Adaptive Optics

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S.1. THE NEED FOR ADAPTIVE OPTICS

The detectability of an interference signal will depend on the visibility of the fringes. Resolved sources will have low visibility in any case, and it is important to minimize losses of visibility caused by atmospheric or instrumental degradation. In the visible spectral range, apertures will have to be limited to a few 10's of centimeters without adaptive optics, and still will suffer a significant visibility degradation. In the infrared the full apertures can be used with reduced visibility. The use of visible light for fringe tracking will be limited by the small apertures which can be used without AO.

Adaptive optics of low order (for the infrared) to moderate order (for the visible) can greatly increase the visibility transfer function of the array, allowing use of the full aperture in the visible. Laser beacons are required for the array to achieve its ultimate performance limits.

S.2. THE MOTIVATION FOR INCORPORATING ADAPTIVE OPTICS IN THE CHARA ARRAY

In Appendix Q it is shown that the performance at all wavelengths will be limited by the ability to track optical path difference. While it should be possible to extend the faint operation limit of the interferometer somewhat with blind fringe tracking, this kind of operation will not achieve phase closure or high dynamic range in visibility measurements.

Until IR detectors achieve noise levels similar to CCD's, the best strategy for monitoring OPD (fringe tracking) will be to use the red part of the CCD range (except of course for a few extremely red sources). Assume a band centered on 0.8 microns. Under conditions of $1''$ seeing, we will have $r_\circ = 10\,\mathrm{cm}$ at $0.5\mu\mathrm{m}$ and $r_\circ = 18\,\mathrm{cm}$ at $0.8\mu\mathrm{m}$. With tilt correction, the useful aperture size for fringe tracking at 0.8,micron will be as large as about 65 cm. With adaptive optics, the useful aperture will be increased to 100 cm, and the useful spectral range extended further into the visible, the two effects together accounting for a gain of about 2 magnitudes in limiting sensitivity for fringe tracking.

S.3. THE SCIENCE IMPACT OF IMPROVED SENSITIVITY

The CHARA Array with tilt correction but without higher order adaptive optics will have sufficient sensitivity to accomplish the primary initial science objectives, especially including studies of close binary systems and of YSO's.

The improved sensitivity achieved with adaptive optics will extend the YSO science to a much larger sample of sources (from 10's to 100's). It will also enable much higher dynamic range imagery of bright YSO's. This capability may be critical in distinguishing relatively low surface brightness regions in the vicinity of a bright central star.

Without adaptive optics, the CHARA Array will have relatively little capability for the study of galactic nuclei. With adaptive optics the improved sensitivity will permit observations of the nuclear regions of the brighter normal galaxies (M31, M32, M81) — in some of these evidence for massive black holes is accumulating and high angular resolution observations are needed. The few brightest active galactic nuclei can be imaged, easily resolving the narrow line region, probably resolving the dusty torus region (if models supposing this structure are correct), and possibly resolving the broad line region.

S.4. THE INTERFEROMETRIC EFFICIENCY OF THE CHARA ARRAY

If telescope i delivers intensity I_i at Strehl ratio S_i to the beam combination detector, then the flux available for interferometric operation is $S_i I_i$. The ideal point source visibility for combination of two telescopes is then,

$$V = \frac{2\sqrt{S_1 I_1 S_2 I_2}}{S_1 I_1 + S_2 I_2} \tag{S.1}$$

The interesting quantity for understanding the efficiency of the array will often be the product of the flux and the visibility, so we can define the interferometric efficiency as,

$$E = (S_1 I_1 + S_2 I_2) V = 2\sqrt{S_1 I_1 S_2 I_2} \tag{S.2}$$

This expression shows several interesting results which follow from square-law detection of the combined beams. The interferometric efficiency follows the geometric mean of the fluxes and Strehl ratios of the two telescopes. This means that improving the Strehl ratio of one telescope of a pair can give significant improvement to the efficiency. For example, if two telescopes with $I_1 = I_2$ each have an uncompensated Strehl of 0.2, the efficiency will be 0.2. Compensating one telescope to give a Strehl of 0.8 will improve the net efficiency to 0.4.

