Design and Testing for the TMT Imaging Spectrograph

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ABSTRACT

The InfraRed Imaging Spectrograph (IRIS) instrument of Thirty Meter Telescope (TMT) will be no exception to the series of high quality optical and infrared instruments designed by UCLA. In order to ensure the quality of the IRIS mechanisms like the diffraction grating turret, tests of their repeatability must be completed and cryogenic conditions of the dewar must be modeled to make informed and progressive decisions about their development. Using the human eye to measure fraction of a pixel shifts of an image of cross hairs reflected off the diffraction grating turret prototype mirror, an even more repeatable design for the stopping mechanism was developed. Using a python model with thermodynamic equations a conclusion was made that helium gas lines have the cooling capacity to decrease the room temperature IRIS optical bench to 75K in 8.6 days under specific conditions. This all suggests the IRIS team will have a definitive direction regarding the quality of their designs for the IRIS instruments.

1. Introduction

The TMT is currently being built in Mauna Kea, Hawaii. Once built, it will be 3x larger than KECK, the largest optical and infrared telescope in existence, giving the TMT 3x the angular resolution power. IRIS contains an on instrument wavefront sensor (OIWFS) which gives feedback to narrow field infrared adaptive optics system (NFIRAOS) of the preformance of the system in real time. IRIS is designed to be a first light instrument and combines a ’wide field’ imager with an integral field spectrograph that covers a wavelength range of 0.84 microns to 2.4 microns (Larkin et al. 2013). The imager will have a 16.4x16.4 arcsec$^2$ field of view and the lenslet and slicer spectrographs can have up to 10,000 spectra at a time on one of the most advanced 4K by 4K HgCdTe detectors from Teledyne (Larkin et al. 2015).

2. Project Motivation

Designing and testing of the IRIS project involved two related mechanical topics. The first of which is that these technologically advanced systems have complex spectral outputs and need to be reduced carefully. Shifting of spectral lines in either direction would result in overlapping or misidentification of spectral position on the detector. To combat these problems the moving components within IRIS need to be repeatable. The science goal was to only allow a 1 micron shift on a pixel that is 15 microns wide on a 4096 x 4096

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pixel detector. The diffraction grating turret will be a 16 sided “wheel“ that contains a stopping mechanism with the capability to catch any diffraction grating in the desired position (Refer to Figure 1). The diffraction grating turret is the only moving mechanism between the lenslet and the detector. This means the diffraction grating turret is the only component that will make the data reduction more complicated. The motivation to observe the repeatability of the diffraction grating turret was to utilize the results of the repeatability tests to make necessary changes in the design to ultimately achieve the optical tolerance of a 1 micron shift. The second issue revolves around the demand for an accurate model of the exchange of heat within the IRIS dewar (Refer to Figure 2) as it is cooled to cryogenic temperatures of 75K. The motivation for the thermal model was to find the cool down time of the optical bench, then add or modify components in the code to get as close to 7 days as possible. The cool down time becomes important when testing IRIS at UCLA before the fabrication phase. The thermal model will have to exemplify how to achieve the shortest development time possible. Since the optics inside weigh about 1200kg, the model will have to show that 180 million joules of heat can be drawn out with the hydrogen gas line refrigeration system.

3. The Diffraction Grating Turret

For the purposes of testing the repeatability of the diffraction grating turret a prototype was made with 8 mirrors in place of the diffraction gratings. The turret can be rotated both clockwise and counter clockwise and the stopping mechanism uses a spring to push a ball bearing wheel into a set of catching grooves. This is where most of the shifts occur. As the ball bearing wheel is pushed in and out of the catching grooves the
Fig. 2.— IRIS Dewar containing the imager in the top half and both spectrographs in the bottom half. The helium gas lines, used for cooling, are represented by blue boxes under both halves.

motor could stall or slip. The abrupt stops as the wheel falls into place could cause also small shifts in the position of the mirror. As the diffraction grating turret rotates in the opposite direction than it was previously rotating backlash or slop is observed and causes a shift. For these reasons and more the team needs to ensure the diffraction grating turret is repeatable enough to fit within the tolerance of a 1 micron shift.

