CHARA TECHNICAL REPORT

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Wobbler Servo Requirements

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1. INTRODUCTION

The Center for High Angular Resolution Astronomy (CHARA) of Georgia State University will build a facility for optical/infrared multi-telescope interferometry, called the CHARA Array. The facility will consist of seven (initially five) telescopes, with tip/tilt correctors feeding evacuated pipes conducting the beams to a central laboratory. The laboratory will contain optical delay lines, beam combination optics, and detection systems. The facility will consist of these components plus the associated buildings and support equipment. The CHARA Array is partially funded by the National Science Foundation and will be located on Mount Wilson in southern California.

1.1. The Wobbler Servo

The basic function of the wobbler system, or tilt correction servo, is to keep the interfering beams of the arms of the Array parallel. If the difference in beam tilt is too large, losses in signal-to-noise ratio will occur in the visibility measurements of the interferometer. The coherence transfer factor[2] caused by tilt error when the beams are combined is given by Buscher (1988) to be

$$\eta = 1 - 1.8 \left\langle (\theta/\theta_0)^2 \right\rangle \quad , \tag{1}$$

where θ is the differential tilt error and θ_0 is the angular radius of the Airy disc formed by the stellar image.

Due to the reduction in beam size imposed by the input telescopes, the angle of tilt caused by the atmosphere is increased by a factor of eight (8), that is, the beams are reduced in diameter from 1 m to 12.5 cm. This has the effect of increasing the required throw of the mirrors. Furthermore, a second stage of beam reduction at the back end of the interferometer results in a final beam diameter of 2.5 cm. There is therefore a total beam reduction factor of 40 before the beam reaches the detector system.

Finally, it should be noted that the wobbler mirror position signals, after passing through suitable low pass filters, will also be used as guidance signals for the input telescopes.

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[2] The coherence transfer factor is defined as the measured visibility of an unresolved source; see for example Tango & Twiss (1980).

The wobbler servo consists of three basic subsystems: the detectors, the mirrors, and the control system. Each will be discussed in a separate section with an emphasis on the mirrors.

2. ERROR BUDGET

Due to the expense of manufacturing high quality surfaces for the main mirror optics in the telescope a large fraction of the error budget for optical surfaces has been allocated to the telescope primary (see Technical Reports 15 and 16). The allowable Strehl for the wobbler optics has been set to 0.98, that is, essentially a perfect optical system. A preliminary breakdown of this for the wobbler system is given in Table 1.

TABLE 1. Coherence transfer factor budget for the wobbler system.

	Required	Goal
System transfer factor	0.95	0.98
Optical surface	0.99	0.995
Servo bandwidth	0.98	0.99
Centroid error	0.98	0.995

3. APPROXIMATION OF TIP/TILT POWER SPECTRUM DUE TO THE ATMOSPHERE

The tip/tilt power spectrum can be expressed (Tango & Twiss 1980, ten Brummelaar 1995) as

$$W_\theta(f) = k \times W_0(f) \quad , \tag{2}$$

where k is a constant of proportionality and

$$W_0(f) = \begin{cases} \left(\frac{f}{f_0}\right)^{-\frac{2}{3}} & f < f_0 \\ \left(\frac{f}{f_0}\right)^{-\frac{11}{3}} & f \geq f_0 \quad . \end{cases} \tag{3}$$

In this equation $f_0 = 2v_\perp/\pi D$, where $v_\perp$ is the transverse wind speed, and D is aperture diameter. To calculate k, we need to consider the total power of the spectrum over all frequencies

$$\sigma_\theta^2 = \int W_\theta(f)\, df \quad . \tag{4}$$

This is the same as the variance, which is given by Greenwood & Fried (1976) to be

$$\sigma_\theta^2 = 0.184 \left(\frac{D}{r_0}\right)^{\frac{5}{3}} \left(\frac{\lambda}{D}\right)^2 \mathrm{rad}^2 \quad . \tag{5}$$

By equating the two expressions, one finds that

$$k = 0.0545 \left(\frac{D}{r_0}\right)^{\frac{5}{3}} \left(\frac{\lambda}{D}\right)^2 \left(\frac{1}{f_0}\right) . \tag{6}$$

The power spectrum of tip/tilt can therefore be written

$$W_\theta(f) = 0.0545 \left(\frac{D}{r_0}\right)^{\frac{5}{3}} \left(\frac{\lambda}{D}\right)^2 \left(\frac{1}{f_0}\right) \times \begin{cases} \left(\frac{f}{f_0}\right)^{-\frac{2}{3}} & f \leq f_0 \\ \left(\frac{f}{f_0}\right)^{-\frac{11}{3}} & f > f_0 \quad . \end{cases} \tag{7}$$

4. THE MIRRORS

The mirrors are probably the most technologically demanding part of the wobbler system. While a number of 'off the shelf' devices exist, none of those commercially available are large enough to be useful in the CHARA Array. It is of course possible that a modified version of an existing system would meet our needs. Alternatively, it may be necessary to build the mirrors in-house.

