# CHARA TECHNICAL REPORT

No. 110 2018 May 3

# CHARA Futures Meeting

D. R. Gies, T. A. ten Brummelaar & G. H. Schaefer

**ABSTRACT:** This is a summary report of a special CHARA Futures Meeting that was held at Mount Wilson Observatory on 2017 September 22. The goal was to consider ways forward for new developments at the CHARA Array that will support the science vision of the next decade in high angular resolution stellar astrophysics. We discussed options for new telescopes and what limitations exist within the topography of the site and the use of the existing OPLE and BCL buildings. We present here several "strawman" concepts in order to promote and focus discussion about the best options for future growth.

## 1. INTRODUCTION

The CHARA Array was built through a series of fortunate circumstances and unwaivering perseverance by the CHARA team under the leadership of Professor Hal McAlister (see the trio of papers by McAlister et al., Ridgway et al., and ten Brummelaar et al. 2014, SPIE, 9146, 91460D-F). The current configuration of the Array was the result of the fiscal and logistical limitations at the time of construction, but the design included options for future growth. We are now entering year 15 of routine scientific operations with the Array, and Array has grown in capability through the introduction of new beam combiners and improvements in alignment and observing protocols. We are currently in the midst of two very significant new initiatives of installing adaptive optics and opening the facility and its archive to the wider community. While these tasks are making new and extraordinary demands on the CHARA staff, it is important to pause and look ahead to what the CHARA Array might become in the decade of the 2020s.

This was the goal of a meeting of the CHARA staff that took place in 2017 September at the CHARA Array at Mount Wilson Observatory. The concept was to consider our strengths and develop ideas about how we might build on these strengths rather than make plans for an entirely new array. Thus, we gave much consideration to reviewing the limitations imposed by the

[*] Center for High Angular Resolution Astronomy, Georgia State University, P. O. Box 5060, Atlanta, GA 30302-5060, USA.; Tel: (404) 413-6021; website: www.chara.gsu.edu

topography of the site, the current layout of the optical light pipes, the space available in the OPLE and BCL buildings, and operational methods. This report summarizes presentations and discussions led by different staff members and offers several specific models for new facilities. These concepts will help spur discussion among members of the CHARA collaboration and beyond in order to develop a plan that will benefit the entire CHARA community and meet the requirements for the scientific journey of the next decade.

## 2. PARTICIPANTS

Matthew Anderson, CHARA/MWO
Fabien Baron, CHARA/GSU
Theo ten Brummelaar, CHARA/MWO
Christopher Farrington, CHARA/MWO
Douglas Gies, CHARA/GSU
Robert Klement, CHJARA/MWO
Hal McAlister, CHARA/GSU
John Monnier, University of Michigan
Alicia Rice, CHARA/GSU
Steve Ridgway, NOAO
Gail Schaefer, CHARA/MWO
Judit Sturmann, CHARA/MWO
Laszlo Sturmann, CHARA/MWO
Nils Turner, CHARA/MWO
Norm Vargas, CHARA/MWO
Larry Webster, CHARA/MWO
Russel White, CHARA/GSU
Craig Woods, CHARA/MWO


FIG. 1 - Participants from left to right: Steve Ridgway, Gail Schaefer, Doug Gies, Judit Sturmann, John Monnier, Craig Woods, Theo ten Brummelaar, Nils Turner, Alicia Rice, Chris Farrington, Larry Webster, Laszlo Sturmann, Matt Anderson, Robert Klement, Hal McAlister, and Norm Vargas. Remote participants: Fabien Baron, Russel White.

## 3. SCIENTIFIC GOALS [Schaefer]

The work of the CHARA Array over the last decade has focused in large part on *fundamental stellar properties* such as radius, temperature, and mass. In recent years pioneering studies have launched the field of stellar imaging, and the CHARA Array is ideally suited to this work because of the number and size of its baselines. These early successes demonstrate the unique power of the Array to map stellar surfaces and show how much more could be done with an expanded Array. The next decades of CHARA observations will see more and more emphasis on *stellar processes* (magnetism, pulsation, mass loss, etc.) that are key to understanding stellar evolution and the Sun's properties in the context of Sun-like stars. Below we outline several areas of critical importance in stellar astrophysics for future investigations with the Array. A comprehensive outline of planned future work in long baseline interferometry from a European perspective is presented in a report by Pott & Surdej (2016)[1].

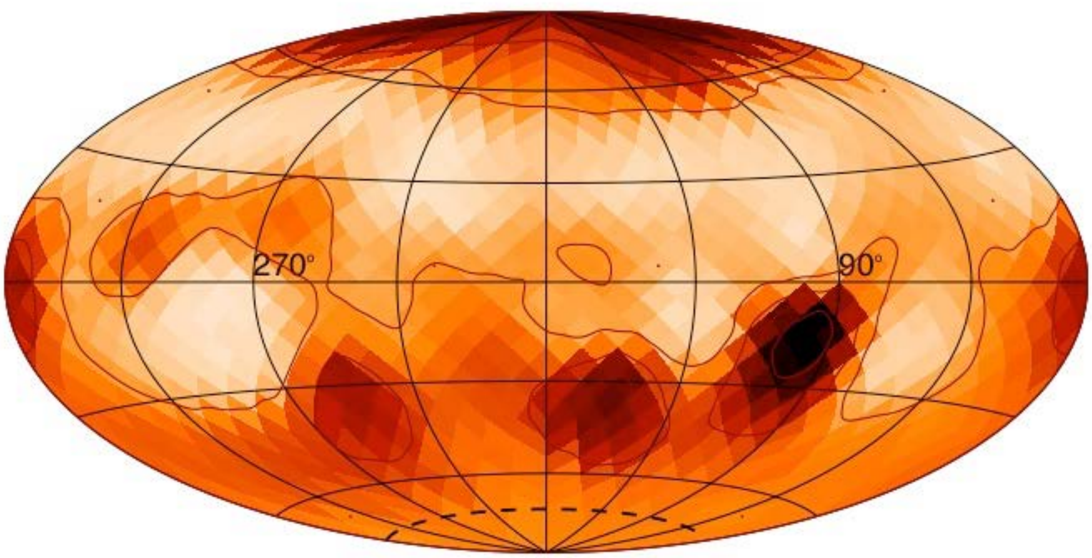


FIG. 2 - Projected map of the starspot distribution on the surface of the giant star Zeta Andromedae (Roettenbacher et al. 2016, Nature, 533, 217). This represents the first direct map of starspots on a star other than the Sun.

