Spectral Calibration of the USAFA 1-Meter for GEO Satellite Spectral Signatures

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Abstract

The Center for Space Situational Awareness Research (CSSAR) at the United States Air Force Academy (USAFA) has developed techniques to characterize and identify satellites since 2014 using a 16-inch telescope (USAFA-16) on campus as well as off-campus telescopes which comprise the Falcon Telescope Network (FTN). Specifically, USAFA has developed calibration techniques to enable identification of geosynchronous satellites through photometry, slitless spectroscopy and the polarization of satellites. USAFA recently acquired a 1-meter telescope (USAFA-1m), and in this paper, we report on the effort to calibrate USAFA-1m for spectroscopy. After the spectroscopy calibration, the USAFA-1m telescope was envisioned to be capable of satellite characterization akin to that of the FTN, but with greater resolution, a larger focal plane, and greater overall capabilities. The greater resolution and larger focal plane, however, presented unforeseen challenges. We expect the USAFA-1m telescope will be capable of furthering USAFA's research into the characterization of geosynchronous Earth orbit (GEO) satellites based on their spectra, furthering our SDA efforts and our ability to develop new techniques to identify orbiting objects in our space domain.

1. Introduction

Slitless spectroscopy using diffraction gratings has been a mainstay of observations of GEO satellites and research conducted by USAFA's Center for Space Situational Awareness Research (CSSAR) for many years [1-5]. The telescopes deployed in CSSAR's FTN are all 0.5-meter f/8 while the USAFA-16 on-campus telescope is 0.4-meter f/8 using 100 lines/mm diffraction gratings for slitless spectroscopy. All these telescopes use either an Andor Alta U47 or F47 CCD camera. The processing pipeline established to analyze the resulting slitless spectroscopy images is well established [4,5]. USAFA also has a 1-meter telescope (USAFA-1m) equipped with a Spectral Instruments E2V CCD sensor dedicated to research in space domain awareness (SDA) and astronomy. Before beginning routine slitless spectroscopy operations, the USAFA-1m telescope and specifically the diffraction gratings will require determination of its pixel-to-wavelength conversion. The next sections will briefly describe the experimental method and USAFA-1m results using both a 200 lines/mm diffraction grating and a 720 lines/mm diffraction grating. The final section will expand on CSSAR's intentions for future research with the USAFA-1m telescope.

2. Experimental and Sensor Details

Fig. 1 is a picture of the USAFA-1m telescope. Details pertaining to the telescope and camera system are listed below.

- Telescope manufacturer: Astro Systeme Austria
  - OTA design: Ritchey-Chrétien
  - M1 diameter: 1 meter
  - F-number: f/6 (effective)

    - Mount: Fork equatorial
- Camera manufacturer: Spectral Instruments
    - Focal plane array: 9216 × 9232 pixel (16 sectors)
    - Plate scale: 0.34"/pixel (10mm pixel pitch)
- Filters:
    - Photometric: Johnson-Cousins UBVRI
    - Diffraction gratings: 200 lines/mm; 720 lines/mm
    - Polarization: P0, P45, P90, P135 (0°, 45°, 90°, 135° relative to camera focal plane)
- Field-of-View: ~52” × 52”

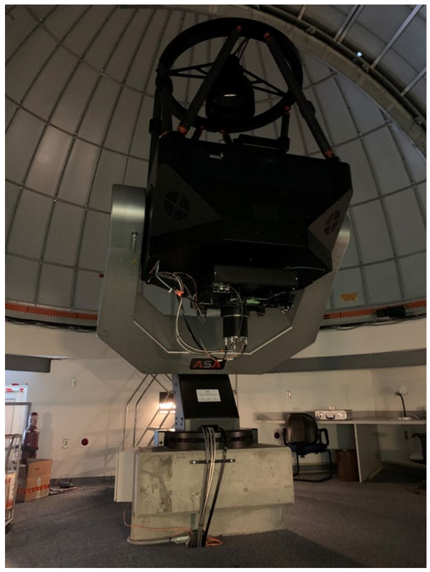

Fig. 1. The USAFA-1m telescope.

