CHARA TECHNICAL REPORT

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Flat Mirror Requirements and Specifications

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1. INTRODUCTION AND GENERAL INFORMATION

The CHARA Array will employ five 1-m size, alt-azimuth style telescopes at a site on Mount Wilson in southern California. The telescopes will be housed separately and operated remotely from a central laboratory. Light from each telescope will follow a path to the Coudé focus of the telescope, where one to three reflections will be required to balance the polarization and phase delay properties of the various beams. The light will be directed by subsequent flat mirrors through vacuum pipes to the central laboratory. There, additional flat mirrors will further balance the polarization and phase delay, then direct the beams into the POPs, which are optical delay segments of various lengths required to equalize the optical delays. Light will then be directed through a periscope arrangement into the OPLEs, for fine adjustment of optical delay. The light will pass through beam compressors, reducing the nominal beam diameter to several centimeters. Finally, flat mirrors will then direct the beams into the beam combination room and various parts of the beam combination system.

This document describes requirements and specifications for manufacture of the numerous flat mirrors required for this optical layout.

2. OPTICAL QUALITY AND SUBSTRATE REQUIREMENTS

The optical error budget described in CHARA Technical Report No. 2 allocates errors to the flat mirrors. An update of that table, taking into account new design details, follows.

This error budget specifies optical flats with an surface quality of 0.025 waves peak to valley, or 1/40 wave. This is a very stringent specification and may be difficult to procure within the CHARA budget.

In addition to high quality optical surfaces, the mirror mountings should not introduce significant additional aberration. An analysis of several simple optical mounts (CHARA Technical Report in preparation) demonstrates that optical aberrations due to mounting can easily be kept to less than 1/50 wave P-V, provided that the thickness of 8–inch diameter optics is at least 1.25 inches. We will tentatively recommend a thickness of 1.5 inches for 8-inch optics to reduce the mounting aberration even further (an additional 40%), and to hence reduce possible accumulated systematic error contributions from a number of similar

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TABLE 1. Error budget for the fixed optical aberrations in the CHARA Array. The column "spec" gives the specification for optical surface quality in waves peak-to-valley at 0.63 νm per surface. This number is multiplied by a geometrical factor, depending on the angle of incidence, and by a factor of two, to convert surface to wavefront error. The root sum square for the number of surfaces of this type is formed and entered in the Contribution column, describing the total wavefront error introduced by this type of components, in this model of the error.

Component	Number Contributing	Spec P-V on Surface	Net Contribution P-V on Wavefront
Telescope (primary & secondary):	1		0.20
Catseyes:	2 (dble pass)		0.18
Beam compressor:	1		0.20
Transmissive elements:	10 surfaces	0.10	0.16
Flats at normal incidence:	1	0.025	0.05
Flats at 30° incidence:	3	0.025	0.10
Flats at 45° incidence:	9	0.025	0.21
Beam combination optics	1	0.20	0.20
Root Sum Square Wavefront Error			0.48

elements and mounts. For 6-inch optics, a thickness of 1 inch will give approximately similar performance. Any additional attention that can be given to optimizing mirror supports over the simple assumptions in the above analysis will help further.

3. MIRROR SCRATCH AND DIG

The scratch/dig specification is described as a "cosmetic" specification, but the concern for CHARA is the possible loss in interferometric efficiency that may result through scattering losses.

A standard scratch/dig specification is 60/40. The "scratch" number signifies scratch width in TENTHS of microns. The specification is defined so that the total amount of "scratch" allowed is equivalent to no more than one scratch of the specified width, extending half over a length equal to half of the full diameter of the optic. The "dig" specification signifies dig diameter in TENS of microns, and the specification allows one of the specified diameter for every 20 mm of diameter of the optic.

A specification of 40/20 may be obtained readily. Beyond that, costs start to go up at many major optical shops, although one CHARA supplier states that anything less then 10/5 is a "used optic". An engineer at Zygo told me that digs are dominated by inclusions, so that reducing dig corresponds to selecting good material.

