CHARA Recent Technology and Science

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\section*{ABSTRACT}

Georgia State University's Center for High Angular Resolution Astronomy (CHARA) operates a multi-telescope, long-baseline, optical/infrared interferometric array on Mt. Wilson, California. We present an update on the status of this facility along with a sample of preliminary results from current scientific programs.

\textbf{Keywords:} optical interferometry, infrared interferometry, telescope arrays, star diameters.

1. INTRODUCTION

This paper continues the series of technical updates on the CHARA Array\textsuperscript{1}, a long-baseline optical/near-infrared interferometric array consisting of six 1-m aperture telescopes providing a maximum baseline of 331 m and located on Mt. Wilson, California. While the emphasis within CHARA has shifted from engineering to science, we continue to be engaged in a series of upgrades aimed at enhancing reliability, stability and automation. Those improvements will be briefly described in the next section. The major remaining technical undertakings include the near-term implementation of a visible light beam combiner, a fringe tracker, and the design and fabrication of a next-generation beam combiner, a task that remains fluid while we gain more experience and guidance from current scientific activities.

CHARA’s primary emphasis during 2004 has been the conduct of an extensive and varied observing program. We are in the midst of that effort at the time of this writing but are able to present some preliminary results here.

2. TECHNICAL OVERVIEW UPDATE

2.1 Light Collecting Telescopes

As originally funded, the CHARA Array consisted of five light-collecting telescopes, one of which is shown in Figure 1. A sixth was subsequently added following a grant from the W. M. Keck Foundation. Fringes with CHARA’s “Keck Telescope” (designated as “W2” in the array) were first obtained in combination with the “S1” telescope on 15 December 2003, thus all telescopes are fully operational and have been used on the sky for scientific measurements. Fifteen possible baselines are now available for science, and ten of those baselines were employed in the spring of 2004 in a campaign involving the star Regulus (see Section 3.3).

The routine procedure we currently follow to changing baselines takes about 1 or 1.5 hours of work in the lab. The necessary preparation for switching to a new baseline includes fine-tuning the beam combiners, and phasing up the visible and IR beam combiners in case the observing project calls for it. In the fine-tuning and co-phasing, we include the optics of the beam samplers belonging to the two lines to be used. All this is done with internal light sources: a HeNe laser and a tungsten halogen lamp. Light from the internal sources is reflected back to the beam combiners by hollow corner cubes on kinematic bases. On the beam sampling tables there are kinematic bases, already aligned for each

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baseline. Some of the kinematic bases are combined with micrometer precision translation stages to allow equalizing the paths.

### 2.2 Toward Fully Remote Telescope Operations

A set of routine tasks has to be performed prior to observing on each telescope to be used on a given night. Most of these tasks are simple, like opening the dome enclosure and dust covers of different optics, but some tasks are more involved like the alignment of the coude optical train. A few years ago observers had to walk out to the telescopes and manually perform these tasks. This was not only time consuming and dangerous but wasteful of observing time. In order to use the array efficiently, it is vital to perform all of these routine tasks remotely and ultimately automatically. Our goal is that no observer has to go out to any telescope to set it up or close it down. We are not there yet but soon will be. These developments, however must not compromise the safety of the telescopes.

Since the telescopes, as delivered, were lacking in the means of remote operation, a number of sub-systems had to be developed. First the telescope enclosure and dome operation were placed under computer control. There were numerous things in the dome to be controlled so it was decided to have a resident controller on each telescope. The following main tasks were addressed: controlling dust covers over a variety of optics, environmental monitoring, optical alignment and maintenance issues.

### 2.3 The Telescope Manager (TEMA)

A microcontroller-based system (TEMA) has been developed and installed in all domes. Its purpose is to control a number of sub-systems on and around the telescopes. It accepts commands from either a remote user through the telescope computer or from a local user through a keypad and hand paddle. The remote and local operations are mutually exclusive for safety.

