Evaluation of the Channel Spectrum

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J.1. SUMMARY

We studied a number of methods for phasing telescope arrays, with concentration on the channel spectrum. We developed a numerical simulation of the channel spectrum to assess the feasibility of using that approach to maintain fringe lock (i.e., keeping the pathlength differences constant to 0.1 μm or less). We also assessed the feasibility of using non-redundant imaging for recovery of phase closure data.

We present the complete formulae for the channel spectrum intensity and the signal-to-noise ratio of the spatial frequencies detected by the non-redundant array. We emphasize that the formulations used by other interferometry groups for the channel spectrum intensity have been too simplistic and thus overly optimistic of potential performance.

We conclude that it is not practical for any telescope array to attempt to maintain fringe lock. Rather, the CHARA Array should implement fringe tracking, keeping the pathlength differences within the central portion of the coherence envelope ($\sim 30\mu$m for 100Å bandpass). In our judgement, the channel spectrum is the best approach for fringe tracking of complicated objects or for arrays that utilize open-air pathlength compensation. In these cases, the white light fringe assumption implicit in other techniques is violated.

We also conclude that a bare CCD detector should be used for detecting the channel spectrum and a photon counting camera should be used for non-redundant imaging. Each of these devices will cost about $100,000.

We project that fringe tracking will be limited[1] to $m_v = 7.5$ for unresolved point sources during $1''$ seeing; with $0''.5$ seeing, $m_v = 9.0$ will be attainable. Progressively higher light levels will be required for fringe tracking of complicated objects. It is possible that object complexity and other complications will limit fringe tracking to $m_v = 5.5$–6.5 for $1''$ seeing and $m_v = 7$–8 for $0''.5$ seeing.

The magnitude limitation for imaging (object phase recovery) depends upon the number of interfering apertures and the object visibility. For interference of 7 apertures and visibility of 0.3, the array will be limited to imaging objects brighter than $m_v = 5.4$ when the seeing is $1''$; $m_v = 6.9$ will be attainable when the seeing is $0''.5$.

J.2. INTRODUCTION

The phasing of a ground-based telescope array is one of the most difficult challenges in high resolution astronomical imaging. By comparison, speckle imaging is simple. In speckle imaging, a telescope mirror is used to combine the interfering light; the mirror is figured to the desired shape to a fraction of a micron. Thus, the pathlength difference (PD) of

[1] Magnitude limitations were calculated using optical throughput parameters obtained from T. ten Brummelaar; these are listed in Section N.5.

the light from different subapertures is dominated by atmospheric distortions; typically the maximum PD is a few microns. Thus, the light interferes coherently, since the maximum PD is much less than the coherence length of most bandpasses used for imaging.

Even high Strehl adaptive optics is easier to accomplish than phasing a telescope array. This is because an adaptive optics (AO) system can make use of the physical principle that a wavefront is continuous. An AO wavefront sensor needs only to measure the first derivative (tip/tilt) of the wavefront in each individual aperture. These individual measurements can be integrated to find the PD between two subapertures which are on opposite sides of the full aperture.

However, phasing a telescope array where the individual apertures are separated by meters of distance requires measurement of both the first derivative (tip/tilt) and the PD between the individual apertures. To our knowledge, the PD measurement can only be accomplished by interfering light from the astronomical object of interest. Thus, the light level required for phasing telescope arrays is, from first principles, greater than that for astronomical adaptive optics.

J.3. FRINGE TRACK VERSUS FRINGE LOCK

An important distinction must be made when speaking of *phasing* an interferometric array. One can maintain the phase difference so that the light from two interfering telescopes is kept within the coherence length of the bandpass being used; we shall refer to this as *fringe tracking*. Or, one can control the phase difference to within a small fraction of a wavelength so as to maintain *fringe lock*. Fringe tracking makes inefficient use of the photons at the science wavelength, since fringe tracking requires that the science data be collected via a series of frames, each of which is shorter than the atmospheric correlation time (5–20 msec). Because the fringes in the science data move randomly, the integration of science data must be done incoherently and the signal-to-noise ratio (SNR) is proportional to the square root of the integration time. However, a system that can maintain fringe lock would be able to integrate the science data coherently so that the SNR is proportional to the integration time. Obviously, coherent integration is highly desirable.

