CHARA TECHNICAL REPORT

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Telescope Specifications *(Draft)*

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1. INTRODUCTION - THE CHARA ARRAY

The CHARA (Center for High Angular Resolution Astronomy) of Georgia State University will build a facility for optical/infrared multi-telescope interferometry. This facility is called the CHARA Array. The facility will consist of seven telescopes, with evacuated pipes conducting the beams to a central laboratory. The laboratory will contain optical delay lines, beam combination optics, and detection systems. The facility will consist of these components plus the associated buildings and support equipment. The CHARA Array will be funded by the state of Georgia and the National Science Foundation, and will be located at a mountain site in the southwestern United States.

2. OVERVIEW OF THE TELESCOPE SPECIFICATIONS

The CHARA Array telescopes will be single-purpose instruments whose essential function is to feed high quality beams to fixed foci in a central beam combination laboratory. As the beams will be combined interferometrically, the outstanding requirements for the telescopes are mechanical stability and image quality. Almost all other performance characteristics can be traded against these essentials.

Achieving adequate mechanical stability will require a telescope structure and enclosure which prevent coupling of wind power into telescope motion, and a drive and control system which do not excite vibrations and which damp out oscillations caused by mechanical irregularities.

The telescopes are the most important component of the CHARA Array. Other parts of the facility can plausibly be improved and upgraded over time, but the facility will never be better than the individual telescopes.

3. NUMBER OF TELESCOPES

The CHARA Array is specified to have seven telescopes. However, for budgetary reasons two of these may be deferred. Therefore the initial contract will specify five telescopes.

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4. TELESCOPE OPTICS

The telescope optics consist of the primary and secondary mirrors, which act as a beam compressor, plus the subsequent flat mirrors required to conduct the beam to a fixed axis.

4.1. Beam Compressor

The telescope clear aperture is nominally 100 cm, although small changes can be considered in a cost tradeoff. The variation in clear aperture diameter between any two telescopes should not exceed 1 cm.

The telescopes are afocal beam compressors, with a compression ratio of 0.125. The compressed beam will thus have a nominal diameter of 12.5 cm. All telescopes will deliver the same diameter compressed beams within 0.2 cm.

The residual wavefront distortion of the output wavefront from the beam compressor portion of the telescope (that is after the primary and secondary mirrors), relative to an input plane wave and measured at 0.63 microns, shall be no greater than 1/5 wave peak to valley over 80% of the unobscured aperture, and shall be no greater than 1/4 wave over 100% of the aperture, *and* the RMS wavefront error over the full aperture shall not exceed 1/17 wave (goal 1/20 wave). This optical quality will be required over a field of view of 3 arcmin.

The secondary mirror will have a central hole slightly smaller than the central obscuration. A glass corner cube (choice to be approved by CHARA) will be permanently located in or behind this hole to provide retroreflection of an on-axis alignment or metrology laser beam.

4.2. Flat Mirrors

The additional mirrors required to conduct the beam to the fixed beam axis will each introduce wavefront errors of less than 1/20 wave peak to valley.

4.3. Optical Coatings

The optics shall be delivered with conventional evaporated aluminum coatings. However, high performance silver coatings are planned for future use and the selection of optical materials and the handling of the optics (chemical treatments, etc) shall not compromise this option.

4.4. Optics Fabrication

CHARA will welcome bids from vendors who are interested in providing both optics and telescope. In this case, the vendor is responsible for allocation of the optical error budget between glass and mount.

CHARA also welcomes bids from vendors who wish to propose for the telescope but not for the optics. In this case the vendor should plan for zerodur primaries and secondaries, each with an optical quality 2× better than the specification.

Other optical materials can be considered following vendor selection subject to negotiation between CHARA and the vendor.

4.5. Mirror Cell

The cell design must include a safe method for mounting the mirror in the cell and removing it from the cell. Any special hardware for mirror handling should be provided. A mirror cover will be required which can be remotely actuated.