[1] https://docs.google.com/a/european-interferometry.eu/viewer?a=v&pid=sites&srcid=ZXVyb3BlYW4taW50ZXJmZXJvbWV0cnkuZXV8aG9tZXxneDoxM2YwNjY5MjJmYTM2Mjc3

**Surfaces of stars:**

- Mapping starspots on a diverse sample of stars to study stellar magnetism properties and cycles in order to make the "solar-stellar connection" to understand the Sun's long-term magnetic dynamo and its influence on Earth.
- Investigating nonradial pulsations of stars to identify modes in a fundamentally new way.
- Study the granulation and atmospheric convection of evolved supergiants and other stars.
- Explore differential rotation and its connection to magnetic dynamos.
- Map the limb and gravity darkening of stars to determine their deep atmospheric structure and energy outflow.

**Exoplanet host stars:**

- Determine the fundamental parameters and habitable zones of host stars that will be discovered by the NASA TESS and ESA PLATO missions.
- Image hot Jupiters directly and in transit.
- Detect exoplanets through astrometric perturbations of binary stars.

**Circumstellar disks and outflows:**

- Map the disks surrounding young stars to investigate sites of planet formation.
- Map the outflowing gas in evolved luminous stars and in rapidly rotating massive stars.
- Explore the mass transfer and mass loss processes in interacting binary systems.

**Massive Stars:**

- Resolve the angular diameters and binary properties of massive stars in the Cyg OB2 supercluster, the nearest example of massive star formation and the progenitors of stellar mass black holes.

**Active Galactic Nuclei:**

- Resolve the geometry and physical properties of the dusty torus regions surrounding supermassive black holes.

## 4. REQUIREMENTS AND STELLAR SAMPLES [Schaefer]

The key targets in the work of the future will tend to be smaller and fainter than those observed in the past. Furthermore, mapping stellar surfaces in detail will require very long baselines in order to sample fringes in the second and higher lobes where the visibility is lower and higher S/N is required (see the simulations by Chiavassa et al. 2014, A&A, 567, A115). We need to consider additions to the Array that will provide for:

- higher angular resolution (longer baselines, shorter wavelengths)
- improved imaging (increased *(u,v)* coverage and baselines)
- fainter targets (larger apertures, higher efficiency optics)

The ability of the Array to work both in the optical and near-IR is especially critical for future applications that will need near-IR for science observations of circumstellar disks and the optical band for high spatial frequencies and better starspot contrast.