However, fringe locking requires a much faster system and a much higher light level. A fringe lock system (which includes phase sensor, computer, data link and OPLE adjustment) would need to run at least 10 times faster than that needed for fringe tracking. Also, the individual exposures require about 20 times higher light level to obtain measurements of sufficient SNR so that single short exposure frames can be used to maintain fringe lock. The combination of fast framing and greater exposure per frame means that objects must be 200 times brighter for fringe lock than for fringe tracking. We estimate that an unresolved point source would need to be at least visual magnitude $m_v = 3.3$ for the fringe locking scheme to work under the best of circumstances ($0''.5$ seeing). With allowance for visibility loss and other degradations, a more realistic limitation is probably 1 stellar magnitude brighter, at $m_v = 2.3$.

Since the fringe locking magnitude requirement limits the approach to a handful of astronomical objects, it is not practicable for any array. Note that none of the other major inteferometry groups (BOA, SUSI, COAST, IOTA) is aiming to achieve fringe lock. They are all relying on the fringe tracking approach.

Fortunately, from a science point of view we will not lose anything by changing to a fringe tracking approach. This is because those objects which are bright enough to implement fringe lock are also bright enough to obtain high SNR data with the fringe tracking approach. And fringe tracking will enable phasing of the array for objects as faint as $m_v = 9.1$; phase closure data can still be obtained to $m_v = 7.3$.

J.4. THE CHANNEL SPECTRUM

The channel spectrum is an intensity pattern that results from interference of the beams from two apertures and dispersion of the interfered beam as function of wavelength. For a point source that is imaged by two apertures that are slightly out of phase, the channel spectrum is a fringe pattern with higher intensity at those wavelengths that are an integer number of wavelengths out of phase, and lower intensity for wavelengths that destructively interfere. If presented in wavenumber space, the channel spectrum of a point source will have equally spaced fringes.

A Fourier transform of the fringe pattern will give a peak at the spatial frequency corresponding to the fringe pattern. This signal can be used to track the PD between the apertures, and if desired, can be used to lock onto a desired PD. (Note that it is not desirable to lock onto zero path difference, since the channel spectrum would then show no fringe structure.)

The number of fringes across the channel spectrum of a point source (for which all wavelengths have the same PD) is given by,

$$\#\text{waves} = \text{PD}\,\frac{\lambda_2 - \lambda_1}{\lambda_1 \lambda_2} \tag{J.1}$$

where λ_2 is the longest wavelength in the channel spectrum and λ_1 is the shortest.

This approach to phasing telescopes is very attractive, since the light of all wavelengths can be used for phasing, and thus fainter objects may be accessible. Also, the capture range of the channel spectrum can be large since the coherence length of the light is given by the width of signal in each increment of the channel spectrum. For instance, if one samples the channel spectrum at 3 nm intervals, the coherence length ($\lambda^2/\Delta\lambda$) of 600 nm light will be 120 μm.

Due to these reasons, two interferometry groups are now actively pursuing the channel spectrum for phasing their telescopes; the Infrared Optical Telescope Array (IOTA) on Mt. Hopkins, Arizona and the Sydney University Stellar Interferometer (SUSI) in Narrabri, Australia. Their analyses have primarily concentrated on using the channel spectrum for simple objects. The channel spectrum is presently being considered for phasing the telescopes of the CHARA array, however in the CHARA case, the intent is to be able to image complicated objects. Thus, we need to examine the behavior of the channel spectrum for objects more complex than point sources.

J.5. CHANNEL SPECTRUM INTENSITY

The general expression for the intensity, I, of the channel spectrum follows the form,

$$I(\sigma, d, \Delta x) = S(\sigma)\,\text{QE}(\sigma)\,\frac{1}{2}\,\mathit{Real}\left(1 + \Gamma(\sigma, d)\, e^{i2\pi\sigma\Delta x(\sigma)}\right) \tag{J.2}$$

where σ is the wavenumber $(1/\lambda)$, d is the baseline of the two interfering apertures, $\Delta x(\sigma)$ is the pathlength difference of the two interfering beams, $S(\sigma)$ is the spectral distribution of the object, $QE(\sigma)$ is the quantum efficiency of the optics-detector system, and , (σ, d) is the mutual coherence function of the object at baseline d and wavenumber σ.