4.6. Adaptive Optics

This section is for background information only, as the adaptive beam correction is not included in this procurement. It does impact the enclosure and pedestal requirements, as discussed below.

In order to use the telescopes for interferometry, it is necessary to introduce fast guiding, often called tilt correction because it removes the tilt component of the atmospheric wavefront distortion. For technical reasons it is necessary to introduce the tilt correction near the telescope.

The tilt correction will employ detectors in the beam combination laboratory which will provide rapidly updated information about the star position. This information will be used to stabilize the star position. It will be necessary to have a correction bandwidth of at least 10 Hz (goal 40 Hz). The range of tilt required is approximately 2 arcseconds on the sky.

Rapid tilt correction will be part of the baseline CHARA Array facility, but is not part of the telescope specification. Rapid tilt correction will be implemented by CHARA after the telescopes have been accepted.

Higher order adaptive optics may be implemented at a future time. This development is not part of the baseline plan and is not currently funded.

5. TELESCOPE FOCUS

Telescope focus stability is very important to the beam optical quality. The telescope structure shall be be self-compensating for thermally induced changes. The telescope optics shall meet the optical quality specifications (after thermal stabilization but without refocus) for a temperature drift of 5° C (goal 15° C). (For reference, with f/2.5 confocal paraboloidal optics, in order to maintain a peak to valley focus induced wavefront error less than 0.06 waves, the actual focus drift must be less than 2 μm).

The mechanical focus shall allow remote actuation by computer control. The focus will be encoded with a precision of 1 μm. The focus motor will have fast, slow and step motions (rates to be approved by CHARA), with the smallest step no greater than 1 μm.

6. VIGNETTING

The telescope aperture diameter will be defined by the edge of the primary mirror, or optionally by a mask at the circumference of the optically useful aperture. The secondary and subsequent optics shall be oversize by 10% to avoid further vignetting of the beam.

The central obscuration shall be defined by the central hole in the primary, or by the projected diameter of the third mirror (depending on the telescope configuration), and shall be 10% greater than the expected beam diameter for an afocal beam of zero field of view. Thus the secondary mounting and focus mechanisms must be contained within a similar diameter (hidden behind the central obscuration).

7. SKY COVERAGE

The telescopes will operate over all azimuths and over zenith distance of 0.5 – 88 degrees. Some vignetting by the enclosure may be allowed for zenith distances greater than 65° .

The optical specifications will be relaxed by 1.1× for zenith angles greater than 40° and by 1.3× for zenith angles greater than 60° .

The pointing specifications will be relaxed by 1.5× for zenith distances greater than 65° .

8. MOUNT AND DRIVES

The telescope mount type is not specified, as both alt-az and equatorial solutions are possible. Only one "instrument position" is required - a Coudé. This beam position (fixed relative to the Earth) will allow the afocal beam to propagate along a fixed path to the central laboratory. Field and pupil rotation are acceptable. We expect that this fixed beam will be achieved by directing the afocal beam along an axis of the telescope mount.

Some errors in the mount structure which would be undetectable in normal use will be revealed in interferometric operation by a spurious displacement of the interference pattern. As with pointing, this can be modeled provided it is repeatable and is small enough that second-order effects are negligible. The two axes of the mount must be orthogonal to within 1 arcminute (goal 20 arcseconds). The axes must intersect to within 100 μm. The total runout of the bearings must not exceed 100 μm.

As the telescopes will be exposed to an outdoor environment during operation, the bearings should have a combination of physical protection and maintenance schedule which ensures continued performance of the bearings within specifications.

The mount shall incorporate limit switches at the limit of travel for each axis. The available travel beyond the sensors will suffice to allow the motors to come to a stop. Bumpers will be provided to protect the mount in the event of failure of the limit switches.

Position sensors will be provided for both axes in the stow position. If the stow position is at a zenith distance greater than 45° , position sensors will also be provided for a position near the zenith.

The backlash of the drives shall be less than 0.3 arcsecond in both axes. This requirement shall apply over the temperature range 0° C to 15° C (goal 0.2 arcsecond over -5° C to 20° C).

