CHARA TECHNICAL REPORT

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Optimum Pixel Size for NIRO Input Optics

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1. INTRODUCTION TO THE CHARA ARRAY PROJECT

The Center for High Angular Resolution Astronomy (CHARA) of Georgia State University has built a facility for optical/infrared multi-telescope interferometry, called the CHARA Array. This array consists of six telescopes distributed over an area approximately 330 m across. The light beams from the individual telescopes are transported through evacuated pipes to a central laboratory, which contains optical delay lines, beam combination optics, and detection systems. The facility consists of these components plus the associated buildings and support equipment, and is located at the Mount Wilson Observatory in southern California. The CHARA Array is funded by Georgia State University, the National Science Foundation, the Keck Foundation and the Packard Foundation.

2. OVERVIEW

As part of the upgrade to CHARA CLASSIC in the winter of 2007/2008 we are designing new input optics for the NIRO camera. The new optics will allow six beams to enter the dewar and be imaged on a 2×3 array of pixels on the detector. There has also been the suggestion that we could use this arrangement as a spatial filter for the output beams of CLASSIC. It is, therefore, necessary to determine the optimum projected size of each pixel on the sky. To determine this optimum size a simple simulation was devised to try and consider the effect of various pixel sizes on raw visibility, visibility stability, throughput and signal to noise ratio. The primary result is that from the point of view of signal to noise the optimum angular size is $2\lambda/D$.

3. MODELING

Using the existing CHARA atmospheric modeling code (ten Brummelaar 1995 & 1996) a total of fifteen atmospherically distorted wavefront simulations were created with $r0$ ranging from 1 to 15cm, where here the $r0$ value is for a wavelength of 0.5μm. In K band this represents a range for r0 of approximately 5 to 75cm.

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Since these simulations are done in terms of Zernike coefficients, the delay line and tip tilt system were modeled by simply setting the first three coefficients to zero. This is somewhat artificial, as it implies perfect fringe tracking and tip tilt servos, but since we are most interested in the effect of spatial filtering it should not concern us too much. Any more realistic modeling of these servos would introduce effects arising from this modeling and might bias the results to show us the problems in the modeling, rather than the effect of spatial filtering.

Each simulation consisted of a sequence of 2500 atmospherically deformed wavefronts calculated in a grid of 65×65 pixels with a time step of 0.01 seconds between each frame. Naturally, two such simulations are required to model a two telescope system. Each frame is then placed in a large zero padded frame and Fourier transformed to obtain the image plane. The amount of zero padding to use was determined by running a series of single frame models with a range of zero pad sizes. These converged to a stable result when the padded area was 8 times the size of the data frame. The image plane is then masked using a square mask to simulate the light hitting a single pixels and inverse transformed back to the aperture plane. Since the operation of masking can spread light outside of the original aperture size, a second mask is imposed to ensure only light inside the defined beam area is included. Strictly speaking, this final step is not realistic since we will not actually be forming another pupil. However, if this is not done the results do not converge as quickly when you increase the area of zero padding making the simulations run much slower.

Of primary interest to us are the throughput, calculated as an intensity ratio before and after the two masking operations, and the correlation or visibility, calculated for a single wavelength using the four phase algorithm as describe in Tango and Twiss (1980). These simulations were performed for a range of spatial filter sizes and r_0 values. An example of the output of one frame of a simulation is given in Figure 1.

Note that since these simulations use a single wavelength, perfect fringe tracking and tip tilt servos, and no photon noise, the raw visibilities produced are bound to be higher than we would expect in a real system. However, as even with these simplifying assumptions the models took many days to run, we will assume that they nevertheless represent a realistic model of the process of spatial filtering.

4. RESULTS

The top part of Figure 2 shows a plot of the raw correlation as a function of spatial filter size ranging from 0.25 to $5.0\lambda/D$ for the full range of seeing conditions. As we would expect, the raw visibility decreases as the size of the spatial filter is increased.

Of more interest to us is how well you might expect these visibilities to calibrate, or in other words, how stable the fringe amplitude is in times of variable seeing. The bottom plot of Figure 2 shows a plot of $\frac{dV^2}{dr_0}$, showing how the raw visibility will change as seeing conditions vary. As one would expect, for all cases, the smaller the spatial filter the smaller the variations in visibility will be as the seeing changes. In the poorest seeing conditions there is an obvious peak in visibility variation, while for the better seeing no obvious peak exists. From the point of view of visibility calibration one would like to have the smallest possible spatial filter. In practice this would be a single mode fiber.

