CHAPTER 2: OPTICAL TABLE

Introduction to Optical Table

An optical table has been designed to smoothly translate into and out of the path of light. It is attached to a large mount in the slitroom that is located about 4.5' from the slit, corresponding to a beam width of just over 1.5" in the f/36 lightpath. All optical table components have a black finish to keep unwanted reflectance to a minimum.

The general layout of the optical table is shown in Figure 4, while mechanical drawings of the individual components can be found in the appendices. The purpose of the table is to pick off the light from the original light path, redirect it to the moveable tip/tilt mirror, and return it to the original light path.

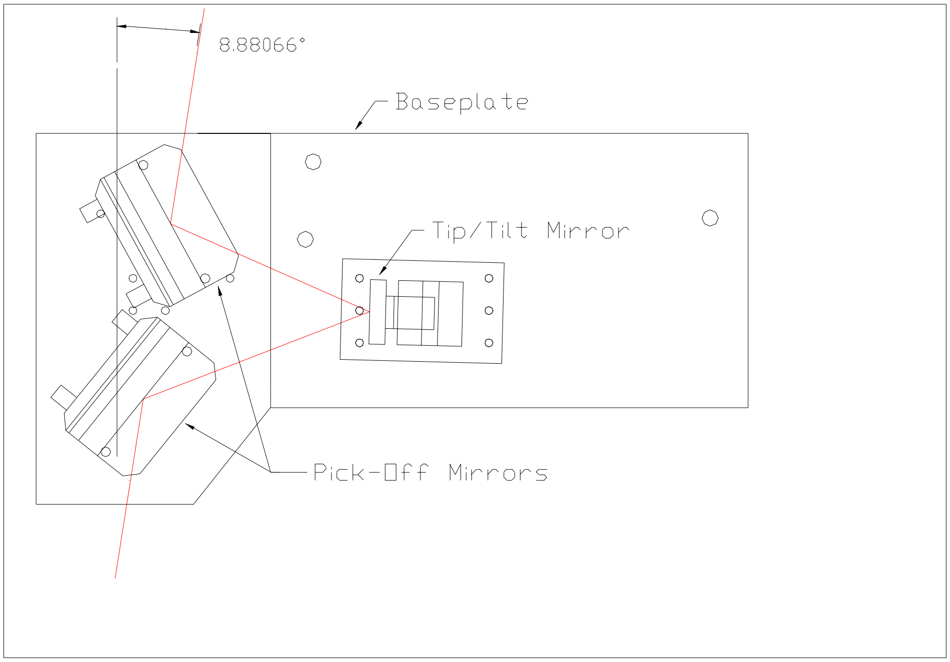

Figure 4. Optical Table Assembly. The dashed line represents the light path of incoming starlight. This light is picked off with the first mirror, reflected off the tip/tilt mirror for corrections and inserted back into the original light path before continuing on its slightly modified path to the slit.

Optical Table Construction

This baseplate is composed of three off the shelf breadboards from Melles Griot chosen for their black anodized finish and excellent flatness tolerances. The breadboards were resized for this application and mounting holes were added as shown in the attachments. The lower base plate is bolted directly to three preexisting mounting holes on the mounting surface.

The mirrors are positioned, in reference to the light path, as shown in Figure 5. The two pick-off mirrors were manufactured at the UCO/Lick Observatory optical shop, while the tip/tilt mirror was purchased "off the shelf" from Melles Griot with an Ag coating. The flatness tolerances for all mirrors are better than $\lambda/10$ (wavefront distortion less than 1/10 of a wavelength). Each mirror will be coated for maximum reflectance at each respective incidence angle. This should result in less than 6% of the incoming light being lost in optical table.