Note that Equation J.2 includes the possibility of PD as function of the wavenumber σ. This will occur for open air delay lines, since it will not be possible to exactly compensate the dispersion due to the air in the delay line. This is not necessarily a bad effect, however, since a smaller PD may be used to achieve a given number of fringes across the channel spectrum. The exact form of $\Delta x(\sigma)$ will depend upon the local atmospheric conditions and the glasses used for longitudinal dispersion compensation (LDC), which entails a study beyond the scope of our investigation. We strongly emphasize that the form of $\Delta x(\sigma)$ should be considered when choosing glass for the LDC, and that this behavior should be well understood for proper operation of the OPLE control loop.

All other investigations of the channel spectrum that we have examined (those for IOTA and SUSI) have utilized a simplified form of Equation J.2. They have simplified , (σ, d) to be an object visibility, V, which is independent of wavenumber. Note that V is only independent of wavenumber if the object is an unresolved point source, for which , (σ, d) = 1 for all wavenumbers. Also, these studies have assumed that the PD is not a function of wavenumber (true for the vacuum delay line used by IOTA) and that the quantum efficiency and the object spectrum are constant for all wavenumbers. Thus, these studies have simplified Equation J.2 to,

$$I(\sigma, d, \Delta x) \approx (\text{constant})\ (1 + V\cos(2\pi\sigma\Delta x)) \tag{J.3}$$

The reader should note that this equation represents the very best case that could be hoped for. This will produce fringes across the channel spectrum that have equal amplitude at all wavenumbers with equal spacing of the fringes. Any real application will have worse performance than that predicted by the above equation.

In order to fully understand and be able to predict the performance of the channel spectrum for phasing a telescope array, we strongly recommend that the CHARA project undertake a full parametric study using a numerical simulation based on Equation J.2. We developed a working simulation, but have not had time to exercise it for the full range of expected parameters. This simulation (diskette and printout) has been distributed to the research groups at Georgia State and Georgia Tech. The simulation does not presently include code which mimics the temporal evolution of PD; that effect should be incorporated for realistic prediction of the channel spectrum performance. Use of the simulation will also enable the development of algorithms for the fringe tracking processor.

We did exercise the simulation to assess the feasibility of the fringe lock approach. Our initial concern was that complicated objects would not be feasible. However, we soon found that even unresolved point sources, which were modeled by Equation J.3, were very difficult objects for which to maintain fringe lock. For this, the simplest of cases, analytical formulae apply, and the analytical predictions match the results that were found with the simulation. After determining that fringe locking is not appropriate for any type of object, we ceased running the simulation, due to resource constraints. However, we strongly urge that the full parametric study be completed prior to hardware or software development.

J.6. SNR OF FOURIER SIGNALS WITH READOUT NOISE AND PHOTON NOISE

It is worthwhile at this juncture to break our discussion to present an important signal-to-noise ratio (SNR) formula. As is presented in Appendix P, the SNR of the power spectrum at spatial frequency ω of a single frame Fourier signal is given by

$$\mathrm{SNR}(\omega) = \frac{N^2\,|\hat{T}(\omega)|^2\,|\hat{O}(\omega)|^2}{\sqrt{N^2 + 2N^3\,|\hat{T}(\omega)|^2\,|\hat{O}(\omega)|^2 + n_{pix}^2\,\sigma_{CCD}^4 + 2n_{pix}\sigma_{CCD}^2(N^2\,|\hat{T}(\omega)|^2\,|\hat{O}(\omega)|^2 + N)}} \quad \text{(J.4)}$$

where N is the number of detected photons, $O(\omega)$ is the complex object spectrum at frequency ω, $T(\omega)$ is the transfer function, n_{pix} is the number of pixels read out of the CCD and σ is the CCD readout noise (rms electrons). Depending upon the imaging camera, the readout noise terms may be eliminated; this is true for photon counting cameras. And depending upon light level, some of the noise terms may be negligible compared to others. This formula does not include an "atmospheric" or fluctuating aberration noise term. Thus, this formula is not appropriate for high light level speckle imaging or channel spectra with apertures much larger than the lateral coherence length, r_0. However, this formula can be applied to the aberrated Hubble Space Telescope, the channel spectrum and the non-redundant imaging approach that is proposed for CHARA.