If you make the spatial filter too small, not enough light will pass through and you will collect no useful data at all. As figure 3 shows, the fraction of light getting through increases

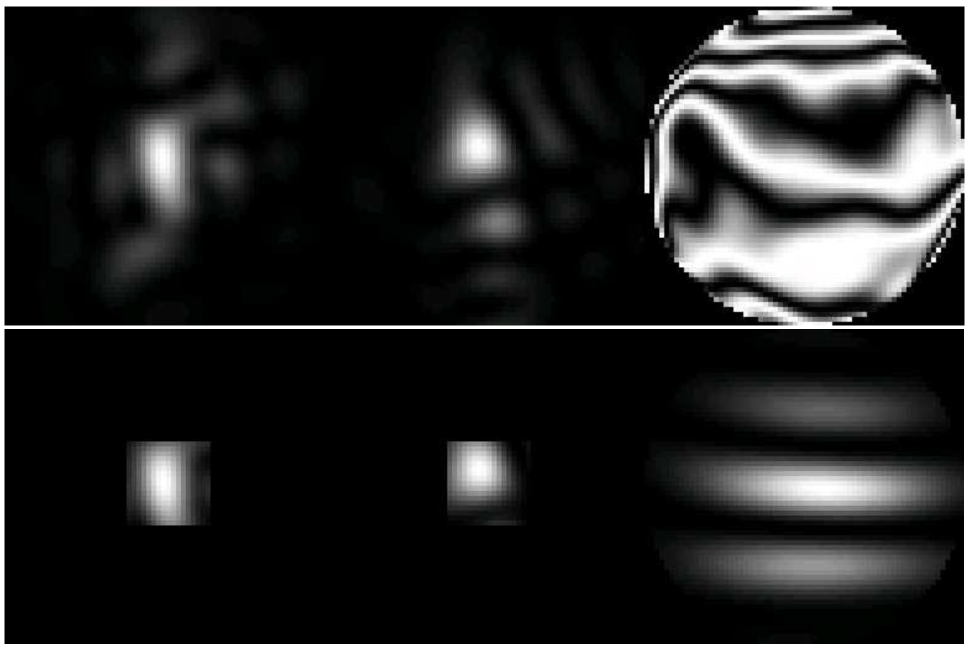
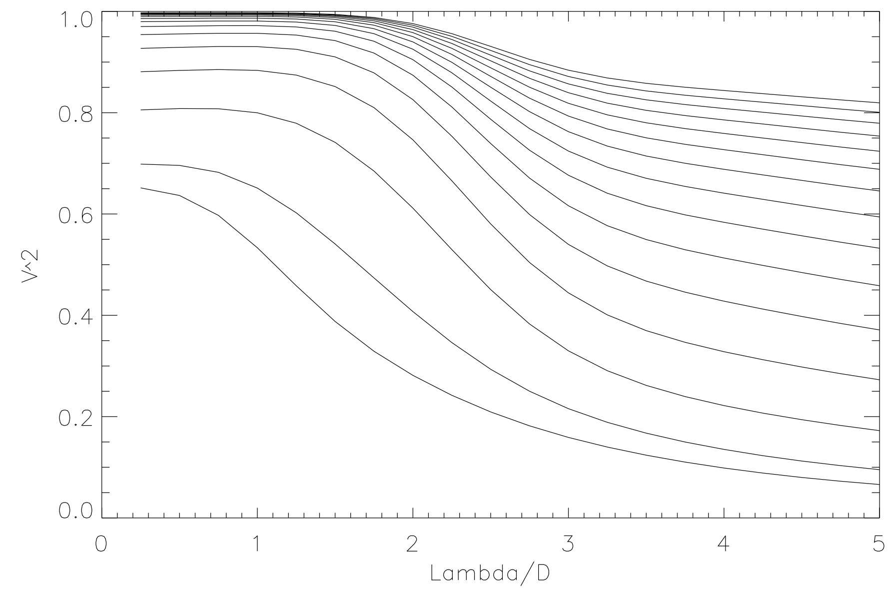


FIGURE 1. Two example frames from the simulation, both for $r_0 = 3$cm. The top plot shows the two image planes and the resulting fringe pattern without a spatial filter, and the bottom plot shows the same frame with a spatial filter of size $2\lambda/D$. In both cases a differential tilt has been imposed on the fringe pattern for display purposes only.