The local systems are under the direct control of TEMA and presently include the following subsystems: primary and M3 mirror covers, acquisition telescope mirror, acquisition camera integration and an 8-channel video multiplexer. The followings items are being built: M2 and M4 mirror covers, finder telescope cover and acquisition telescope cover.

Other tasks, like slewing the telescope or opening the dome, can be indirectly controlled form the telescope through TEMA. A user at the telescope instructs TEMA to request these operations from the telescope computer. Thereby, any task the telescope computer knows about can be initiated from the telescope. This is very convenient during telescope maintenance.

Environment monitoring in the enclosure includes the measurement of relative humidity and temperature at the primary mirror. The goal is to control the environment to protect the telescope and improve dome seeing. This analog system is an extension of TEMA. This system is prototyped and will be installed during the summer months.

Two video surveillance cameras have also been installed on each telescope. One is up looking to the dome slit while the other is down looking toward the

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**Fig 1.** Light collecting telescope W1 is shown pointing at the zenith. Features visible in this mosaic include the 1-m diameter primary, the elevation drive, the Invar rod tie-in structure between the primary and secondary mirror support assemblies. *Photo by Steve Golden*
primary mirror. The reason for these cameras is that there is no status feedback from the dome slits, and there was a
danger of leaving a dome open after a long night. Taking a look at the video screen was the easiest way to make certain
that the domes are closed. There are red LED clusters to illuminate the scene for the cameras during night. This
illumination is sufficient for the red sensitive CCD cameras and does not disturb other observations on the mountain.
The surveillance cameras, acquisition and finder cameras are connected to the video multiplexer in TEMA so that an
observer can easily select any of them.

Sometimes, audio is much more informative than video. A failing motor is not noticeable on video but very obvious on
audio. Also, microphones can listen in the dark and warn the operator about potential problems. So we plan to install
microphones in each dome as part of the analog extension of TEMA.

The every day optical alignment at the telescopes involves the tenth mirror in the optical train (M10). Our experience is
that the optical alignment of the coude train at the telescopes is stable over the course of several weeks. Unless we
switch discrete delay segments, we align only one mirror (M10) per telescope to make sure the beam properly goes
through the long pipes connecting the telescopes to the lab. This alignment is performed at the telescope and is an
example of indirect TEMA control. The operator uses the hand paddle to command a remote mirror controller. A
complete coude train alignment is performed after changing POP mirrors. Another, more comprehensive alignment tool
has been designed to perform quickly and conveniently both azimuth and elevation alignment before every observation.

We are in the process of installing small weather stations at each telescope site. The data produced by these stations will
be logged and the units will communicate with the telescope control computer in each dome. If weather conditions
deteriorate TEMA will be able to close down a telescope.

2.4 Coude Alignment Tool

A laser beam is sent out to each telescope from the central lab for alignment. The coude alignment procedure uses this
beam to properly align mirrors M10, M7, M6 and M5 in the coude train. The azimuth alignment is done first by M10
and M7 then the elevation by M6 and M5. Both beam shear and beam angle alignment are important. This is an iterative
procedure that requires the presence of two at the telescope.

To make remote coude alignment (only checking at first) possible, a new device has been designed. The device will be
mounted at the top section of a telescope and consists of the combination of a movable screen, which also serves as a
cover for M2, and a small flat mirror as well as some optics and a video camera on the side of the telescope. During
alignment, the screen is in the beam in front of M2. The central spot of the diffracted laser beam is clearly visible on the
screen. A fraction of the laser light is reflected by the flat mirror toward the relay optics. The video camera sees both the
laser spot on the screen and the image of the laser simultaneously.

On the one hand, the displacement of the laser spot on the screen is sensitive to beam shear but not angular
misalignment. On the other hand, the position of the image of the laser source is insensitive to beam shear but sensitive
to angular error. When the telescope is turned first in azimuth then in elevation, one can quickly assess the status of the
azimuth and elevation alignment by watching how the spots move. Computer programs have been written to analyze the
video so the whole procedure will take only a few minutes.

