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Reducing Binary Star Data from Long-Baseline Interferometers

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Abstract. Processing long-baseline interferometry data presents a unique set of complications: How does one derive relative astrometry from interferometric data? How can 1-D interferometric results be used to solve a 2-D orbit? How can baseline-only solutions be combined with historical data and how should interferometric data be published so that they can be combined with archived data? What new techniques for interferometers are coming on line? This paper contains a brief review of interferometric data analysis in the context of binary star astrometry.

Keywords. Binary Stars, Interferometry, Astrometry, Closure Phase, Imaging.

1. Introduction

Ground based optical and infrared long baseline interferometry (OLBI) has in recent years come of age and is now producing some outstanding results in many areas of stellar astrophysics. With more than 60 publications in 2006 at the time of writing this paper, and many more on the way, the comparatively small number of instruments available to the community are very scientifically productive and with new instrumentation now being commissioned this productivity will continue to expand.

The techniques of OLBI are particularly well suited to the study of binary stars because the high resolution of these instruments makes it possible to resolve astrometric orbits with unprecedented precision and accuracy. In the next few years the gap between astrometric and radial velocity measurements will rapidly close and calculating masses, stellar radii, and other fundamental characteristics of stars at the 1% level or better will become common place.

In this paper, I will attempt to give a broad overview of how OLBI data is collected and interpreted in the context of binary star astrometry. A more detailed explanation of the techniques of OLBI (Lawson (2000)), in the form of lecture notes for the 1999 Michelson Summer School run by the Michelson Science Center†, is available for free from the Jet Propulsion Laboratory‡ (JPL). A good source of historical information on the subject can be found in Lawson (1997) and more up to date information, including a list of publications, can be found on the OLBIN web page¶ maintained by JPL. Note that while many of the examples in this text come from the CHARA Array (ten Brummelaar *et al.* (2005)), principally because I have easy access to these data, they are generally applicable to any existing or planned long baseline interferometer.

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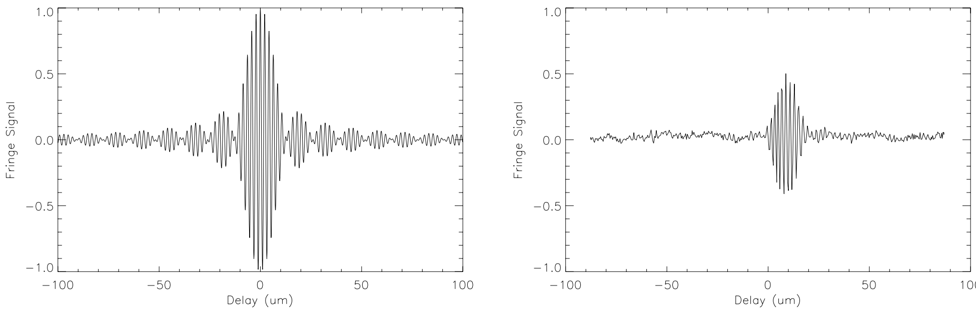

Figure 1. Examples of raw fringe data: *Left*: Modeled data *right*: Real data.

2. Basic Theory

An interferometer takes the light from two, or more, telescopes and combines this light together in a single position known as the beam combiner. Each pair of telescopes, whose separation is known as the baseline, will create a fringe packet, that is, an interference pattern, whose width depends on the optical bandwidth of the system and whose magnitude and phase depend on the object, the baseline, the central wavelength of the optical filter, and numerous instrumental and atmospheric effects. The mathematical form of a fringe packet is given by

$$I(t,\nu) = 1 + V(t,\nu) \times \frac{\sin\left(\pi\, x(t,\nu)\, \Delta\nu\right)}{\pi\, x(t,\nu)\, \Delta\nu} \times \cos\left(2\pi\, x(t,\nu)\, \nu + \Phi_{\rm obj} + \Phi_{\rm atm}(t)\right) \qquad (2.1)$$

where I is the measured intensity, t is time, V is the fringe amplitude, x is the path length difference between the two beams, $\nu = \frac{1}{\lambda}$ and $\Delta\nu$ are the central wavenumber and width of the optical filter, $\Phi_{\rm obj}$ is the visibility phase of the object and $\Phi_{\rm atm}$ is the phase error introduced by the atmosphere. An example of a theoretically perfect fringe is given in the left plot of Figure 1.