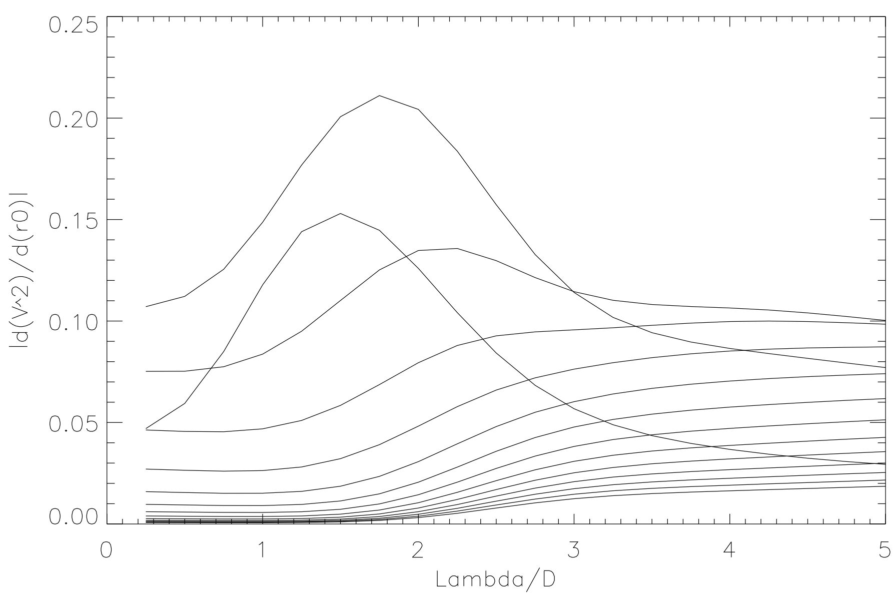


FIGURE 2. Top:Final V^2 for a range of r_0 values from 1 to 15cm. Bottom: the same data plotted as $\frac{dV^2}{dr_0}$.

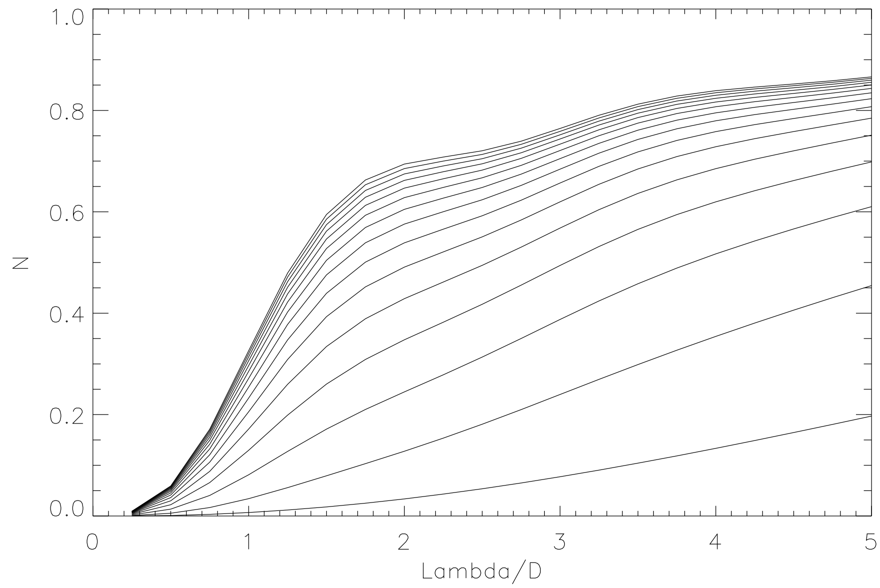


FIGURE 3. Final throughput for a range of r_0 values from 1 to 15cm.

as the size of the spatial filter increases, exactly as one would expect. The amount of light rises fairly quickly in good seeing and starts to plateau near the $2\lambda/D$ spatial filter size.

In the end, if we are looking for sensitivity gains, and in this case it is the signal to noise ratio that is most important. Figure 4 shows plots for signal noise for a camera with no read noise (NV^2) and one for a noisy detector (NV). The NV case continues to rise as the size of the spatial filter is increased, while the NV^2 case shows a clear maximum at around $2\lambda/D$. This result is slightly different to the one derived by Keen et al (2001) who find maximum signal to noise at a diameter of $2.4\lambda/D$, the size of the Airy spot. However, their simulation used a round pin hole, rather than the square pixel used in this study, and also a different model of the effects of the atmosphere. A square spatial filter has a larger area than a round hole by a factor of $4.0/\pi$ which is very close to the ratio of $(2.4/2.0)^2$, so to first order we can say that our two simulations agree very well.

5. CONCLUSIONS

These simulations show that in order to maximize sensitivity we should use a spatial filter of size $2\lambda/D$ while to maximize fringe amplitude stability we should use a smaller spatial filter. Unfortunately, it is not possible to optimize for signal to noise ratio and calibration stability at the same time. Indeed during times of poor seeing Figure 2 shows that the calibration is at its worst when sensitivity is at its best. However, in the case of CHARA CLASSIC it is sensitivity that is the most important consideration, and a good compromise might be to choose a size slightly smaller than $2\lambda/D$.