### 3.1. Experimental Set Up

To test the repeatability, a pair of cross hairs served as the light from an astronomical object. Then they were angled toward one of the mirrors on the diffraction grating turret prototype. A standard Canon digital camera took an image of the cross hairs reflected off the mirror and those images were uploaded onto DS9, an image processing software. From DS9 the centers were measured “by eye” and recorded for each image. Then the shifts between images were measured. The reason for the “by eye” measurement of the centers is because the cross hairs produce an irregular illumination pattern and therefore could not be fit with a standard Gaussian. Static tests were carried out by taking images of the cross hairs without rotating
the turret to test the stability of the camera. Active tests were carried out by rotating the turret 2 positions clockwise then rotating 2 positions counterclockwise back to the original position, then an image was taken. This process was repeated 10 times. Another set of active tests were conducted the same way except the turret rotated 2 positions counterclockwise first.

3.2. Data Analysis

The static tests showed a slight shift in the positive $x$ direction and negative $y$ direction. The team attributed this “droop” to the fully extended lens of the camera and the effects of gravity. After tightening the tripod a shift was noticed in the same downward direction. To combat the droop, a bag of beans was placed under the lens of the camera and another test was run. Unfortunately the droop still occurred. In another attempt to stabilize the camera, a stack of thin text books was placed under the lens but a droop still occurred. This led to the assumption that a new stabilization method had to be implemented, however, for the sake of moving forward the team needed to continue testing the repeatability with active tests. In earlier tests the diffraction grating turret achieved a repeatability of 0.5 pixels in the $x$ direction and roughly a 0.5 pixel shift, with an occasional shift of 5.0 pixels, in the $y$ direction. These shifts were too large to fit within the 1 micron tolerance of the science goals. In an effort to correct for that the shifts were traced back to the ball bearing pivot of the stopping mechanism (Refer to Figure 3). The spacing in between the balls was stretched and squeezed as the stopping mechanism rolled in and out of the catching grooves. Therefore, the team took out the ball bearing pivot and implemented a flexural pivot, designed by Caltech, to allow minimum translational movement (Refer to Figure 4). The active tests from the newly implemented pivot showed shifts of 1.18 pixels in the $x$ direction and 29.38 pixels in the $y$ direction. These were much worse.

Fig. 3.— Stopping Mechanism of the diffraction grating turret prototype.
Fig. 4.— Flexural Pivot is a pair of nested cylinders that act like a spring than the previous active tests. These shifts were fundamentally due to the mechanical stresses placed on the flexural pivot being pushed and pulled with the lever arm. Due to the mechanical stresses the flexural pivot broke after one test.

3.3. Results

The static tests showed that a new stabilization method must be designed to correctly measure the shifts. The active tests found that the broken flexural pivot warranted the creation of a new design for the stopping mechanism. The team calls this design an active detent system (Refer to Figure 5). The idea is to remove all ball bearings and keep the flexural pivot for its minimal translational shifts. The new design will have a motor that pulls a bullet shaped detent in and out of the catching grooves before the diffraction grating turret rotates. The team anticipates that the active detent system will reduce the shifts in both directions as well as meet the tolerance of a 1 micron shift.

4. Thermal Model of the IRIS Dewar

The need for a thermal model of the dewar stems from the need to shorten the integration phase of the IRIS instrument itself. As previously mentioned, IRIS will need to be tested before it is delivered to the summit. The camera needs to be warmed and cooled while being integrated so the cool down time needs
Fig. 5.— Active detent stopping mechanism from a side view of the diffraction grating turret prototype.

to be minimalized. A thermal model was created to keep track of the exchange of heat inside the dewar and modifications were implemented to minimize the cool down time. The thermal model had to include many aspects of the mechanical system. Figure 2 shows that the green corrugated shape inside the dewar walls represents multiple layers of a reflective mylar floating shield, followed by a lighter green G10, fiber glass, support strut that connects the optical instruments to the dewar walls. Finally, an aluminum cold shield, with a surface area of 16.2m$^2$, encapsulates the optical bench containing the imager in the top half and both spectrographs in the bottom half, all of which weighs about 1200kg and stands about 2.7m tall. As previously mentioned, the helium gas refrigeration system will need to draw out 180 million Joules of heat to cool down the optical bench to 75K.