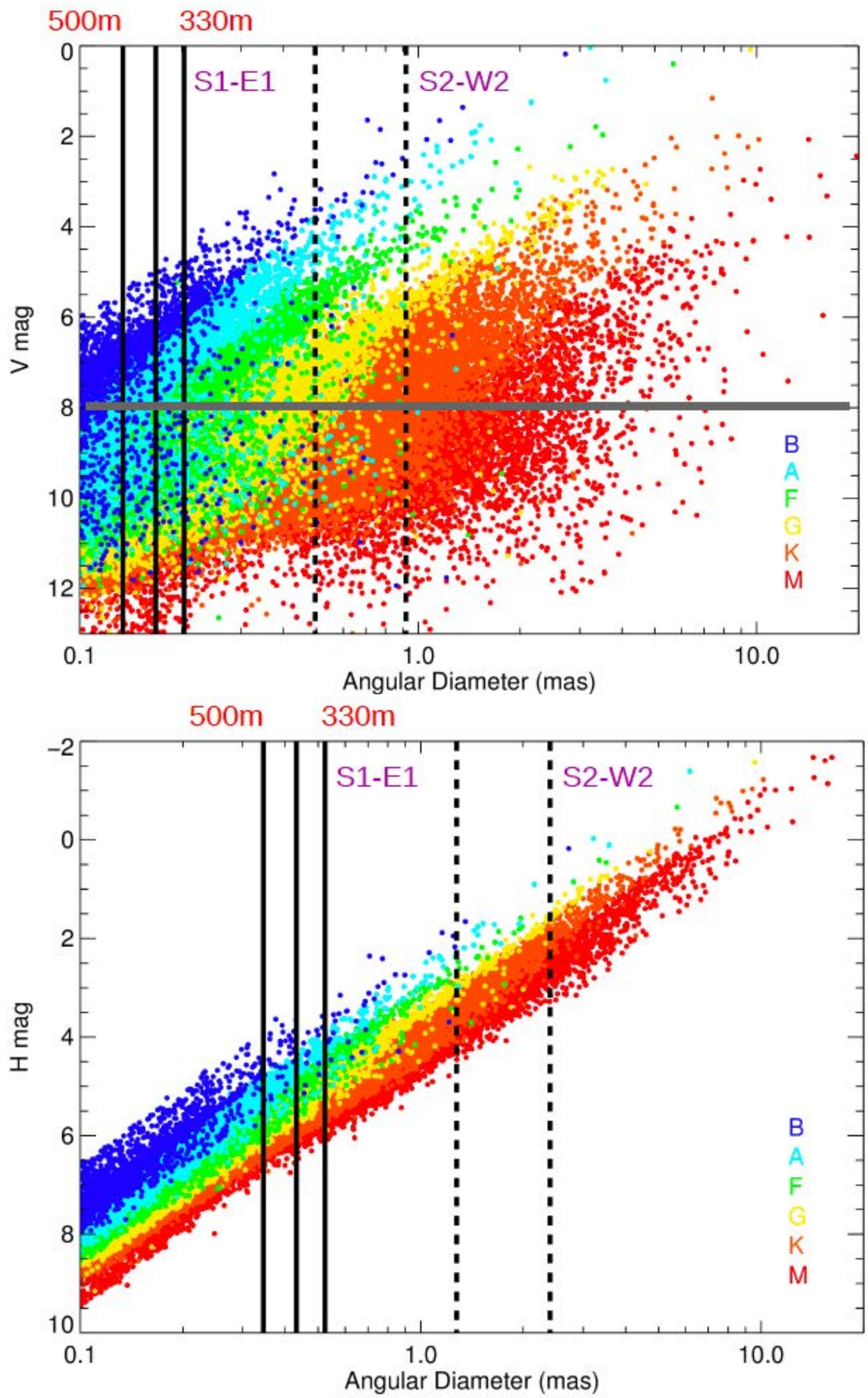


FIG. 3 - The plots above show the samples of stars available for observation as a function of angular diameter, apparent magnitude, and spectral classification for stars with declination > -20 deg (from the JMMC Stellar Diameter Catalogue). The solid vertical lines show the limit of smallest resolvable angular size for baselines of 500, 400, and 330 m (left to right, respectively).

Figure 3 shows the available samples of stars that are resolvable with current baselines and larger potential baselines. In the *V*-band (top), using longer baseline and/or observing fainter targets than the current *V*=8 limit will greatly increase the number of targets available for measurement. Note that the increase in sample size with baseline is particularly striking for the hot O- and B-type stars. In *H*-band (lower plot), longer baselines increase the available sample irrespective of magnitude (all the potential sample stars are brighter than the limit of *H*=8). The near-IR sample almost doubles to 36,000 stars for a baseline of 500 m compared to 330 m, the current largest baseline.

Stellar surface imaging will require longer baselines to obtain higher spatial frequencies that sample the second and higher fringe visibility lobes. The visibility is lower in these lobes, so the fringe measurements are more difficult (except for brighter targets with higher fluxes or for telescopes with larger apertures that deliver higher flux). One promising approach is to use the shorter baseline pairs to sample the first fringe lobe that is brighter and easier to track, while the longer baselines sample the second and higher lobes (baseline bootstrapping). The vertical dashed lines in Figure 3 delimit the current "good imaging" zone where an object is large enough that the long baselines record the second and higher lobes (left line) and where the object is not so large that S2-W2 remains in the main lobe (right line). Adding longer baselines would enlarge this zone to smaller size while adding shorter baselines would permit mapping of larger stars that are currently over-resolved. Observing in the IR for short baseline fringe tracking would facilitate science observations at long baselines in the optical band. These considerations also apply generally to observations of circumstellar disks and outflows and AGN cores.

## 5. MOUNT WILSON TELESCOPE SITES [Gies, Webster]

The goals of greater resolving power and more (*u,v*) coverage will probably require adding additional telescopes to the CHARA Array. This is a significant challenge given the terrain at Mount Wilson and the layout of existing buildings. Connecting telescopes by light pipes as currently done presents the most difficulties, because it requires a direct line of sight from telescope to the OPLE building. On the other hand, there are many more options for situating outlying telescopes connected by fiber optics. Here we focus on locations that would use light pipes in keeping with current operations.

Figure 4 shows a topographic map of Mount Wilson Observatory and its immediate vicinity. The Observatory is built around an east-west ridge line connected to a shorter north ridge. The arms of the CHARA Array were built to fit around the dome of the 100-inch telescope and to place a Y-configuration into the available space. The terrain has a very sharp descent to the east and south of the Observatory grounds, so the regions to the west and north offer the best options for future telescope sites. The dashed lines in Figure 4 show two options of potential interest.

The first is a sight line from the OPLE building to the northwest where there is a ridge line along an eastern-facing cliff. According to Larry Webster this site had been considered by G. E. Hale as a possible location for the 60-inch telescope. Figure 5 shows a Google Earth map of the sight line together with an elevation map that shows a telescope placed near or above ground level would have a clear view to the west end of the OPLE building. This arm would be about 500 m in length, and it would form a 660 m baseline with S1 (590 m to E1).