The spectroscopy calibrations will utilize a method established and proven on the USAFA-16 and FTN telescopes, which involves the capturing of spectral images for celestial bodies with known absorption or emission features and determining a pixel-to-wavelength conversion based on the pixel distance between the zero- and first-orders of the diffraction grating image [1, 2]. This conversion can then be applied to GEO satellite images to display the spectra as a function of wavelength. Comparing the satellites’ spectra with a solar analog or with each other can provide insight into qualities of the satellite such as material and color. Additionally, during glint season, the spectral signatures of satellites observed from the USAFA-1m are expected to produce distinct, identifiable profiles which can aid in the classification of the satellite’s orientation and purpose.

The majority of light that comes from satellites is attributed to sunlight reflecting off the various surfaces as shown in Fig. 2. As the reflected light passes through the diffraction grating prior to the camera’s focal plane, it results in an interference pattern. The zero-order is the central bright spot that passes straight through to the focal plane and remains a point source, whereas the first order corresponds to that portion that diffracts equally to both sides of the zero-order. However, a diffraction grating can be manufactured such that the majority of the incident light is preferentially diffracted to one side of the zero-order compared to the opposite side; this is known as the blaze angle. Fig. 3 shows examples of a transmission grating image taken with the USAFA-1m telescope using both the 200 lines/mm and the 720 lines/mm gratings. In both cases, the first-order spectra below the zero-order is the “blazed” order. Additionally, the second-order is also present and a fanning out of the diffraction orders more distant from the zero-order is evident. This fanning out is caused by the curved focus of the higher orders and were not previously observed with FTN images due to the coarser grating (100 lines/mm) and the smaller sized focal plane.

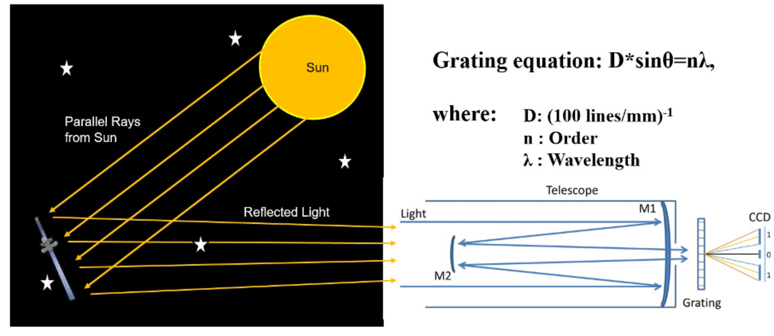

Fig. 2. Image shows the imaging scenario between the sun, the satellite, and the observer. Light reflects off the satellite, goes through the telescope where it passes through the diffraction grating. The light is then spread out onto the focal plane based on the grating equation.

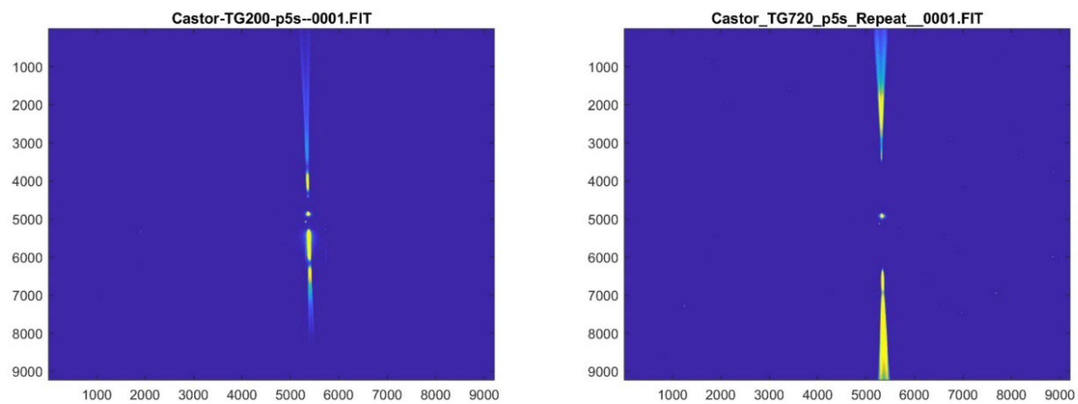

Fig. 3. USAFA-1m telescope 0.5-s exposures of Castor on 2023 Feb 25 using the 200 lines/mm grating (left) and 720 lines/mm grating (right).

Fig. 4 demonstrates how the focus position of the telescope affects the resulting CCD images by plotting images of the same star for the 720 lines/mm grating while varying the focus. One obvious difference in the resulting higher orders depends on whether the imaging camera is inside or outside the telescope's focal length. Traveling left of the center image, the camera is inside the focus, whereas the images on the right correspond to the camera located outside the focus. The characteristics of the diffraction grating (e.g., the number of lines per mm) and its orientation with respect to and distance to the camera focal plane plays a major role in the resulting higher orders.

