CHARA Technical Report

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Fringe Tracking and Visible Imaging: Camera Specifications

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1. INTRODUCTION TO THE CHARA ARRAY PROJECT

The Center for High Angular Resolution Astronomy (CHARA) of Georgia State University is building a facility for optical/infrared multi-telescope interferometry, called the CHARA Array, on the grounds of Mt. Wilson Observatory in southern California. The CHARA Array will consist of six 1-m aperture telescopes distributed over an area approximately 350 m across. The light beams from the individual telescopes are transported through evacuated pipes to a central laboratory containing optical delay lines, beam combination optics, and detection systems. The facility consists of these components plus the associated buildings and support equipment. The CHARA Array is funded by the National Science Foundation, the W. M. Keck Foundation, the David and Lucile Packard Foundation, and by Georgia State University.

2. OVERVIEW

The final goal of the CHARA Array is high angular resolution measurements of astronomical objects of scientific interest. These data can either be found by direct imaging or by model fitting, but in either case high precision visibility measurements will be required. Apart from pointing the telescopes in the correct direction and keeping the beams from each telescope stable, the two critical tasks will be providing an error signal for the Optical Path Length Equalizer (OPLE) and the fringe measurements themselves. The OPLE error signal will be provided by an optical system known as the Fringe Tracker (FT) while the visibility and phase closure measurements will be made using another optical system called the Visible Imager (VI). Before the VI is completely functional the FT will also be used to provide visibility measurements. Both of these optical systems will require high quantum efficiency low noise multi-pixel detectors, herein assumed to be CCDs, with similar characteristics. The fact that the fringe tracker must provide an error signal in real time for the OPLEs while the imager data can be reduced off-line means that the specification of these two cameras differ slightly.

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3. FRINGE TRACKING CAMERA

The method chosen for the fringe tracker is group delay tracking (GDT), as discussed in Appendix I of the Array Proposal. Basically, the beams are combined pair-wise, and each combined pair is broken up into six or seven sub-apertures. The intensity within each sub-aperture can be written

$$I(\nu) = I_s\left[1 + |V(\nu)|\cos\left(2\pi\nu\,\mathrm{OPD} - \phi\right)\right] + I_b \tag{1}$$

where ν is the wavenumber ($\frac{1}{\lambda}$), I_s is the intensity of the unmodulated stellar spectrum, OPD is the optical path length difference or delay, $|V(\nu)|$ is the wavenumber-dependent fringe visibility magnitude, ϕ is visibility phase, and I_b is the background intensity.

Each of these patterns will be dispersed into a spectrum, and unless the OPLE is exactly at the center of the fringe envelope, this spectrum will have fringes across it, known as channel fringes. If the number of these fringes is n the optical path length difference will be given by

$$\mathrm{OPD} = \frac{n}{\nu_{\mathrm{max}} - \nu_{\mathrm{min}}}. \tag{2}$$

There are various ways of telling how many fringes lie across the spectrum. The simplest approach is to look for a peak in the power spectrum (Lawson 1995) of the fringe pattern and I will assume for now that this is to be the method employed.

The requirements of the camera used in the fringe tracking system are summarized in Table 1 and discussed in more detail in the sections below.

3.1. Number of pixels

The proposed band for fringe tracking at the time of writing this report is from 600 to 800 nm. Using Equation 2 this means that each fringe across the spectrum reflects an OPD of approximately 2.5 μm. If there are N pixels across the spectrum, the maximum number of measurable channel fringes will be $N/2$, and the fringe envelope size will be approximately $N \times 2.5$ μm. Thus, from the point of view of maximum trackable error, it is advantageous to have as many pixels as possible. On the other hand, increasing the number of pixels will reduce the number of photons in each pixel and increase the probability of tracking error.