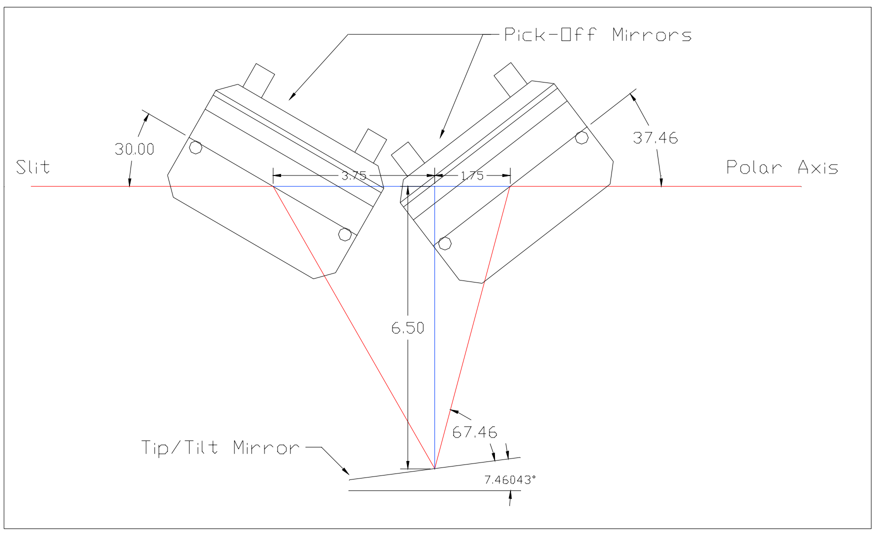

Figure 5. Mirror Layout. Mirror layout on optical table and angles with respect to the ideal light path.

Figure 6 shows the kinematic stage type mirror mount used for the pick-off mirrors. These mounts are adjustable up to 8° with three degrees of freedom and have a resolution of 0.75 arcseconds. These mounts are standard items from Edmund Scientific.

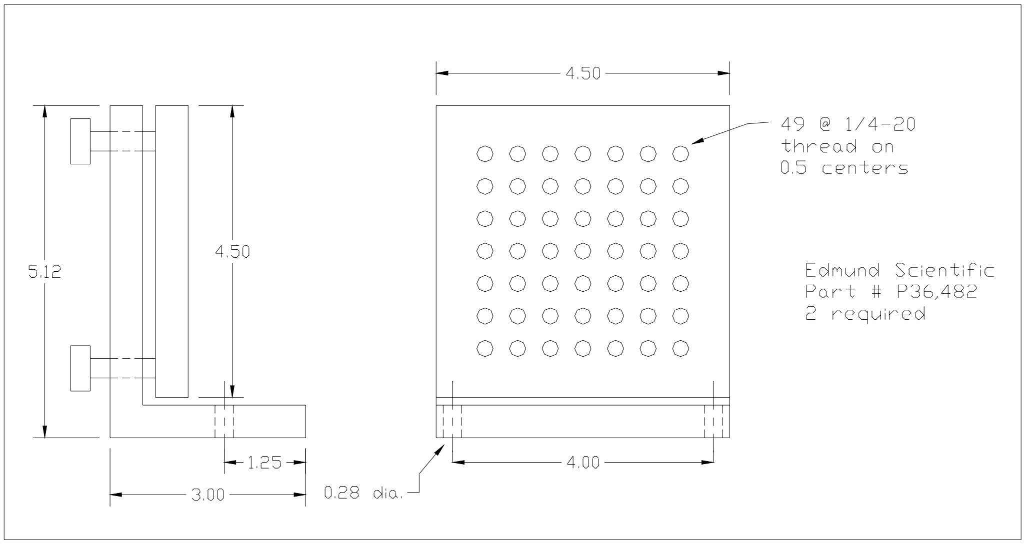

Figure 6. Pick-Off Mirror Mount. Mount is on a kinematic stage with 8 degrees of adjustability.

Effect of Optical Table on Lightpath

A relationship between the incoming starlight angle and the required correction angle of the tip/tilt mirror must be found as well as the relationship between the change in tip/tilt angle and the angle of approach to the slit in order to determine the resultant offset of the beam on the face of the collimator. The collimator is the first component of the Hamilton Spectrograph that sees the light after it passes through the slit.