A second result is that, again for $I_1 = I_2$, if $S_1 = S_2 = S$, then the optimum net interferometric efficiency will be numerically equal to S.

Of course for a resolved source the visibility will be significantly reduced (more than 10× for a fully resolved source). In order to fringe track on baselines which resolve the source, it will be especially important to maintain high interferometric efficiency. Even if fringe tracking is carried out on unresolved baselines, high interferometric efficiency will be needed to obtain spatial information for faint sources beyond the first visibility null.

In order to estimate the Strehl ratio for the CHARA telescopes under a variety of conditions with and without adaptive optics, we have used a model for the AO corrected point spread function (PSF) recommended by Parenti (1992) as implemented by Ridgway (1993). This approach is based on a schematic error budget which assumes that the total residual wavefront error is 4× greater than the residual error just associated with the uncorrected higher order aberrations.

Figure S.1 shows the results from PSF computations for 1 m apertures with $r_\circ = 0.1$ m at $0.5\,\mu$m (that is, normal "good" seeing with $1''$ visible images). The lowest curve in Figure S.1 corresponds to the expected Strehl with no adaptive correction (n=0). The third curve up corresponds to the tilt corrected Strehl ratio. This would be the prediction for the initial CHARA configuration without adaptive optics.

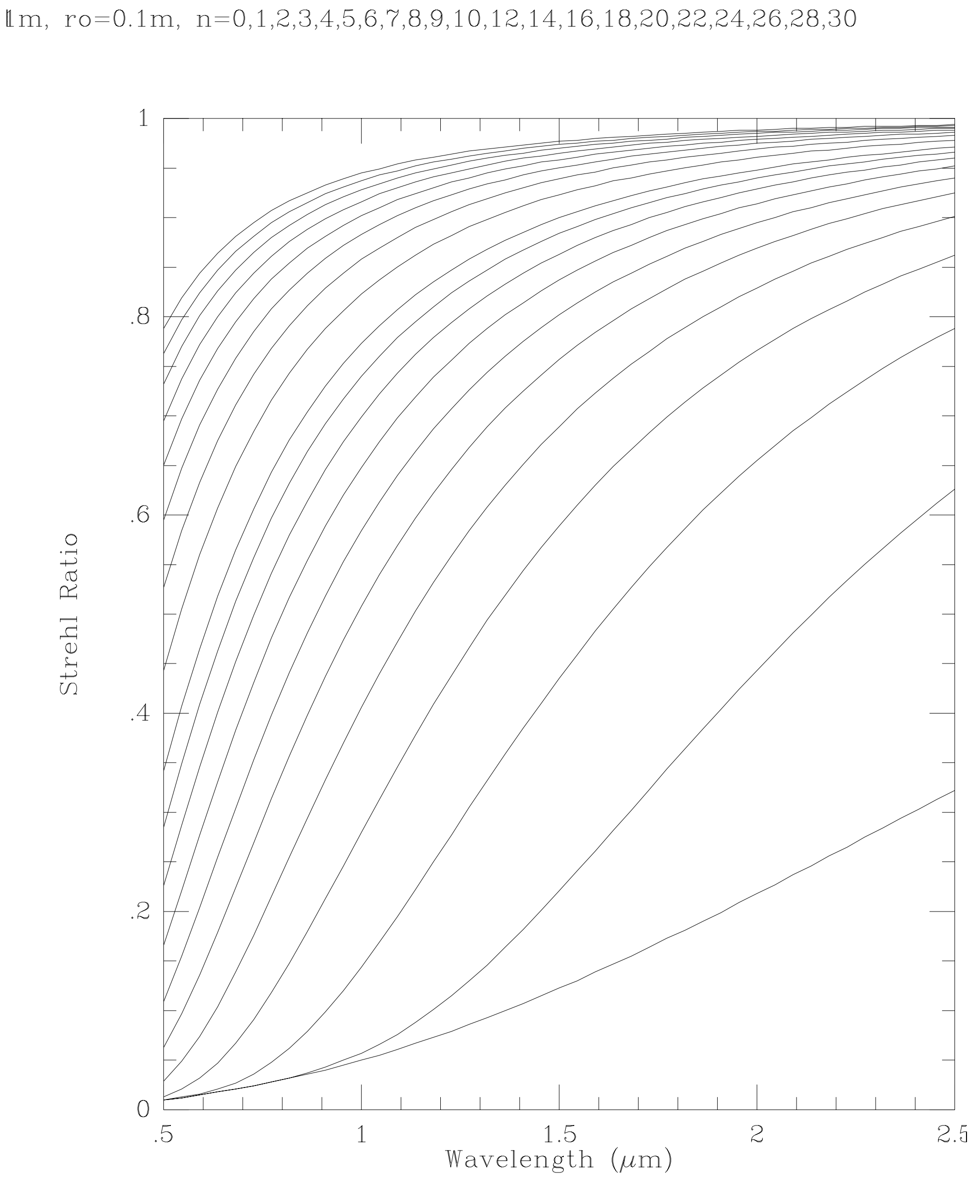

FIGURE S.1. Predicted Strehl for various orders of correction from n = 0 (uncorrected) to n = 22 for a 1 m aperture and $r_o(0.5\,\mu\mathrm{m}) = 10\,\mathrm{cm}$. The predictions are based on a simple PSF model, and a conservative error budget which assumes total wavefront aberrations 4× greater than the wavefront fitting error (Ridgway 1993). The n = 0 case is the lowest curve. Tilt only correction corresponds to the third curve (n = 2).

From Figure S.1 it is easy to see why the full aperture cannot be employed for interferometric measurements at visible wavelengths without adaptive optics. However, at 2.2 μm the expected full-aperture tilt-corrected Strehl ratio is about 0.7. Though not ideal, this is certainly adequate for useful operation. With $r_o(0.5\,\mu\mathrm{m})$=20 cm, the tilt corrected Strehl at 2.2 μm is over 0.9!

S.5. THE VALUE OF ADAPTIVE OPTICS