The Van Citter-Zernike theorem (See for example Thompson *et al.* 2001 or Born & Wolf 1999) states that the complex quantity called the visibility, that is the amplitude and phase of the fringe packet, represents one Fourier component of the intensity distribution of the object on the sky. In principle, one need only measure the visibility of the fringes at many baselines and perform an inverse Fourier transform to derive an image of the object in question. The power of interferometry derives from the fact that the angular resolution of this image is proportional to the central wavelength divided by the largest baseline. Thus for a baseline of 100 meters and a wavelength of 1 μm the best resolution attainable will be 1.0^{-8} radians or about 2 mas. For binary star observations the resolution can be much higher.

Of course there are many factors that make the real situation much more complex. In order to see any fringes at all one must overcome many engineering challenges, and like any other ground based technique the data are distorted by the atmosphere and instrumental effects. For example, one must have tip/tilt servo systems on each telescope, or even a full blown adaptive optics system on the larger apertures. Furthermore, the optical path length of the light from the star, through the two telescopes and within the instrument all the way to the beam combiner, must be controlled to a precision of much better than 1 μm. For example, at the CHARA Array, the delay lines are kept stable with an RMS error of less than 10 nm, and this figure will be similar at other facilities. These path lengths are always changing as the earth rotates, and the atmosphere is constantly adding wavefront and phase errors that change on the time scale of milliseconds which can severely restrict sample times and data rates. Thus, an interferometer consists of many servo systems, each with time constants faster than the atmospheric modulations. An example of real fringe data is given in the right hand plot in Figure 1.

All of these instrumental and atmospheric effects cause changes in the fringe amplitude and phase, almost always reducing the amplitude and totally destroying the phase information on a single baseline. Worse yet, the amplitude modulations are constantly changing as the turbulent atmosphere blows by the telescopes. A comparison of the modeled and real fringe data shown in Figure 1 reveals many of these problems. First of all, despite the fact that this is unusually high signal to noise data†, there is still a great deal of noise present in the signal, so much so that the first side lobes of the fringe packet are barely visible and the rest not visible at all. Some of this noise is due to scintillation, but most of it is camera and photon noise. Since the output signal is a subtraction of the two outputs of a beam splitter scintillation noise cancels out to a large extent. Secondly, the fringe is not centered within the delay scan indicating that the phase information has been lost. Thirdly, the shape of the fringe envelope has been distorted due to the fact that the atmospherically induced phase and wavefront errors are constantly changing. Finally, despite the fact that the object is unresolved, the fringe amplitude is much less than 1.0.

In order to get around these difficulties the standard practice is to measure many, often several hundred, fringe scans and take the mean of the fringe amplitude. In this way the random fluctuations of amplitude are averaged out. One then repeats this measurement on a nearby unresolved source and takes the ratio of the, hopefully resolved, science target and the, hopefully unresolved and spherical, calibrator object. This yields a good estimate of the fringe amplitude of the science target for the baseline in question.

In a so called “open air” beam combiner with no spatial filtering this calibration procedure typically yields precisions of $\approx 5\%$, while a single mode fiber based instrument will filter out much of the atmospheric distortion and achieve results of $\approx 1\%$. Spatial filtering does, however, come at the cost of a lower magnitude limit. In excellent seeing conditions one can do better, but these values are fairly representative of the two techniques.

This process is repeated for many baselines in order to collect a data set of fringe amplitudes for many spatial frequencies. One can then fit a model to these data in order to extract the scientific parameters of interest. Three examples of such models, for a resolved symmetric uniform disk and two binary stars of different differential magnitude, are given in Figure 2.

Unfortunately, with single baseline measurements the phase information can not be calibrated and is normally ignored. Techniques for recovering phase information for multiple baseline measurements will be discussed in section 6.