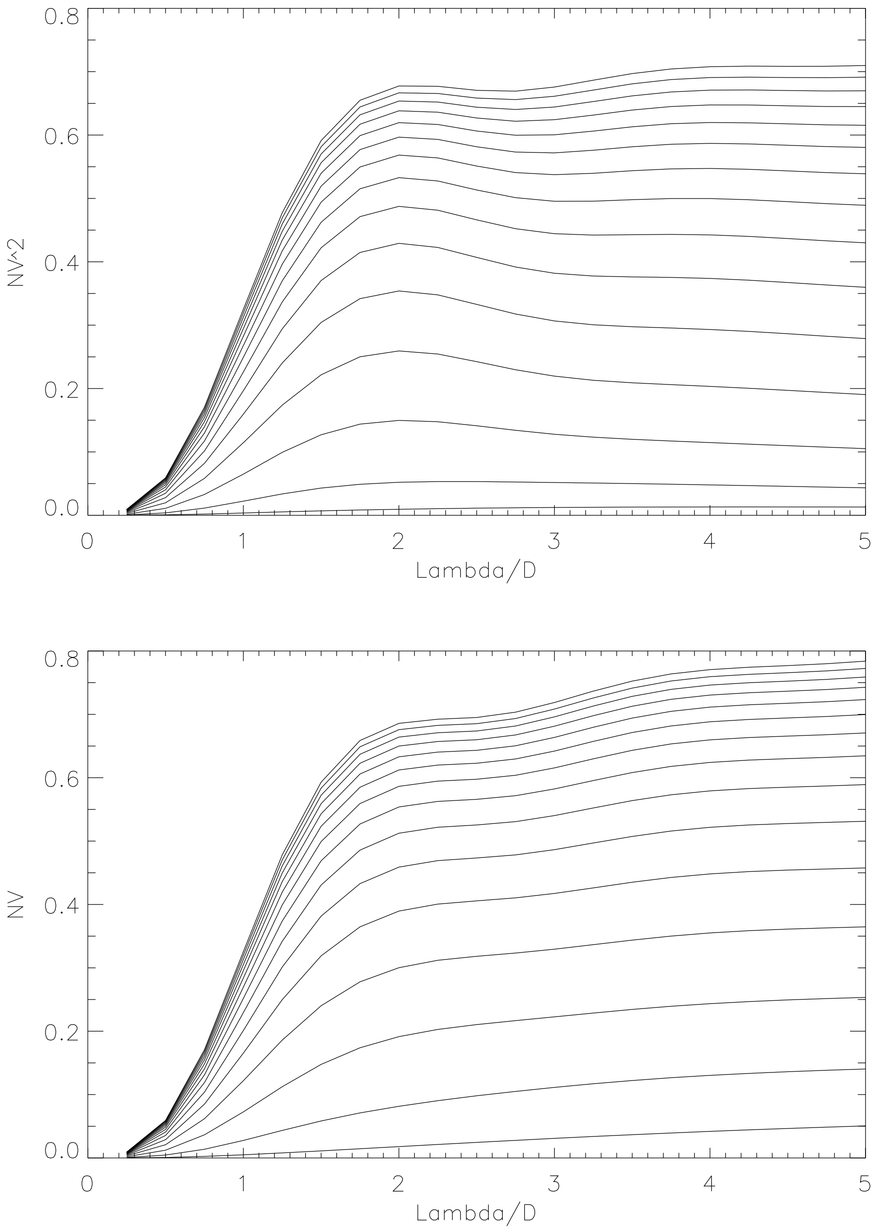


FIGURE 4. Final signal to noise ratio for a range of r_0 values from 1 to 15cm. The top plot shows NV^2, while the bottom plot shows NV

A final consideration is that we will be using a range of wavebands in the system, which will of course change the equivalent angular extend of the spatial filter. We should consider the three primary wavebands of J (1.25μm), H (1.65 μm) and K' (2.13 μm). The size of the spatial filter, in terms of λ/D scales with λ, so for example if we make the spatial filter $2\lambda/D$ in H band it will be $2.64\lambda/D$ in J band and $1.55\lambda/D$ in K'. On top of this, the seeing scales as $\lambda^{-\frac{6}{5}}$, so the r0 values in J band will be about two times smaller than in K band. In Figure 4, the effect on signal to noise ratio of a larger spatial filter is less dramatic than for a smaller size. Therefore, I propose that we choose a spatial filter size optimized for the longer wavebands, which are in any case used more often. Using the mean wavelength between the H and K' bands of 1.90μm, a spatial filter of $2\lambda/D$ represents an angular size of 0.78 arcseconds on the sky or 42 arcseconds in the beam combining lab.

6. REFERENCES

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