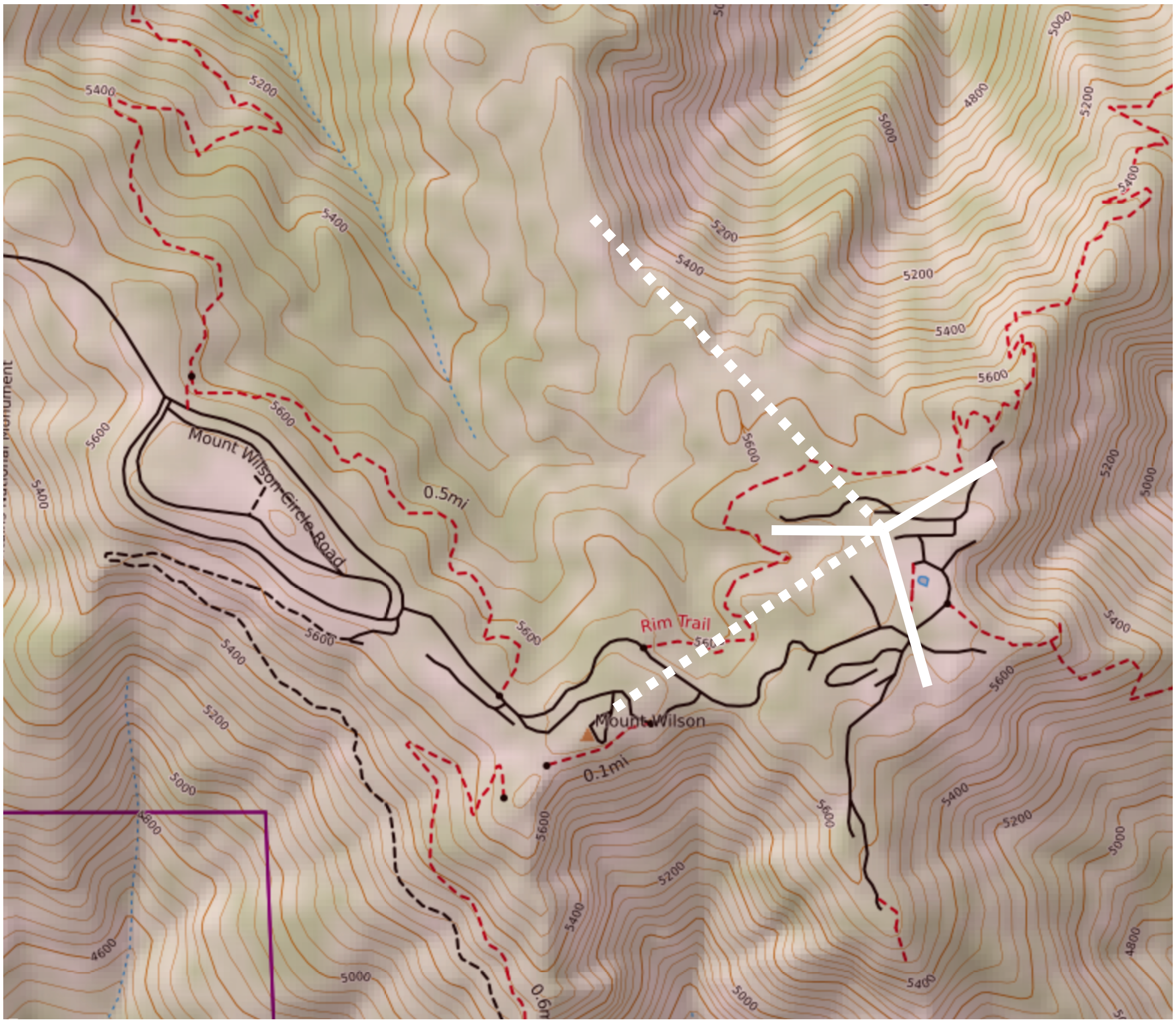


FIG. 4 – Topographic map of the Mount Wilson Observatory and vicinity (from caltopo.com). The solid white lines show the approximate locations of the three arms of the current Array. The dashed lines show two possible sites for additional telescopes.

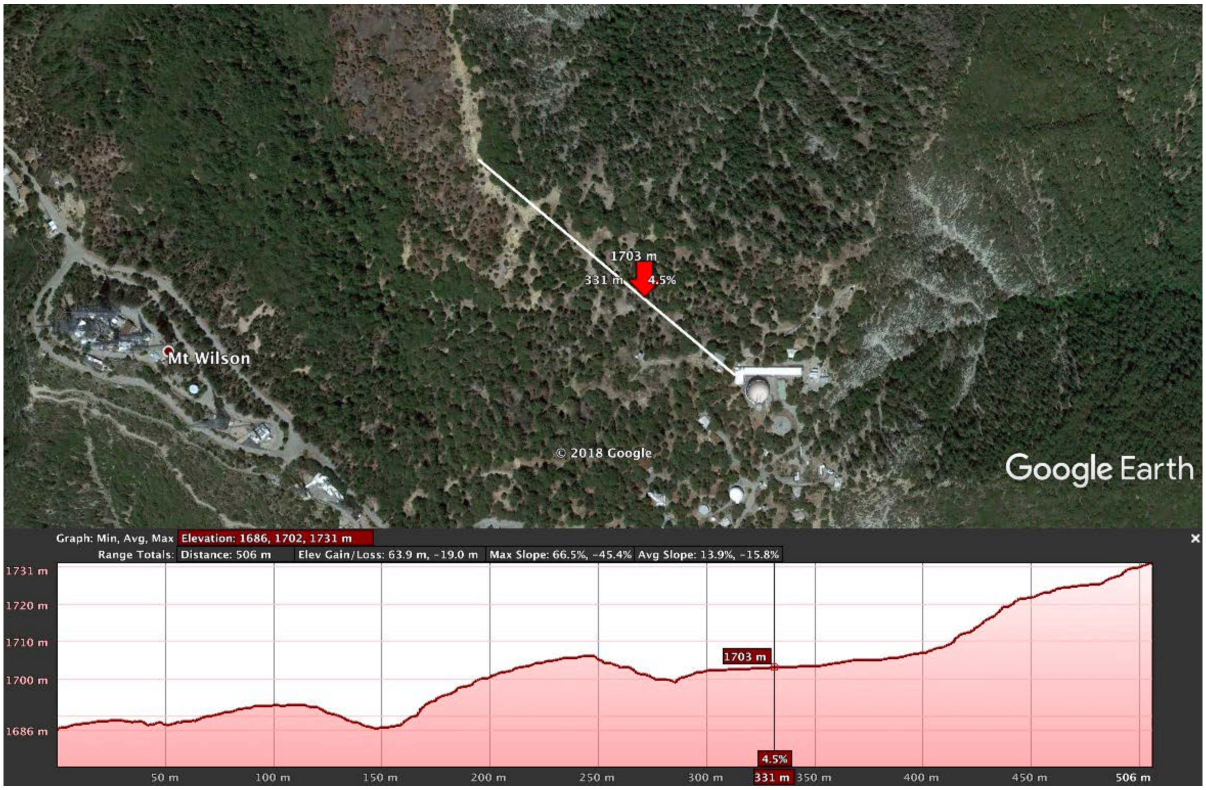

FIG. 5 – Map of the sight line to northwest ridge (Google Earth).

