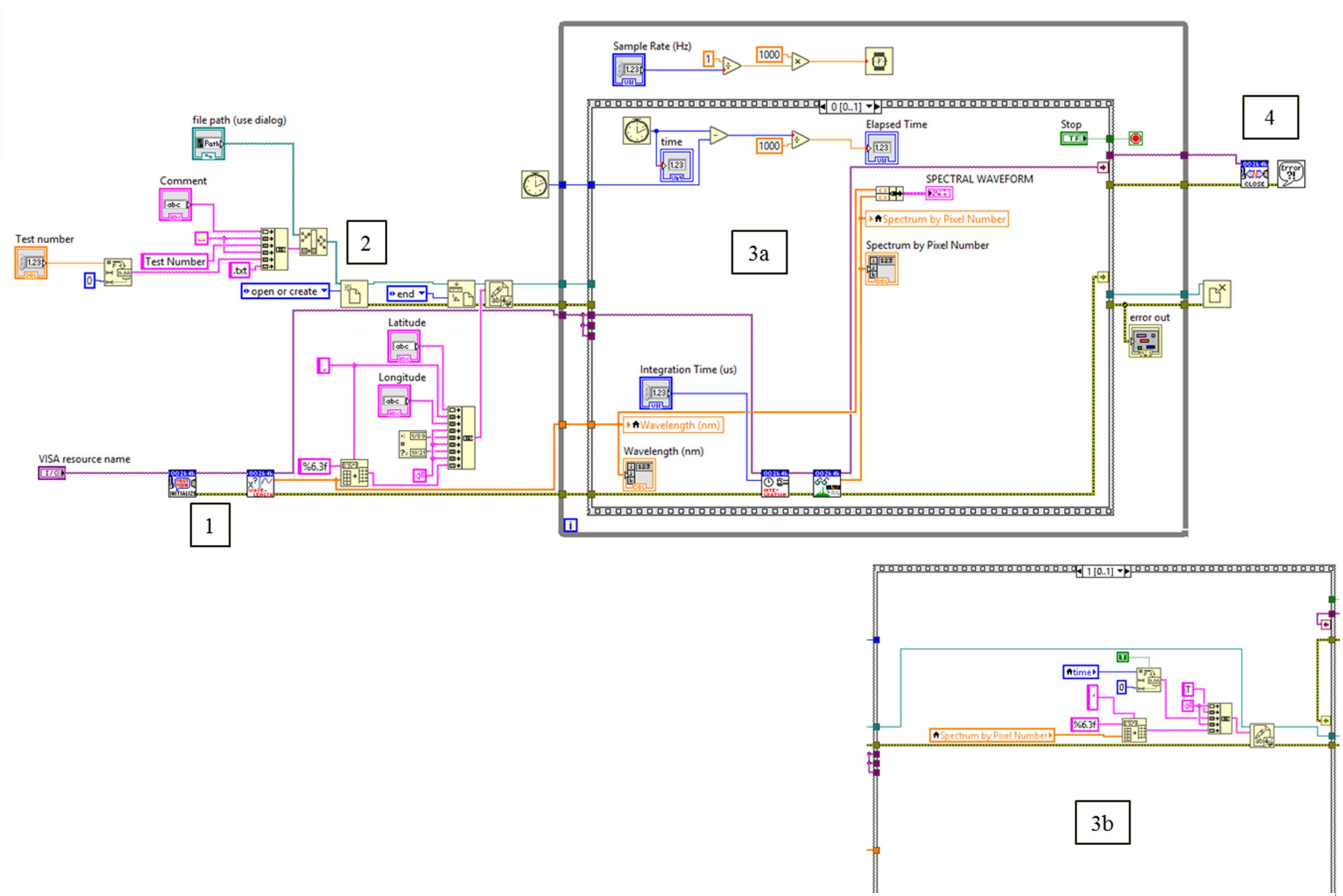

Figure A2: The first section of code is the spectrometer code. Outside of the while-loop is 1. initialization procedure for the spectrometer and 2. Creating and naming text file for recording data. Once inside the loop, 3a., a flat sequence structure is used to take spectra, display the spectra and create the local variables spectrum, and time which are written to the text file in 3b. 4. Shutdown subVI for the spectrometer and error readout.