4.1. Location and Size

The mirrors will be mounted on a small optical breadboard on the side of each telescope (see Figure 1). A better description of the telescope design can be found in CHARA Technical Reports 8, 9, and 10. Basically the telescopes employ an Alt/Az mount and it is intended that the wobbler mirrors will become part of the coudé system of these telescopes. The mirror mount should therefore take up a small amount of extra space on the mount platform, which must also hold the acquisition and atmospheric refraction corrector systems.

The beam size reaching the wobbler mirrors is 12.5 cm at a 45° angle and will therefore have a maximum extent of 18 cm. In order to allow for alignment areas and a safety margin we should specify a 20 cm diameter on all the mirrors. There is no requirement for a circular mirror, a rectangular or elliptical shape would do the job, although it may be a cost advantage if we use the same type of mirror as used in the rest of the optical system. In fact it is not necessary for the vendor supplying the mirror drive system to supply the mirror itself, although from a logistics and testing point of view it would be preferable.

4.2. One or Two Axis?

In all of the existing tip/tilt systems investigated to date a single dual-axis mirror is used as the active optical element. Due to the tight constraints on path length changes, bandwidth and throw it may be easier and cheaper to construct two single axis mirrors. As Figure 1 shows there are already two symmetric mirrors in the optical chain and it would be possible to use both in the tip/tilt servo. The only disadvantage to this technique is that the beams will not be fully tilt corrected before passing through the atmospheric refraction correctors, although this can be considered to be a second order effect (ten Brummelaar 1995). Both dual-axis and single axis solutions will be considered and the decision will probably be determined by cost.

4.3. Bandwidth

In almost all tip/tilt servos the bandwidth of the system is limited by the performance of the wobbler mirror itself. The criterion to be used to specify the mirror bandwidth is that the remaining wavefront tilt should contribute less error than the higher order atmospheric aberrations. Previous analysis by ten Brummelaar et al. (1995) has shown