Figure 7 shows an exaggerated view of an incoming beam with a larger error than will actually be seen by the system. As the light approaches from a 40 arcsecond downward angle, it is reflected off the bottom edge of Mirror #1, the left edge of the tip/tilt mirror, and high off pick-off mirror #2. This causes the image to be seen above its ideal position at the slit. To correct for this error, the tip/tilt mirror is rotated slightly clockwise to intersect the beam at a lower position on the surface of pick-off mirror #2 at a smaller incedence angle causing the image to enter the slit at its focal plane.

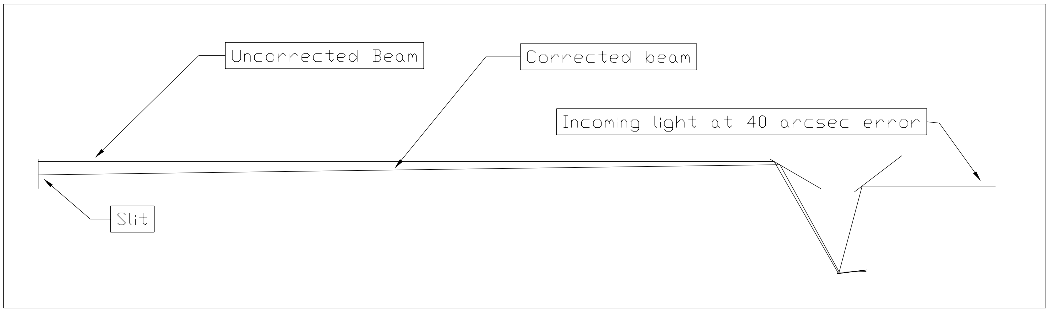

Figure 7. Exaggerated Corrected and Uncorrected Lightpaths. The tip/tilt mirror is rotated clockwise slightly to compensate for the 40 arcsecond downward error.

Because the tip/tilt mirror does not lie at the focal plane of the telescope, changes in the angle of incoming starlight result in an offset on the three mirrors of the optical table making the relationship between tip/tilt angle and error angle nontrivial. This relationship was found by analyzing all mirror surfaces and lightpaths in rectangular coordinates with the slit as the origin. Each mirror surface and lightpath was assigned a linear function of the form y=mx+b as shown in Figure 8. The points requiring solutions are labeled (x_n,y_n).

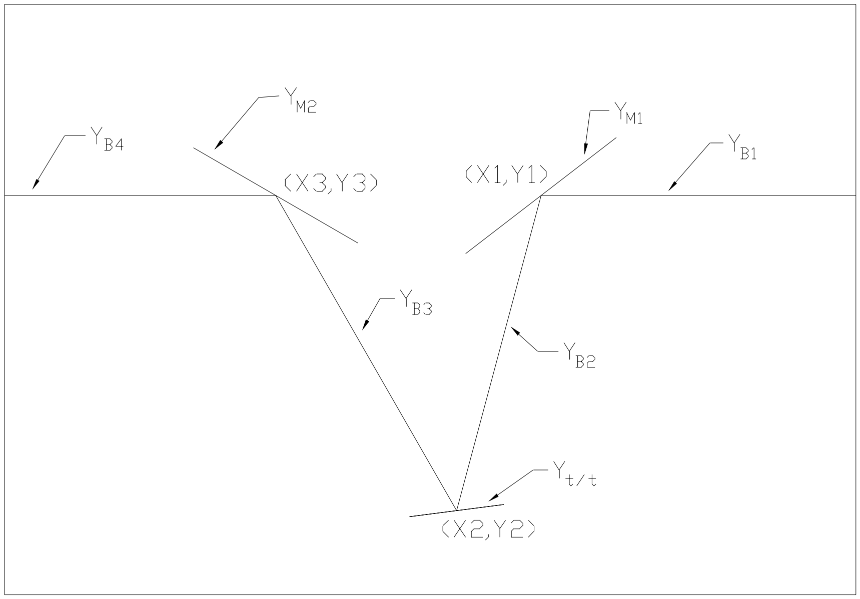

Figure 8. Layout of Mirror Surface Lines and Lightpath Segments.
The lines are defined in rectangular coordinates of the form Y(X).