The mount motion resolution must be 0.02 arcsecond or better. That is, the smallest incremental step of the motor should correspond to this motion at the mount axis.

9. TELESCOPE CONTROL SYSTEMS

The telescopes will be controlled from standard commercial computer systems. The software will permit local control (a terminal in the dome), remote control from a terminal at a distance of at least 300 m (via serial line or other standard interconnection), and remote software control via terminal emulation or other standard protocol.

Each telescope will also have a conventional "hand-paddle" type of control for slew, guide and focus.

Remote actuation should be supplied for the following: startup operations, including mirror cover opening, enclosure opening, enclosure rotation and tracking (if required); normal telescope operation; closedown operations, including return of telescope to stow position, closure of mirror cover and enclosure, and power down.

The telescope control system should reset automatically to a reasonable and documented configuration after a power failure.

The telescope control system should provide the following operations: reset of telescope encoders at a home position; slew, acquire and track, with tracking at sidereal rate or at non-sidereal rates required for solar system objects (observer specified); guiding (tracking correction) at several speeds (to be approved by CHARA); drift rates (scanning at a defined direction and rate relative to the nominal track vector).

10. POINTING AND TRACKING

Computer directed pointing will have an error no greater than 5 arcsecond RMS.

Under computer control, when commanded to point to new coordinates, the telescopes will acquire a new position at a distance of 1° within 20 seconds, and will acquire a new position at a distance of 60° within 3 minutes (goal 2 minutes).

Under computer control (closed loop tracking with reference to the encoders and telescope model, but without feedback from the observed star position), the telescopes will track with a peak error no greater than 0.1 arcsecond in one minute and with a tracking jitter not exceeding 0.02 arcsecond peak to peak. The tracking jitter in the presence of wind (from any direction) may be increased as follows: for 10 mph wind, to 0.05 arcsecond; for 20 mph wind, to 0.1 arcsecond; for 30 mph wind, to 0.2 arcsecond.

11. OPTICAL PATH VARIATION

The most insidious wavefront disturbance for interferometry is the erratic variation of the optical path. The telescope can contribute to this through vibration of the whole or of its parts. The mapping of telescope vibration to optical path change can be derived from an opto-mechanical model. Generally, variation of the separations between optical elements are the most serious, while whole telescope motions are less serious.

The criterion for telescope induced optical path variations is set by the characteristic optical path differences through the atmosphere for typical conditions. From Tango and Twiss (1980), the power spectrum of the optical phase variations in rad^2/Hz introduced by the atmosphere may be represented by,

$$W(f) = 0.157(\frac{v_t}{r_\circ(\lambda)})^{\frac{5}{3}} f^{-\frac{8}{3}} \tag{1}$$

where v_t is the transverse wind velocity, f is the frequency, and $r_\circ(\lambda)$ is the Fried parameter at the wavelength of interest.

This can be rewritten in terms of $r_\circ$ at the standard wavelength of $0.5\,\mu$m, and describing the variation of optical path in units of μm^2/Hz (which is independent of wavelength),

$$W(f) = 0.0040(v_t/r_\circ)^{\frac{5}{3}} f^{-\frac{8}{3}} \tag{2}$$

The integral of this power diverges at zero frequency, but in practice frequencies lower than about 1 Hz will be corrected by active fringe tracking.

For typical good conditions, $v_t = 5$ m/sec and $r_\circ = 0.2$ m, the power spectrum is,

$$W(f) = 0.85 f^{-\frac{8}{3}} \mu m^2 \tag{3}$$

This result can be compared to fringe position power spectra (difference between two telescopes separated by 12 m) in Colavita and Shao (1987), showing a power at 1 Hz of approximately $1\,\mu m^2/Hz$.

The integral of this power from 1 Hz to infinity (with a factor of two to include negative frequencies) is, $1\,\mu m^2$, corresponding to peak to peak path fluctuations of about $3\,\mu m$.