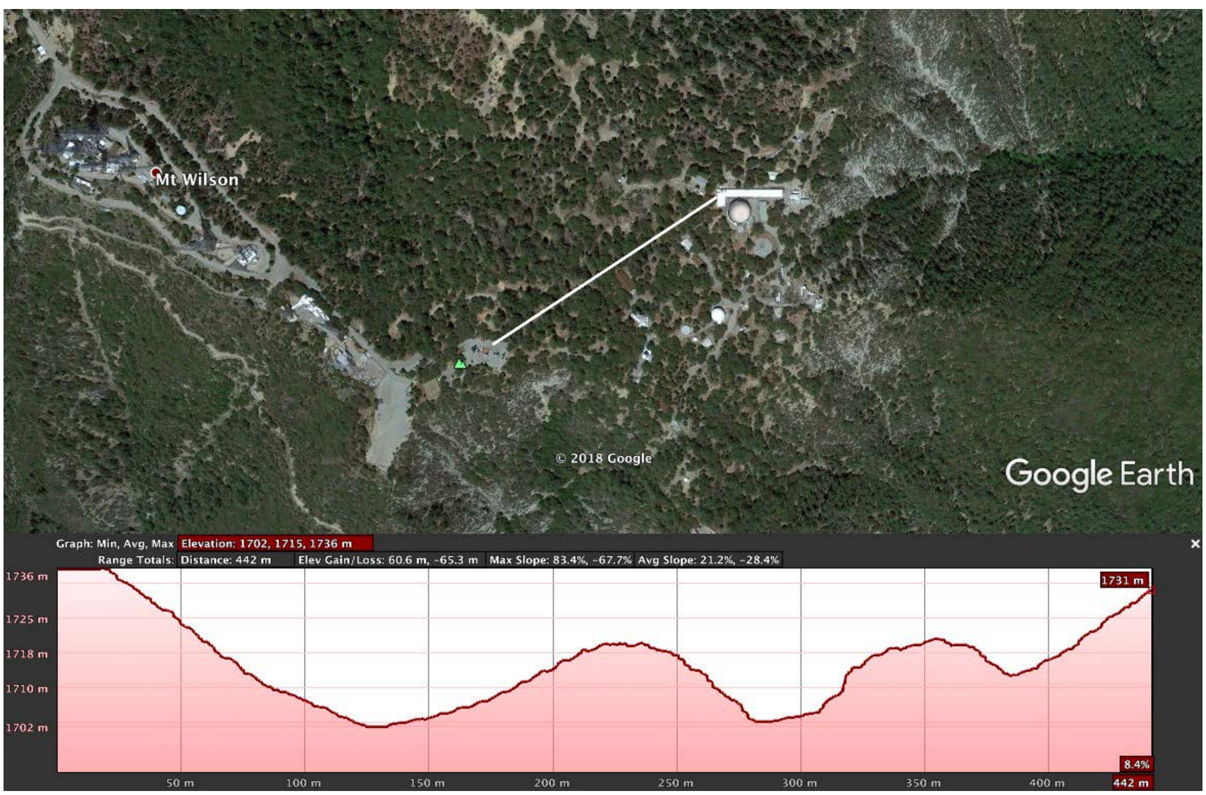

FIG. 6 – Map of the sight line to southwest parking lot (Google Earth).

A second potential sight line is shown in Figure 6 that extends southwest from the OPLE building to the upper parking lot behind the Cosmic Café. The elevation plot shows that this line would cross one valley to a point behind the Museum, cross a second valley to the MWI building west of the reservoir, and then cross a third valley before reaching the OPLE building. This would require a substantial bridge structure to span the valleys and support the light pipes, but it could also serve as a tree-top walkway that would allow visitors to experience the upper canopy along a walk from the parking lot to the 100-inch dome building (and perhaps be annotated with historical and astronomical signposts). This southwest arm would be 385 m in length, and it would form a 590 m baseline with E1 and a 550 m north-south baseline with the potential northwest site. Both the northwest and southwest sites are outside of the current MWO boundary line and are part of the national park.

It is also worthwhile considering extending the current arms of the Array. Figure 7 illustrates the case of the southern arm. Further south of the S1 telescope the terrain begins to drop, so placing a telescope further along this arm would require placing it high enough to see over the hill. The example shown has a S0 location placed 265 m south of the OPLE building, and it would require about 11 m of elevation to be in line with the light pipe axis of the southern arm. An extension of the western arm is shown in Figure 8. This terrain drops further west, so a W0 telescope placed 250 m west of the OPLE building would need 7 m of elevation to be aligned with the western light pipes.