Fig. 5 illustrates this focusing effect for the zero-order in focus (green) and the zero-order focus both in front of the focal plane (red) and beyond the focal plane (blue). The widening of the higher orders is the result of the focus of the curved wavefront of these orders on the large format CCD. Fig. 5 illustrates that when the zero-order is inside the focus as indicated in red, the first order will never be in focus. If the zero-order is outside the focus as indicated in blue, the first-order will neck down to a pinch point. Red arrows in Fig. 4 indicate how the "pinch point" for the higher orders moves further away from the zero-order as the zero-order becomes more out of focus. Finally, when the zero-order is at focus (as indicated in green), the first order will gradually diverge.

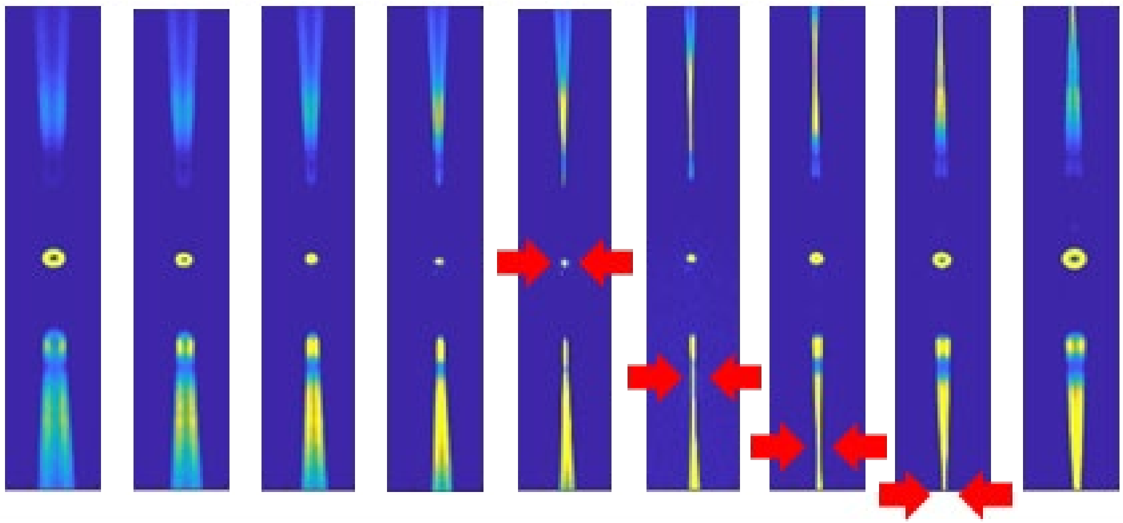

Fig. 4. Images of zero and higher orders of Castor using USAFA 1-m telescope and 720 lines/mm grating (2023 Feb 25). The center image shows the zero-order in focus, while the images left and right of the center image shows how the higher orders are affected when we defocus in either direction. The lefthand images are when the zero-order is inside the focal length while the righthand images correspond to when the zero-order is outside the focal length.

