A Technical Update of the CHARA Array

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ABSTRACT

The CHARA array achieved first fringes late last year and is currently being expanded on Mount Wilson CA. This presentation is a follow on from the overview given by Hal McAlister and will give more technical detail on the optical systems, with a focus on the telescopes, the delay lines, the control system, and the beam combining scheme. Combining more than three beams is not a simple problem with no obvious best solution, and we have by no means locked ourselves into a particular design. Preliminary designs will be shown, the first beam combiner will also be discussed along with our plans for future development.

Keywords: Interferometry, Control Systems, Tip/Tilt, Beam Combining

1. INTRODUCTION

The CHARA Array consists of six telescopes distributed in a Y shaped array on Mount Wilson and achieved fringes in the early morning of November 23rd last year using the first two telescopes on the southern arm. In this paper we will attempt to describe some of the more technical aspects of its construction.

Like any interferometer there are a large number of complex subsystems and it is impossible to cover them all in the kind of detail one would like, so we will concentrate on what we hope will be of most interest: the telescopes including the tip/tilt system, the delay lines, the control system and the beam combiners. A more general overview of the array can be found in Ref. 1 so we will not spend time describing the general layout of the instrument. Similarly, we will not discuss here the evacuated light pipe system\textsuperscript{2} or the telescope enclosures.\textsuperscript{3}

2. TELESCOPES

The telescopes are extremely massive, but more or less standard Alt/Az mounts and are an afocal system, or beam reducer, taking a 40 inch beam down to 5 inches. In order to reduce costs, the telescope design by Larry Barr\textsuperscript{4} was finished through to workshop drawings and these were then sent out to bid. The telescope frame is built from large steel tubes welded together, while the telescope tube consists of a welded steel frame and employs invar rods to maintain the primary/secondary distance. Friction drives are used to move both axes of the telescopes.

The primary mirrors are 40 inches in diameter and have been light weighted by boring out sections of the back side. The optical mirrors more than met the specification of 0.03 waves rms across the surface, and better than 0.02 waves within any 30 cm patch. To date we have been using an aluminum coating on all telescope optics, since there is a large coating facility already on the mountain. In all likelihood, optics exposed to the weather will remain aluminum coated while those in more protected locations will eventually have a silver coating of some kind. A more modern coating facility has recently been donated to the Mount Wilson Institute and we expect that the expertise for silver coatings will be developed on the mountain itself.

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The mirror is held in place by two separate systems as shown in Figure 1. A cylindrical steel pipe passes through the central hole of the primary and prevents any lateral motion of the mirror, and also holds the tertiary mirror in place. The mass of the mirror is held by an eighteen way whiffle-tree mount. Each of these eighteen mount points consists of a pad glued to the mirror and a small steel pin. Thus, while the whiffle-tree holds the weight of the mirror, it does not constrain it from lateral motion at all. Each of these mounting pins was carefully aligned to form a plane prior to installing the mirror itself. The mirror as a whole can then be adjusted by turning three bolts that connect the whiffle-tree to the telescope tube.

The telescope secondary is mounted on a flex pin and held against three fiducial points with a spring, as shown in Figure 2. The secondary mounting system has a very small profile, less than the secondary mirror diameter itself and contains both the focus/alignment drives and the tip/tilt actuators. The mirror itself can be removed from the mount by undoing the top bolt above the spring and releasing two hard stops leaving a hole through the mounting tube. This is extremely useful for re-coating the mirror and for alignment of the telescope tube and primary.

The original design of the secondary mount included three motor driven micrometers that can be used to both align the mirror and to focus the telescope. It was realized later that PZT actuators were also available that could be mounted on the ends of these micrometers. Initial modeling of the mirror and spring system predicted that the first resonance frequency was in excess of 100 Hz, and so it was decided to install these PZTs and use the secondary itself as the tip/tilt actuator. Laboratory tests have since shown that the mirror can be driven at 50 Hz at high amplitudes (±5 arc-seconds) and close to 100 Hz at lower amplitudes before there is any chatter in the system. While there is no momentum compensation we have, to date, seen no evidence that any is required. Should we ever find that this system is not adequate we plan, as a backup, a smaller high speed tip/tilt mirror in the beam combining lab and we...
will use the secondary for low frequency corrections only.