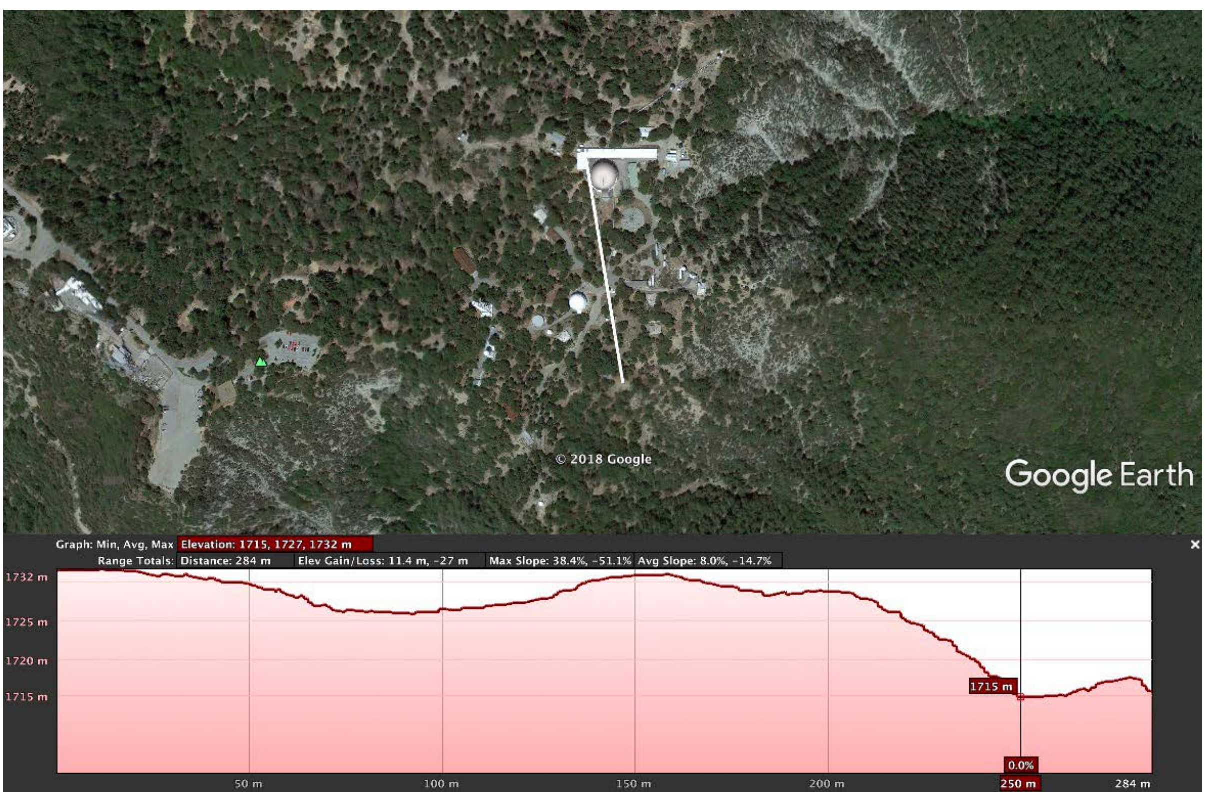

FIG. 7 – Map of the sight line extending the south axis (Google Earth).

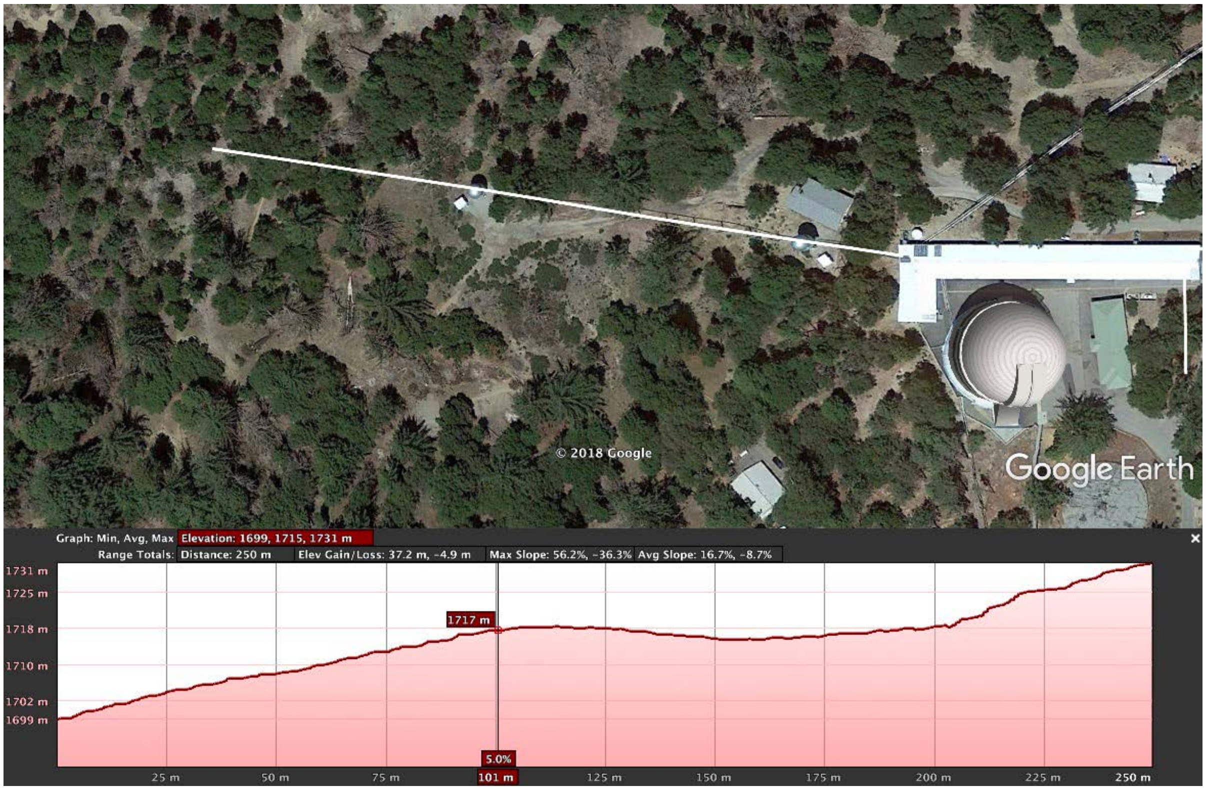

FIG. 8 – Map of the sight line extending the west axis (Google Earth).