If one integrates the power spectrum, or bispectrum, the SNR will increase by the square root of the number of frames. Special cases of Equation J.4 will be used in the following analysis.

J.7. USE OF THE CHANNEL SPECTRUM FOR MAINTAINING FRINGE LOCK / NUMERICAL SIMULATION

It has been proposed that the channel spectrum be used to maintain fringe lock, so that science imaging (phase closure) data could be integrated coherently by a non-redundant imaging approach. This would be ideal, since a high efficiency bare CCD detector could be utilized for imaging and low speed readout could be used to minimize readout noise. Also, coherent integration has a SNR that grows linearly with integration time.

If fringe lock can not be maintained, the phase closure data would need to be collected in frames which have exposures comparable to the atmospheric correlation time (5-20 msec). These data would need to be accumulated by an incoherent integration scheme, for which the SNR only increases as the square root of integration time.

Thus, there is great motivation to being able to achieve fringe lock. The main purpose of this study was to investigate if fringe locking was feasible. Our motivation was an intuitive feeling that fringe locking was going to be very difficult, if not impossible, to achieve for complicated objects unless the light level was unrealistically high. Since, the performance of the channel spectrum for complicated objects is not analytically tractable, we undertook development of a numerical simulation. We exercised the numerical simulation for relatively simple, "best case", conditions and found that it is not feasible to attempt fringe lock with any array, even for simple objects. This is because most astronomical objects are too faint to provide enough photons for accurate PD measurement. In hindsight, we find that the analytical formulae are appropriate for making this assessment; the analytical predictions match the results of the numerical simulations for an unresolved object.

The flowchart for the numerical simulation is shown in Figure 1. In

this simulation, the two dimensional object intensity distribution is collapsed to one-dimension, since we only need to examine single baselines at a time. Reducing the intensity to a 1-D function allows us to sample the distribution very finely and pad with a large number of zero values so that the FFT algorithm gives very fine sampling over the entire bandpass of interest. Typically, we sample to 0.5 nanoradians with a field of view of $3''.4$ (32,768 samples). The Fourier transform of the intensity pattern provides the object's mutual coherence, , (σ, d), as a function of spatial frequency. As is well known from the Zernike-van Cittert theorem, the object's mutual coherence function is the quantity we will measure with the CHARA Array. We obtain the desired intensity distribution by inverse Fourier transform techniques. The infinite light level channel spectrum is obtained via Equation J.2, with information about the baseline d, the pathlength difference $\Delta x(\sigma)$, and the wavenumber range of the detector. It is at this juncture of the simulation that the optics-detector response function should be incorporated. A Fourier transform of the channel spectrum gives the ideal signal response for this approach. In practice, the channel spectrum signal comprises a limited number of photon detections and readout noise signal. The fringe tracking algorithm processes the Fourier transform of the channel spectrum with the aim of detecting and tracking a fringe in the channel spectrum.

For our simulation, we made some "best case" assumptions to evaluate the very best performance that could be obtained with the channel spectrum; these are:

- "white" objects – object intensity distribution is identical at all wavelengths and intensity is constant across the wavenumber domain ($S(\sigma)$ in Equation J.2 is constant versus σ)
- zero readout noise, concentrating on effects of photon noise
- PD constant for all wavenumbers
- detector-optics quantum efficiency is constant for all wavenumbers

We used the numerical simulation to generate channel spectra, which were Fourier transformed so that the peak in the Fourier domain could be analyzed to obtain fringe lock data. We utilized a simple peak centroiding algorithm to "track" the peak. Since the infinite light level channel spectrum did not change during our Monte Carlo trials, the variation in peak centroid was due solely to photon noise.

We ran the simulation for a range of light levels, with the aim of "tracking" the peak in the Fourier domain. Using guidelines from T. ten Brummelaar, we specified the channel spectrum to operate from 600 to 800 nm. With this bandpass, the channel spectrum will add one fringe for each $2.4\,\mu$m of PD. Thus, if we wish to maintain $0.1\,\mu$m positional accuracy, we will need to measure the centroid of the Fourier peak to 1/20 of a pixel.