The detector for the tip/tilt system, for first fringes, was the acquisition camera running at video rates. This system achieved a closed loop bandwidth of only 2.5 Hz, but we found that this was adequate for the K and H bands under most observing conditions. We are in the process of installing a quad-cell photo-multiplier based system in the beam combining laboratory to replace this low bandwidth system. The new tip/tilt detectors will have a software configurable sample time of 1 millisecond or more with the position and PID calculations being done by a computer in the laboratory and then sent via fibers to each telescope control system. The software and communications for this new detector scheme has been completed and tested and we are currently testing the electronics. We expect to have this new system installed by the time this conference takes place. A possible future upgrade will be to use APDs or a CCD in place of the photo-multipliers.

Acquisition is done using a commercial CCD camera and a frame grabbing board. This frame grabber has several spare inputs so it is also possible to view images from other cameras installed in the telescope dome and in the control ‘bunker’. The acquisition camera is mounted on the side of the telescope fork between mirrors M4 and M5. A six inch paraboloid can be inserted halfway into the beam and a 0.3 arc-second per pixel image created on the CCD. Thus, half the light is used for acquisition, and in the case of our first light system, for tip/tilt detection. The rest of the light passes by and down the light pipe towards the beam combining facility. In order to ensure that the acquisition camera is properly aligned with the rest of the downstream optics a small retro-reflector is mounted in the center of the secondary mirror and the alignment laser is propagated from the laboratory through the entire optical system. Half of this laser light can pass by the acquisition mirror, be reversed by the retro-reflector and then bounce off the acquisition mirror into the camera. This gives a fiducial for the acquisition system and we have found that it is best to repeat this operation every time the telescope is slewed over a large distance. Once we have the downstream tip/tilt detectors and more stable alignment we expect that the frequency of this procedure can be

Figure 2. Left: Secondary mirror and mounting. The spring that holds the mirror against the fiducials is at the top of the tube, and two of the three focus and tip/tilt drive systems can be seen at the front and to the left. A small retro-reflector is attached to the center of the mirror. Right: Example images of Jupiter and Saturn made using the acquisition camera.
Figure 3. The Optical Path Length Equalizer area. The two fully functional carts can be seen close to the front of the rails. Three other carts are parked at the far end of the delay lines. A set of spare supports for a possible expansion to eight telescopes can be seen on the right. Insert: A closeup of the cart drives showing the two voice coils and the stepper motor drive cart.

reduced. This small retro can also be used for finding internal white light fringes.

In order to avoid re-inventing wheels we decide to use a commercial telescope control package by ComSoft* called TCS. TCS is a complete package including several built-in star catalogues, dome and mirror cover control, and it interfaces with the rest of the CHARA control system via a serial port. The flexure and pointing model used is also a commercial product called Tpoint† and currently the pointing model for the two functional telescopes are good to better than 20 arc-seconds rms and we expect this to improve with time. Tpoint has also provided us with baseline solution software, but due to metrology problems (see section 3), we have been restricted to observations only in the south. Nevertheless, a preliminary baseline solution of the first two telescopes yielded an rms of less than 2 mm. We have had a universally good experience with both TCS and Tpoint.

Apart from some trouble with the drive system, which we believe we have resolved, we are very happy with the performance of the telescopes. The optical quality is superb and the control software is reliable and flexible. Some example images taken using the acquisition system are given in Figure 2.

3. DELAY LINES

Using similar reasoning we decided that developing a new design for a delay line would be time consuming, expensive and require the development of in house expertise much needed elsewhere in the project. We therefore chose to go to

*http://www.comsoft-telescope.com
†http://www.tpsoft.demon.co.uk
'Delay-Lines-R-Us' at the Jet Propulsion Laboratory. Our delay lines, which we call Optical Path Length Equalizers (OPLEs), from a hardware point of view, are a copy of those used at the Palomar test bed interferometer (PTI) but with a newer, although perhaps no better, version of the software.