Ideally, the incoming lightpath travels directly to the slit along the X axis, resulting in $\angle Y_{B1}$ and $\angle Y_{B4}$ equal to zero. Setting Y_1 and Y_3 equal to zero, knowing the corresponding X values from taking measurements and knowing the angles of the mirrors M_1 and M_2, Y_{M1} and Y_{M2} can be defined as

$$Y_{M1} = 0.76623X - 1085.3269 \qquad (5)$$

and,

$$Y_{M2} = 737.1300 - 0.57735X \qquad (6)$$

in units of mm. These are the only constant lines as $Y_{B1\text{-}B4}$ depend on the angle of incoming starlight and $Y_{t/t}$ depends on the angle of the tip/tilt mirror.

The point (X_1,Y_1) and the line Y_{B2} are found by first determining the line Y_{B1}, in terms of it's angle of approach δ (see Figure 9). The slope of Y_{B1} is simply tan(δ), and the Y-intercept is 108000*tan(δ) as the slit is located 108m from the primary mirror. The result for line Y_{B1} is

$$Y_{B1} = \tan(\delta)*X - 108000 * \tan(\delta). \qquad (7)$$

Setting $Y_{B1} = Y_{M1}$ and solving for X results in

$$X_1 = \frac{1085.3269 - 108000\tan(\delta)}{0.76623 - \tan(\delta)} \qquad (8)$$

and Y_1 can be found as

$$Y_1 = 0.76623*X_1 - 1085.3269\ . \qquad (9)$$

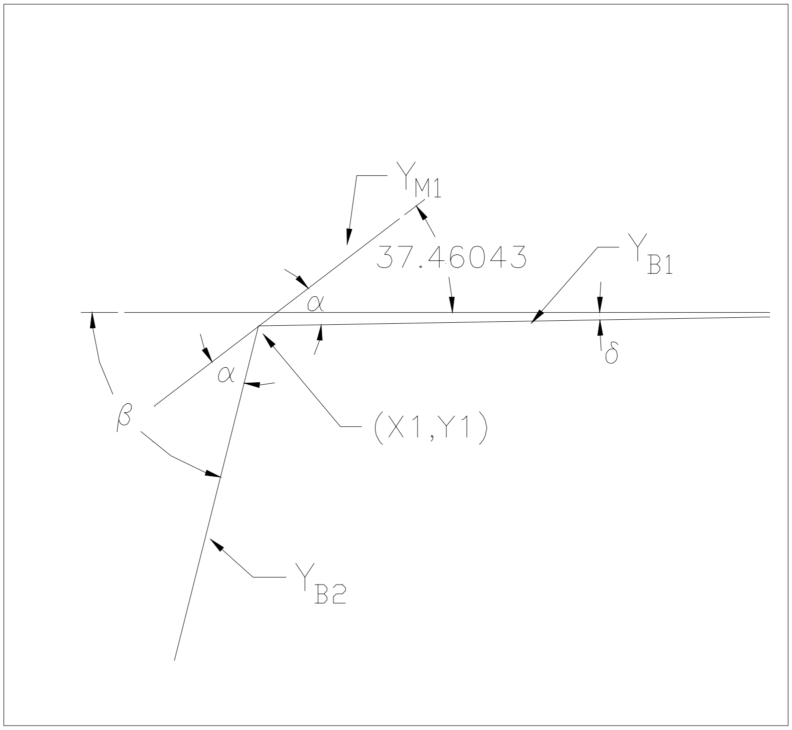

Figure 9. Mirror 1 Reflectance Angles. Angles are in terms of incoming starlight angle δ.

