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A high resolution echelle spectrograph for exoplanet searches with small aperture telescopes

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ABSTRACT

High precision Doppler observations of bright stars can be made efficiently with small aperture telescopes. We are constructing a high resolution echelle spectrograph for the new 0.6 m telescope at Central Washington University. The spectrograph is fed by a multi-mode fiber and operates in the visible wavelength range of 382–767 nm. The spectrograph uses a white pupil design with 100 mm beam diameter and a monolithic R4 echelle grating.

Keywords: echelle spectrographs, multi-mode fiber, exoplanet, Doppler spectroscopy, ultra-stable, thermal and pressure control, radial velocity

1. INTRODUCTION

High resolution spectroscopy is an indispensable tool for studying a wide range of astronomical objects and processes, from characterizing objects in the solar system to detecting planets around distant stars. Currently there are not enough modern spectrographs that deliver the required precision of ~1 m/s or better. This paper presents mechanical design work done and finite element analysis on major optical components (echelle grating and collimator) for a high resolution echelle spectrograph in the visible range (382–767 nm). The instrument will be deployed at Central Washington University on a new 0.6–meter telescope installed in 2017. A spectrograph of similar design with a smaller grating will be deployed at the Macquarie University Observatory, with the largest telescope size being 16 inches. The spectrographs will be pressure- and temperature-controlled in vacuum chambers.

Since the first planet was discovered orbiting a Sun-like star,[1] nearly 2000 exoplanets, and several thousand additional exoplanet candidates, have been identified. The main technique used for exoplanet science is Doppler spectroscopy, which measures the periodic motion of the host star due to the gravitational pull of a planet, also known as the radial velocity method. This method is crucial for validating and characterizing transiting exoplanets and also for detecting planets in wide orbits and planets around giant stars.

The stars targeted for this type of high precision spectrograph are red giants of spectral classes F, G, K and M. Stars with masses greater than the Sun can be studied via the radial velocity method only when they are in the red giant phase of their life, because at this stage they rotate slowly and have cooled down enough to display a sufficient number of spectral lines. Red giant stars also have the advantage of high luminosities, making them observable with a smaller telescope like the one at CWU. Their main disadvantage is the high level of 'noise' in the Doppler signal from stellar oscillations, which produce radial velocity variations of the same magnitude as the signal from a reasonably sized planet. This disadvantage can be overcome with sufficient observation time. Although it has been suggested that planets may be more common around red giant stars than Sun-like stars,[2] most exoplanet research to date has focused on Sun-like stars. These stars have a large number of spectral lines and low levels of noise because of their relatively small size.

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Figure 1. CWU 0.6–meter telescope (left) and Macquarie University Observatory (right) which features 12 and 16 inch telescopes.

One of the most valuable aspects of the Central Washington University instrument and its twin at Macquarie University is our ability to plan and conduct observations with guaranteed access to these facilities for many years. This is crucial because some planets have orbital periods of decades and the Doppler technique requires sampling over the full orbital period. The proposed spectrograph will allow us to embark on a long-term monitoring program of interesting targets previously identified in shorter term surveys. The echelle spectrograph is the only instrument that combines the necessary throughput, bandwidth, and high resolution to efficiently conduct these Doppler observations.

2. OPTICAL AND MECHANICAL DESIGN

The optical design is based on the NEID spectrograph.[3] The design for this instrument centers around a single parabolic mirror for the white pupil relay.[4] This spectrograph achieves a low optical height by hanging the collimator off the back end of the optical table. In addition, the echelle grating is mounted face-up, making for a simpler design as the components will ultimately be operated in a vacuum chamber. Mounting the spectrograph in a vacuum chamber will allow for precise temperature and pressure control. We anticipate that using strictly kinematic mount designs, precise temperature control and a massive optical bench will aid in achieving excellent RV precision over long timescales.

2.1 Optical Layout

The white pupil optical layout of the spectrograph is shown in Figure 2. Figure 3 is an orthographic view of the opto-mechanical design, showing the beam exiting the fiber and passing through the echelle, collimator, cross-disperser, and camera lenses. The optical design is simplistic with a minimum of optical elements which leads to high throughput. Despite its simplicity the design produces diffraction-limited image quality.

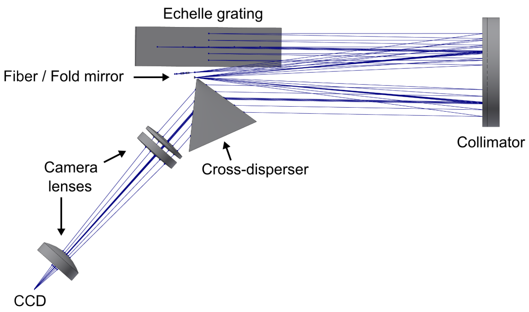

Figure 2. Top view of the optical layout.