In an attempt to place the discussion on a more quantitative level, we refer to an article by Parks (1980) which gives a table showing the total fractional scattered light for both scratch and dig classifications.

TABLE 2. Theoretical amount of scattering due to defects as calculated on an area basis, from Parks (1980), for an optical surface 100 mm in diameter. An additional column giving the total scattering loss corresponding to a series of 40 surfaces — a number representative of CHARA.

Designation	Group	Parts per Million	Fraction Scattered for 40 surfaces
Dig	10	125	0.005
	20	500	0.020
	40	2000	0.080
	50	6400	0.256
Scratch	10	6	0.0002
	20	12	0.0005
	40	25	0.0010
	60	38	0.0015
	80	50	0.0020
	120	76	0.0030

A dig specification of 50 gives 6400 PPM, or 0.6% scattering loss (per surface). For 40 surfaces (a fair estimate for CHARA), the total scattering loss from dig would be 26%, as shown in the last column.

There seem to be two possible effects of scattering on interferometric efficiency. If the light is scattered out of the beam, then there is just the loss of throughput. Alternatively, light can be disturbed in phase but still cause interference that is out of phase, hence spurious. The sum of the lost light and the spurious signal should be no greater than the total scattering estimate above. Therefore, the total scattering loss can be used as an estimate of the efficiency loss.

This is seen in the following schematic analysis. Suppose that each of two telescope beams, E_1 and E_2, contain light amplitude A, and that a fraction a is scattered out of the beam and another fraction b undergoes a phase shift, but remains in the beam. Write the amplitude from the beams as,

$$E_1 = E_2 = A(1-a)e^{i\phi} + Abe^{i\psi} \tag{1}$$

where ϕ is associated with the good phase and ψ is associated with the bad phase. The intensity of the combined wave, $I = E_1 E_2^*$, neglecting higher order terms, has two terms that contain the bad phase: the intensity is reduced by fraction a, and there is a disturbing interference term with a maximum fractional amplitude of b. So the maximum fractional efficiency loss is given by $a + b$.

There is clearly a strong interest in obtaining a dig specification of in the vicinity of 20 or less, and a specification of 50 would be very unsatisfactory. On the other hand, the scratch specification appears to be much less important. The worst scratch specification tabulated contributes a fraction of one percent scattering loss, even with 40 surfaces contributing.

4. SCATTERING DUE TO SURFACE FIGURE

In the limit of a continuous distribution of surface error, from large to small scale, with error dominated by small scale structure, an estimate of the scattering should be available from the approximation that Strehl ratio is given by $S = \exp(-\sigma^2)$, where σ^2 is the mean square surface figure error in radians. In the limit of large Strehl, the mean square figure error is equal to the Strehl loss, so a 1% Strehl reduction (1% scattering loss) corresponds to a surface error of 0.1 radians, or 0.016 waves RMS.

Turning the issue around, a specification of 0.025 waves P-V would correspond to about 0.007 waves RMS. Interpreting this as an upper limit to the Strehl loss including scattering corresponds to scattering loss of less than 0.2% per surface. This calculation applies to $0.63\,\mu$m. Since this is an upper limit, it is probably acceptable.

While surfaces can be imagined which would violate these assumptions, they may be an unlikely product of conventional optical polishing techniques. Diamond turned optics would require a different approach to estimation of scattering.

5. MIRROR SUBSTRATE MATERIALS

For the mirrors in the Telescopes and in the Coudé Boxes, use of a low expansion material is obligatory. The most suitable materials are Zerodur or ULE.

For the mirrors inside the OPLE building, the temperature will be sufficiently stable that conventional glass could be utilized. However, such material requires additional care in the optical shop to ensure temperature uniformity during polishing and testing, so it may be preferred to specify low expansion materials throughout.

6. NOMINAL BEAM SIZE

With a clear aperture of 1 meter and a beam reduction factor of $8\times$, the nominal beam diameter from the telescope will be 12.5 cm. This diameter was chosen as a compromise, minimizing diffraction effects, and also allowing use of moderate, readily available optics.