This then is the approach to specifying the stability of the telescope. It should not introduce optical path variations which exceed the envelope of the power spectrum $W(f)$.

For comparison with this requirement, laser interferometer measurements by Bourlon et al (1991) of a number of telescopes at La Silla show power spectral densities at 1 Hz in the range $0.01 - 1\,\mu$m^2/Hz, indicating that the requirement is in the range of conventional telescope fabrication practices.

12. ENVIRONMENTAL FACTORS

The telescopes must be designed and constructed to withstand normal conditions and hazards associated with mountain top observatories in the southwest U.S.

12.1. Range of Storage Conditions

The telescopes will be installed and operated at a mountain site in the southwestern United States, at an altitude of 6000 – 8000 feet. Telescopes will be subject to temperature extremes in the range -15° C to +35° C. Winds may be as high as 70 mph (sustained) and 120 mph (gusts).

Additional environmental hazards include frequent, heavy thunderstorms with abundant lightning; relative humidity up to 100%; infrequent but possibly heavy snowfall; irregular power and occasional power failures; assault by squirrels, mice and other small animals; seasonally, large numbers of insects of various types.

The telescopes, as shipped, shall have a storage life under these conditions of at least 60 days.

The telescopes as installed in the enclosures shall withstand these hazards while in a normal closed configuration.

12.2. Range of Operating Conditions

Facility operations will be limited to temperatures in the range -10° C to +25° C, winds no greater than 30 mph sustained (45 mph gusts), humidity no greater than 90% (non-condensing).

13. ENCLOSURE REQUIREMENTS

In order to achieve the required beam quality, we expect that it will be necessary to cool the enclosures and telescopes during the day to temperatures near the expected nighttime temperature. In order to facilitate this, the telescopes will provide access ports for circulation of conditioned air. However, the system to cool and circulate air is not included in the requirements.

It will be necessary to minimize dumping of heat into the telescope enclosure. Power loads in excess of 50 watts (average total) must be isolated from the telescope, for example in a separately ventilated compartment.

The telescope enclosure may play an important role in protecting the telescope from wind induced vibrations. The dome footings will be isolated and physically separated from the telescope pedestal, in order to minimize mechanical coupling between them.

The thermal response of the enclosure must be short. A combination of low mass, low heat capacity materials, insulation and radiation barriers will be used to ensure that the thermal time constant will be no greater than 30 minutes.

The enclosure will open sufficiently to allow thorough ventilation by natural local air flow. The enclosure air should be renewed at least every 5 minutes with 5 mph winds from any direction.

The opening and closing of the telescopes must be remotely controlled. The functions which must be remoted include: dome aperture; the primary and other mirror covers; any enclosure ventilation louvers.

The CHARA Array site is expected to have good seeing above a boundary layer whose height is not currently known. It may be advantageous to raise the telescopes a few meters above the ground. Raising the enclosures above the ground would also enable airflow under the enclosures, reducing the thermal time constant. A concept incorporating elevation of the telescopes and enclosures at moderate cost will be considered a strong point of any proposal.

13.1. Space Requirements

As the CHARA telescopes will not be general purpose telescopes, the enclosures can be relatively compact. There will be no observer presence during normal operation, no conventional instrument package, no instrument changes, and no requirement for storage space in the enclosure.

The enclosure must provide sufficient space for technician access to carry out maintenance with the enclosure closed (ie weather tight). It is acceptable to require opening of the enclosure to facilitate mirror removal and installation.

In expectation that the fixed beam will exit the mount parallel to the azimuth or declination axis, the pedestal must provide space and access for installation of a mirror to bring the beam out of the pedestal into a small instrument space which will house tilt correction and (eventually perhaps) adaptive optics.

14. PORTABILITY

The CHARA plan calls for telescopes which can be relocated among several locations over distances of several hundred meters. In the simplified plan, portability of telescopes is deferred. In order to ensure that portability can be achieved in the future, several requirements are added for the telescopes.