3. Separated fringe packet astrometry

It is of course, not all bad news. There are numerous techniques for getting around the difficulty in calibrating visibility amplitudes. Consider, for example, the case when the stars in a binary system are far enough apart so that the fringe packets from each star do not overlap in delay space. For example, taking once again a filter centered at 1 μm with a 10% bandpass, the fringe packet width will be $\frac{1^2}{0.1} = 10\ \mu$m, so on a 100m baseline this represents an angular separation of $10^{-5}/100 = 10^{-7}$ radians or about 20 mas. These numbers scale directly with wavelength and baseline. By measuring the separation of the two fringe packets in a scan one can derive a one-dimensional measurement of the

† One might say “typical” data.

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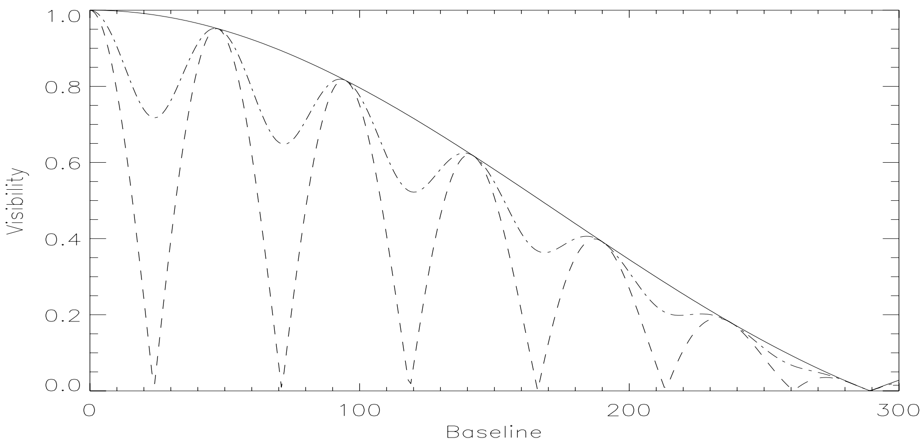

Figure 2. Examples of visibility functions in K band (2.3 μm): *Solid line*: Uniform disk of diameter 2 mas. *Dashed line*: Binary star, each star of diameter 2 mas with a separation of 10 mas and a differential magnitude of 0. *Dash-dot line*: Same binary star with a differential magnitude of 2.0.

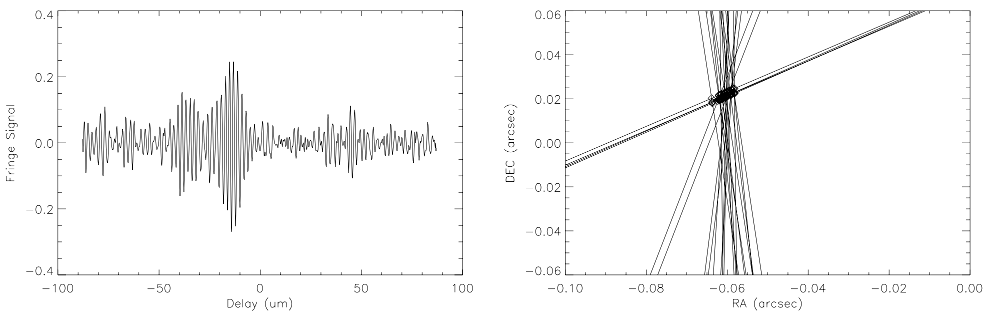

Figure 3. Examples of separated fringe packet data of HD 19332 taken at the Chara Array. *Left*: Single scan showing two fringe packets, one from the primary and one from the secondary. Note that since the primary is resolved, it is in fact the fringe packet on the left, the one with a lower fringe amplitude. Each scan of this type gives a single 1-D separation of the binary star on the sky. *Right*: Resulting astrometry from many scans on two baselines. Each line in this shows the possible position of the secondary with respect to the primary, and the intersection of these lines gives the full astrometric solution of $\rho = 64.0 \pm 1.8$mas and $\theta = 289 \pm 1.6°$ for this epoch.

separation of the binary system on a line parallel to the projected baseline. With more than one baseline one can get a full astrometric data point including ρ and θ, for that epoch. This technique was pioneered by Dyck *et al.* (1995) and an example data set from the CHARA Array for the star HD 19332 is given in Figure 3.