4.1. Equations and Results

The thermal model initially starts at room temperature or 300K and uses a model of the refrigeration efficiency that is assumed to decrease linearly with temperature. The refrigeration system is not able to carry out as much heat at colder temperatures due to the smaller energy difference between the molecules. This
means the smaller the energy difference between the incoming molecules and the preexisting molecules the longer it takes to cool down the system. The model keeps track of the radiation from the dewar walls, the heat conducted from the G10 support struts and uses multiple interpolation routines for the varying heat capacities and conductivities of the different materials. The following equations were used in the model:

\[
Q_{\text{refrigerator}} = -(200.0/235.0)(T_{\text{bench}} - 65.0) + 200.0
\] (1)

\[
Q_{\text{radiation outer}} = (SA)(\sigma)(\varepsilon)((T_{\text{out}})^4 - (T_{\text{float}})^4)
\] (2)

\[
Q_{\text{radiation inner}} = (SA)(\sigma)(\varepsilon)((T_{\text{float}})^4 - (T_{\text{bench}})^4)
\] (3)

\[
Q_{\text{conduction}} = (A/L)(\kappa)((T_{\text{out}}) - (T_{\text{bench}}))
\] (4)

\[
T_{\text{float new}} = T_{\text{float previous}} + ((-Q_{\text{radiation inner}} + Q_{\text{radiation outer}})/(m_{\text{float}})(c))
\] (5)

\[
T_{\text{bench new}} = T_{\text{bench previous}} + ((Q_{\text{radiation inner}} + Q_{\text{conduction}} + Q_{\text{refrigerator}})/(m_{\text{bench}})(c)
\] (6)

One of the methods used to minimize the cool down time was to add the reflective mylar floating shield. Increasing the reflectivity of the shield allowed us to decrease the emissivity and decrease the amount of heat as radiation hitting the optical bench. It can then be inferred from the following plot that with an emissivity of 2% it will take 8.6 days to reach the fixed final temperature of 75K (Refer to Figure 6). This was a day and a half longer than the target cool down time but a small amount of changes in the dewar mechanical design could be made to decrease this time by a small amount. Other than calculating the fastest cool down

Fig. 6.— Plot of Temperature (K) vs. Time (min) showing how the temperature of the mylar floating shield cools (green) as well as how the temperature of the optical bench (blue).

time for the dewar, some other relevant information we learned from the thermal model includes verifying the cooling capacity for the refrigerator will satisfy the need to reach 75K, the G10 support strut isolation is sufficient and will not drastically contribute to the heat transferred by conduction, and that the dominant
source of heat for the system is radiation. With the preceding information known the team can move forward and make minor changes to the design.

5. Summary

The quality of the science results are often dependant on small aspects of the instrument itself. If the diffraction grating turret fails to repeat astronomers spectrum will not be reliable and could effect the results from the science data. For astronomers to achieve the scientific potential of TMT the instruments and all of their components must be of very high quality. Concluding that the IRIS team needs to implement an active detent stopping mechanism justifies the time spent on testing the repeatability of the diffraction grating turret prototype and the broken flexural pivot because it should result in more stabilized spectra. The thermal model of the IRIS dewar will allow the team to make necessary changes but ultimately go through with the helium gas refrigeration system. Future work will involve testing the new stopping mechanism’s repeatability with a more stabilized set up and finding ways to cool the dewar at a faster rate.

REFERENCES

Larkin et al. 2013, Development of the InfraRed Imaging Spectrometer (IRIS) for the Thirty Meter Telescope, MSIP Proposal to the NSF for IRIS Construction

Larkin et al. 2015, IRIS Optical Summary, Design Report, Optical Review