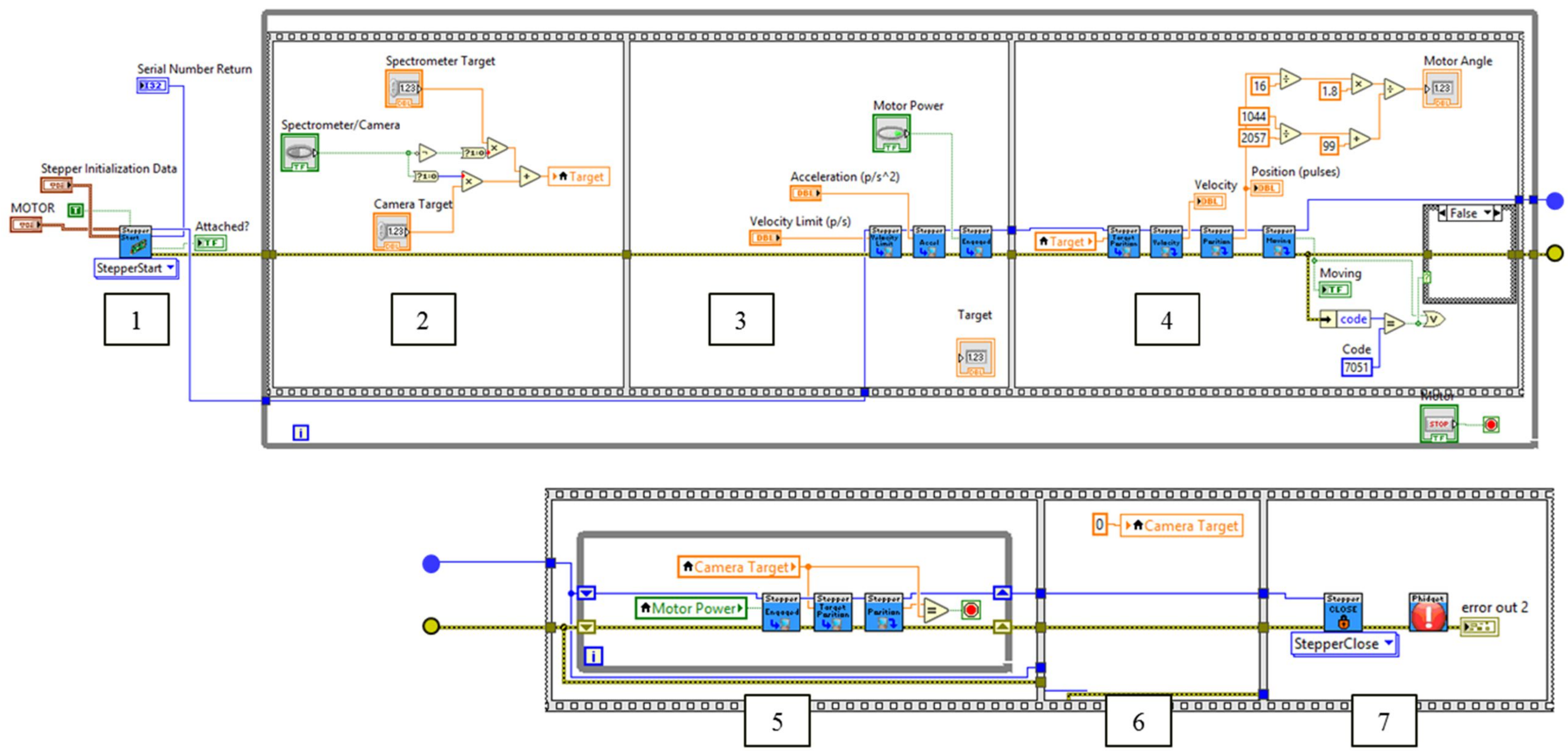

Figure A3. Labview Code for motor control. 1. Stepper Initialization Data. Inside the while loop and flat sequence structure: 2. Designation of target position for spectrometer and camera and switch for selecting desired phase. Local Variable target created. 3. Velocity and acceleration limit set, motor power enable switch. 4. Target position sent to motor controller, velocity and position feedback from motor controller, position in pulses converted to motor. 5. Once the main while loop has ended the motor returns to the camera target position. 6. Value of zero is assigned to Camera Target variable. 7. Motor shutdown procedure and error readout.