The precision of this technique depends, for the most part, on the measurement of the fringe packet separation. This in turn depends on the calibration of the system used to scan through the fringes, knowledge of the projected baseline, and the algorithm used to identify the center of the fringe envelope. In the case of the data shown in Figure 3 the fringe envelope center was found by fitting a Gaussian to the demodulated fringe amplitude and the scanning mirror calibration was good to about 1%. Since the position of the baseline is known to within 100 μm, or one part in 10^6 it has little effect on the final precision. Furthermore, since it takes a finite amount of time to scan from one

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fringe packet to the next, the atmosphere can move the fringes around further blurring the results.

There are several ways to avoid these difficulties. If you are lucky, the fringe packet of the secondary lands on one of the side lobes of the primary and in these cases the central wavelength of the filter itself becomes an excellent reference for phase (Bagnuolo, *et al.* 2006). In this case, the precision is dependent on the knowledge of this wavelength, so using the baseline and wavelength of our previous example, and assuming we know this wavelength to 5% the precision can be as high as $\frac{0.05^{-6}}{100} = 5^{-10}$ radians or about 100 μas, and on larger baselines much better than that. If you have more than one delay and beam combiner, the two stars in the system can be measured simultaneously, totally removing the effects of the atmosphere and even greater precision can be achieved (Muterspaugh, *et al.* 2006).

There is another way in which these separated fringe packet objects can be used to study binary stars. In a surprising number of cases, the "primary" is in fact itself a spectroscopic binary star. For objects of this type, you have the lucky coincidence of having a calibrator within the same scan as the object of scientific interest. So, rather than slewing between object and calibrator, it is possible to collect both calibration and science data in each single scan. This means that the calibration object is spatially and temporally very close to the science target and this not only more than doubles the data throughput but improves the calibration process considerably. Work is now underway to take advantage of this special class of object.

4. Visibility amplitude astrometry

If the fringe packets of the two stars in the system do overlap you must measure the fringe amplitude on a range of baselines and a range of epochs. For example, Figure 4, shows data from the Michigan Infra Red Combiner (MIRC, Monnier, *et al.* (2006)) at the CHARA Array using four telescopes, yielding six baselines, each with eight spectral channels. These data took about 20 minutes to collect and the binary star signature is clear yielding an instant ρ and θ measurement, as well as the diameters of both components. Using the phase closure techniques outlined in section 6, these data can also be used to create an image of the system.

Data of this type can be directly fitted to models of the binary star yielding astrometric results. Furthermore it is possible, indeed it is now standard practice, to produce a combined fit of the interferometric and radial velocity data resulting in a full three dimensional solution of the system. This has been the aim of interferometric binary stars studies for many years, and will certainly become a very powerful method for measuring stellar masses, and other fundamental parameters, in the years to come. A great deal of exciting work in this area has been done at the Palomar Testbed Interferometer (PTI Colavita *et al.* 1999) for example in Torres *et al.* 2002, a study of HD 195897, where they measured the mass of the primary to 2%, the secondary to 1% and have a factor of two better precision on the parallax than Hipparcos. This sort of precision is an upper limit of what can now be achieved and we should expect this to improve in the near future.

5. How should we present our results?

There are many in the community who would prefer us to report all our results in the form of ρ, θ and epoch, as has been traditionally done in binary star science. This simplifies cataloging of these data and makes it easier to combine them with other astronomical measurements. In many cases this is possible — separated fringe packets, dual