Figure 2 presents an example of the output of the

simulation. This plot shows the standard deviation of the centroid measurement as a function of the number of incident photons. The standard deviation was computed from the statistics of 100 realizations at each light level. For this case, with a PD of $20\,\mu$m, there are 8.33 fringes across the channel spectrum. The figure shows that an unresolved point

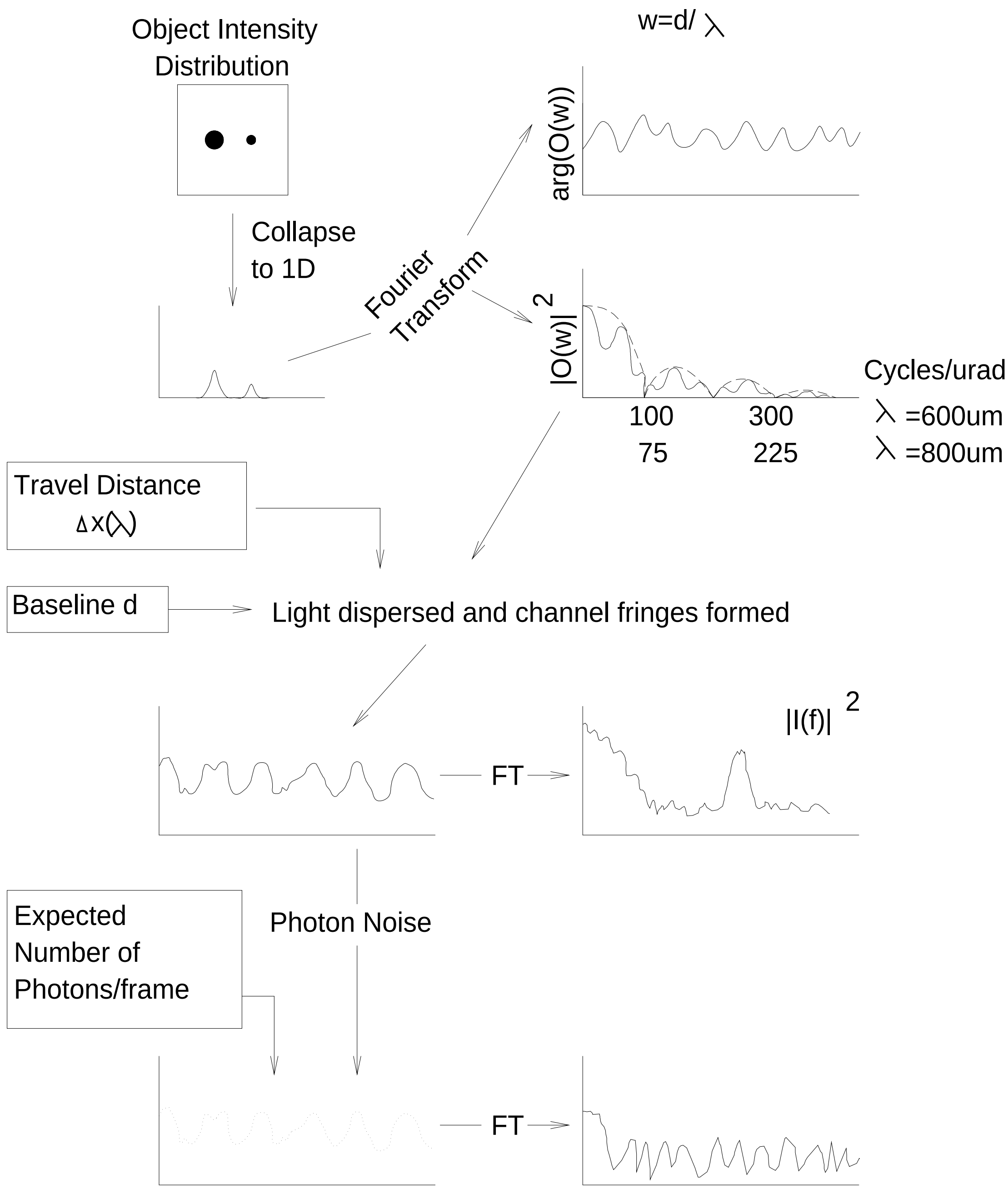

FIGURE J.1. A schematic of the channel spectrum simmulation.