Two fully functional carts are installed, and apart from the metrology launchers, the hardware is complete for three more. A sixth cart is currently under construction and is very close to completion (see Figure 3). Five sets of rails are installed, with two fully aligned, and the cabling for all six OPLEs is in place. The carts are 'cats eyes' and use a four tiered servo system consisting of a PZT driven secondary running at 5 kHz for high speed/small throw control, an inverted pendulum driven by a voice coil running at 200 Hz, a voice coil coupling between the optics cart and the drive cart running at 20 Hz and a stepper motor for large movements running at 2 Hz. Currently the performance of the two existing systems is 20nm rms or better and, with a bit more tweaking of the servo parameters and metrology, we expect to be able to halve this.

Serious problems still exist with the metrology system. The metrology uses a single laser and feed system with independent launching systems for each cart fed by polarization preserving single mode fibers. We currently have two working metrology launchers, and we have every confidence that we can get the rest of them online this summer. Due to a number of design faults in the system as delivered we have found it necessary to re-engineer parts of the beam launching system. The original design, while valid on paper, has turned out to be unstable and all but impossible to align properly. We hope these problems can be ameliorated by replacing the fiber mounts used to deliver the laser light into the launchers.

Like TCS and Tpoint, the control software, based on RICST, is robust and stable. It runs on a VME/VxWorks based platform and communicates to the rest of the CHARA control system via a TCP/IP socket. Apart from a few remaining ‘undocumented features’ (which do not interfere with the essential operation of the delay lines) and the addition of the control code for the sixth cart, the system is complete and fully functional. We expect the remaining work to be completed by late spring.

4. CONTROL SYSTEM

Of course, it was not possible to buy a fully functional and complete control system for the array as a whole, so we have been forced to develop our own. We did, however, use as much as possible of the existing code and coding practices already developed for the Sydney University Stellar Interferometer (SUSI).
The CHARA Array control system, like all other interferometers, is a distributed one, with many separate CPUs located at various positions around the mountain (see Figure 4). This, together with the large amount of RFI on Mount Wilson, presents communication and synchronization challenges. All long distance communication is done via fibers, while internal communications is via copper TBase100 or RS232. If a device was available that could easily interface to a simple serial port we would use it in preference to other more esoteric methods: UNIX is very well suited to talking to many RS232 lines simultaneously. Synchronization is achieved by distributing GPS derived, 1 second and 1 millisecond ticks throughout the array using twisted pairs. Thus the fundamental time unit of the CHARA array is 1 millisecond.

The operating system used, apart from TCS running the telescopes and RICST running the delay lines, is Real-Time Linux\(^1\), while all code is written in C or C++. RT-Linux gives you the full development environment of UNIX while maintaining direct control of the lower level interrupts and hardware. What it lacks in the sophistication of other real time systems like VxWorks, it more than makes up for in price and flexibility. Indeed, our experience to date is that the ‘online’ support, in the form of an email news bulletin, is superior to the commercial support we have had from many commercial vendors. The standard RT-Linux scheduler was modified to run from the external 1 millisecond clock, rather than the on board PC clock, and so jobs can be run synchronously over many CPUs across the mountain. For example, this allows tip/tilt detector computer and the telescope control computers to close a 1 millisecond servo loop across hundreds of meters.

The user interface is the same as that used at SUSI, with a number of extensions. An X-Windows library has

\(^1\)http://rtlinux.cs.nmt.edu/ rtlinux

**Figure 5.** One of the authors (TtB) at the user interface for the interferometer during an observing session on December 12th 1999. Note the primitive logging technology on the left.
Figure 6. A schematic layout of the proposed fringe tracking optics. The six beams from the telescope come in from the lower right. Each is split and combined with a neighboring beam. Six sets of fringes are created, which is slightly redundant but it does allow for internal checks. An alignment laser beam and white light source enter from the upper left.

been added to allow the display of images and data, a socket library has been added so that each control interface will except commands from the sequencer, and the system is now ‘mouse friendly’. The control system is still rather unwieldy to operate as we have had little time to develop sequencing software. This means that the operator must have an excellent understanding of the system as a whole (although someone from the SUSI team would not feel out of place behind the CHARA control computer). Since each control interface can be run via a socket we plan to eventually write a single GUI interface that will allow an operator to run the entire array from a single screen, even remotely from Atlanta. To date, the limited sequencing that does exist is in the form of shell scripts.