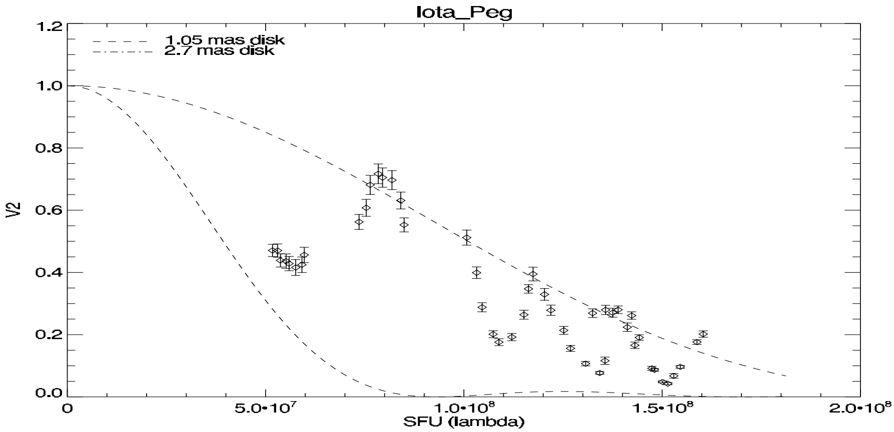

Figure 4. Sample data of the binary star ι Peg taken with the MIRC beam combiner at the CHARA Array in H band (1.6 μm). *Dashed lines*: Models of uniform disks of 1.05 and 2.7 mas. *Data points*: Measured visibilities on six baselines each with eight spectral channels.

star systems, slow moving systems, objects or system for which we can obtain a lot of data quickly, phase closure data (see section 6) — but in many cases it is not possible, nor even appropriate.

Since it is the binary stars with full double lined spectroscopic orbits we are most interested in, and these tend to have short periods, it isn't always possible to collect data quickly enough to solve for ρ and θ for a single epoch. By the time you have moved to a calibrator and returned to the object enough times to get an astrometric solution, the system can move significantly and a single astrometric data point no longer makes any sense. The same is true for an object for which you have a very dispersed data set and objects close to the resolution limit of the interferometer. In these cases you might as well combine the spectroscopic and interferometric data and solve for the complete orbit and stellar parameters all at once.

So how then do we report our results so that they can, at some future time, be combined with other measurements of the same object? The same way we have traditionally combined our data with radial velocity measurements. First of all, we could report our visibility amplitudes and baseline projects as raw data and an IAU standard format already exists for this kind of data exchange (Pauls *et al.* 2005). If it is possible to derive ρ and θ that should be done and reported. The same goes for the 1 dimensional data of separated fringe packet astrometry.

In the not-too-distant future we are all going to have to learn to deal with complex data sets that cross many boundaries between experimental methods. What is really needed is software that will combine radial velocity, ρ/θ, visibility amplitude, phase closure, lunar occultation and Ouija board data into a single orbital solution. This may be, as they say, an excellent exercise for a student.

6. Phase Closure and Imaging

So far we have only dealt with fringe amplitude data, having dismissed fringe phase as being totally washed out by the atmosphere. Fortunately, if we have three or more telescopes, we can borrow a technique developed for radio interferometry called phase closure (see again Thompson *et al.* 2001). If you add the phases of the fringe packets in

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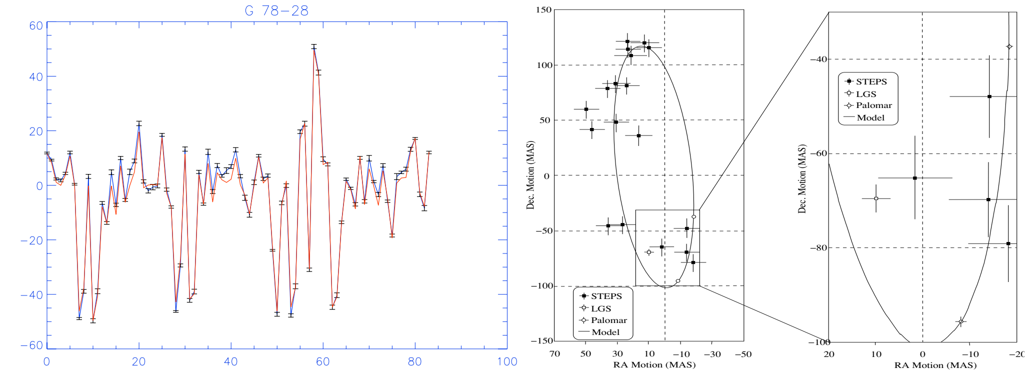