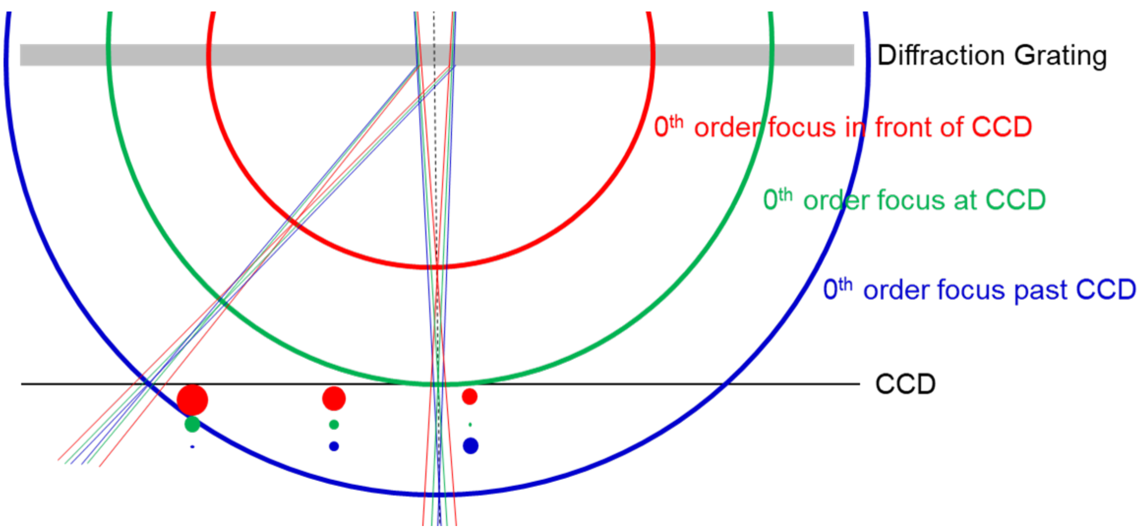

Fig. 5. First-order focusing issue for large-format CCDs when zero-order is in focus (blue), the first-order is more and more out of focus the further from the zero-order it is. By focusing the zero-order past best focus (orange), more of the first-order can be put into focus.

For spectroscopy calibrations this focusing issue poses a problem. An out-of-focus first-order makes observations of the absorption or emission features difficult or impossible. The issue is more pronounced with the 720 lines/mm grating due to the first-order being further removed from the zero-order, increasing the difficulty of determining the pixel-to-wavelength conversion. Fig. 6 displays the profile of the blazed and unblazed spectrum on opposite sides of the zero-order when the zero-order is in focus (top), as well as the next two images when the focus sweeps through the first-order. Across these three examples, the only situation where the absorption features are clearly visible in the first-order is when the focus is in between the first and second orders.

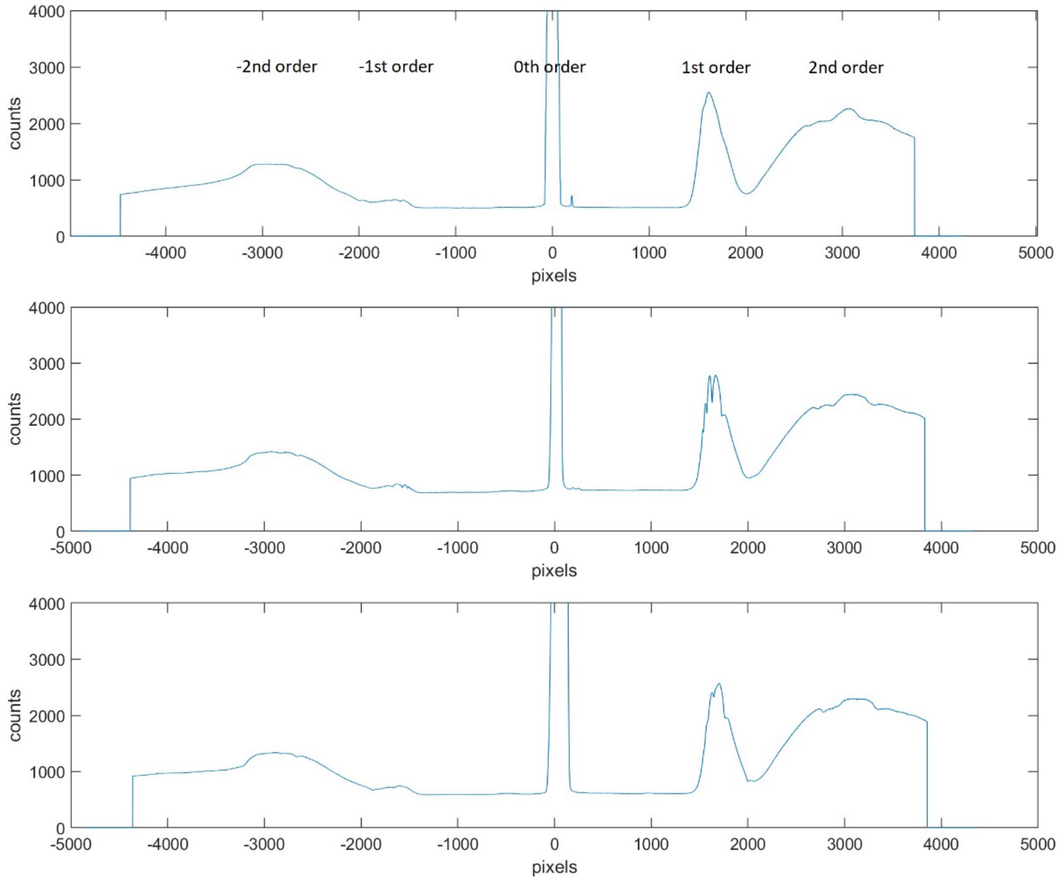

Fig. 6. Extracted spectra for Castor images (0.5-s exposures) at three different focuses. Zero-order in focus (top), between first and second orders in focus (middle), end of second order in focus (bottom).