Line Y_{B2} must now be found. The angle α can be found as 37.46043 - δ, and β is just 37.46043 + α, or

$$\beta = 74.92086 - \delta \tag{10}$$

Knowing the point (X_1,Y_1) and the angle β, Y_{B2} can be found as

$$Y_{B2} = \tan(\beta)*X + Y_1 - X_1\tan(\beta) \tag{11}$$

Figure 10 shows the geometry required for determining (X_2,Y_2) and Y_{B3}. The tip/tilt mirror angle τ is variable, so lines $Y_{t/t}$, Y_{B3}, Y_{B4} and points $(X_{2,3},Y_{2,3,4})$ must be expressed in terms of this angle.

The centroid of the t/t mirror is located at (1372, -165). Knowing this location, the line $Y_{t/t}$ can be found as

$$Y_{t/t} = \tan(\tau)*X - 1372\tan(\tau) - 165. \qquad (12)$$

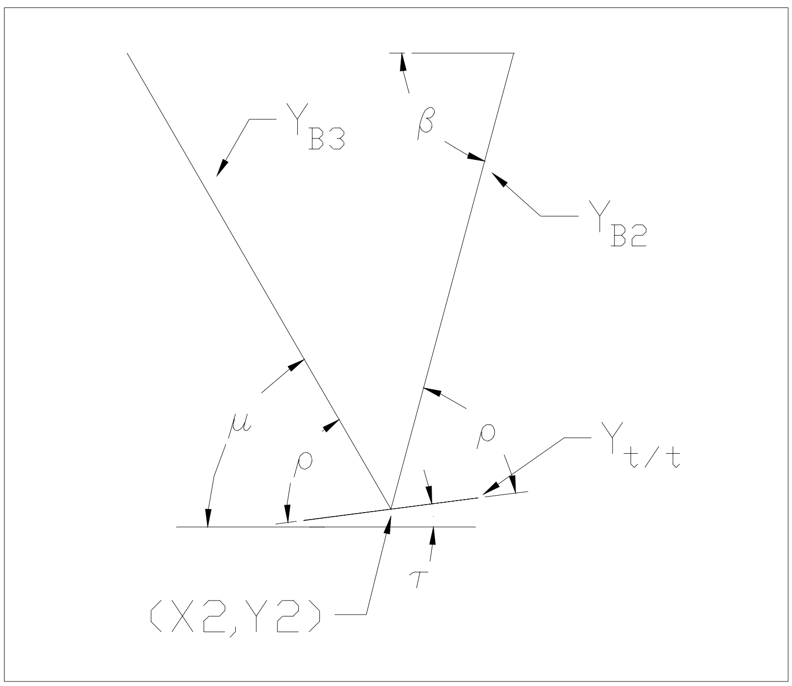

Figure 10. Geometry for Tip/Tilt Mirror and Beam Angles.

Equating $Y_{t/t}$ and Y_{B2} will give the result for X_2 in terms of τ. Plugging X_2 into (12) yields the value Y_2. Substituting (10) into (11) to keep the equations in terms of δ and τ,

$$X_2 = \frac{X_1 \tan(74.92086 - \delta) - Y_1 - 1372 \tan(\tau) - 165}{\tan(74.92086 - \delta) - \tan(\tau)} \qquad (13)$$

and,

$$Y_2 = X_2\tan(\tau) - 1372\tan(\tau) - 165 . \qquad (14)$$

Solving for μ as

$$\mu = \beta - 2\tau = 74.92086 - \delta - 2\tau, \qquad (15)$$

Y_{B3} can be found as

$$Y_{B3} = -X^*\tan(\mu) + Y_2 + X_2\tan(\mu). \qquad (16)$$

The point X_3 can now be found by equating (16) and (6), Y_{B3} and Y_{M2} respectively.