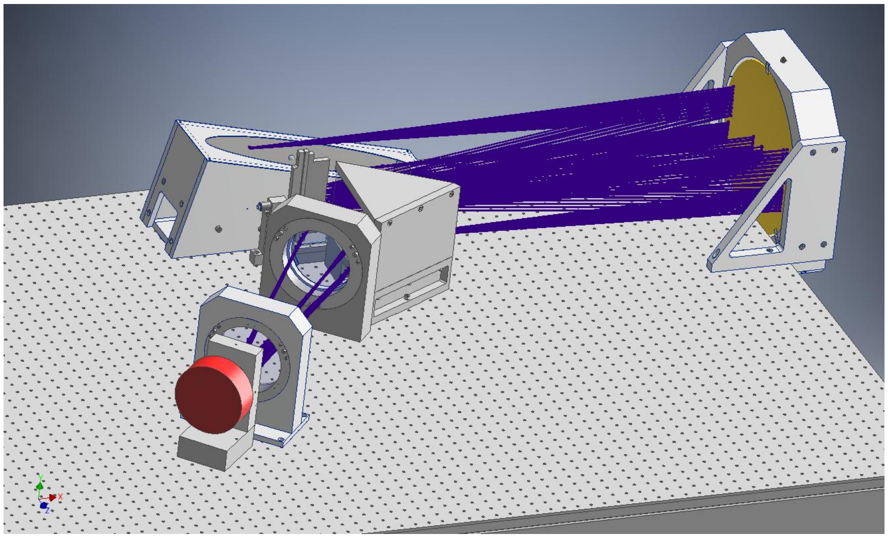

Figure 3. CAD rendering of the spectrograph mounted on an optics table. The table will be used for testing, and will be replaced by a 1.5" thick custom AL6061–T6 bench for mounting inside the vacuum enclosure.

2.2 Echelle Grating

The R4 echelle grating (76 degree blaze angle) has 31.6 grooves/mm and is replicated onto a 420×110×70 mm Zerodur substrate. The grating mass is 8.2 kg; we have designed a massive mount holding the grating facing upwards. We do not expect contamination problems as we use a vacuum enclosure. The mount consists of an aluminium prism under the grating with sidewalls screwed onto it, see Figure 4.

2.3 Collimator

The collimator mirror has 300 mm diameter, 56 mm thickness, and a focal length of 814 mm (f/2.7). The mass of the mirror is about 8.5 kg and with housing the total mass is 16.2 kg. It is supported by two side brackets as shown. The collimator mount design is based on a spectrograph for the Waltz Telescope in Heidelberg.[4] The design is shown in Figure 4. It hangs off the optical table to achieve a low optical beam height, thus improving stability. The mirror is held on three axial and two radial contact points with spring-loaded retainers opposite.

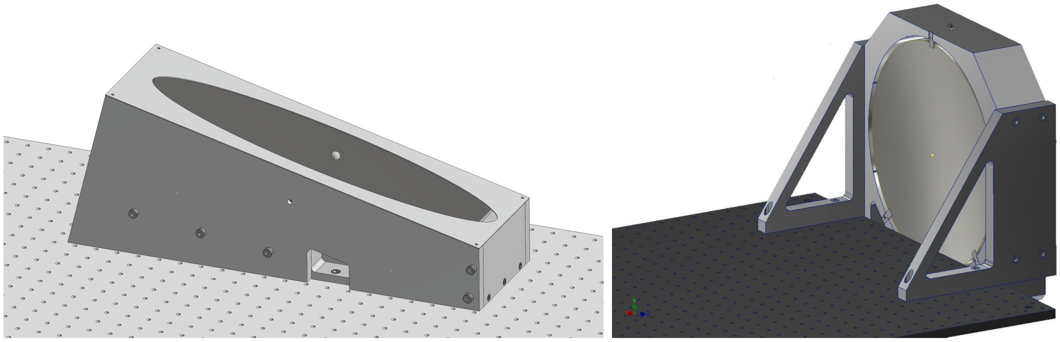

Figure 4. Echelle grating (left) and collimator (right) mount design.

2.4 Cross-disperser

The cross-disperser is an equilateral prism with side length 200 mm, height 120 mm, and mass of about 4.5 kg. It is made of Ohara PBM2Y lead crystal glass with a refractive index of 1.61655 at 632.8 nm. A preliminary mount design is shown in Figure 5. The bottom and top surfaces of the prism are held by three flat pads and two more pads are located at the back wall. We will investigate the use of indium foil between the glass and the mount, to hold the fragile prism safely.