With this system in place, it is possible to do automatic coude alignment by motorizing M7, M6 and M5. This can be
easily done for the “in-house” designed M7 and M5 mirror mounts. The M6 mount is a commercial product, which
needs more substantial modifications. A prototype of such a system is being built, and the optics have been successfully
tried in the lab. Installation of the first unit is expected no later than the summer of 2004.

2.5 Vacuum Light Pipes

All six vacuum systems are now operational, and we regularly observe with the light pipes under vacuum. Although we
are still tracking down small leaks, those we have completed pump down to about 1 Torr and hold this vacuum
throughout the night. The pressure in each line, as well as the pressure in the IR camera, is monitored automatically
every five seconds and logged to a file every five minutes.
The vacuum tubes to the three arms of the array all run downhill by as much as 6°, and it was observed in 2003 that the tubes were suffering a downhill migration attributed to thermal cycling. The tubes were readjusted to their original positions and a new protocol for clamping was adopted that more effectively holds one end of each 30-ft section of tube in place while providing for expansion effects in the other end.

2.6 Path Length Delay Compensation

Path length compensation is provided for by fixed and variable delay components. The fixed delay lines, dubbed the “Pipes of Pan” or simply the “PoPs”, which are in vacuum, provide fixed increments of delay through the insertion of flat mirrors into the beam. We have completed the installation of the optics and control system for the PoPs and can now access the whole intended sky coverage of the array, which means almost full sky coverage on all baselines. The vacuum system is also fully operational, which means that the PoP system is in a 1-torr vacuum while observing.

The lower periscope mirror, which is the last mirror in vacuum before the beam enters the lab, is remotely adjustable in azimuth with an encoded motor, and in elevation with a motorized micrometer. All PoP mirrors have a small center hole, which we can remotely illuminate from the backside of the mirror with an LED, to check the alignment of the lower periscope. All PoP mirrors move remotely in or out of the beam and can be accurately tilted remotely. Details of a PoP unit are shown in Figure 2.

During an observing campaign in early 2004 for which a wide variety of baselines was desirable, we first encountered a requirement to switch PoPs relatively frequently. We are now in the trouble-shooting phase with the PoP system. There is more work to be done to minimize the time required (presently 7 or 8 hours) to change to a different PoP mirror.

In order to align the optical train with a new PoP, it turns out that we need to check the beam at another point, which is in vacuum. So now, each PoP change requires breaking the vacuum in order to be able to open the turning box and to check the alignment at the M10 mirror by manually inserting a target. A new type of target, which would be remotely put in front of M10 at the entrance of the PoP pipe when needed, is under construction. With this addition, we hope to avoid the lengthy process of opening the vacuum system for PoP mirror switching.

Fig 2. Details of a PoP “box” are shown above. The PoP mirror is shown out and in the beam in the two lower photographs. Photos by Steve Golden
To make PoP mirror switching significantly quicker and more convenient, the light should find its way through the long evacuated tube to the telescope after a new PoP was aligned to look precisely at the mirror at one end of the tube. To achieve this, we have found out that we need to line up the PoP mirrors in each line more accurately. Although fine positioning of the PoP mirrors is not facilitated by the mounting system, we hope that sufficiently accurate alignment can be achieved using the available adjustments.

A two-mirror periscope receives light from the PoP, directs it upward and out of the vacuum system to feed the continuous delay lines, known in CHARA parlance as the “optical path length equalizers” or “OPLEs”. All six OPLE lines are now fully operational and provide up to 92 m of continuous delay for each telescope while tracking with an RMS error of 10 nm. The discrete and continuous components of delay compensation are shown in Figure 3.

