An Update of the CHARA Array

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\textbf{ABSTRACT}

The CHARA Array is a six element optical and near infrared interferometer built by Georgia State University on Mount Wilson in California. It is currently operating in the K and H bands and has the largest baseline (330 m) in operation of any similar instrument in the world. We expect to begin I band operations in 2002. We will present an update of the status of the instrumentation in the Array and set out our plans for the near term expansion of the system.

\textbf{Keywords:} Interferometry, Control Systems, Tip/Tilt, Beam Combining

\section{1. INTRODUCTION}

The CHARA Array consists of six telescopes distributed in a Y shaped array on Mount Wilson and achieved first fringes in the early morning of November 23rd 1999 using the first two telescopes on the southern arm. Since that time we have commissioned the largest operational baseline in the world (330m), and we now have four of the total of six telescopes fully on-line and operational in interferometric mode. The remaining two telescopes are expected to be online later this summer. Many of the smaller sub-systems in the array have advanced since the last update paper\textsuperscript{1} and we will attempt to briefly cover each of these.

We will not describe the CHARA Array itself in any detail as that has been covered by many papers in the past, for example in Ref. 2. Instead we will briefly describe the array and then divide it into sections that roughly correspond to the path of photons through the instrument. In each section we will try and describe both the progress made, and our near term plans.

\section{2. OVERVIEW OF THE SYSTEM}

The input apertures of the CHARA Array are alt/az mount 1 m afocal telescopes. There are six of these telescopes distributed around the mountain in a Y shaped array, surrounding the Hooker 100 inch telescope, with the delay line or optical path length equalizer (OPLE) and beam combining lab (BCL) just to the north of the 100 inch. The telescopes all have active secondaries for tip/tilt control and focus, and direct the light into evacuated aluminum tubes, or light pipes, which bring the light into the OPLE/BCL.

Once inside the OPLE area the light, still within vacuum, is directed through the long delay lines, which allow increments in delay up to 146 m. The light is then sent through the continuous delay lines called the OPLEs, which are not inside the vacuum, and then goes through a second beam reduction. The resulting beam is 19 mm in diameter, a size that makes it possible to use off-the-shelf optical components as much as possible.

The reduced beam then goes through the beam sampling system (BSS) where it is split into the IR band (\(>1 \mu m\)) and the visible band (\(<1 \mu m\)). The BSS units also control which telescope output is fed into the beam combiner(s). The optical train, and the beam combiner in particular, are described in more detail in Ref. 3.

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### Table 1. Available baselines as of July 2002

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<th>Telescopes</th>
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<th>North (m)</th>
<th>Up (m)</th>
<th>Baseline (m)</th>
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</table>

3. TELESCOPES

The CHARA telescopes are 1 m aperture alt/az afocal systems with an output beam size of 12.5 cm. They are driven by COMPUMOTOR DC servo motors via a gear reduction and friction drive. We use the TCS control software package written by ComSoft (http://www.comsoft-telescope.com) and the Tpoints pointing model developed by Patrick Wallace (http://www.tpsoft.demon.co.uk). Acquisition is done using a small CCD located on the side of the telescope which, via a small corner cube in the middle of the secondary, is also able to image the bore sight laser sent out from the beam combining laboratory. As of the writing of this paper all six telescopes have the optics installed and have pointing models developed. Four of these, those on the southern and eastern arms of the instrument, have been used in interferometric mode, and we expect the remaining two on the western arm to come into full operation later this year. A table of the currently available baselines is given in Table 1.

The only serious problems encountered in commissioning the telescopes have been caused by the DC servo motors used to drive the telescopes, which suffer from “stick-slip” problems at the low velocities required to track stellar objects. At its worst, this can result in a sub Hertz oscillation with an amplitude of approximately 1 arc-second. While this is easily removed by the tip/tilt servos we continue to search for ways to remove these oscillations from the telescope drives themselves. We have found that, with judicious tuning of the COMPUMOTOR controller, this oscillation can be removed. Unfortunately this tuning is temperature sensitive and must be repeated on a regular basis. We remain optimistic that a more recent version of the drive system may have less susceptibility to temperature fluctuations. In the interim, we are installing air conditioners in the control bunkers that house the electronics and are looking into replacing the small trim pots used to tune the servo with computer controlled resister chains.