The additional curves in Figure S.1 correspond to progressively higher orders of correction. The curves, from the bottom of the figure, correspond to correction to Zernike order $n=0$, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, 18, 20, 22.

A Strehl and interferometric efficiency of 0.8 would be an excellent goal for an interferometric array. This performance should certainly be achievable in the infrared, and possibly in to the visible. In the context of our approximation, we can see that for operation at 0.65 μm, we would like to have adaptive correction to about $n=20$, although $n=14$ would already give a large gain in performance. At 2.2 μm a correction to $n=3$ would suffice. (A more detailed model of AO performance, reported in Appendix Q for several sets of assumptions, shows that slightly lower order of correction in the visible may be adequate).

Of course this discussion considers only the atmospheric contribution to wavefront error. Adaptive optics also offers the possibility of ameliorating residual fixed aberrations of the optical components and varying aberrations caused by imperfect optical supports and collimation changes.

S.6. ADAPTIVE OPTICS SYSTEM REQUIREMENTS

The adaptive optics system required for the CHARA Array is modest in comparison with much of the hardware that has been employed in DOD experiments, but near the frontier of technology currently operating for astronomy. In particular, no astronomy systems currently operate with laser beacons, although this situation is expected to change over the next few years.

The following discussion is not intended to substitute for a design study, but serves to suggest the relative availability and cost of critical components. The following is based on $1''$ visible seeing, and a wavelength is 0.65 microns.

The Strehl ratio is related to the residual wavefront error by,

$$S \approx \exp\left(-\sigma^2\right) \tag{S.3}$$

A requirement of $S=0.5$ corresponds to a wavefront squared error of 0.69 rad^2. For current purposes we will suppose that this allowable error is allocated equally (0.23 rad^2 each) to wavefront sensing, wavefront fitting, and servo lag.

S.6.1. Adaptive Mirror

The wavefront fit error for a rectangular array of actuators is approximated as

$$\sigma^2_{fit} = \kappa \left(\frac{r_a}{r_s}\right)^{\frac{5}{3}} \tag{S.4}$$

where r_s is the actuator spacing and $\kappa \approx 0.35$ for a Gaussian influence function. For $r_\circ = 0.16\,\mathrm{m}$, the actuator spacing would be $r_s \approx 0.12\,\mathrm{m}$, requiring approximately 70 actuators in total (fewer for an optimized configuration of actuators).