The portability concept would entail duplicating the enclosures and pedestals, and moving the telescopes, mounts and control electronics. Therefore, the telescopes should separate conveniently from the mount. The mount should be located on the pedestal with a kinematic type interface. The mount and the mount+telescope center of gravity should be within the footprint of the kinematic support points for all telescope positions.

The axis adjustments should be made in the pedestal hardware so that when moved the telescopes achieve proper alignment kinematically on each pedestal. The electronics should be packaged for convenient transportation - ie, easily accessible connectors and only one or a minimum number of electronics racks.

15. RELIABILITY AND LIFETIME

Each telescope must have an expected Mean Time Between Failure of at least 2000 operating hours, with a goal of 4000 operating hours. This should be documented with manufacturers' MTBF ratings for moving parts and electronics modules and any high failure rate components.

A list of recommended spare parts will be provided, based on estimated MTBF and current and projected future availability.

The design lifetime of the telescopes should be 20 years of nightly use. Specifically, replacement of main bearings, optical support mechanisms or focus mechanisms should not be expected over the lifetime.

16. DOCUMENTATION

The vendor will supply user and engineering documentation. The user documentation (one set for each telescope) will contain instructions for the operation of the telescope from a local (in dome) terminal.

The engineering documentation (two sets) will include "as built" mechanical layouts and mechanical interfaces, and complete identification of all replaceable components or units, "as built" drawings of all electronics, and wire and timing diagrams (as appropriate) of all electrical and electronic interfaces. It will also include results of any modeling or simulations used in verifying the design.

A maintenance schedule will be provided, and all installation, alignment and maintenance procedures will be documented.

Electronic versions of documentation will be provided if available.

CHARA prefers to have source code for the telescope control software to facilitate maintenance and trouble shooting.

17. SCHEDULE FOR INTERACTION BETWEEN CHARA AND THE VENDOR

It is expected that there will be routine telephone contact between the vendor and CHARA. CHARA may also engage an engineering consultant to participate in discussions and design decisions.

The following specific meetings are planned: kickoff meeting, preliminary design review, critical design review, preliminary acceptance review of the first telescope, and installation visit. All except the installation visit will take place at the vendor's facility. The installation visit will take place at an as yet undetermined site within the southwestern U.S.

Vendor will be responsible for travel costs incurred by the vendors employees, and CHARA will be responsible for travel by CHARA staff.

18. VENDOR OPTIONS

A potential vendor may choose to quote on a complete telescope package to include mount, control system and optics. Alternatively, CHARA will accept bids for mounts with drive motors and controllers provided by the vendor but without software and computer control systems and without optics. A third option is mounts with drives and control system but without optics. For the second and third options, CHARA accepts responsibility for integration of control system and/or optics.

The telescope enclosure specifications are also included in this document for completeness. Vendors are welcome to bid on the enclosures as well, but CHARA recognizes that most vendors of telescope will not be interested in this part of the package.

19. DELIVERY

It is possible that the first telescope will be completed before the site is available. Therefore it will probably be installed temporarily at a site to be determined for acceptance testing. Subsequent telescopes may be similarly staged to a temporary location. Owing to the uncertainty of destination, shipping costs will be the responsibility of CHARA. Packing and other preparation for shipping will be the responsibility of the vendor.

20. ACCEPTANCE TESTING

Some of the specifications of the telescopes are difficult to check in operation. An example is the performance under wind loading. Therefore, some specifications will be verified by design. These are indicated in the accompanying summary table of specifications. Verification by design will be carried out during the design phase of the project. The vendor will provide design recommendations to meet these specifications for approval by CHARA.

Some of the specifications are readily verifiable in the shop, or are of such importance that special effort is justified to confirm adherence. Specifications requiring verification by test are also noted in the accompanying summary. In carrying out these tests, the vendor may propose a testing procedure for approval by CHARA, or may request assistance from CHARA in designing and carrying out the tests.

The most important of these tests are for low vibration of the telescope while tracking (requiring testing with a laser interferometer) and the integrated optical performance (requiring testing on a star). Both of these tests will require special test equipment. CHARA will provide the equipment and assist in carrying out the tests on request by the vendor.