Aligning the afocal telescope optics is, of course, not as easy as we would like. We are still discovering new techniques for this alignment and these are discussed in more detail in Ref. 4.

4. LIGHT PIPES

The light pipes are constructed from 20 cm diameter aluminum pipes joined together by rubber sleeves and hose clamps. These pipes bring the light from the Coudé boxes beneath the telescopes to the turning boxes within the OPLE/BCL building itself (see figure 1). From here the light moves into the delay line area.

Due chiefly to time constraints, almost all of our experiments to date have been done without a vacuum in the light pipe, or POP systems. We are now completing the installation of optics into these systems and will begin operating under a vacuum later this summer.

5. DISCRETE DELAY LINES: POPS

The light pipes feed the light into the DC delay line (called POPs for historic reasons) which are mounted directly below the continuous delay lines, or optical path length equalizers (OPLEs). Each POP has 5 selectable optical delay lengths of 0 m, 36.6 m, 73.2 m, 109.7 m and 146.3 m. We are just completing the installation of the optics and control systems for the POPs. The combination of the POPs and OPLEs give a total controllable optical delay of 238 m allowing almost complete sky coverage on all baselines.
6. CONTINUOUS DELAY LINES: OPLE

Having passed through the POPs, the light is directed up through a periscope system into the OPLEs (See Figure 2). The OPLEs are similar to those in many instruments and consist of a “cats eye” arrangement where the incoming light hits one side of a parabola, comes to a focus on a small secondary, and is then re-collimated on the other side of the parabola and reflected back towards the beam sampling tables. The path is controlled via a four stage servo system consisting of a PZT stage behind the secondary, two voice coils and the stepper motor that drives the carts along the rails. A laser metrology system operating at 1.3 μm is used to monitor the cart positions. The OPLE carts and control systems was designed at JPL under contract to GSU, while the carts themselves were manufactured in the GSU machine shops.

While we have, in the past, had a great deal of trouble with the metrology for the delay lines, we have now solved these problems and the OPLEs work very reliably for the full rail length of 46 m, giving us a continuously controllable optical delay of up to 92 m for each telescope. Four of the six delay lines are fully operational and can track with an rms error of 10 nm. The control system has recently been upgraded to handle all six carts, and five carts have been completed and installed on the rail supports. All six metrology systems are completed, with the first four installed and the sixth cart is now under construction in the GSU machine shop in Atlanta.

7. BEAM SAMPLING TABLES

The light that leaves the OPLEs then moves towards the Beam Sampling Tables (BST) (see Figure 3). The BST contain three subsystems; the Beam Reducing Telescopes (BRT), the Longitudinal Dispersion Correction system (LDC) and the beam sampling system (BSS).
Figure 2. The optical path length equalizer (OPLE) room. The cart for the E1 telescope is parked at the bottom left. Each set of rails is 46 m in length. Below the rails lie the DC delay lines called the POPs.

7.1. Beam Reducing Telescopes: BRT
The BRTs consist of a fairly ordinary afocal telescope and reduce the beam by a factor of 6.66, so the final beam size is 19 mm. While we could have used off-axis paraboloids for the BRTs, we decided that it would be cost neutral to have the full circular optics constructed and mounted and use only one half of the full aperture. While this does take up a little bit of extra space, it makes optical alignment of the system a great deal easier.

7.2. Longitudinal Dispersion Correction: LDC
Since our continuous delay lines are not under vacuum at the shorter wavelengths we can suffer from a reduction in correlation due to differential dispersion between the light arriving from different telescopes. This can be corrected by introducing different amounts of glass to equalize the dispersion in each arm of the interferometer. The LDCs consist of two opposed wedges that can be moved past one another to place an accurately controlled amount of glass into each arm (see Figure 4). While they have yet to be tested on the sky, preliminary tests within the beam combining lab show that they are operating well within specification.