2.5 Camera Setup

The spectrograph features a high performance camera design derived from NEID which focuses the spectrum onto the CCD detector. The camera is composed of two singlets which form an air-spaced doublet, and a field flattener. All three lenses have a diameter of 127 mm. A ring-spacer with three contact points is used to achieve the needed lens spacing (15 mm) of the two single lenses.

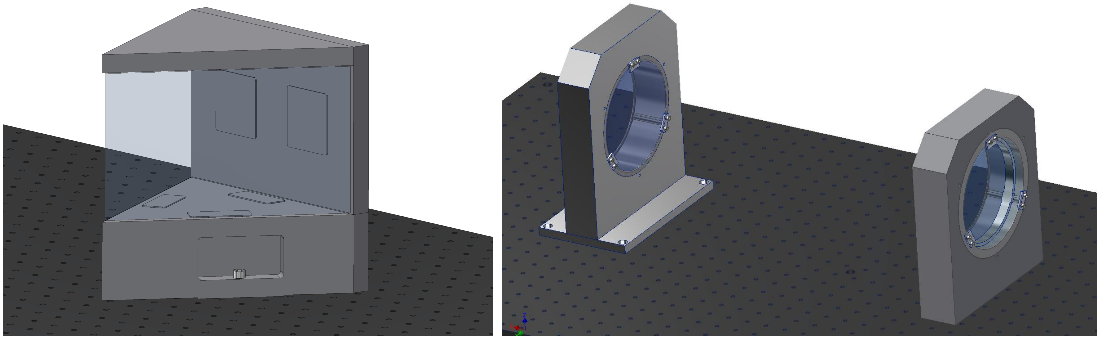

Figure 5. Prism cross-disperser (left) and lens cell (right) mount design.

3. FINITE ELEMENT ANALYSIS

Finite Element Analysis (FEA) is an important part of the design of this spectrograph because of the stability requirements. Here we investigate deformation due to mechanical design choices using FEA. To reach design targets, it is important to minimize deformation of the optical surfaces, especially the echelle grating and collimator. Autodesk Inventor and Simulation Mechanical programs have been used for the FEA. The FEA parameters are shown in Table 1. The average element size is 0.05 (fraction of bounding box length). The magnification applies to figures with deformations shown in Figures 7, 8.

Table 1. Finite Element Analysis parameter.

Component	No. Nodes	No. Elements	Magnification
Echelle Grating	355023	241542	2000
Collimator (Assembly)	1025259	670836	1000

3.1 Echelle Grating

The echelle mount features grating contact points as shown in Figure 6. The grating is kinematically supported by 10 mm ceramic spheres at the contact points: three on the bottom, two on the front, and one on the left side. The right side and back are each supported by a spring plunger.

The crucial deformation to minimize is the deviation of the grating surface from a plane when gravity acts on the substrate; the simulation results presented here focus on this deformation in the Y-direction. Figure 7 shows the Y–displacement with a maximum value of just under 20 nm at the center and back of the grating. The W-shape is ideal because it minimizes the peak-to-valley displacement along the length of the grating. This is achieved by optimizing the spacing of the bottom support contacts, which are 94 mm from the front/back edge of the grating and 232 mm apart. Moving the spherical contact points closer or further apart by only a few mm results in a significant increase of deformation. The right-hand side of Figure 7 shows the surface Y–displacement relative to the fitted plane. For the optimal spacing of the contact points, the peak-to-valley displacement is about 11 nm or $\lambda/36$ at our shortest wavelength.

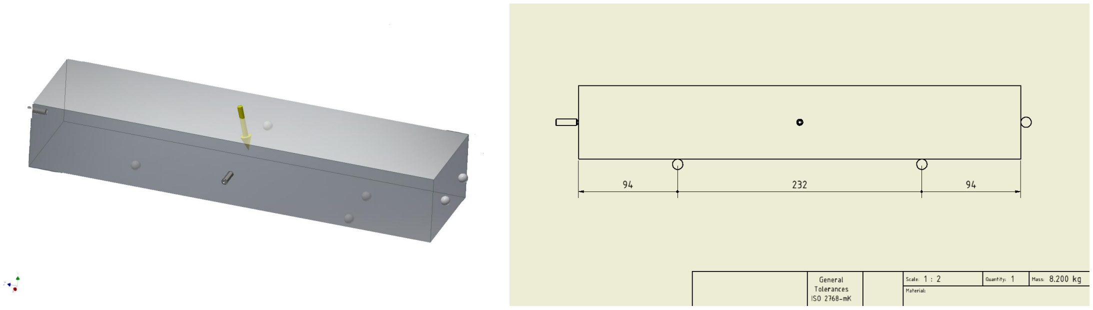

Figure 6. Solid model of the echelle grating with contact points and gravity load vector (left). Technical drawing showing the configuration of the bottom supports (right).

