CHAPTER 1: INTRODUCTION

When an image is focused on the slit of a ground based telescope, atmospheric turbulence causes the image to wander slightly about its mean position. This is a problem for the 120" Shane Telescope at UCO/Lick Observatory. To collect data, the light gathered by the telescope must converge to a focal plane at the slit of the Hamilton Spectrograph as shown in Figure 1. Unfortunately, the wandering effect mentioned above causes the image to spend only a small amount of time on the slit depending on atmospheric conditions. The amount of time that the image spends on the slit is directly proportional to the length of the observation time required to get a sufficient SNR (signal to noise ratio) for that observation. On particularly bad nights, the image may spend as little as 50% of its time on the slit resulting in a doubling of the required exposure time. Telescope time is very limited and a user must get as much data as possible during the allotted time. Stabilizing the image on the slit will result in a more efficient use of the telescope by allowing an equivalent SNR to be achieved in a shorter exposure time for each stellar observation, increasing the possible number of observations each night.

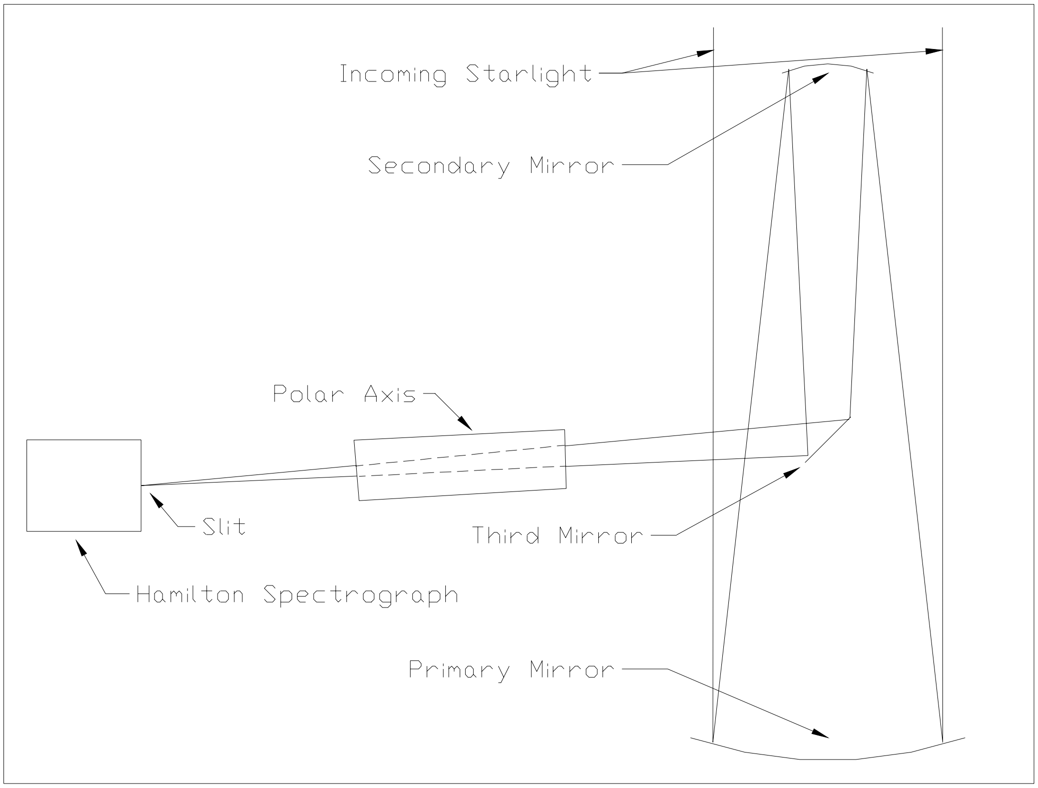

Figure 1. Telescope Configuration. Incoming starlight is reflected off the primary and secondary mirrors into an f/36 beam. This beam is steered through the polar axis to its focal plane at the slit via a flat third mirror.