$$X_3 = \frac{737.13 - Y_2 - X_2 \tan(\mu)}{-\tan(\mu) + 0.57735} \qquad (17)$$

and plugging (17) into (6),

$$Y_3 = 737.1300 - 0.57735X_3. \qquad (18)$$

Finally, the Image position at the slit, Y_4, and the angle of approach to the slit, σ, can be calculated using the geometry shown in Figure 11. The angle of approach is simply

$$\sigma = 2(30) - \mu = 60 - \mu. \quad (19)$$

Knowing X_3, Y_3, σ, and X_4=0, Y_4 is easily found to be

$$Y_4 = Y_3 + X_3\tan(\sigma) = Y_3 + X_3\tan(60\text{-}\mu). \quad (20)$$

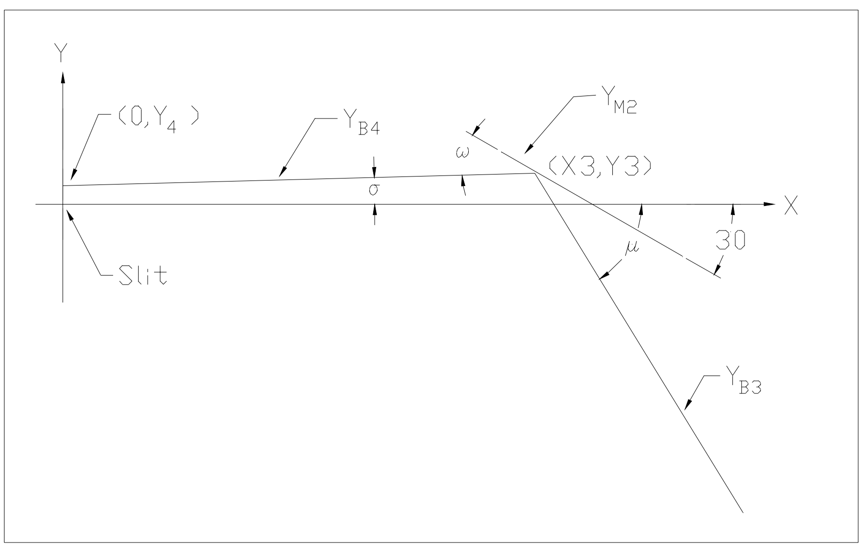

Figure 11. Mirror 2 and Slit Position and Angles. The slit lies at the intersection of the X and Y axes.

The above derivation was placed into an Excel spreadsheet. Various values of δ, angle of input from the telescope, were used to solve for Y_4. The "Goal seek" function was used to force Y_4 to zero by adjusting the tip/tilt mirror angle τ. With Y_4 forced to zero, the light will pass through the slit and result in an offset at the face of the collimator as shown in Figure 12. The resulting relationships, τ(δ) and σ(τ), were found to be

$$\tau = 36.36*\delta \qquad (21)$$

and,

$$\sigma = 2\tau. \qquad (22)$$

The collimator offset can then be determined in terms of both τ and δ as

$$\text{Offset} = 7000*\tan(2\tau) = 7000*\tan(72.72\delta) \qquad (23)$$

where 7000 is the distance from the slit to the collimator in mm.

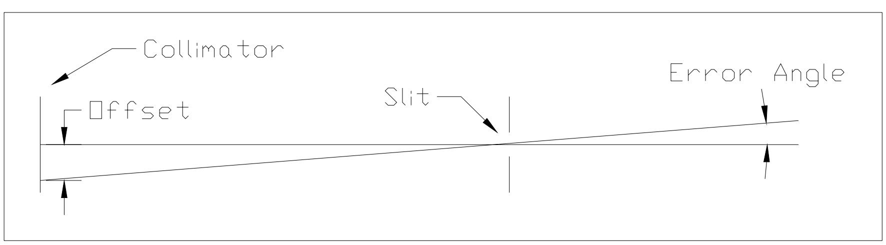

Figure 12. Error Angle (σ) Vs. Collimator Offset.

Tip/Tilt Mirror and Actuator

The tip/tilt mirror is mounted to the commercially available Melles Griot "Nanomover^{TM} Gimbal Mirror Mount Kit" shown in Figure 13. A gimbal type mirror mount is designed such that the two orthogonal axes of rotation intersect at the front surface of the mirror resulting in a constant optical path length, regardless of angular changes in mirror position. The total angular range of the gimbal mount is 3°, or ±72.1mm of linear travel at the slit. Recalling the range constraint given in (4), R > ±2.62mm, this is much more than adequate.