In order to set a minimum number of pixels, consider that the rms path length fluctuation of the atmosphere for large baselines is of the order of 10μm (Davis et al. 1995). Thus, at least 8 pixels will be required to track to the rms error, and 24 to track to three times this. It is reasonable, therefore, to say that 32 pixels will be capable of tracking all but the most unusual path-length change due to the atmosphere; indeed, this is the number of pixels used in the NPOI fringe engine.

Of course, Equation 2 and the preceeding analysis assumes that the pixels are evenly spaced in wavenumber, something that can be achieved on a CCD with on-chip binning, an essentially noiseless process. Thus there must be more physical pixels on the CCD than logical pixels used in the fringe tracking algorithm. If we have 32 logical pixels across the spectrum, the pixels at the long wavelength end will be approximately 8 nm wide, while they will be approximately 4 nm wide at the short wavelength end. In order to achieve a reasonable distribution of logical pixels evenly spaced in wavenumber then, we could say that we require four times as many physical pixels as logical pixels, that is 128 physical pixels, across the spectrum. Other algorithms than Fourier analysis exist for finding the peak in the power spectrum that do not require pixels evenly spaced in wavenumber; however, as using a fast Fourier transform is likely to be the technique we use first we need to specify that the detector have at least 128 pixels across the spectral axis.

There will be many such spectra to be measured. Five pairs of beams, each with two sides of a beam splitter and seven sub-apertures results in 70 spectra. It will be all but impossible to align these spectra exactly with rows of pixels on a detector without cross talk and so at least another 70 pixels will be required in one dimension as separators. Of course, these rows need not be read out. Thus in the direction of the detector perpendicular to the spectral axis there needs to be at least 140 pixels. If we are to expand to eight telescopes (the maximum possible in the current OPLE layout), this would become 224 pixels.

So, since most CCD arrays are square, and it is convenient to use powers of 2, we will say that the detector used must have at format of at least 256×256 pixels. More pixels would of course be helpful, but will have serious readout noise implications as discussed below.

3.2. Readout Rates

The readout rates required depend on the sample time used for each spectrum and the number of logical pixels required. As stated above, it is assumed that on-chip binning is essentially noiseless and that pixel rows that fall between spectra can be skipped. The minimum number of pixels to be readout (for five telescopes) is then $70 \times 32 = 2240$ while the maximum number (for eight telescopes) is $112 \times 256 = 28672$. The sample time used depends on the current seeing conditions, and, approximately twice the coherence time of the atmosphere is a good sample time to use (ten Brummelaar 1997). Anecdotal evidence for atmospheric coherence times of tens of milliseconds exist, although only during the best of seeing conditions. For a margin of safety we can say that the worst seeing conditions under which we can observe would be when the the coherence time was 1 millisecond. Thus, the readout rate required to track will range from 2.2 kHz up to 28.7 MHz.

For the faintest stars we will require the best performance and highest number of photons per pixel, while for the brightest objects more pixels, and higher readout rates, can be used. For simplicity we will specify that the slowest readout rate will be 30 kHz, while the fastest will be 30 MHz.

3.3. On-Chip Binning and Readout Capabilities

Since this camera will be used in a real-time setting, it will be important that one frame can be readout and processed while the next frame is being exposed. So a camera with frame-transfer capability is preferred over one that does not, although this technique could perhaps be replaced by a device with a much higher readout rate.

The discussion above makes it clear that the camera must have very flexible on-chip re-binning capabilities. For simplicity I will assume that the spectra are placed across the horizontal axis. In order to obtain logical pixels evenly space in wavenumber the horizontal binning must be completely flexible, that is, it must be possible to specify logical pixels of different sizes across the horizontal axis of the chip. Of course, each spectrum should be the same, and use the same binning; in a real system this is rarely the case, however. A device with very flexible horizontal binning capabilities will be preferred, although one that forces the same binning pattern onto each row will be adequate. In the vertical axis, the spectra only need to be separated, so the re-binning requirements are less strict. It must be possible to easily combine rows of physical pixels and to skip rows of physical pixels.