The factors introduced by atmospheric turbulence can be broken down into two components: wind gusts actually moving the telescope and "seeing". The effect of wind on the telescope is very common, but limited to small motion since the telescope dome must be closed when the windspeed reaches 40mph to protect the telescope's mirrors. “Seeing” is a term used to describe the blurring effect that the atmosphere has on the incoming light from a star and the resulting lateral motion of the image at the slit. As the starlight travels through the Earth's atmosphere it passes through air pockets with variable refractive indices. The index of refraction of the molecules in the atmosphere is a function of temperature, causing the refractive indices to vary during turbulent atmospheric conditions. As the photons travel through a non-homogenous medium such as the our atmosphere, the path followed between the star and the telescope varies slightly causing the position of the focused image at the spectrograph to vary. During good seeing, the image of the star will come to a good, sharp focus at the slit with little lateral motion of the image. The image diameter for best case seeing at the Coude focus is ~0.75 arcseconds, or ~0.4mm. Bad seeing can cause the image at the slit to blur and expand to diameters as large as 10 arcseconds (~5mm) and move chaotically around the slit.

The modern method of eliminating the problems introduced by atmospheric aberrations is known as adaptive optics. Adaptive optics generally performs two functions, compensating for wavefront distortion as well as correcting for seeing. Wavefront distortion compensation and correction of the blurring effect caused by seeing are performed using a deformable, rubber mirror. These mirrors are constructed with hundreds of actuators which deform the mirror to reconstruct the image as it should be without atmospheric influence. This is a very difficult task, resulting in many difficulties implementing such a device. Fortunately, the efficiency of the Shane Telescope can be greatly improved by compensating for the motion of the image at the focal plane without correcting for wavefront distortion. This is achieved with the use of a movable mirror that rotates about two axes which lie 90° apart from each other and perpendicular to the normal, or tip and tilt. This process involves measuring the position of the stellar image, relative to the slit, and rotating the mirror to compensate for any errors.

The motion at the slit varies with atmospheric turbulence. The extreme values of this motion can be approximated to a maximum velocity of 10arcsec/s and a total range of motion of ±5arcseconds. These values can be easily converted from angular to linear units at the slit of the Hamilton Spectrograph. As shown in Figure 2, if the star is 1arcsecond off when leaving the primary mirror, the error at the slit can be found as

$$X = \tan(1\text{arcsec}) * 108\text{m} = 0.524\text{mm} \tag{1}$$

or,

$$1\text{arcsec} = 0.524\text{mm}. \tag{2}$$

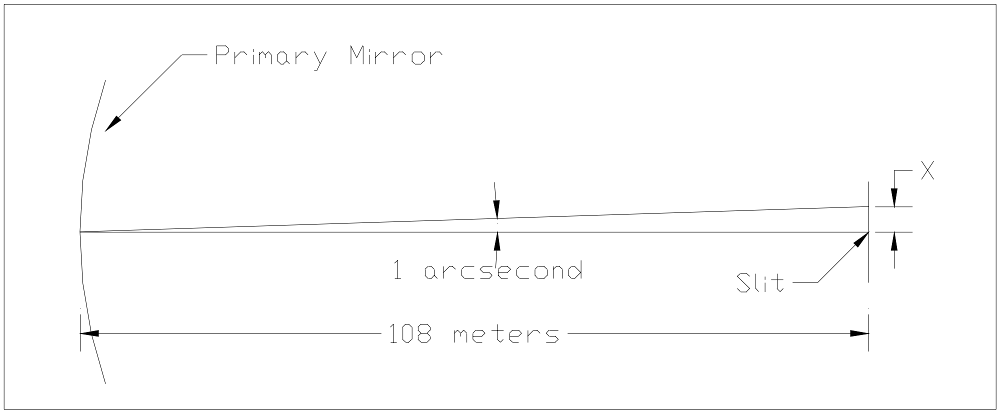

Figure 2. Geography of Angular Errors to Linear Units Conversion at the Slit. X is the resultant linear offset at the slit of an angular error of the beam coming from the primary mirror.

Using the conversion in (2), the maximum velocity, V_{max}, and range of motion, R, can now be found as

$$V_{max} > 5.24\text{mm/s} \tag{3}$$

and,

$$R > \pm 2.62\text{mm}. \tag{4}$$

Parameters (3) and (4) can be used as the minimum performance constraints required for a tip/tilt system to efficiently compensate for atmospheric disturbances.