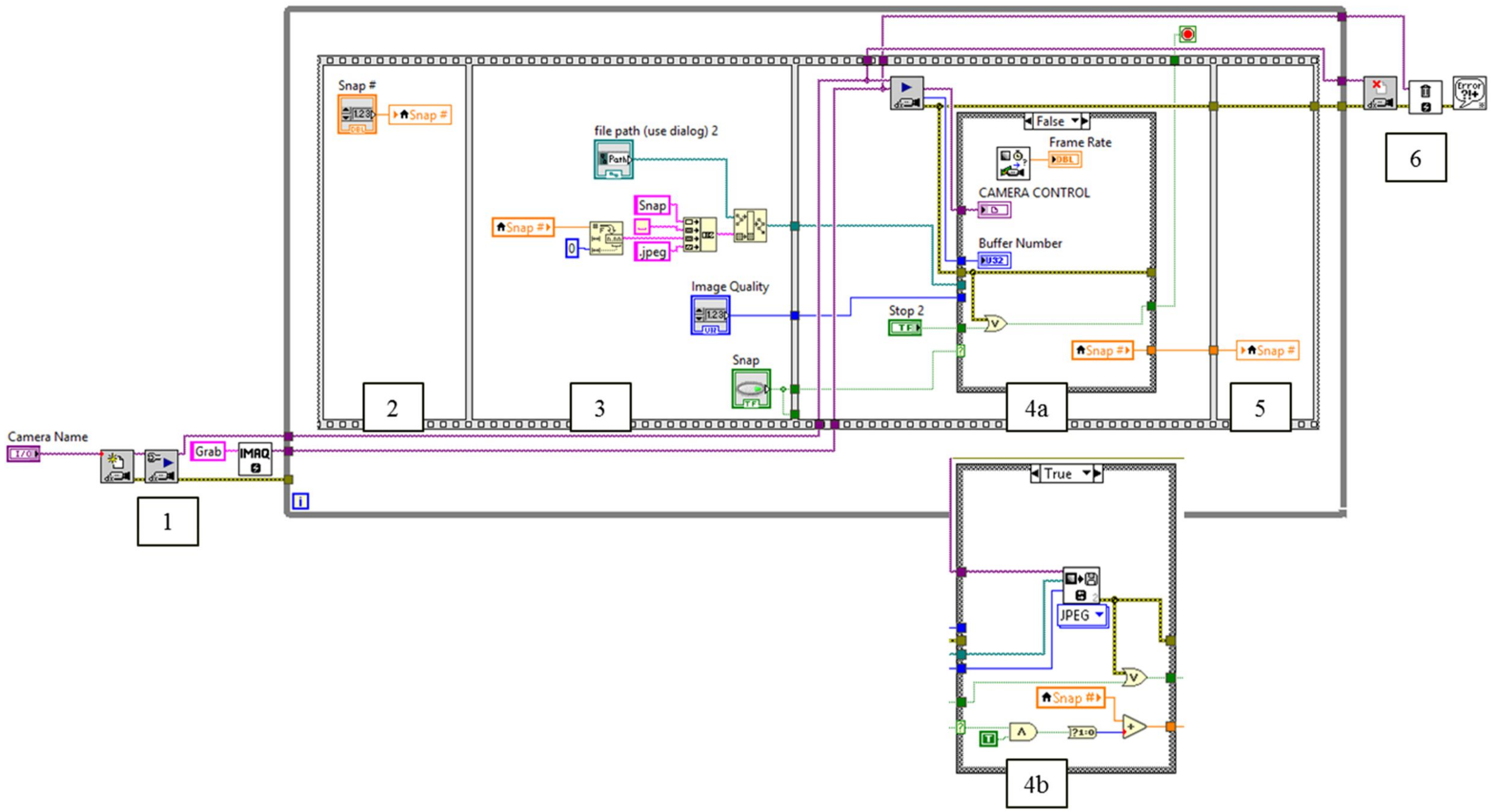

Figure A4. Labview Code for Camera control. 1. Create camera session and start a grab acquisition, which refers to continuous video capture. 2. Control for naming snaps (still images) taken. 3. File naming for snapped images and Image quality control value [1-1000]. 4a. Case structure input False, when not taking a snap, video is output to front panel display. 4b. Case structure input True, snap saved as JPEG file. 5. snap number variable incremented by 1 if snap was taken in previous frame. 6. Video camera close procedure and error output.