3. Results

The existing CSSAR spectroscopy pipeline code was modified slightly to process and evaluate the slitless spectroscopy images obtained by the USAFA-1m telescope using both the 200 lines/mm diffraction grating and a 720 lines/mm diffraction grating. Images were evaluated with the results presented here. Modifications to the code were required to accommodate the USAFA-1m telescope's larger field-of-view and different wavelength-to-pixel conversion.

Four calibration stars were observed on UT 2023 Feb 25 using the 200 lines/mm grating. Three of the calibration stars were A-type spectral stars (HIP33018, HIP37811 and HIP38722), but had weak absorption features. The fourth star (HIP33165) is a Wolf-Rayet star with known emission lines. Fig. 7 shows a sample image using the 200 lines/mm grating with the USAFA-1m telescope. Note the grating's physical size is smaller than the CCD, so only the center portion of the CCD is illuminated. Fig. 8 displays a sample resulting pixel-to-wavelength calibration (for HIP33165), where the average slope is 0.827 ± 0.004 nm/pixel and average offset is 17.8 ± 3.0 nm.

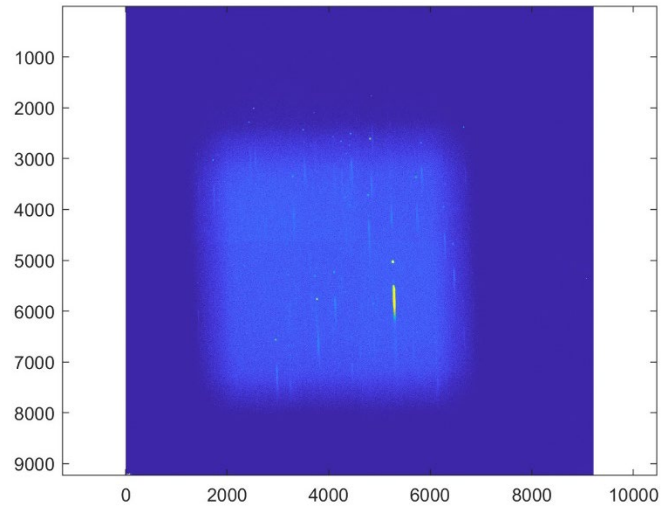

Fig. 7. Image of HIP33165 using the USAFA-1m telescope and 200 lines/mm grating.

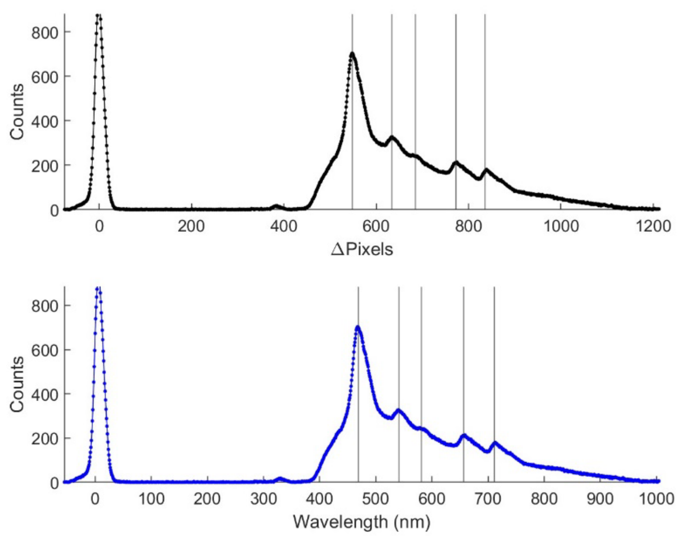

Fig. 8. The spectrum of HIP33165 in pixel space (top plot) and wavelength space (bottom plot) for the 200 lines/mm diffraction grating on the USAFA-1m telescope.