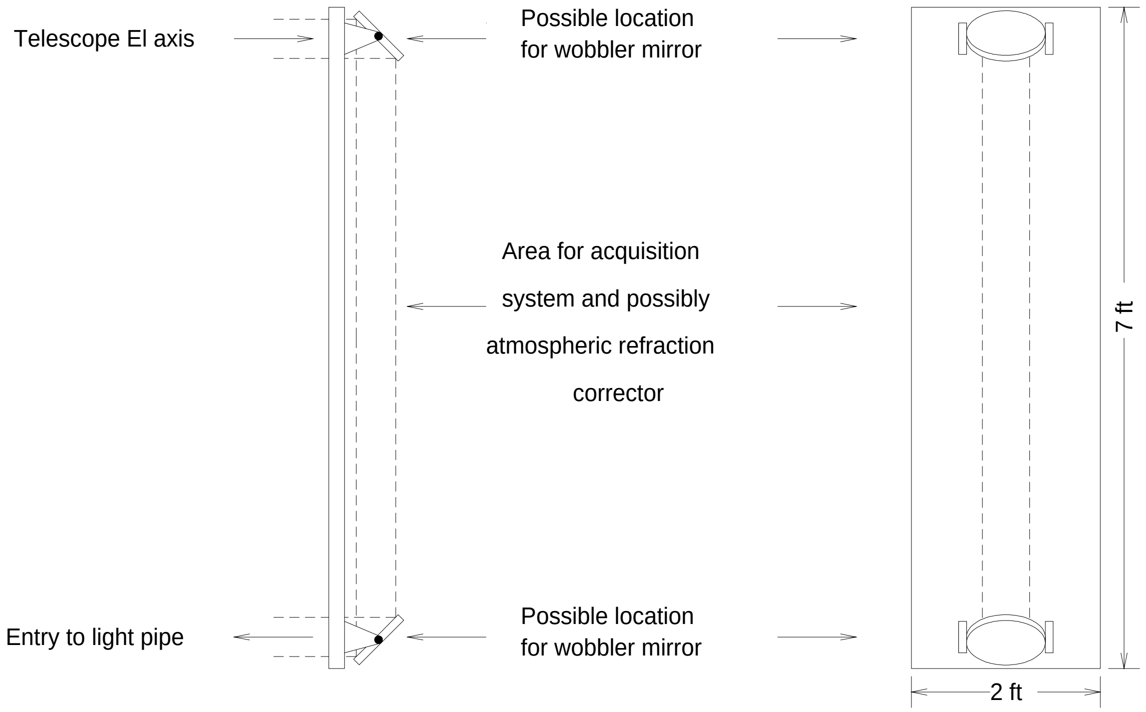

FIGURE 1. Side and top view of the plate on which the mirrors will be mounted. Note that the acquisition system and atmospheric refraction corrector will in all likelihood also be mounted here. The plate is mounted on the side of the telescope itself.

that the coherence transfer factor is well approximated by the Strehl ratio, which in turn can be estimated by using the work of Noll (1976). Thus we can say that the coherence transfer factor for the atmosphere, not including tilt or piston phase, is given by

$$\eta_{\mathrm{atm}} = \exp\left[-0.134\left(\frac{D}{r_0}\right)^{\frac{5}{3}}\right] \quad . \tag{8}$$

We will use Equation 1 to calculate the coherence transfer factor due to the remaining tilt variance after correction and write

$$\eta_{\mathrm{tilt}} = 1 - 1.8 \times \left(\frac{D}{1.22\lambda}\right)^2 \times 4\sigma_\theta^2 = 1 - 4.838\left(\frac{D}{\lambda}\right)^2 \sigma_\theta^2 \quad , \tag{9}$$

where the Airy disk size has been replaced by $1.22\lambda/D$, σ_θ^2 is the residual variance of tilt after the servo, and a factor of four has been added because for each set of fringes there are two beams, each with two axes. In order to estimate the residual tilt variance we assume that the servo removes tilt at all frequencies up to the maximum bandwidth of the mirror f_m, assumed to be greater than or equal to f_0. Therefore

$$\begin{aligned}\sigma_\theta^2 &= \int_{f_m}^{\infty} W_\theta(f)\, df \\ &= 0.0205\left(\frac{D}{r_0}\right)^{\frac{5}{3}}\left(\frac{\lambda}{D}\right)^2\left(\frac{f_m}{f_0}\right)^{-\frac{8}{3}} \quad .\end{aligned} \tag{10}$$

Given that we set a transfer factor of 0.98 (goal 0.99) for the bandwidth we can combine equations 9 and 10 and solve for f_m/f_0 for any given seeing conditions. Thus

$$\frac{f_m}{f_0} = \left(\frac{D}{r_0}\right)^{\frac{5}{8}} \left(\frac{0.1}{1-\eta_{\rm tilt}}\right)^{\frac{3}{8}} \quad . \tag{11}$$

For the visible this is a very large bandwidth, for example for $D/r_0 = 10$ we get a bandwidth of $f_m/f_0 = 7.8$ (goal $f_m/f_0 = 10$) which can imply a bandwidth of over 100 Hz. In the infrared the lower D/r_0 values imply bandwidths of $f_m/f_0 = 2.37$, something more easily attainable.

If we instead impose the constraint that the coherence transfer factor for the residual tilt is equal to, or less than by some factor n, that of the higher order aberrations introduced by the atmosphere. Combining Equations 8, 9, and 10, adding the factor n, and solving for f_m/f_0, we get

$$\frac{f_m}{f_0} = \left(\frac{D}{r_0}\right)^{\frac{5}{8}} \left(\frac{0.1}{1-\exp\left[-\frac{0.134}{n}\left(\frac{D}{r_0}\right)^{\frac{5}{3}}\right]}\right)^{\frac{3}{8}} \quad . \tag{12}$$

Note that this result depends only on the current seeing conditions as defined by D/r_0 and the quality factor n. A plot of this result is given in Figure 2 for various values of n. Also plotted are lines of constant $\eta_{\rm tilt}$.

It is clear from this plot that $f_m/f_0 = 2$ is adequate for all 'good' seeing conditions ($D/r_0 < 10$) and a figure of $f_m/f_0 = 3$ will cover all seeing conditions up to $D/r_0 \leq 20$. Furthermore for the best of seeing ($D/r_0 = 2$) and bandwidth of $f_m/f_0 = 3$ we achieve a transfer factor of 0.983, which meets the specification. We can therefore state that a bandwidth defined by

$$f_m = \frac{6v_\perp}{\pi D} \tag{13}$$

will be sufficient for any conditions underwhich we would observe with the array.