3.4. Quantum Efficiency and Readout Noise

According to the calculations in ten Brummelaar (1997), in order to successfully track fringes and also make visibility estimates, the quantum efficiency of the detector needs to be greater than 80% and have a readout noise of 6 or less, with 3 or better being the goal. Of course, for brighter objects it is possible to withstand more readout noise, but in order to reach the faintest possible objects, the best possible detector performance is required. I will therefore specify that that DQE must be greater than 80% and that the readout noise must be 3 or lower at the slowest readout rates, and no higher than 6 at the fastest readout rates.

3.5. Interface Requirements

Many FFTs will have to be calculated for each set of spectral data, and this will be performed either by DSP boards or a very fast and powerful computer. It must be possible to get all the data out of the chip and into the data reduction system within a single sample time, that is at up to 30 MHz. There are no strong restrictions on how this is implemented, but standard buss or communications systems will be preferred over propriety systems. Since this is a high-speed real-time system a parallel interface of some kind will be preferred over a serial interface.

TABLE 1. Requirements of the Fringe Tracking Camera.

Type	Required	Preferred
Type	plain CCD	frame-transfer CCD
Format	256×256	512×512
Horizontal Binning	same binning for each row	completely flexible
Vertical Binning	adding and skipping of rows	completely flexible
Lowest Pixel Readout Rate (LPRR)	30 kHz	20 kHz
Highest Pixel Readout Rate (HPRR)	30 MHz	50 MHz
Readout Noise at LPRR	3	< 3
Readout Noise at HPRR	10	< 6
Interface	any standard interface	parallel interface
Detected Quantum Efficiency	80%	$> 80\%$
Waveband	600-800 nm	500-900 nm

4. VISIBLE IMAGER CAMERA

The camera used for the imaging system will have very similar requirements to those of the fringe tracker. The main difference between the two is that the imaging system is not necessarily a real-time instrument: we have the luxury of logging data for analysis at a later time, although some real time estimates will be useful in monitoring the performance of the Array as a whole.

The design concept of the imaging system was discussed in detail in Appendix K of the Array Proposal. We intend to use spatial encoding of the fringes across one dimension of the detector and form spectra across the other dimension.

The requirements of the camera used in the imaging system are summarized in Table 2 and discussed in more detail in the sections below.

4.1. Number of pixels

For five beams, combined in a non-redundant pattern, the maximum fringe spatial frequency will be 12, that is there will be 12 fringes across the Airy disk, while for eight beams this will be 38. In order to successfully measure these fringes we must do better than the Nyquist limit, and a good margin of safety is four times the maximum fringe frequency, and that is 152. As for the fringe tracker a power of 2 is probably more useful, especially since we will in all likelihood use a fast Fourier transform for data reduction. We can therefore say that there should be 256 pixels in the fringe dimension of the imaging detector. To begin with, a smaller number of pixels will be adequate, so the minimum allowable will be 64.

In the spectral dimension the number of pixels will, to some extent at least, determine the spectral resolution. The more available pixels there are the better, in this sense, although too many pixels will make the data archiving and readout noise major problems. For the sake of simplicity I will stick to a square format, so the minimum requirement will be 64, while the preferred value will be 256.

4.2. Readout Rates

The sample times used in the imaging system will be similar to those used in the fringe tracker, that is, of the order of milliseconds. However, the imaging system is not a real-time system and it is possible to sacrifice observational efficiency for improved readout noise characteristics: it is always easier to make a system work slower. Let us set the maximum frame rate at 1 kHz, and the minimum frame rate to 10Hz. Note that this assumes that it is possible to independently adjust the exposure time and the frame rate.

With a 256×256 chip this means that the minimum pixel readout rate will be 0.66 MHz while the maximum will be 66 MHz. For the 64×64 configuration these reduce to 41 kHz to 4.1 MHz. For simplicity we will specify this range to go from 40 kHz to 50 MHz, with a preference for systems that can reach as high as 70 MHz.