After the optical delay, a beam compressor will impose an additional reduction of $5\times$, to a nominal beam diameter of 2.5 cm. However, diffraction will cause some beam divergence. This will be computed below.

7. BEAM WIDTH DUE TO FIELD OF VIEW

The acquisition field of view has not been specified yet. However, vignetting of this field off the optical axis may be acceptable. Tentatively, no requirement is imposed on optics size to accommodate acquisition.

The operational field of view at the beam combination lab is necessarily limited to the absolute minimum, since enlarging it to even a few arcsec would result in prohibitive optics sizes. The CHARA Array is expected to operate interferometrically within the Airy disk, so the required field of view will be basically set by diffraction.

8. BEAM DIVERGENCE DUE TO DIFFRACTION

The classical result for a circular aperture describes the diffracted image, in the Fraunhoffer limit, in terms of the Airy function. The diameter of the diffracted beam, to the first zero of the intensity, is $2.44\lambda/D$, where D is the clear aperture of the telescope. Diffraction will thus depend on aperture and wavelength.

The choice of the first zero of the intensity can be debated. It does seem clear that any vignetting to this diameter will directly impact the interferometric efficiency of the Array.

8.1. Diffraction in the Infrared

In the infrared, the full telescope aperture will normally be used. Under the best conditions, the telescope will be nearly diffraction-limited. For example, with $r_o = 20$ cm at $0.5\,\mu$m, the value of r_o at $2.2\,\mu$m will be 118 cm.

At the longest design wavelength, $2.4\,\mu$m, the diffraction diameter will be 1.20 arcsec. One could alternatively use the mean wavelength in the K band, about $2.2\,\mu$m, giving a slightly smaller diffraction diameter, 1.1 arcsec.

8.2. Diffraction in the visible

In the visible, the estimation of diffractive beam spread is more tricky. There are several ways to proceed, none fully satisfactory.

Under exceptional seeing, one might suppose $r_o = 30$ cm. There will be diffraction from the 30-cm "seeing cell", but it isn't clear how to calculate that. The simple calculation, for diffraction at $0.5\,\mu$m to the first zero of intensity from a 30-cm aperture, is 1.26 arcsec. This is probably an upper limit to the actual diffraction, which is also not likely to have a zero since the effective aperture does not have a hard edge.

The 0.8 enclosed energy angle in $1''$ seeing is approximately 1.2 arcsec. In the following, the angle 1.2 arcsec will be adopted, as it appears to be a reasonable estimate for a variety of situations.

With the telescope demagnification of $8\times$, the beam spread angle from the telescope will be 9.6 arcsec.

9. REQUIRED MIRROR DIAMETERS

The mirror diameter requirement will be based on the diameter of the diffracted beam, including any appropriate geometric projection factor. An additional margin of mirror diameter may be added in some cases in order to allow for alignment errors, especially in the long paths from the telescopes to the central facility. Finally, it may be useful to round up some mirror sizes to standard commercial dimensions, or to reduce the number of component sizes.

The various mirrors or mirror groups will be considered, beginning at the telescope and following the beam into the beam combination lab.

9.1. Telescope Mirrors — M3, M4, M5, M6

At the telescope, diffraction has negligible effect, due to the short propagation distance.

The tertiary, M3, is at 45° to the incident beam. This is the only place in the Array where it is expected to require an elliptical mirror. Here, M3 must be of an elliptical shape, preferably with tapered edges, since the telescope central obscuration is determined by this mirror diameter. The clear aperture should be 125×177 mm, with allowance for bevel and alignment errors in the substrate specification. M3 requires a special cavity on the back surface for installation in the M3 mirror mount.

The M4 and M5 mirrors, on the side of the telescope, are both at 45° to the incident beam, and the footprint of the beam is 125×177 mm.

The M6 mirror, on the azimuth axis, is also at 45° to the incident beam. M6 requires a special cavity on the back surface for installation in the M6 mirror mount. There is no requirement for an elliptical substrate.