Thus, assuming a maximum wind speed of 25 m/s and modeling the mirror as a low pass filter, we can say that the bandpass should have a -6 dB (that is the point of 45° phase lag) of 50 Hz and at zero lag response up to 25 Hz. A larger bandwidth would of course be desirable. The first resonance frequency of the mirror system should be higher than this maximum drive frequency by a factor of two, that is greater than 100 Hz.

4.4. Throw

Due to telescope tracking errors and downstream alignment errors the maximum throw of the servo may be considerably larger than the conditions that are implied by $W_\theta(f)$. The throw required to track atmospheric tilt can be approximated by taking the square root of Equation 7:

$$W_\theta(f) = 2.64 \left(\frac{D}{r_0}\right)^{\frac{5}{6}} \left(\frac{\lambda}{D}\right) \left(\frac{1}{f_0}\right)^{\frac{1}{2}} \times \begin{cases} \left(\frac{f}{f_0}\right)^{-\frac{1}{3}} & f \leq f_0 \\ \left(\frac{f}{f_0}\right)^{-\frac{11}{6}} & f > f_0. \end{cases} \ \text{rad} \quad . \tag{14}$$

Note that the angles have been multiplied by 8 due to the telescope magnification and a factor of $\sqrt{2}$ as an estimate of peak motion. We show a plot of the rms mirror motion over

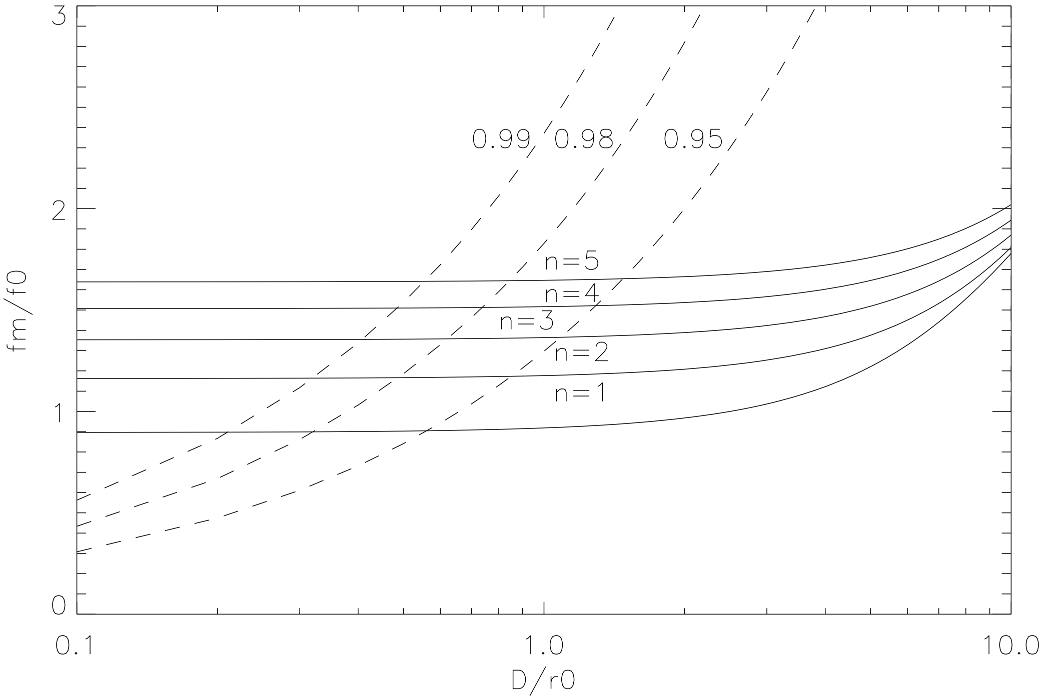

FIGURE 2. Plot of f_m/f_0 for various amounts of correction compared to the rest of the aberration due to the atmosphere (solid lines) and lines of constant $\eta_{\rm tilt}$ (dashed lines).

a range of frequencies in Figure 3. We can see from Figure 3 that a throw of $\pm 10''$ will be required for the low frequencies ($f \leq f_0$ Hz) while the throw can decrease for higher frequencies going down to only $\pm 1''$ at $2f_0$. This is the throw required to track atmospheric turbulence. The very low frequency, or 'DC' range should have the capability of correcting for small pointing errors in the telescopes and the rest of the optical system. A full throw of $\pm 1'$ would allow pointing errors as high as $\pm 7''\!.5$ while a full throw of $\pm 0'\!.5$ can be considered the minimum.