After the vendor has been selected, CHARA and the vendor will negotiate the suite of tests.

Some of the tests will be carried out in the vendor's shop. CHARA may participate in or even carry out some of these tests. After these tests have been passed satisfactorily, one telescope unit with mount and optics will be be delivered to CHARA for further testing. After CHARA has about 60 days to check out the mount, the vendor will travel to the telescope location for a week to demonstrate the various alignment, installation and maintenance procedures. If the required specifications are not met at the CHARA site, the vendor will work with CHARA in good faith to try to fix the problem while staying within the contract budget. If it is deemed necessary to return the telescope to the vendor, CHARA will pay for transportation both ways. The vendor will have 90 days to make any required modifications and ship the telescope back to CHARA.

Any required last minute changes shall then be incorporated into the remaining telescopes and the vendor shall provide updates for any documentation that has changed.

21. QUALITY AND WARRANTY

The design and construction efforts must be consistent with good design and shop practices, as appropriate for a state-of-the-art scientific instrument. The vendor must design the telescopes to meet the specification goals as well as the required specifications. CHARA will engage in a dialogue with the vendor concerning the vendors design, with the understanding that the vendor will undertake the construction and assembly of the telescopes in the expectation that the required specifications and goals will be met. At delivery, the vendor will be responsible for a telescope which meets the required specifications.

22. PRICING AND PAYMENT

The CHARA Array project is on a fixed and very limited budget, and the telescope contract will be fixed cost. The number of telescopes purchased may depend on cost and possible additional funding, so vendors should bid on quantities of five and seven.

It is expected that the telescope work will proceed in phases, with progress payments to be made at the approved completion of each phase. The details will be negotiated after the vendor has been selected.

23. SUMMARY OF REQUIREMENTS, GOALS AND VERIFICATION

This table summarizes the requirements and goals described in the previous sections. This table is only an overview of the specifications described in detail above. In case of differences, the foregoing discription of the specifications shall take precedence over the contents of this table.

The intended verification of specifications is also noted.

TABLE 1. Summary of Requirements

Parameter	Requirement	Goal	Test
Primary aperture	100 ± 0.5 cm		
Afocal beam diameter	12.5 ± 0.2 cm		
Beam compressor wavefront error	1/5 wave ptv	1/6 wave ptv	On sky test
Flat mirrors	1/20 wave ptv	1/30 wave ptv	Vendor test
Focus temperature compensation	5° C range	15° C range	Design
Focus encoding	1 μm		Vendor test
Orthogonality of axes	1 arcmin	20 arcsec	Vendor test
Intersection of axes	100 μm		Vendor test
Bearing runout	100 μm		Vendor test
Backlash at axes	0.3 arcsec	0.2 arcsec	Vendor test
Motion resolution	0.02 arcsec		Vendor test
Absolute pointing	5 arcseconds RMS		On sky test
Acquisition speed	1° in 20 seconds		Vendor test
	60° in 3 minutes		Vendor test
Tracking accuracy	0.1 arcsec in 1 minute		On sky test
Tracking jitter	0.02 arcsec ptp		Vender test
Optical path variation	3 μm ptp $\geq$ 1 Hz	1 μ m ptp $\geq$1 Hz	CHARA test
Enclosure time constant	30 minutes		Design
Enclosure air renewal	5 minutes (5 mph wind)		Design
Reliability (MTBF)	$\geq$ 2000 hours	$\geq$ 4000 hours	Design
Lifetime	20 years		Design

24. REFERENCES

Bourlon, P., Ducros, T., & Faucherre, M. 1991, "Results of Vibration Measurements on La Silla Telescopes", in *High-Resolution Imaging by Interferometry*, ed. J.M. Beckers and F. Merkle (ESO, Garching), 1215-1225

Tango, W.J. & Twiss, R.Q. 1980, "Michelson Stellar Interferometry", in *Progress in Optics* **XVII**, 239-277