FIG. 9 – Map of the sight lines close to the OPLE building east end (Google Earth).

There are several sites close to the OPLE building that might also be considered if a more central location is desirable. Figure 9 shows two possible light pipe configurations that would fed the light from the telescopes to the eastern end of the building. The first is a location immediately behind the Control Room and Office (CRO) building that would send the light northward over a short distance. This location was actually approved by the U.S. Forest Service during an early review of CHARA telescope sites. The second location is on a height just north of the Cadman Cottage and trailer area. This would have the advantage of being close to the electrical and machine shops, and any new construction in this area might include new shop and office space.

## 6. TELESCOPES / LIGHT PIPES / OPLE / BCL CONSIDERATIONS [Farrington, Ridgway, J. Sturmann, L. Sturmann]

The current six CHARA telescopes would need to be matched in general configuration and number of reflections in order to maintain similar polarization properties. There is an extra set of M1, M2 optics in hand for a seventh 1 m telescope.

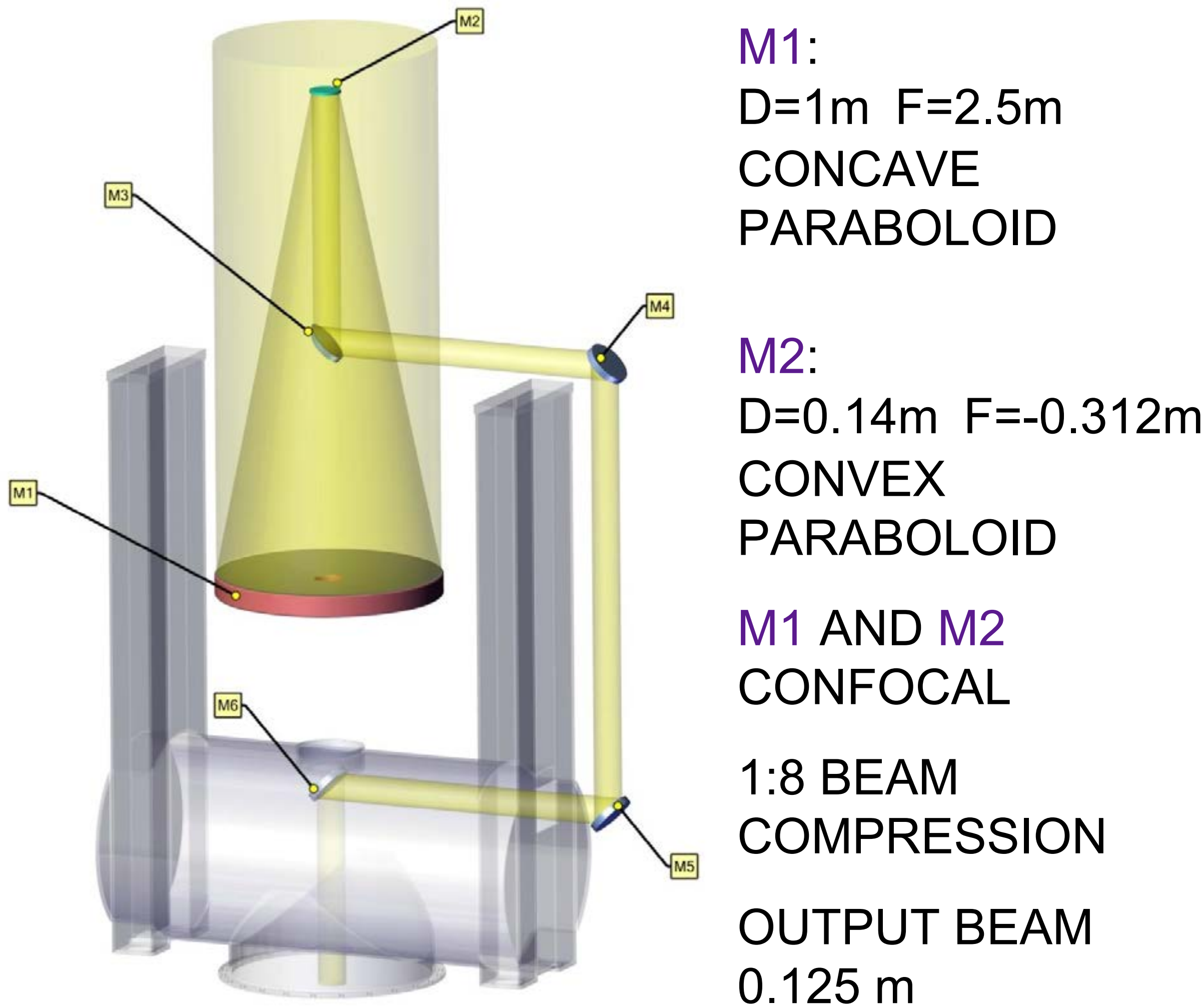


FIG. 10 – Light path in current telescope design.

Using telescopes of mixed aperture (and throughput) is feasible. An upper limit on aperture size is probably set by the size of the aluminizing chamber for the 100-inch telescope (2.5 m) that we currently use for recoating CHARA optics. A more practical limit may be in the 1.5 to 2.0 m range for ease of mirror transport over the roads on Mount Wilson.