7.3. Beam Sampling System: BSS
At the very rear of the BSTs are a system of movable mirrors and dichroics called the Beam Sampling System (BSS) shown in Figure 5. The BSS allows us to direct the light from any telescope into any of the six beams entering the beam combining lab. Since we only have dual beam combiners at this time this means we can easily switch between telescopes. We have found that the Newport stages used, while exceeding the precision requirement in linear motion, do impose small angular offsets as they move along the tracks. This means performing a small realignment of one
Figure 3. The beam sampling table for the eastern line. The light enters from the delay line, located below the table in this orientation, into the beam reducing telescopes, through the longitudinal dispersion correctors and then enters the beam sampling system. Having been split into IR and visible beams, the light moves of to the left of this picture into the beam combining laboratory.

of the optics on the BSS each time we switch between telescopes. Fortunately, these angle changes are extremely repeatable making this adjustment quite simple, and we are developing an auto-alignment system that will allow us to do this adjustment from the control position. Until that alignment system is complete, however, changing telescopes still requires a manual re-alignment of the BSS.

The BSS is also responsible for splitting the light between the optical ($\lambda < 1 \mu m$) and IR ($\lambda > 1 \mu m$) systems. The first optic is a dichroic which reflects the light into the visible system, while the IR light passes through onto a mirror and is then sent into one of the IR beam combining systems. As with most of the subsystems within the Array, all six of the BSSs have been constructed and assembled, while only four of these have been fully commissioned.

8. TIP/TILT DETECTION

All of the light blue of 600 nm is directed into the tip/tilt detectors located on the same table as the visible beam combining system. These detectors consist of quadrant photo multipliers sampled in programmable increments of 1 mS. This gives a maximum sample rate of 1 kHz, and a closed loop servo bandwidth of 100 Hz, although we have found that on the fainter objects servo bandwidths of as little as 10 Hz are quite adequate during periods of good seeing. The control signals generated by these detectors are de-rotated into the telescope frame of reference and then sent to the telescope secondaries to actively control the beam angle. The tip/tilt correction system can keep the RMS jitter of the stars to below 100 mas, and frequently less during times of good seeing.

As shown in Figure 6, the power spectra of mirror motion obtained while tracking a star obeys the simple theoretical power laws$^6$ indicating that the atmospheric disturbances dominate within the optical system. The
Figure 4. Two of the longitudinal dispersion correctors located just behind the BRTs. They consist of two wedges of glass, one of which can be moved to give a controlled amount of glass in each arm of the interferometer.

Figure 5. An example of one of the newly installed beam sampling units. The optic on the right is a dichroic, reflecting all light with a wavelength of less than 1 µm. Other wavelengths reach the mirror on the left which reflects the remaining light into the IR beam combiner(s). Both optics can be positioned anywhere on the long stage.
current PMT based system is very blue sensitive and, since most of our observations to date have been of very red objects, it is this system that sets the magnitude limit for the entire array. Our long delayed CCD cameras finally arrived this year and we are now working on replacing the PMT detectors with a CCD based system. This will give us much greater sensitivity and the ability to track at longer wavelengths and thus expand the list of available science objects.

9. IR BEAM COMBINER

Our current beam combiner in the IR band is a fairly straight-forward two beam combiner using open air optics. We use a PZT mounted mirror to modulate the path-length of one beam (See Figure 7), and the light is then fed into an infrared camera based on the Rockwell PICNIC 256x256 HgCdTe array. This camera also contains a filter wheel with J,H and K filters along with several narrow band filters. To date the faintest object for which we have obtained fringes is 6th magnitude in K band. We expect to add several magnitudes to this by improving the coupling of the light to the camera and improving optical coatings within the beam laboratory, which so far have all been raw aluminum. This beam combiner is more fully described in Ref. 3. We are currently adding optional spatial filters to this beam combiner in order to improve it’s measurement precision.