Despite the greater resolution, however, the resulting spectra for the USAFA-1m telescope system are decidedly of poorer quality than spectra obtained by the FTN and USAFA-16 telescopes. For example, the USAFA-16 spectra were taken with a 100 lines/mm diffraction grating and an Andor Alta U47 CCD camera resulting in a plate scale of 0.8 arcsec/pixel with a pixel pitch of 13µm. Fig. 9 compares the resulting spectra obtained the same night by the USAFA-16 telescope to that of the USAFA-1m telescope for the G2V-type star HIP51993. Of particular note is the atmospheric molecular oxygen absorption feature at 760 nm which is prominent in the USAFA-16 spectra but not visible in the USAFA-1m spectra. We speculate that the focusing effect between the zero-order and first-order for the USAFA-1m telescope is cancelling the benefit of having a finer diffraction grating and supposedly higher resolution. The larger diameter, however, enables the spectra of fainter objects to be obtained with shorter exposure times.

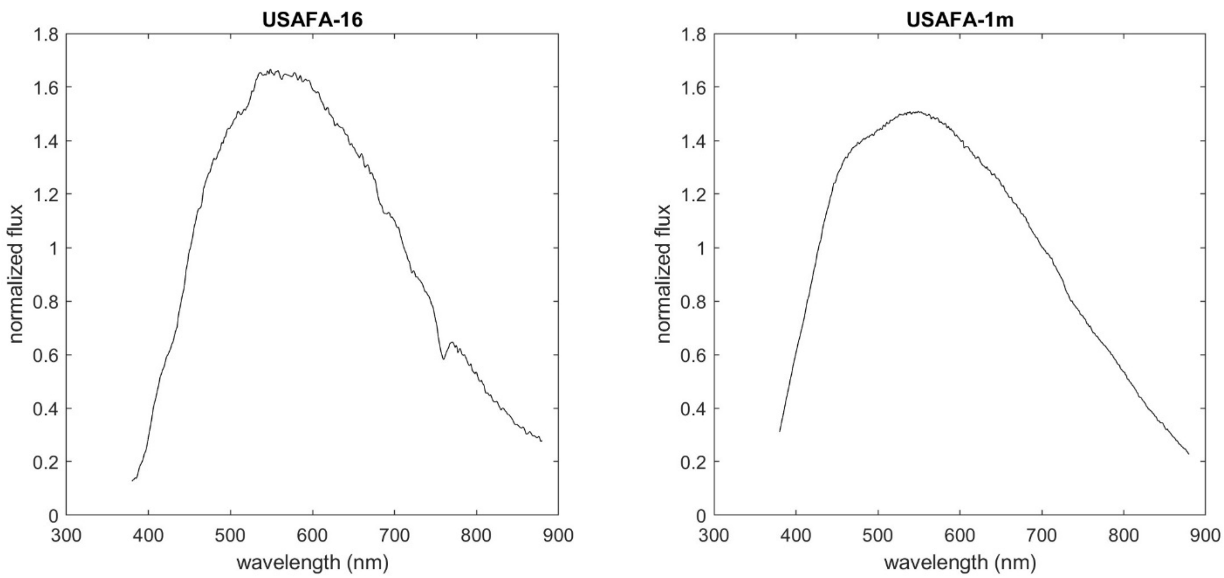

Fig. 9. HIP51993 (G2V type star) spectra using the 100 lines/mm diffraction grating with the USAFA-16 telescope (left) and the 200 lines/mm diffraction grating with the USAFA-1m telescope (right).

Fig. 10 displays a sample image of the Wolf-Rayet star HIP33165 (zero-order near center of image) using the 720 lines/mm grating with the USAFA-1m as a comparison to Fig. 7. Note the more pronounced widening of the higher orders of the adjacent brighter star as one moves further away from the associated zero-order. Note also that the brightest star (both the zero and higher orders) almost contaminates the spectrum of HIP33165. This image, however, proved to be insufficient to use for calibration due to the smearing of the resulting emission lines and confusion between the first and second orders.

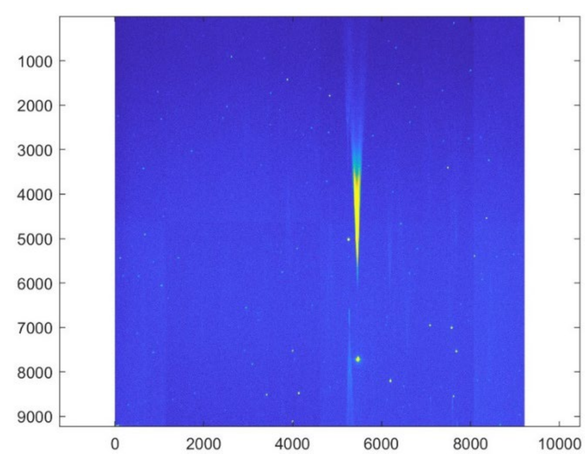

Fig. 10. HIP33165 (zero-order near center of image) using USAFA 1-m telescope and 720 lines/mm grating (2023 Feb 25). Higher orders are defocused the further from the zero-order, which is most evident for the brightest star also in CCD frame.