Figure 13. Gimbal Type Mirror Mount with Stepper Motor Actuators.

A set of Nanomovers^{TM} are used as the actuators for the gimbal mount. These are very precise stepper motor driven micrometer leadscrews designed for direct replacement of manual micrometer adjusters. The stepper motors are two phase with 400 steps/revolution. The Nanomovers™ have a linear resolution of 10nm resulting in an angular resolution of 0.25nrad on the gimbal mount, or 0.686 microns (1.3 milliarcseconds) at the slit. The maximum velocity of each Nanomover™ is 2.5mm/s. Converting this to motion at the slit results in a maximum slew rate 171.28 mm/s, or 326.8 arcsec/s of angular motion of an image across the telescope field of view. This easily meets the constraint given in (3).

A piezoelectric actuated tip/tilt mirror is the most commonly used type for tip/tilt applications. Piezoelectric actuators offer excellent positioning resolution with bandwidth capabilities as high as 10kHz. The downfall of piezoelectric actuators is their lack of a satisfactory range of motion. Most piezoelectric actuators have a linear range of less than 100 microns, limiting a tip/tilt platform to a range of less than ±1mrad depending on how closely the actuators are placed to the axis of rotation. In many applications the tip tilt mirror can be placed far from the slit resulting in a long moment arm, or lots of throw from a small range of motion. The tip/tilt mirror at the Shane telescope was placed fairly close to the slit to avoid requiring large optical table components in the f/36 beam and to keep the optical table accessible. At a distance of 1.3m from the slit, the range of motion using a piezoelectric unit would correspond to less than 3 arcseconds of motion at the focal plane. To reach the range constraint given in (4), the optical table would have to be moved to a distance greater than 4.6m from the slit. At this distance the f/36 beam diameter is 128mm. A tip/tilt platform would have to be specially made to handle a mirror this large and would be very expensive. Also, this would position the optical table inside the polar axis of the telescope, which is very inaccessible. For these reasons, the stepper motor system was selected for this application. The Nanomovers have the sufficient resolution and can make arcsecond corrections at rates of up to 70Hz. The high bandwidth of the piezoelectric actuators is not necessary, as this system has been proven to correct sufficiently at bandwidths less than 20Hz.

Mirror Coatings

The mirrors are currently in for recoating by Denton Vacuum. The coating used will be an FSS-99 front surface Silver, protected with multilayer overcoats. This coating is very resistant to damage from the environment and should not require recoating for at least 2-3 years. The average reflectance in the visible spectrum is about 97%, 98% in the 500-600nm range (target range for the SFSU Planet Search Project), and 99% in the IR. Another area of interest to the SFSU Planet Search Project is at 850nm, the reflectance is approximately 99% at this wavelength. This coating should meet the requirements of all observers acquiring data above 400nm. Polarization is negligible with this coating.

Control of Optical Table Position

A link has been installed between the optical table mount and a polar quartz lamp. The lamp is used for calibrating the spectrograph and is only in place when the optical table is not needed. The lamp is moved into the light path using an air cylinder controlled by the HSC (Hamilton Spectrograph controller) in the Shane read out room. The installation of the link allows the user to specify which component will be in the light path. When the polar quartz lamp is in the "off" position, the optical table is in the light path. Turning the lamp to the "on" position pushes the optical table out of the light path and moves the lamp into the light path. The link is removable for non-tip/tilt users. The tolerance required for this degree of freedom is ±0.1". Testing has shown that the optical table positioning is repeatable to well within these parameters.

Optical Table Alignment

Alignment of the optical table is a fairly simple procedure. The optical axis of the telescope can be found by installing a laser into the light path as shown in Figure 14. The laser is then adjusted until the beam passes through two known points, the slit and the center of the Collimator (first optical component in the Hamilton Spectrograph camera room). A mount was constructed for this purpose, allowing for easy installation of a laser on a kinematic stage.