Alignment of the telescope requires that the beam should be coincident with the altitude axis between M3 and M4, and with the azimuth axis between M6 and M7. Furthermore, optical alignment will be require that the beam fall on the center of M2. These are fairly difficult constraints. Furthermore, it is possible (likely?) that the telescope will sag enough to cause minor misalignment as it rotates around the sky. Correcting alignment may require active tilting of M2, M4 and M5. We may be able to avoid active tilting of M3, M6 and M7 provided M4 and M5 are slightly oversize and we do not require the beam to be centered on them. An oversize of a few mm should suffice. Additional oversize may simplify the installation of M4 and M5 at no penalty.

9.2. M7 and Coudé Box Mirrors

The mean distance from the telescope secondary (M2 mirror) is about 10 meters. The beam divergence over this distance will be approximately 0.5 mm, and can be neglected.

The M7 mirror will be inclined 45° to the incident beam. The beam footprint will be 125×177 mm.

There will be from zero to two additional mirrors in the Coudé Box, depending on which Array arm is under consideration. These will be oriented approximately 30° to the incident beam, and the footprint of the beam will be approximately 125×144 mm.

The last mirror in the Coudé Box, whether it is M7, M8 or M9, will require remote actuation, since the beam angle from this point is almost certain to drift with temperature from day to night by amounts which are significant with respect to subsequent optical surfaces.

9.3. POP Input Mirrors

The beams enter the central facility at the west end, where between one and three flat mirrors deflect the beams into the POP segmented optical delay. The distance from the telescope to these mirrors is approximately 220 m. The diffraction divergence over this distance is 10.2 mm, for a beam diameter of 135.2 mm. The flat mirrors at the POP entrance will be at approximately 30° to the incident beam, and the beam footprint will be approximately 135×156 mm.

The minimum angular adjustment increment on the last mirror in the Coudé Boxes might in practice be on the order of a few arcsec, which corresponds to a translation of the beam at the central facility of about 3 mm, so this much oversize will be required as a minimum. Furthermore, remote actuation will be needed for the two mirrors to correct for this offset.

9.4. POP Mirrors

When the full POP sections are installed, the longest beam travel to the last POP station will be 300 m from the telescopes. The diffraction divergence over this distance will be 14.0 mm, giving a total beam diameter of 139.0 mm. The POP mirrors may be near normal incidence (139 mm beam diameter) or near 45° incidence (197 mm beam footprint).

These mirrors must fit into a very cramped space, and over sizing of them is not advisable.

9.5. Periscope Mirrors

The Periscope will be at a maximum beam travel distance of 370 m from the telescope. The diffraction divergence over this distance will be 18.8 mm, giving a total beam diameter of 143.7 mm. These mirrors will be at 45° angle to the incident beams, for a footprint size of 203 mm. These mirrors must be used to align the beams precisely to the OPLE translation axis, and some oversize will facilitate that alignment.

9.6. OPLE Aperture

The OPLE will be at a maximum beam travel distance of 420 m from the telescopes. The diffraction divergence over this distance will be 19.7 mm, giving a total beam diameter of 144.7 mm. This diameter can be compared to the current OPLE faceplate aperture diameter of 136.5 mm.

9.7. Beam Compressor Input and Output

The Beam Compressor will be at a maximum beam travel distance of 470 m from the telescopes. The diffraction divergence over this distance will be 22.0 mm, giving a total beam diameter of 147.0 mm. This will be the desired beam diameter at the input. To simplify alignment to the OPLE axis, a small oversize would be convenient.

The Beam Compressor demagnification factor is 5×, so the maximum beam diameter at output will be 29.4 mm.

Following the Beam Compressor, the beam divergence angle will be increased by 5×, to 48 arcsec.

9.8. Beam Sampling Mirror

The right angle reflection from the OPLE area into the Beam Combination area is accomplished by the Beam Sampling mirror, so-called because it can be moved east-west to shift any of the telescope beams into a given input position in the Beam Combination Laboratory.

The Beam Sampling Mirrors will be approximately 2 m from the Beam Compressor, for a beam divergence of 0.5 mm. The maximum beam diameter is thus 29.9 mm. The mirrors are at an angle of 45° to the incident beam, for a footprint of 29.9×42.3 mm.