Figure 5. *Left*: Closure phase data on the Binary star G78-28 of data taken with an aperture mask at Palomar. *Right*: Orbit for G78-28 with data from STEPS (Pravdo *et al.* 2006), LGS data and two new points from aperture masking. Note the size of the error bars for the aperture masking data.

a closed circle of baselines you have the closure phase, something very similar to a bi-spectrum, and it turns out that the atmospheric phase errors are related to the telescopes and not the baselines and cancel out. While you are still throwing away some phase information, this yields a good measurable which is extremely sensitive to asymmetries in the object being studied. Since binaries stars are inherently asymmetric this technique is ideal for binary star astrometry.

The most impressive results to date using the technique of closure phase have been obtained by placing a mask on a large aperture telescope. These masks have many small holes of approximately $3r_0$ diameter in a two dimensional non redundant pattern. In this way, the telescope becomes an interferometer and is forced to have an extremely well defined point spread function. For example, Figure 5 shows on the left the raw and fitted closure phase signals measured at one epoch using a mask at the Palomar telescope (Pravdo *et al.* 2006). It is not possible to differentiate the raw and fitted signal as the fit is so good. On the right of Figure 5 is shown the resulting new orbit for this object combined with some data obtain with other techniques. The interferometric data are clearly the most precise and help to confine the orbit. This represents a λ/D result.

Phase closure data can, as it does in radio interferometry, also be used to create images. Because imaging requires many baselines and closure phases, this has been most clearly demonstrated with aperture masking. For example, Figure 6 shows images of the prototype pinwheel nebula WR 104 (Tuthill *et al.* 1999). This is a binary star with a period of 243.5 days and an internal separation of 1 mas with a Roche Lobe overflow precipitating the WR stage in this system.

Despite the relatively small number of apertures, ground base long baseline interferometers have been making images of binary stars for some time. The first of these was done by the COAST group in Cambridge England (Baldwin *et al.* 1996), followed closely by the NPOI group (Benson *et al.* 1997) and later the IOTA group (Monnier *et al.* (2004)) in the United States. More recently, interferometers with more than three apertures and multi-way beam combiners have, or will soon, come on line like Amber/VLTI (Malbet *et al.* (2006)) and MIRC/CHARA Array (Monnier, *et al.* (2006)), and not far off in the future the MROI (Creech-Eakman *et al.* (2006)). These new generation instruments combine many telescopes at once and can collect more data more quickly than single baseline instruments. For example, the MIRC/CHARA system currently combines four telescopes, with eight spectral channels for each baseline, resulting in 48 amplitude and

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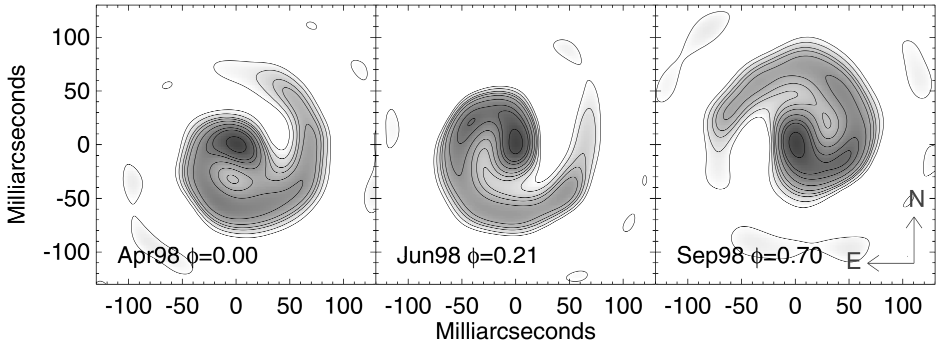

Figure 6. Images of WR 104 at three separate epochs taken using an aperture mask on one of the Keck telescopes. This is a binary star system and the motion of the spiral is clearly visible with time.