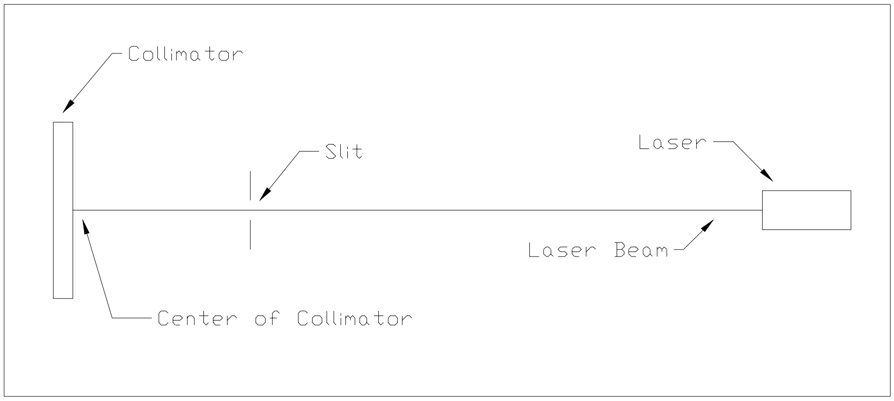

Figure 14. Alignment Laser. Laser simulates optical axis by aligning it to pass through two known points of the optical axis.

Once the optical axis has been found, the optical table must be slid into place and the beamsplitter must be installed as shown in Figure 15. It is important that the beamsplitter be in place so the alignment procedure compensates for the beamsplitter offset which will be discussed in the following section. Using the micrometer adjusters of the kinematic stage type mirror mount, Pick-off mirror #1 must be adjusted until the laser hits the center of the tip/tilt mirror. Pick-off mirror #2 must now be adjusted until the beam passes through the same two points used in the previous step. During the initial setup of the system it is necessary to adjust the home position of the tip/tilt mirror to accomplish this. For the nightly setup procedures it is unlikely that any adjustments will be required as the optical table slides repeatably into place. Unless the pick-off mirror mounts are moved, the alignment has been experimentally shown to remain constant for numerous tests of sliding it in and out of the light path. Detailed step-by-step alignment procedures are included in the attachments as well as the Coude Tip/Tilt User's Manual.

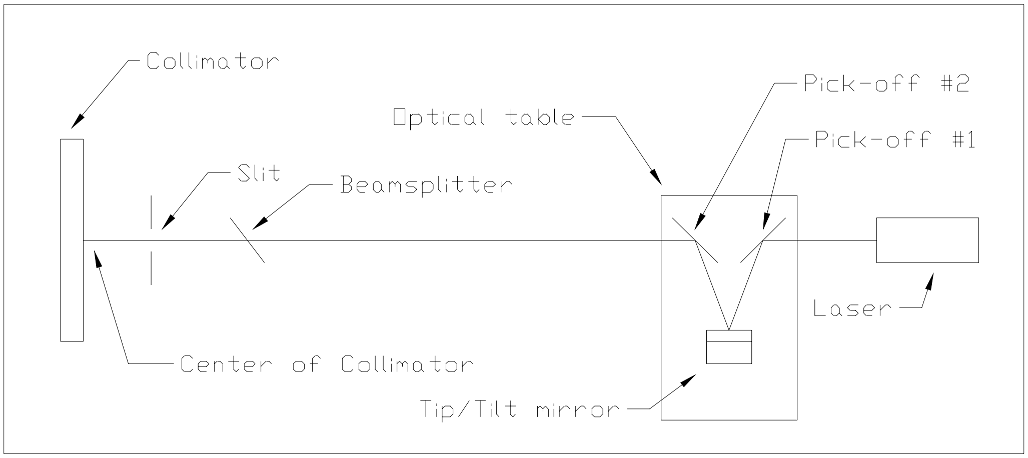

Figure 15. Optical Table Alignment Setup. The optical table is aligned by adjusting the pick-off mirrors such that the laser passes through the slit and the center of the collimator.