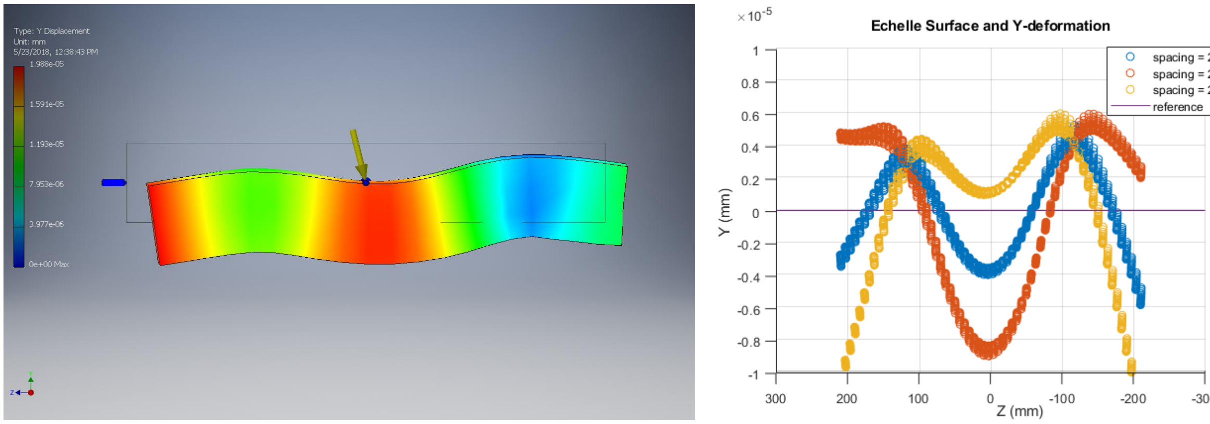

Figure 7. Y–displacement of the echelle grating (left). Note the near W-shape. Plot of deformed echelle top surface (grating tilt removed) at different bottom support spacings (right).

3.2 Collimator

We have performed a brief analysis of the current mirror mount design to minimize areas of high stress and deformation. The gravity load scenario is shown in Figure 8. There are four M6 screws to mount the brackets to the table (not shown). These are fixed in the FEA scenario to examine how the brackets and mirror mount will bend when it hangs off the end of the table, see Figure 4.

Figure 8 shows the displacement magnitude, which has a maximum of about 6 microns, shown in red at the top of the mount near the back surface; the displacement is an effect of the hanging mount design. As the displacement is static, it is acceptable for our purpose.

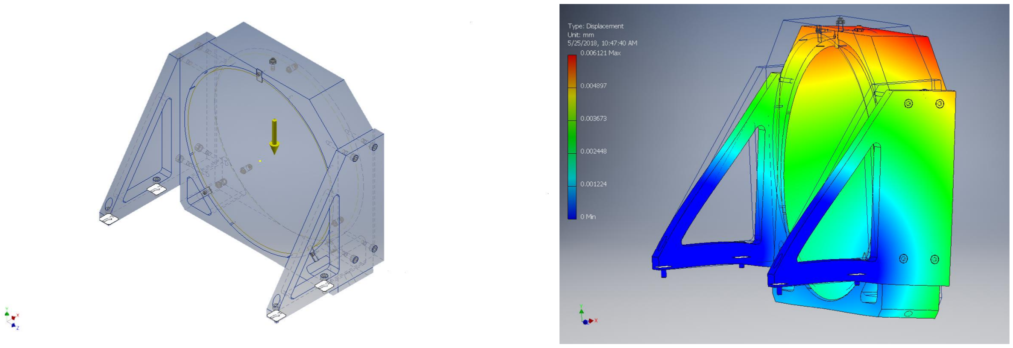

Figure 8. Collimator assembly showing the gravity load at the centroid (left) and the FEA result of the collimator mirror plus mount with the color bar representing displacement magnitude (right).

4. CONCLUSION

This stable high resolution spectrograph offers the potential of more precise radial velocity measurements, one of the key requirements for exoplanet searches and follow ups. Precision and stability is attained by a compact white pupil design with a low optical beam height, reinforced mounts with minimal constraints on optical components, a temperature controlled environment, and a vacuum enclosure. The mechanical aspects were evaluated with FEA, and more work is planned investigating thermal changes and gradients. The next steps will be to complete the mechanical design including the vacuum enclosure, and integrate the optics. In parallel we are working on a front-end design including atmospheric dispersion correction to feed the optical fibers at the telescope. We anticipate to start with commissioning in the fall of 2019.

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