4.3. On-Chip Binning and Readout Capabilities

Once again, because we wish to be able to independently adjust the exposure times and readout rates, the chip used in the imaging system should use frame-transfer technology, and will also require an independent shutter. In order to adjust spectral resolution and also to optimize the detector for various numbers of telescopes (we won't have eight for some time to come!) some on-chip re-binning will be required, although it need not be as flexible as required for the fringe tracker. Simple square pixels bins will be adequate, although the vertical and horizontal rows must be capable of different bin sizes.

4.4. Quantum Efficiency and Readout Noise

Once again, the higher the quantum efficiency, the better the signal to noise, so I will specify that the DQE must be 80% or higher. The signal to noise ratio of the power spectrum of the signal, the way we will actually measure the visibility, was discussed in Appendix P of the Array Proposal and is given by

$$\mathrm{SNR}(\omega) \;=\; \frac{\frac{1}{4}N^2V^2(\omega)}{\sqrt{N^2+\frac{1}{2}N^3V^2(\omega)+n_{\mathrm{pix}}^2\sigma_{CCD}^4+2n_{\mathrm{pix}}\sigma_{CCD}^2(\frac{1}{4}N^2V^2(\omega)+N)}} \tag{3}$$

where V is the visibility, N is the number of photons in the entire measurement and n_{pix} is the number of pixels. In Figures 1 and 2 the SNR of the visibility squared measurement for several cases of pixel number and readout noise are plotted. These plots where generated assuming five telescopes, a 0.025% throughput (See Appendix R of the Array Proposal), an 80% DQE camera, a 10 mS sample time and a 30 minute integration time. Note that a small increase in throughput will have a large affect on these results. Also plotted on these graphs are lines for a 20% noiseless camera, representative of intensifier based detectors. Clearly, if we are striving for a SNR of 1% things don't look great. What we need is a completely noiseless camera, and unfortunately, this does not exist in a high DQE device. It is also clear that in order to go beyond 10th magnitude in any reasonable time we must have a noiseless camera. As noted above, it would be possible to reduce readout noise by reducing the readout rate, and also therefore the observing efficiency. An intensifier-based system would require longer integration times but may be capable of reaching the fainter stars. As long as it is possible to fringe track we do have the 'luxury' of integrating for as long as we need to in the imaging system.

4.5. Interface Requirements

The interface requirements are the same as those for the fringe tracking camera.

TABLE 2. Requirements of the Visible Imaging Camera.

Type	Required	Preferred
Type	plain CCD	frame-transfer CCD
Format	64×64	$256{\times}256$
Binning	same binning for each row/column	completely flexible
Lowest Pixel Readout Rate (LPRR)	40 kHz	40 kHz
Highest Pixel Readout Rate (HPRR)	50 MHz	70 MHz
Readout Noise at LPRR	3	0
Readout Noise at HPRR	6	0
Interface	any standard interface	parallel interface
Detected Quantum Efficiency	80%	> 80%
Waveband	600-800 nm	500-900 nm