5. BEAM COMBINATION

It is in the area of beam combination that most of the work remains to be done. While our ideas for the particulars have changed significantly over the years, and no doubt will continue to develop, we still hold with our original notion of separating the fringe tracking and imaging systems. This is so that each system can be optimized for its particular task, a process that is not necessarily the same in both systems.

We plan to do fringe tracking by combining pairs of beams separately. In this way the maximum amount of light is available for each tracking baseline and we are free to choose the set of smallest baselines that still include all telescopes. The current proposed layout is given in Figure 6. Once combined in the aperture plane each output beam is divided into several smaller apertures with a lenslet array and coupled to multimode fibers. These fibers form a pseudo slit in a low resolution spectrograph. Since we are not very concerned with large angle astrometry our
current thinking is to use channel spectra and group delay tracking.\textsuperscript{9} Of course, the OPLEs have full beam dithering capability so we will also have the ability to do phase locking if that proves to be more desirable. Alternatively, it would be possible to implement dithering using the fringe tracking optics thereby decoupling the dithering speeds and the baselines. Furthermore, as we have a measurement on either side of the beam splitter we will be able to derive correlation measurements from the fringe tracker data, although only for the baselines represented within it. These correlation measurements will be available for each sub-aperture which can then be averaged. Finally, if each sub-aperture is a different size it will allow us to measure and calibrate out the spatial seeing effects. Simultaneous measurements across many different sample times are also planned as a way of calibrating for the temporal component of seeing.\textsuperscript{10}

The next visible system that will be developed is the imager, which will provide data on all baselines and phase closures. It will use single mode fibers to form a linear non-redundant pattern with a dispersed spectrum in the orthogonal axis. A three beam prototype has already been constructed\textsuperscript{11} and we plan to build the IR imaging system in a similar way. These imagers are unlikely to be constructed until all six telescopes and delay lines are functioning and the fringe tracker has been fully constructed and tested. In the mean time we plan to continue to operate using the existing two beam combiners, and to get all six telescopes on-line as soon as possible.

As things stand today we have two dual beam combining systems, one for visible (600-800nm) and one for the IR (H and K bands). The light not used in the visible beam combiner is directed towards the tip/tilt detectors discussed in section 2. Both layouts, while containing a number of folds, employ the familiar method of combining the beams in the aperture plan using a beam splitter and compensation plate. The IR combiner is shown in Figure 7, while the fringe tracker optics are shown in Figure 8. The IR combiner works well on the sky (see Figure 9) in both the K and H bands. So far the visible beam combiner has only been used to find internal white light fringes for alignment purposes. We plan to try and obtain visible fringes on the sky early in the new observing season.

6. CONCLUSION

No project of this size is ever truly finished, they are a living and growing beast and like many similar projects we are man power limited. At some point, however, one must stop playing with the hardware and do some science. We will, therefore, start a scientific campaign as soon as possible in the coming observing season. We have two fully
Figure 8. The two beam visible beam combiner on the left and the current group delay tracking optics on the right. The beam paths in the fringe tracker have been drawn in for clarity. The GDT system consists of (from left to right) a prism, an iris, a lens and a camera. The video camera shown here has since been replaced by a digital camera and we are in the process of developing automated fringe identification and tracking software.

Figure 9. Some example fringes in the K band on the left and H band on the right. The K band fringes were collected on our second night observing (the first in which we got fringes) and on the second object we observed. The raw visibility is 0.6. The H band fringes were collected on our last night of observing last year and have low visibility and SNR due to poor seeing and the loss of one of the H band dewars. These were the first H band fringes detected by CHARA.

The second two telescopes, those on the eastern arm, should be operational this summer, with the western arm following not far behind. The plan is to operate the array as three, more or less, independent single baselines and evolve towards full integration over 2001. In the mean time, we will endeavor to mix engineering and science, a difficult balance, but one we are determined to achieve.

ACKNOWLEDGMENTS

This work was supported by the Center for High Angular Resolution Astronomy at Georgia State University as part of the CHARA Array project. The CHARA Array is funded by the National Science Foundation through NSF grant AST-9414449, Georgia State University, the Keck Foundation and the Packard Foundation.
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