4.5. Pointing Precision

Apart from servoing out tilt errors, the wobbler mirrors will also be used for internal alignment and acquisition. The mirrors must therefore be able to return to some well know position, normally the central or null position. For the sake of downstream alignment the repeatability of this position should be less than the size of the Airy disk, which at a wavelength of 0.5 microns and the beam diameter of 12.5 cm is of the order of $1''$. We therefore set the requirement that the central position of the mirror is repeatable to less than $1''$.

Once set to the central position it is not necessary for the wobblers to have manual adjustments as enough flexability exists in the rest of the optical system. The mount will, however, need to hold the mirror in it's null position to within $10'$ of 45° to the table surface.

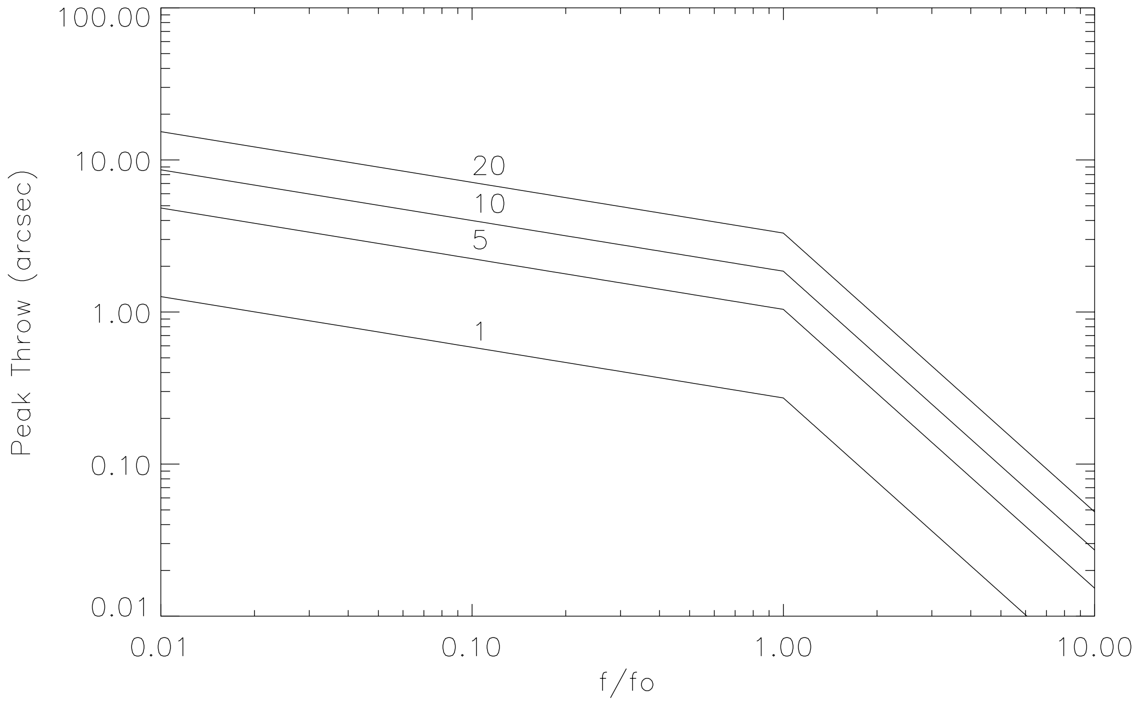

FIGURE 3. Plot of mirror throw for a range of frequencies in units of f_0 and seeing conditions. The numbers above the lines indicates the D/r_0.

4.6. Mirror Quality

The transfer factor allocated for the mirror surface quality over the appropriate sub-pupil is 0.99 (goal of 0.995). This corresponds to $\lambda/60$ (goal $\lambda/100$) rms error. The peak error should be no greater than $\lambda/20$. This is a very tight constraint in the visible but easily attainable in the infrared. Since CHARA will have to acquire dozens of these mirrors for down-stream optics it may be cheaper, and safer, for us to supply the mirrors. The matter of whether the wobbler mirrors need to be light-weighted will depend on the actuator system. Furthermore, the mirror mounts must take into account the need to preserve the flat surface.