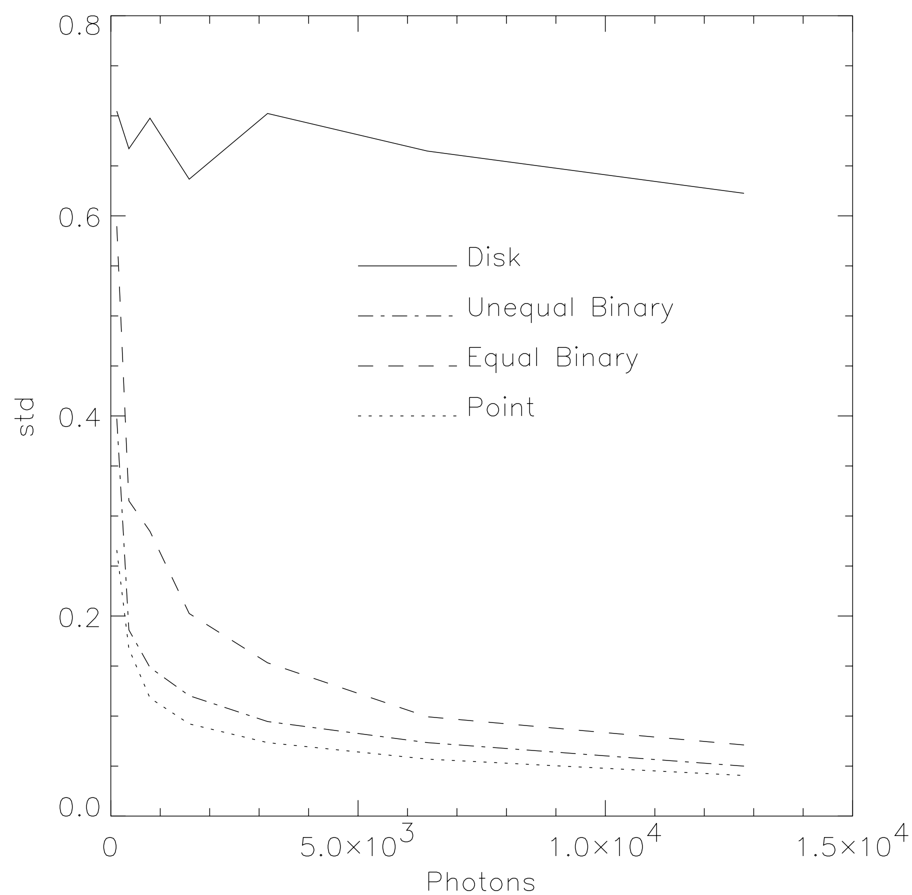

FIGURE J.2. An example of the results of the simulation of the channel spectrum. The path length difference is 20 μm and is the same for all wavenumbers.

source will require about 1400 photons to achieve 1/10 pixel centroid accuracy and about 9000 photons in a single frame to achieve 1/20 pixel accuracy (using 1 σ criterion).

This can be compared to a simple analytical model for centroid estimation. If the errors are Gaussian, the standard deviation of a centroid measurement is approximately equal to the full width half maximum (FWHM) of the peak divided by the SNR. For a pure sinusoid of a single frequency, the FWHM is one pixel. However in this case, the sinusoid resides between two frequencies and the FWHM is about twice as large. Thus, an SNR of 20 is required to obtain a standard deviation of 1/10 pixel.

From Equation J.4 we see that without readout noise and in the high light level limit with the object spectrum equal to 1 at all spatial frequencies, that the SNR of the channel spectrum reduces to,

$$\mathrm{SNR}(\omega) \approx \sqrt{N}\frac{\sqrt{T}}{\sqrt{2}} \tag{J.5}$$

The transfer function is the same as that obtained from Young's two slit experiment, thus $T = 1/2$ at all frequencies. The SNR is approximately 1/2 the square root of the number of photons detected. For a SNR of 20, a total of 1600 photons would need to be detected. For a FWHM equal to a two pixels, the standard deviation would be 1/10 pixel with 1600 photons. In the case shown in Figure 2, for which the FWHM is nearly 2 pixels, a total of 1400 photons is required to obtain a standard deviation of the centroid equal to 1/10 pixel. (Note that this is still only half the accuracy required for fringe locking.)