S.6.2. Wavefront Sensor

The servo error can be approximated by

$$\sigma^2_{servo} = 0.96\left(\frac{\tau_d}{\tau_0}\right)^{\frac{5}{3}} \tag{S.5}$$

where $\tau_0 \approx 0.007\,\mathrm{sec}$ at $0.65\,\mu\mathrm{m}$, and τ_d is the dwell time of the wavefront sensor. Requiring $\sigma^2_{servo} = 0.23\,\mathrm{rad}^2$ gives $\tau_d = 0.003\,\mathrm{sec}$, or a servo bandwidth of about 30 Hz.

In the photon noise limit, the wavefront error due to sensor noise is (Rigaut 1992),

$$\sigma^2_w \approx \left(\frac{\lambda_{ws}}{\lambda_{im}}\right)\left(1+\frac{r_s^2}{r_0^2}\right)\frac{8}{N_{ph}} \tag{S.6}$$

where λ_{ws} is the wavelength of the wavefront sensor and λ_{im} the wavelength imaged. Assuming $\lambda_{ws} = \lambda_{im}$ and $r_s = R_a$ and requiring $\sigma^2_w = 0.23$ leads to $N_{ph} \approx 50$.

S.6.3. Laser Beacon

The foregoing discussion indicates that a laser beacon must produce approximately 50 detected photons over a subaperture of 0.12 m diameter in 0.003 sec. With a system efficiency of 0.5, this corresponds to a photon flux of about 300 photons/cm^2/sec. (This beacon would have an apparent magnitude of about R = 9.) If a sodium wavelength laser were employed, the required output power would be about 10 W (per telescope). LLNL is currently developing such a laser for use in astronomy (Gavel, private communication). It may be possible to consider using a single launch telescope to illuminate multiple spots, suitable for several CHARA telescopes.

A Rayleigh beacon could also be considered for CHARA. With the 1 m aperture, focal anisoplanatism already will contribute to the wavefront degradation, limiting the Strehl to about 0.5. However, it would be advantageous to employ a blue laser wavelength which would be outside the science bandwidth. Launch from an independent telescope would avoid the fluorescence problems reported at Starfire (Fugate, private communication). Suitable lasers are currently available (Thompson, private communication).

S.7. ADAPTIVE OPTICS STRATEGY

The CHARA Array will accomplish its primary science goals without adaptive optics. However, adaptive optics will significantly improve the performance for this science (e.g. YSO studies), and will extend the capability to include significant new areas (e.g. galactic nuclei and AGN's). Adaptive optics can improve the array performance greatly, even if only deployed on a limited number of telescopes.

We do plan to develop the array with several options for retro-fitting of adaptive optics. The options include: implementation of an adaptive mirror at the secondary or in the coudé optics; launching a laser beacon with the full telescope aperture of one or more telescopes, or from an independent laser launch facility. As the array comes into operation and we begin to have confirmation of the actual performance, we will expect to plan an upgrade of the telescopes to include adaptive optics with laser systems.

Our proposed strategy is to implement the CHARA Array initially without adaptive optics, since suitable AO systems are not yet available as turn-key systems, the cost would be inconsistent with our budget guidelines, and engineering of suitable systems would over-extend our technical resources. However, the addition of both funding and a collaborating organization with expertise in adaptive optics would tip the decision in the other direction and we would implement adaptive optics immediately.

S.8. AVAILABILITY OF ADAPTIVE OPTICS

We have contacted several possible sources of adaptive optics equipment. Although there is not currently a commercial supplier of adaptive optics systems for astronomy, there are several firms which have stated an intent to market such systems if the demand exists. United Technologies, TTC, and Laserdot have reported this position. UT and Laserdot have distributed literature describing systems similar to the CHARA requirement, though without the laser beacons. We have communicated with university research groups currently developing adaptive optics systems, including the Lawrence-Livermore, University of Hawaii, and the University of Chicago. In a more speculative direction, we are in touch with TURN Ltd (Moscow) which has expressed the intention of marketing AO technology developed in the FSU. These discussions have suggested that the hardware cost for the CHARA AO systems is likely to be on the order of $500K/telescope including laser beacons.

S.9. REFERENCES

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