Adaptive Optics Image Stabilization System

An adaptive optics image stabilization system (tip/tilt system) has been implemented to compensate for the position disturbances caused by atmospheric turbulence and to stabilize the stellar image on the slit of the Hamilton Spectrograph. An overall system diagram is shown in Figure 3. This system routes the incoming starlight through an optical table consisting of two rigid mirrors and a tip-tilt mirror mounted to a stepper motor driven gimbal mount. These mirrors, currently aluminum coated, will be Silver coated for 98% average reflectance in the 500nm-IR wavelengths resulting in a total transmission of approximately 94% for the entire optical table. Upon exiting the optical table the starlight passes through a beamsplitter that sends approximately 94% of the light exiting the optical table to the slit, and approximately 4% to a quadrant PMT (photomultiplier tube consisting of four anodes in a quadrant array configuration). The PMT outputs a signal from each quadrant to a PC that acquires the data and uses Visual Designer software (control software by Intelligent Instruments) to implement the control algorithm developed to determine the image position error and necessary corrections. The position of the image, relative to the slit, is determined by the ratio of light in each PMT quadrant, with the position set-point being represented by an equal amount of light in each quadrant. Once the errors are determined by the software, the controller signal is computed and sent to the tip/tilt mirror for tip/tilt compensation. The total light transmission of the system, after Ag coating, will be approximately 88.5%, or 11.5% losses. With ideal control, this is the amount of light that will be transmitted through the slit. On many nights the image spends less than 50% of its time on the slit with no feedback control, so the 11.5% losses are acceptable and will result in a net gain. The PMT has been tested and shown to respond to stars as dim as 10th magnitude, the dimmest star on the SFSU Planet Search Project's target list for this telescope. Testing has shown the system to approximately double the throughput (amount of light that reaches the spectrograph) of the telescope for various stars observed during a variety of seeing conditions.

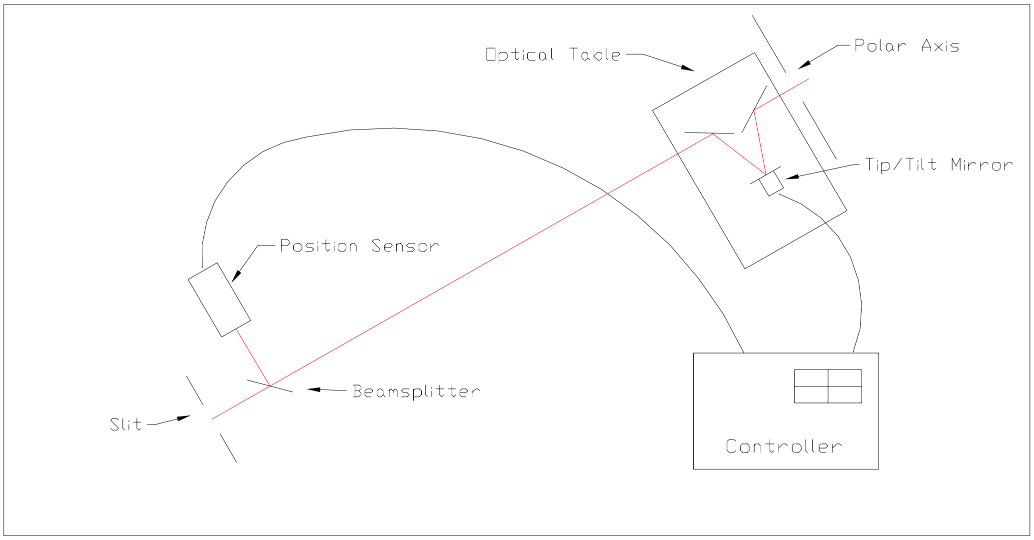

Figure 3. General Layout of Tip/Tilt System. The light path is rerouted through the optical table and the position relative to the slit is sensed by a PMT. The controller changes the angle of the tip/tilt mirror to compensate for errors.

An additional benefit to having the tip/tilt system in place can be seen from a human factors perspective. The telescope operator requires a few minutes to find a star when pointing the telescope to a new object. Once the star is in the telescope's field of view, the operator must center it on the slit. This last step is eliminated with tip/tilt. Once the star is in the field of view, tip/tilt can pull it to slit as soon as it's activated, shaving off even more time. Another problem that is sometimes encountered is that the autoguider (TELCO) will sometimes lose the star, causing it to leave the slit during an observation. Unless the error is noticed by the telescope operator or observer immediately, the observation will usually have to be restarted. This could result in losses of up to 20 minutes, depending on how far along the exposure was. Tip/tilt helps prevent this from occurring by guiding more efficiently than TELCO.