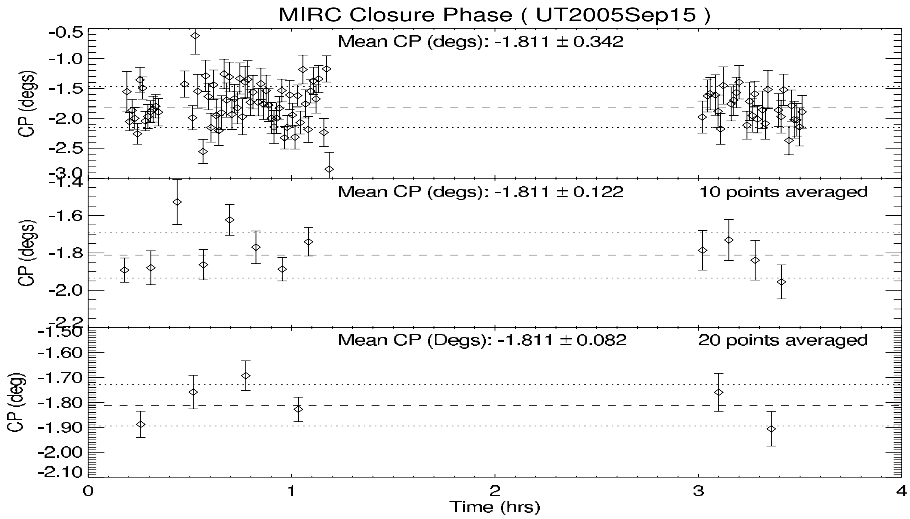

Figure 7. Closure phase measurements taken using the MIRC beam combiner at the CHARA Array. Re-binning and averaging of these data shows that the errors in these data are close to the limit required for planet detection.

32 closure phase measurements in a single data cycle. MIRC will, in 2007, be expanded to combine all six of the CHARA Array telescopes. High resolution imaging of binary stars, and more complex structures, will soon be common place.

As a final example, we can consider the use of an interferometer in the study of extra-solar planets. In order to directly detect the planet known to exist in the 51 Peg system and using the largest baselines at the CHARA Array, a closure phase precision of 0.05 degrees or better is needed. Figure 7 shows the first closure phase results using MIRC at CHARA in late 2005, and even with this early data set a precision of 0.082 degrees was achieved. It is not unreasonable to expect that direct planet detection from the ground using this sort of technique will one day be possible, even routine.

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7. Conclusions

I have attempted in this short review, to cover the basics of the reduction of binary star data using a long baseline interferometer. This technique is not new, indeed it has been around for almost 100 years, but is only now beginning to live up to its long touted potential. It is the highest resolution technique available and will make visual binaries out of many double lined spectroscopic binaries, furthermore, it has an accuracy that is competitive with eclipsing systems and can provide more, and complimentary, information for these objects. There is also great potential for studies of tidal interactions. Brown dwarfs are now being measured with aperture masks and planet detection is not far away. It is my belief that long baseline interferometry will soon do for binary star astrometry what Speckle interferometry did in the seventies and eighties. It's obvious: if you have access to an interferometer you should be studying binary stars.

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Discussion

Nancy Evans: Can you say anything about (say) the fraction of triples as a function of mass? Let me challenge you. For well studied Cepheid binaries (massive stars) we find as many as half the binaries are triple.

ten Brummelaar: I apologize, I was obviously not clear enough. While we do have surveys underway for double and triple systems they are far from complete. My intention here was to point out that once you have found a triple system, you can take advantage of the fact that it can contain a calibrator and binary star in a single scan. I'm afraid I can not, as yet, give you an answer to your question.

Ted Gull: Re: the assumption that the stars are spherical. Massive stars $> M_{\circ}$, with rotation, are predicted to be non-spherical. Have you looked at the these massive star systems for evidence of oblate geometry?

ten Brummelaar: Indeed we have, and checking that calibrator stars are not likely to be non-spherical is extremely important. Two of the first three CHARA Array scientific publications dealt with exactly this sort of object (McAlister *et al.* (2005) & van Belle *et al.* 2005), and it is likely to be a very hot topic in the field of interferometry for some time to come.