In the best case, which employs all of the assumptions about "white" objects and "flat" response functions and produces a pure sinusoid on the channel spectrum, we will need at least 1600 photons to achieve the accuracy required for fringe lock. In actual implementation, the number will need to be higher, but this value is sufficient for us show that fringe locking is not feasible. These photons would need to be detected and read out within a few msec. Let us assume that we will utilize 2 msec frames and require a total of 1600 photons to be detected. If we have 1″ seeing and employ 10 cm diameter subapertures and use the following assumptions discussed with T. ten Brummelaar, we can compute the magnitude level required for fringe locking.

TABLE J.1. Light Level Parameters

Aperture Diameter	10 cm
Frame Time	2 msec
Atmospheric Transmission	90%
Light throughput (to tracker split)	10%
Polarization loss (split at tracker)	50%
Bandpass of tracker	200 nm
Quantum efficiency of detector	80%
Flux of $m_v = 0$ star	942 photons/sec/cm^2/Å

We also assume that the light from one aperture is split into two channel spectra, but that the light from the second aperture is split the same, so that the number of photons per channel spectrum is the same as the number of photons from a single subaperture. Thus, a point source of stellar magnitude 2.1 is required to run a fringe locking system. On a good night with $0''.5$ seeing, 20 cm diameter subapertures could be used but one should also note that the above magnitude limit is for a point source with ideal conditions. Thus, it is conceivable that there is no object in the sky bright enough to run a fringe locking system.

Given this dismal prognosis for fringe locking, let us proceed to examine the capabilities of fringe tracking.

J.8. MAGNITUDE LIMITATIONS OF FRINGE TRACKING

For fringe tracking, we can frame the CCD much slower, 10 msec will be adequate. And slow readout can be employed to minimize the readout noise. The power spectra of up to 10 frames (1/10 sec) could be integrated to increase the SNR of the signal. If we specify that we wish to obtain integrated SNR of at least 3, then the individual frame SNR should be at least unity. For this calculation, we need to incorporate the effect of CCD readout noise, which will be the dominant noise source at the lowest light levels.

It will be best to limit the number of pixels in the channel spectrum, so as to reduce the effects of readout noise. We suggest that 64 pixels be used across the channel spectrum, thus sampling of about 3 nm per pixel. A readout noise of 2 electrons per pixel should be achieved by careful camera construction. Thus, the low light level SNR of the channel spectrum is given by,

$$\mathrm{SNR}(\omega) = \frac{N^2\,|\hat{T}(\omega)|^2}{\sqrt{N^2 + 2N^3\,|\hat{T}(\omega)|^2 + n_{pix}^2\sigma_{CCD}^4 + 2n_{pix}\sigma_{CCD}^2(N^2\,|\hat{T}(\omega)|^2 + N)}} \tag{J.6}$$

With T equal to 1/2, n_{pix} equal to 64 and σ_{CCD} equal to 2, we will need to detect 55 photons to have a SNR equal to unity. Using the assumptions of Table J.1, with a frame time of 10 msec, we find that this corresponds to $m_v = 7.5$. When the seeing is very good and we can use 20 cm subapertures, $m_v = 9.0$ will be the limit of fringe tracking. *It should be emphasized that these predictions employ all of the best case assumptions that were stated in the previous section. Object color spectrum, detector q.e. changes vs. wavelength, object structure, wavefront distortions, etc. will all contribute to make the magnitude limit 1 to 2 stellar magnitudes brighter than that predicted above.*

J.9. MAGNITUDE LIMITS TO PHASE CLOSURE DATA WITH FRINGE TRACKING

If we cannot lock onto fringes, then we must frame the imaging / phase closure data into exposures which have duration comparable to the atmospheric correlation time, which is about 10 msec. Due to the poor throughput of the optical fibers and the spectral dispersing that will be employed in the imaging system, we can not use a CCD camera. As of this time, the only available technology are photon counting cameras. The best quantum efficiency that we can presently obtain will be 10%, although even this figure can be considered to be optimistic.