2.7 Beam Management Subsystems

Upon exiting the delay lines, each light beam undergoes further compression, correction for longitudinal dispersion, separation of the visible and infrared wavelength regions, and redirection to the Beam Combination Laboratory. At visible wavelengths, an air path difference greater than a few meters reduces the visibility by a significant amount. The Longitudinal Dispersion Compensators (LDCs) are used to equalize path lengths that are chromatically dephased by mismatched, non-evacuated path delay. Stationed between a Beam Reducing Telescope (BRT) and a Beam Sampling System (BSS), each LDC consists of two opposing wedges of high-density flint glass. The effective thickness is adjusted remotely via high-precision translation stages. The LDCs’ effectiveness has been proven using simulated stellar sources, but await further testing on the sky using the visible band detector. All six BRTs, LDCs and beam samplers are installed and fully operational. The S1/S2 beam management table is shown in Figure 3.

2.8 Beam Combiners

There have been few changes to the basic, pair-wise near-infrared beam combiner, called “CHARA Classic”. Experiments with spatial filtering have continued although given lower priority in favor of completing the implementation of PoP and periscope control. The FLUOR beam combiner now incorporates computer controlled
alignment systems. A visible light beam combiner is about to be tested on the sky in the I band. Fiber injectors and a fiber based output module are on order and are expected to arrive in the summer of 2004 following which we anticipate having I-band fringes.

Formal, collaborative efforts are underway with the University of Michigan (through John Monnier) and the Observatoire de Grenoble (through Jean-Phillipe Berger) for the development of a three-way infrared beam combiner and an integrated optics beam combiner, respectively, and with the University of Sydney (through Peter Tuthill) involving collaborative observing programs between the SUSI and CHARA Arrays. CHARA’s own development of a new beam combiner to succeed CHARA Classic has been deferred somewhat due to staffing realities as well as our desire to obtain more experience with science operations to provide feedback into the optimal path to take. Options include going forward with a full-up six-telescope system, or proliferation of three-way or even pair-wise systems that incorporate spatial filtering with pinholes or fibers. We are also still considering the use of adaptive optics with our light-collecting telescopes, although that is clearly a large, new and unbudgeted undertaking. For 2004, a decision was made to focus our activities on science operations, and we expect to return to the future beam combination question in 2005.

2.9 Tip/Tilt Detection

Each of the light-collecting telescopes incorporates an active secondary for tip/tilt compensation. The control signal for this system is detected in the Beam Combining Laboratory where a CCD-based detector system is now under development and will replace the photomultipliers now in use. This should add several magnitudes to our magnitude limit and allow us to track on much cooler stars.

2.10 Control System

It is probably in the area of control software where most advancement has taken place. The control system is based on a client/server model. For each subsystem there is a single server program running at all times. Small client programs, normally using the GTK-GUI library, connect to these servers. Any number of clients can be connected at any time, and it is now possible to control any subsystem from any terminal within the array control system. This includes a number of small laptops and a wireless network inside the beam-combining laboratory. Example GUI’s are shown in Figures 4 & 5.
The most important client for the observer is called the "Central Scrutinizer" which is used to sequence observations. The CS is a client of almost all systems within the facility and allows the observer to select up to two calibrators along with the object. Moving to a new target can be accomplished with a single mouse click. Besides helping with science data collection, the system also logs many aspects of array operation, including the tip/tilt errors, baseline and pointing model data, pressure in the vacuum system and a complete log of all actions taken by the observer.

![Screen Shot from Fig 4](image1.png)

**Fig 5.** A continuation of the screen shot from Fig 4. shows adjacent back and forth fringe scans.

### 3. EXAMPLE SCIENTIFIC RESULTS

#### 3.1 CHARA’s First Scheduled Observing Season

With all six telescopes operational and beam combiners available for two classes of science dependent upon moderate- or high-accuracy visibilities, observing proposals were solicited from within the CHARA team for the first scheduled season of observing covering the period March through August 2004. Science programs allocated time include such topics as the shape of rapidly rotating stars, astrometry of separate fringe packet binaries, diameters of late-type dwarfs, orbits of selected spectroscopic binaries, characteristics of young stellar objects, and stellar mass loss phenomena. We briefly describe two of these efforts now underway.