4.7. Path length Changes

Although the Optical Path Length Compensator corrects for the atmosphere, there still exist further path length errors due to the wobbler mirrors. The extra path introduced by the mirrors should not exceed 0.01 μm. If we assume that the incoming beam is subjected to a deviation of θ the tilt mirror will require a tilt of $\theta/2$. This will result in an inherent path length difference of the wavefront which must be taken into account.

Initially, assume that the tilt mirror is in a pupil plane. If the tilt axes are in the plane of the mirror, there will be no OPD error. If the tilt mirror rotation axis is distance r below the mirror surface, there will be an OPD error. If the beam is normal to the tilt mirror, the OPD error will be $r\theta^2/4$, and if the tilt mirror is inclined 45 degrees, the OPD error will be $\sqrt{2}r\theta^2/2$.

If in addition the apparent pupil plane is not in the surface of the tilt mirror, but at a distance L, the OPD will be approximately

$$[\frac{r}{4} + \frac{L}{2}]\theta^2 \tag{15}$$

for normal incidence, and

$$[\frac{\sqrt{2}r}{2} + \frac{L}{2}]\theta^2 \tag{16}$$

for incidence at 45 degrees.

The OPD produced by fast tilt correction should be negligibly small. For a typical tilt motion of 1 arcsec on the sky, the afocal beam will deflect by 8 arcsec. In order to limit the OPD changes associated with tilt correction to less than 0.01 μm, the distance $\frac{\sqrt{2}r}{2} + \frac{3L}{4}$ must be no more than about 7m. Since r will naturally be no more than a few cm, this constraint falls primarily on L which should not exceed about 7m.

4.8. Momentum Dissipation

Many tilt correcting mirrors built for telescope operation employ momentum compensation in order to minimize the transfer of vibration to the telescope structure. Vibration in the CHARA telescopes may lead to optical path variations and resultant loss of efficiency. Momentum compensation need not be complex (eg Close and McCarthy, 1994), but it undeniably adds additional complexity and potentially cost. Will momentum compensation be required for CHARA?

In the CHARA telescope design, the tilt correction mirrors will be located on a vertically mounted optical table on one side of the telescope altitude fork (Fig. 1). We can make an estimate of the tilt mirror back reaction by first considering the optical table as an isolated rigid body coupled to the tilt mirror through the tilt mirror drive. Considering the tilt mirror plus table as a closed system, the tilt drives will impart to the table an angular momentum equal and opposite to the angular momentum imposed on the tilt mirror.

A mirror 20 cm diameter by 3 cm thick with a cell of similar mass and shape will have a moment of inertia about a central tilt axis of about 10^{-2} kg-m2. A steel honeycomb core table will have a mass of about 100 kg/m2. A table 60 cm wide and 180 cm long will have a moment of inertia about one end of about 90 kg-m2, and about a longitudinal axis of about 3 kg-m2.

From conservation of angular momentum, the motion of the table will be smaller than the motion of the tilt mirror by the ratio of the moments. Tilt mirror motions of 8 arcsec (1 arcsec on the sky) will produce table rotation about the longitudinal axis of about 0.05 arcsec (0.008 arcsec on the sky), but to first order no OPD change. This is clearly not important in a closed loop tilt correction. Tilt mirror motions of 8 arcsec will produce rotation of the table about one end of about 9×10^{-4} arcsec, with a resultant OPD change (due to displacement of the mirror at the opposite end) of about 0.004 μm, again clearly negligible.

The optical table will not move freely, but will be constrained by attachments to the telescope. The torque from the tilt mirrors will produce some flexure of the table, but less than the rigid body motion estimates, provided mechanical resonances do not amplify the disturbances. Optical tables are available with excellent internal damping. We will require that the lowest table resonance should be above the required bandwidth of the tilt correction, or above about 50 Hz. For a table of the dimensions prescribed, a lowest resonant mode of about 100 Hz should be available as a stock product.

The motion of the telescope due to tilt mirror vibration should be very low, partly because the disturbance will couple into a massive part of the telescope mount, the elevation fork, and partly because part of the power will be dissipated in the damped optical table.

In conclusion, no momentum compensation will be required. However, common sense indicates that in order to minimize the amplitude of the disturbing torques, the weight of the tilt mirror and the associated moving mechanism should limited. Thus we suggest moderate, but not extreme, light-weighting of the mirror, and likewise of the mirror mount. This will be advisable in any event in order to obtain the desired correction bandwidth with low drive power.