At the time of writing this paper we are busy installing the FLUOR fiber based IR beam combiner and fully expect to have obtained fringes on the sky by the time of the meeting itself. FLUOR will use the same camera as our open air combiner, and, while it will not have the same magnitude limit, will yield a much better dynamic range and visibility precision.

While a multiple beam combiner capable of measuring phase closure in the IR bands is not a fully funded part of the CHARA Array, we are working on several new collaborations to fund and develop IR phase closure systems at CHARA which we expect to be testing on the sky in late 2003 or early 2004. In the mean time we will concentrate on bringing the remaining telescopes online and will peruse visibility amplitude science. For examples of our two-beam work to date see Refs. 9, 10, and 11.

10. VISIBLE BEAM COMBINER AND FRINGE TRACKING

The construction and testing of our visible beam combiner and fringe tracking system has been delayed due to the unfortunate two year wait for our CCD detector systems. Fortunately these detectors are now in hand.
Figure 7. The dither mirrors used to modulate the path in the open air beam combiner. We use a simple PZT stack in open loop mode. Once the hysteresis has been calibrated the devices are linear to 1 µm over the range of 100 µm.

and the relevant RT-Linux drivers are now being developed under sub-contract to Schneider Engineering (real-timekahuna@charter.net). The CCDs are 80x80 devices with four read out ports and can download the full chip in less than 5 mS with a readout noise better than 5 electrons.

We have had a two beam visible combiner for many years, but due to the lack of sensitivity of the older detector system, have never been able to try this system with star light. We will replace this detector with one of the newer CCD systems directly after this meeting and expect to obtain first visible light fringes shortly thereafter. The initial experiments will use a smaller sub-aperture but we will quickly move towards using multiple sub-apertures and a fiber based feed system. The visible fringe tracking system will allow measurements on a subset of 6 of the 15 baselines at any given time, reconfigurable using the BSS systems described above. We will start by using group delay tracking and will then move towards phase locking.

All fringe tracking to date has been envelope tracking derived from measurements of the fringe packets as we scan through them in the IR beam combiner. In the last few months we have been experimenting with a Tango/Twiss type four bin scheme for phase locking in the IR band within the open air beam combiner. This will allow us to track in either H or K band while doing science measurements using FLUOR, and/or the visible beam combiner, or alternatively, track in the red part of the visible system while doing science in H or K with the IR beam combiner. We are trying very hard not to exclude any particular beam combination or fringe tracking schemes in our beam combining system.

11. CONTROL SYSTEM

The CHARA Array control system is based on Real-time Linux (http://www.rtlinux.org) except for the delay lines developed by JPL which run under VxWorks and the FLUOR system which uses Labview. All systems are based on a client/server model using standard TCP/IP sockets for communication. The entire array can be controlled
from a single CPU (see Figure 8) which can, at least in theory, be done from anywhere on the Internet. We have of course placed our entire control system behind a firewall, but the Arrington Remote Operations Facility (AROC) has been built in Atlanta and we have, on various occasions, controlled the array from there. An example of one of the remote interfaces is given in Figure 9. A second remote facility is now being developed in Paris to allow remote operation of the FLUOR system. This will allow students and scientists on both continents to observe using the CHARA Array without the need to travel to the actual mountain top.

12. CONCLUSION

While we have much left to do, we have begun our scientific programs using the CHARA Array and continue to bring more systems online. Soon we will have all six telescopes and our choice of 15 baselines and several beam combiners. Use of the remote operation facility in Atlanta will allow the staff on the mountain to continue the development of the array while our science program gets underway and will also allow our graduate students to become involved in the Array without the need for travel. The next few years will be very exciting at the CHARA Array.

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REFERENCES

Figure 9. Example GUI interface. This is the JAVA based GUI that controls the IR two-beam combiner and scanning mirror. The hardware itself is controlled by a series of Real-Time Linux threads, which in turn are monitored by a server. This server accepts commands from a socket interface, and this is how this GUI connects to the system. There is no restriction on the number of such GUIs being run allowing control of the system from anywhere on the network.