#### 3.2 Angular Diameter of the A-Supergiant Star Deneb

The brightest, nearest, and best-studied A-type supergiant is Deneb (α Cygni)\(^3\). A-type supergiants are the brightest stars at visual wavelengths (up to \(M_V \sim -9\)) and are therefore among the brightest single stars visible in galaxies. In addition, these supernovae Type-II progenitors show potential as independent distance indicators via the Wind Momentum-Luminosity Relationship\(^4\). Long-baseline interferometry together with expanding model atmospheres promise to help calibrate this relationship by providing independent mass-loss rate estimates for the closest and brightest
blue supergiants. Deneb is one of the very few blue supergiants for which we can compare several independent mass-loss rate estimates and thoroughly test the relationship.

Simulations indicate that the mass-loss rate of Deneb's stellar wind can be estimated by model atmosphere fits to precise limb-darkening measurements. The models predict that higher mass-loss rates lead to lower visibilities in the 2nd lobe of the star's visibility function. At the CHARA Array, the second lobe of Deneb's visibility function is accessible with the 331-meter S1-E1 baseline. Precise measurements in the first lobe are also required to best constrain the models. Thus far we have obtained six visibility measurements of Deneb in the first lobe in the K-band with the FLUOR beam combiner at CHARA using the E2-W2 configuration. Figure 6 shows a preliminary uniform disk fit to these data. This uniform disk angular size of $\Theta_{UD} = 2.372 \pm 0.013$ mas is consistent with that measured by the Navy Prototype Optical Interferometer (2.40 $\pm$ 0.06 mas$^3$).

Fig 6. First lobe visibility measurements of the A-type supergiant Deneb obtained by CHARA/FLUOR in the K-band in the E2-W2 configuration. The line represents a best-fit uniform disk model to these data. The fit residuals are shown below.

3.3 Shape of the Rapidly Rotating Star Regulus

Long-baseline interferometers with good (u,v)-plane coverage offer the possibility of directly measuring the shape of rotationally distorted stars$^5$, a potential which has recently been realized in the cases of Altair$^6$ and Achernar$^7$ from observations with the PTI and VLTI, respectively. The B7V star Regulus ($\alpha$ Leo) presents another opportunity to directly observe the dramatic degree of rotationally-induced oblateness expected for this star with a rotational velocity of $V\sin i \sim 330$ km/sec. The uniform disk angular diameter of the star was first measured by the Narrabri Intensity Interferometer to be $1.32 \pm 0.06$ mas$^8$ with subsequent lunar occultation observations yielding diameters of $1.32 \pm 0.12$$^9$, $1.37 \pm 0.11$$^9$, $1.46 \pm 0.37$$^{10}$, and $1.42 \pm 0.10$$^{10}$ mas.

Observations of Regulus, along with bracketing observations of a calibrator star and a check star, have been obtained on 20 nights between 10 March and 16 April 2004 with 10 of the 15 available baselines of the CHARA Array using the CHARA Classic beam combiner. The results of a preliminary reduction of these data to calibrated visibilities are shown
in Figure 7, where the top plot shows the result for the check star and the lower plots show the results for Regulus separately calibrated against the calibrator star and the check star. Inspection of these plots makes it qualitatively clear that the Regulus data cannot be fit as a simple uniform disk, in confirmation of expectation. At the time of this writing, we are proceeding with an analysis in which stellar surface intensity models incorporating rotation, limb darkening and gravity darkening will be fit against the visibilities at each of the observed (u,v) points to determine inclination of the spin axis, the orientation of this axis on the sky and the equatorial diameter of the star.

- **Fig 7.** Calibrated visibilities are shown for observations of a check star (top) and for Regulus (middle and bottom). Fits of a uniform disk are indicated with 10% error bars.
4. CONCLUDING REMARKS

Although technical developments and improvements will continue indefinitely, the CHARA Array is now a fully operational facility for high spatial resolution astrophysical studies. Currently possessing the world’s longest operational baselines, the array is now being actively and continuously utilized in observational programs that benefit from its unique capabilities.

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REFERENCES