4.9. Driver Electronics

There is no requirement that the driver system be inductive coils, piezo stacks, or any other kind of actuator, only that the mirror meet the specifications set out above. In order to avoid any extra turbulence near the telescope the driver electronics must be able to be located away from the mirrors themselves and the actuators must create as little extra heat as possible.

The drive system can either accept analogue signals (for example in the form of two DC voltages in the range of ±10volts) or a digital signal (IEEE-GPIB or RS424 for example). An analogue interface will be sufficient although having both would be an advantage. The use of a digital interface will imply some bus latency. Such lag due to the digital bus must be kept less than 0.5ms.

4.10. Environmental Factors

The array will be installed and operated at Mount Wilson in California at an altitude of 5715 feet. Facility operations will be limited to temperatures in the range -5° C to +25° C, winds no greater than 30 mph sustained (45 mph gusts), humidity no greater than 90% (non-condensing).

Additional environmental hazards include thunderstorms with lightning; infrequent snowfall; occasional power failures; assault by squirrels, mice and other small animals; seasonally, insects of various types. Furthermore, Mount Wilson is the site for many of the TV and Radio transmitter towers for the L.A. area and is an extremely noisy RF environment. While the telescope housings will provide some shielding the ability of any system to withstand RF noise is important.

The mirrors, as shipped, shall have a storage life under these conditions of at least 60 days.

The mirrors as installed on the telescopes shall withstand these hazards while in a normal closed configuration.

5. SERVO CONTROL SYSTEM

It has not yet been determined whether an analogue or digital servo system will be employed. Both present different design problems and functional advantages. The system must have a digital interface in order for it to be remotely controlled from the central laboratory. A digital system will also facilitate easy changes of servo equations and parameter adjustments, while an analogue system is likely to be much less expensive and faster to get on-line. More work in the laboratory once we have a mirror to work with will help choose between these options.

6. THE DETECTORS

The detectors will be some kind of centroiding device, most probably a quadrant detector. The preliminary detector of choice is a fast-readout, low read-noise CCD, broken up into multiple quadrants, one for each beam. Other types of detectors are under investigation, including photodiode arrays and position sensitive photomultiplier tubes.

6.1. Location

The detectors will be located at the very back end of the optical chain, as close as possible to the beam combining system. The detectors will need to periodically re-aligned with the optical axis of the beam combining system. This can be achieved either by moving the 'feed' mirrors for the detector(s), as in the current design, or by moving the detectors themselves. If some kind of 'off the shelf' quadrant detectors were used the second option would probably be the easiest and cheapest to implement, while if we stay with a CCD the first solution will be used.

6.2. Throughput and Signal to Noise Issues

The current estimate for the fraction of photons entering the telescope aperture reaching the tip/tilt detectors (see Appendix R of the NSF proposal) is 5.5%. An approximation frequently used in astronomy is that a magnitude zero star has a flux of 10^7 photons $\mathrm{m}^{-2}\mathring{A}^{-1}\mathrm{s}^{-1}$. Thus, assuming an optical bandwidth from 0.4 to 0.8 microns and a sample time of 10 ms we can write the expected number of photons detected in one sample for a star of magnitude V as

$$N_{\mathrm{ph}} = 1.73\ \mathrm{DQE} \times 10^{(7-V/2.5)}. \tag{17}$$

The signal-to-noise ratio for a quadrant detector (see Appendix O of the proposal text) is given by:

$$\sigma_\phi = \frac{\pi \frac{3}{16}\left(\frac{\lambda}{D}\right)}{\mathrm{SNR}} \quad , \tag{18}$$

where SNR is the signal-to-noise ratio of the four detectors summed to act as a single detector:

$$\mathrm{SNR} = \frac{\sqrt{N_{\mathrm{ph}} + 4\sigma_{\mathrm{read}}^2}}{N_{\mathrm{ph}}} \tag{19}$$