9.9. Beam Combiners

The Beam Combiners will be approximately 22 m from the Beam Compressor, for a beam divergence of 5.2 mm. (The distance of 22 m is the distance from the northern-most (most distant) Beam Compressor to the southern end of the Beam Combining Laboratory, thus it is not the extreme possible path, but it is a extreme probable path.) The maximum beam diameter will be approximately 34.6 mm. For optics at an angle of 45° to the incident beam, the footprint will be up to 34.6×48.9mm. Since the clear aperture of small optics is typically 80% of the nominal diameter, the required nominal diameters for optics at 45° incident angle will be 61.2 mm.

10. SUMMARY OF MIRROR APERTURE REQUIREMENTS AND RECOMMENDATIONS

The foregoing calculations and discussion is summarized in Table 3. The required diameters of the mirrors is noted, the advisability of increasing the diameters over the minimum required, and recommendations for possible standard mirror sizes and materials that may be satisfactory for CHARA.

Table 4 considers the beam sizes in the more benign case of observation near the zenith, where optical delays are smaller and total beam paths are also smaller. This leads to the minimum beam sizes. Finally, the beam paths used in computation of the beam expansion are collected in Table 5.

TABLE 3. Computed maximum beam sizes at various positions, suggested mirror sizes (substrate size, to allow required clear aperture plus any suggested clearance margin), and whether or not low expansion material is required. The "maximum" beam size corresponds to the maximum beam paths for observations near the horizon.

Location	Mirror	Incident Angle	Beam Size (mm)	Beam Size (inch)	Possible Size (inch)	Low Expansion?
Telescope	M3	45	125×177	4.92×6.96		Yes
Telescope	M4	45	125×177	4.92×6.96	8.0	Yes
Telescope	M5	45	125×177	4.92×6.96	8.0	Yes
Telescope	M6	45	125×177	4.92×6.96	8.0	Yes
Coudé Box	M7	45	125×177	4.92×6.96	8.0	Yes
Coudé Box	M8	30	125×144	4.92×5.70	6.0	Yes
POP Input		30	135×156	5.31×6.14	6.5	No
POP		45	139×197	5.47×7.76	8.0	No
POP		~0	139	5.31	6.5	No
Periscope		45	142×200	5.59×7.91	8.0	No
OPLE	Input	0	145	5.70		No
Compressor	Input	0	147	5.79		
Compressor	Output	0	29.4	1.16		
Sampling		45	29.9×42.3	1.18×1.67	2.2	No
Combiners		45	34.6×48.9	1.36×1.93	2.5	No

TABLE 4. Computed minimum beam sizes at various positions, recommended mirror sizes (substrate size, to allow required clear aperture plus any suggested clearance margin), and whether or not low expansion material is required. "Minimum" beam size corresponds to the minimum beam paths for observations overhead. Only POPs and downstream optics are different in this case.

Location	Mirror	Incident Angle	Beam Size (mm)	Beam Size (inch)	Recommended Size (inch)	Low Expansion?
POP		45	136×193	5.36×7.60	8.0	No
POP		~0	136×157	5.36×6.19	6.5	No
Periscope		45	135×190	5.31×7.48	8.0	No
OPLE	Input	0	137	5.40		No
Compressor	Input	0	137	5.42		
Compressor	Output	0	27.5	1.08		
Sampling		45	28.0×39.0	1.10×1.54	2.2	No
Combiners		45	32.7×46.2	1.29×1.82	2.3	No

TABLE 5. The beam paths used in computation of the beam expansion. The first seven lines give the distance from the telescope secondary. The last two lines give the distance from the beam compressor output.

Location	Maximum Path (meters)	Minimum Path (meters)
Telescope	5	5
Coudé Box	10	10
POP Input	220	220
POP	300	240
Periscope	370	250
OPLE	420	260
Compressor	470	270
Sampling	2	2
Combination	22	22

11. REFERENCES

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