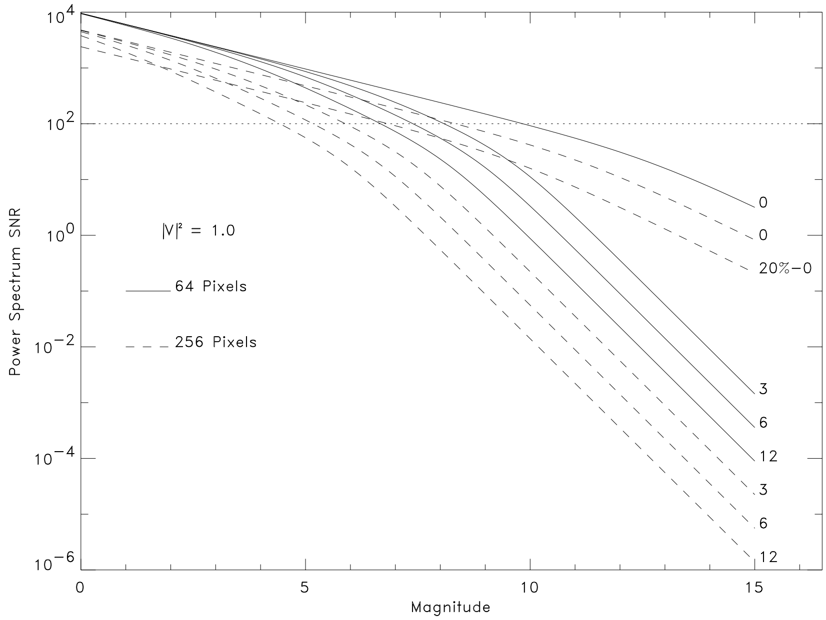

FIGURE 1. Visibility Measurement signal-to-noise ratios, for a visibility of 1.0 for various read-noise levels and pixel numbers. A throughput of 0.025% and a DQE of 80% has been assumed, along with five 1m telescopes, a sample time of 10 mS and an integration time of 30 minutes. The solid lines represent the SNR for 64 pixels while the dotted lines are for 256 pixels across a 200 nm bandpass. The line marked 20%-0 is for a 20% DQE noiseless camera. The 64 pixel line for a DQE 20% noiseless camera is the same as that for a 256 pixel 80% DQE camera.

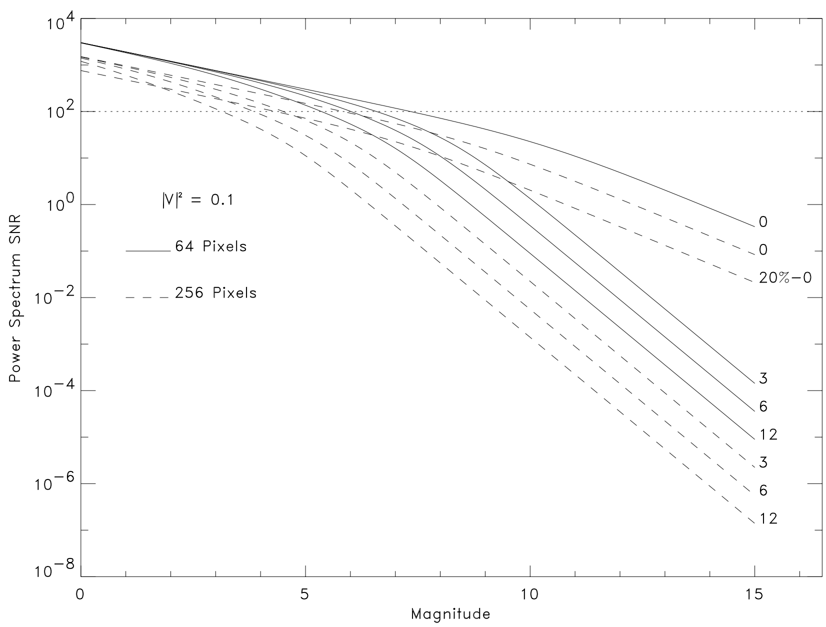

FIGURE 2. Same as the plot above but for a visibility of 0.312

5. CONCLUSION

There is probably no camera (at least one we can afford) that will deliver what we really need. An intensifier-based system can do better than the CCD, especially at longer integration times and assuming it is truly free of readout noise, but will suffer other problems such as flat-fielding errors and ion events. With a reduction in observing efficiency, a CCD may also do the job and I can not at this time recommend either solution. It is also possible that more than one device will be required in order to achieve the high readout rates required. In the mean time we can hope that time something amazing will happen to detector technology before we are forced to make a decision.

6. REFERENCES

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