Instead, one of the defocused images of Castor from Fig. 4 was used for calibration where the first-order of the spectrum on the image was in focus (i.e. the middle spectrum in Fig. 6). These absorption lines correspond to the Hydrogen Balmer lines as seen in Fig. 11 in pixel space (top plot) and wavelength space (bottom plot). The corresponding pixel-to-wavelength conversion for the 720 lines/mm diffraction grating using the absorption lines in results in a slope of 0.47 ± 0.02 nm/pixel with offset of -324 ± 34 nm. The offset is more difficult to determine in this instance because the zero-order is out of focus.

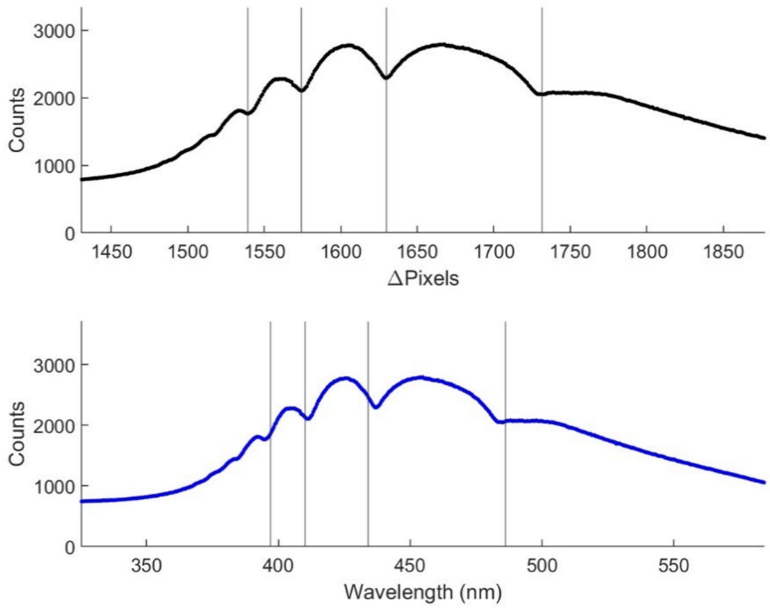

Fig. 11. Pixel-to-wavelength calibration using Castor's spectrum resulting in a slope of 0.47 ± 0.02 nm/pixel and offset = -324 ± 34 nm. The Hydrogen Balmer absorption lines are located at 397 nm, 410.2 nm, 434 nm, and 486.1 nm.

4. Conclusion

CSSAR has used slitless spectroscopy successfully for GEO characterization with the FTN (0.5-meter, f/8) and the USAFA-16 (0.4-meter, f/8) telescopes outfitted with a 100 lines/mm diffraction grating. It was hoped that the new larger USAFA-1m telescope (1-meter f/6 with 200 lines/mm and 720 lines/mm) would provide an opportunity of obtaining higher resolution spectra of fainter objects. However, due to the finer gratings employed and the much larger focal plane, created challenges not encountered with the FTN/USAFA-16 slitless spectroscopy measurements. While the pixel-to-wavelength conversion was successfully obtained for the USAFA-1m telescope, the focus of the curved wavefront of the zero and higher diffraction orders on the large format CCD presents a challenge of realizing this improved resolution in practice. Given what we have learned using the 200 lines/mm and 720 lines/mm gratings on the USAFA-1m telescope, new diffraction gratings are being purchased in the hopes of finding the "sweet spot" that allows for the highest spectral resolution without it being compromised by the curved wavefront.

Additionally, CSSAR is currently upgrading the FTN with new mounts, sensors, dual filter wheels, and a variety of filters, and replacing the USAFA-16 telescope with a Falcon telescope. Dual filter wheels will allow us to obtain single filter measurements (e.g., broadband photometry, slitless spectroscopy, and linear polarization) as well as dual filter measurements (e.g., polarized broadband spectra and polarized slitless spectra).

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6. References

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