If we assume that 25% of the light will be collected by the optical fibers, we can compute the magnitude limits to collecting phase closure data. The phase closure data can be integrated for the duration of the fringe tracking, which we have been advised by T. ten Brummelaar to be a maximum of 5 minutes; which corresponds to 30,000 frames. In order to measure phase closure data, we need to get an integrated SNR of at least 3. Since we will be in the low light level limit with no readout noise, Equation J.4 can be reduced to,

$$\mathrm{SNR}(\omega) = \frac{N^2\, |\hat{T}(\omega)|^2\, |\hat{O}(\omega)|^2}{\sqrt{N^2 + 2N^3\, |\hat{T}(\omega)|^2\, |\hat{O}(\omega)|^2}} \tag{J.7}$$

At the very lowest light levels, the first term in the denominator is strongest and thus the integrated SNR equation simplifies to,

$$\mathrm{SNR}(\omega) = \sqrt{M} N\, |\hat{T}(\omega)|^2\, |\hat{O}(\omega)|^2 \tag{J.8}$$

where M is the number of frames integrated. If we assume that we are attempting to image something more complicated that a point source, which is the goal of the CHARA array, we will have an object spectrum less than one. A value of $|\hat{O}(\omega)|^2 = 0.1$ corresponds to a relatively simple object, so we will use that to assess magnitude limitations. With 7 interfering subapertures, $T = 1/7$. For 30,000 frames integrated, we will need at least an average of 8.5 photons per frame to attain an integrated SNR of 3.

We cannot integrate more than about 15 nm on the imaging sensor, due to the PD required for the fringe tracker, combined with the different PD values for pairs of baselines. In order to obtain 8.5 photons into a 10 msec frame, with a 10% q.e. detector, 25% efficiency into optical fibers, the object's stellar magnitude must be at least $m_v = 5.4$ for 10 cm subapertures. (Note that one must include all of the light contributed from all apertures for this calculation.) With good seeing and 20 cm subapertures, $m_v = 6.9$ may be the limit of imaging.

Note that the imaging magnitude limit appears to be about 2.2 stellar magnitudes brighter than that of the fringe tracker. But also note that the imaging included a reduction of visibility that is not included in the fringe tracker, so in practice, both approaches may be limited to about $m_v = 5.5$ on an average night and $m_v = 7$ on a very good night.

J.10. DETECTORS

The channel spectrum sensor can utilize presently available CCD arrays, although care should be taken to minimize the readout noise; this detector can be obtained for about $100,000. The parameters that one should specify are:

- quantum efficiency > 80% over the wavelengths used by the channel spectrum
- readout noise less than 2 electrons per pixel
- flexible readout and binning structure

The technology for the imaging (phase closure) instrument should be carefully tracked during the next few years. Presently, the only feasible option for that sensor is a photon counting camera. There are at least three commercial sources for this item, each would be about $100,000. The drawback of these devices is their relatively low quantum efficiency; a peak of about 10% is the highest presently available. We recommend that CHARA track three technologies to ascertain which camera is best in a few years time:

- there is a possibility of 30-40% q.e. from photon counting cameras, all dependent upon the evolution of image intensifiers
- basic physics shows that CCD devices can be made noiseless, but this is considered highly unlikely with the present funding pattern
- avalanche photodiode arrays may progress to the point that they are useful (128 pixels square); with the deep pockets of the medical community anxiously awaiting these devices there is a market to spur this development.

J.11. SUMMARY

We have presented several of the formulae involved in fringe tracking and imaging, and we developed a numerical simulation for the channel spectrum. We show that fringe locking is not feasible and estimate magnitude limits for the fringe tracker to be $m_v = 7.5$ and 9.0 for subapertures of 10 and 20 cm diameters, *under the best of conditions.* For real objects and system limitations, the fringe tracker will probably limited to m_v of 5.5-6.5 for $1''$ seeing (10 cm subapertures) and $m_v = 7$–8 for very good seeing (20 cm subapertures). The magnitude limitations for the imaging array are approximately $m_v = 5.4$ for average seeing and about $m_v = 7$ for the best of conditions. We recommend that bare CCD detectors be used for fringe tracker and that a photon counting camera be used for imaging. The photon counting technology is evolving and it should be closely followed for the next few years before a procurement is made.