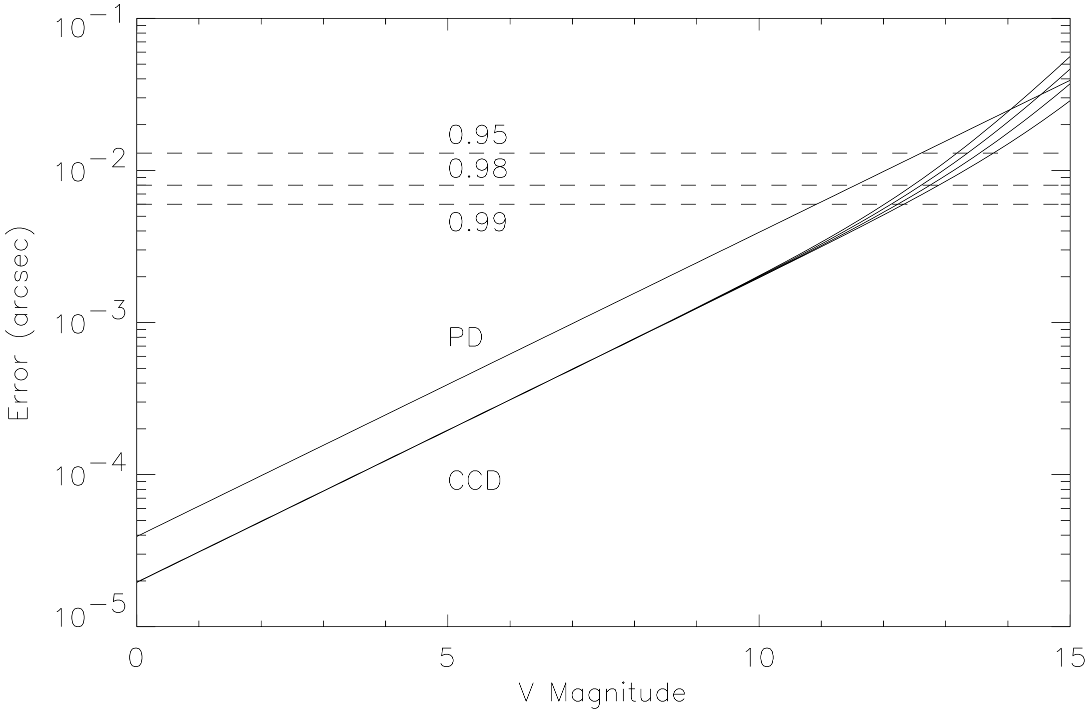

FIGURE 4. Expected error in tilt measurement for a %20 noiseless detector (top line) and an %80 efficient CCD with 2 (bottommost line) to 5 electrons read noise. The dashed lines represent various values for the coherence transfer factor.

and $\sigma_{\rm read}$ is the read noise of the detector. The resulting standard deviation of tilt measurement is plotted in Figure 4 for a %20 efficient noiseless detector (such as a photodiode) and an %80 efficient CCD with read noise ranging from 2 to 5 electrons.

It is clear that either detector will work satisfactorily for magnitudes less than V=10, and a limit of V=12 is attainable if we are willing to relax our spec for $\eta_{\rm quad}$ to 0.95. Furthermore the read noise only becomes a problem at very low light levels. It could be advantageous to also have cheap photodiode quad arrays near the telescopes in order to push the magnitude limit by 3 magnitudes, although this will present alignment difficulties down stream. Based on this analysis either detector type would be suitable for the initial commissioning of the CHARA Array, although it would be hoped that more efficient noiseless detectors and/or better CCDs will be available in the next few years.

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TABLE 2. Summary of Wobbler Requirements.

	Required	Goal
Number of units	5	Same
Beam diameter	12.5 cm	Same
Beam incidence angle	45°	Same
Mirror diameter	20 cm	Same
Mirror quality	$\leq \lambda/60$ rms $\leq \lambda/20$ peak	$\leq \lambda/100$ rms $\leq \lambda/30$ peak
Mirror thickness	Vendor to Specify	Same
Mount platform	Small optical table on the side of telescope (See Figure 1)	
Mirror Mount	$45° \pm 10'$ to table top	$45° \pm 1'$
Mirror Mount Adjustment	None Required	
Zero lag bandwidth	25 Hz	50 Hz
45° phase lag bandwidth	50 Hz	100 Hz
First mechanical resonance	≥ 100 Hz	≥ 200 Hz
Low frequency throw	$\pm 0\overset{'}{.}5$	$\pm 1'$
Dynamic throw to 25 Hz	$\pm 10''$	$\pm 15''$
Dynamic throw 25-50 Hz	$\pm 1''$ at 50Hz	$\pm 2''$ at 100Hz
Repeatability of null position	$< 1''$	$< 0\overset{''}{.}5$
Mirror translation due to rotation	$\leq 0.04\mu$m per arcsec	$\leq 0.01\mu$m per arcsec
Temperature range	$-5°$ to $+25°$ C	Same
Operational humidity range	$\leq 90\%$ (non-condensing)	Same
RF noise immunity	High	Complete
Storage life	≥ 60 days	1 year