The current telescopes have both favorable and difficult features. The positive features include:

- optical design
- altitude-azimuth arrangement
- stiff open tube design
- friction drives
- incremental encoders on the drive journals
- cable wrap
- the telescopes are elevated from the ground
- compact domes
- idea of cylinders

The negative features include:

- there was no provision for optical alignment
- difficult/very difficult servicing and maintenance
- cable management
- inadequate mirror removal fixtures
- two fixed idler plus a spring loaded AZ drive wheel
- drive oscillations
- cable wrap cut cables
- coupling between the dome and the telescope
- dome drive
- implementation of cylinders
- poor overall workmanship
- poor painting, lack of rust proofing

We need to investigate the use of protected silver coatings that may offer significant gains in overall throughput at the expense of more frequent re-coatings.

Any new telescopes would need new light pipes (unless a fiber optics connection is selected); sharing an existing light pipe with another telescope would be difficult.

Connecting any new light pipes into the OPLE building will be a significant challenge that will affect the positions of the beam switchyard tables and beam combiner optics. Ideally any new arms would be approximately parallel to the existing arms to deal with polarization differences. The easiest option may be to bring in new beams from the western side of the building near the wall with the beam combining lab (BCL). This will probably require building two additional turning boxes exterior to the existing building. Less optimal alternatives include bringing beams in from the south adjacent to the current S1 and S2 pipes or finding a new scheme of directing beams in from the eastern side of the OPLE building.

**Adding pipes and keeping polarization, so || with the current Y:**

- Two pipes from the West (repeat of existing design all along), but why 4 in the West.
- One West + one South (with new type turning box) possible.
- One West + one East (turning box outside!) possible.
- One South (new type turning box) one East (turning box outside!) possible.

The OPLE building was designed with space on the south side for two additional OPLE carts, so while adding two more beams is feasible, more than two would require a new and independent OPLE scheme. New fixed-delay POPs for the new beams could in principle be built underneath the OPLE tracks. Path length correction for very long baselines will require rapid speeds for the carts and thus shorter time spans for variable delay correction over the length of the tracks. Possible solutions include extending the tracks into the storage area at the east end of the OPLE building (adding another 10 m to the tracks) and/or developing a double pass system for the delay carts so that each cart increment results in twice the delay increment.

Adding two additional beams would probably result in a reconfiguration of the beam switchyard in a very restricted space and would require moving the tables in the BCL to accommodate the horizontal distribution of the incoming beams. None of the existing beam combining instruments are designed for more than six beams, so operation with of subsets of six beams or less would probably be the most efficient mode until new kinds of combiners are built.

## 7. CHARA DEVELOPMENT CONTEXT [McAlister, Ridgway, ten Brummelaar]

The CHARA Array was built under difficult financial limitations that required flexible working plans. We benefitted from a talented staff, good will from experts in the field, and the strong support of vendors in optics, engineering, fabrication, and site development. Expanding the Array will require similar dedication and making connections with interested parties in industry and academia.

We are currently devoted to two demanding projects, completing the Adaptive Optics (AO) installation on the telescopes and providing open access to the community through telescope time and a data archive. By 2020, both of these programs will be mature, and then we will be in a good position to turn our efforts to the growth of the Array. However, planning for the next decade needs to start now as we refine our plans and make our ambitions known through the U.S. Decadal Survey process.

We are still in the initial phase of the emergence of optical long baseline interferometry as a central tool for studies in astrophysics. Fortunately, we are not alone in promoting long baseline interferometry with the Very Large Telescope Interferometer in Chile playing a key role in energizing the European community. Here in the U.S. the Large Binocular Telescope Interferometer continues to work at shorter baselines, larger telescopes are planned for the Navy Precision Interferometer, and the second telescope of the Magdalena Ridge Optical

Interferometer will soon be delivered. The CHARA Array will remain unique in the number of telescopes and baselines into the next decade, and thanks to its extraordinary productivity and widening user community, we should enjoy the broad support of our peers for our efforts to grow the Array. In particular, the CHARA Array will be an important technology testbed in the steps toward the next generation Planet Formation Imager (http://planetformationimager.org).

Expanding the Array will require significant coordination with the Mount Wilson Institute, the Carnegie Observatories, Carnegie Institution, the U.S. Forest Service, and Los Angeles County. Environmental assessment and agency coordination will likely involve a long lead time.

Funding of an expansion will be a significant challenge and will include overtures to state, federal, and private foundations. GSU is much more engaged in fundraising now than during the years of CHARA's construction, so we may expect the active support of both the College and University.

## 8. CONCEPTUAL MODELS [Baron, Gies, Ridgway, Schaefer, L. Sturmann, ten Brummelaar]

We offer a number of "strawman" models of what the future expansion might include. These are offered to spur discussion and generate new ideas from the entire CHARA community. All of these options need to be evaluated in terms of the most important scientific goals and in value for improved imaging on expanded spatial scales.

a) Use the extra set of M1 and M2 optics to build one additional 1 m telescope like our current design at a pre-approved location behind the CRO to improve short baseline performance (with E2, W2). However, the (u,v) plane coverage may not be too different than that with existing baselines.
b) Build one larger aperture telescope (2 m) at a location in the southern part of MWO with a fiber link to S1 or the OPLE building. This would provide a large north-south baseline and begin the exploration of fiber optics for all the telescopes. Chene et al. (2014, SPIE, 9151, 915147) describe the use of a 270 m fiber for optical wavelengths (500 – 950 nm) that connects the GEMINI North telescope and ESPaDONS spectrograph at CFHT. Special fibers would be needed for the infrared bands (perhaps extending into the L and N bands).
c) Construct a new telescope close to S1 to add a very short baseline capability for imaging of large supergiants and exozodiacal structures. A small triangle is needed with some east-west coverage.
d) Add two 2 m telescopes with very long baselines (like the SW and NW locations discussed in Section 5).
e) Replace all six of the current telescopes with 2 m class telescopes and high reflectivity optics. This would enable observations of fainter targets such as YSOs and deal with the problems of aging telescopes.
f) Combinations of the above. For example, combine (c) and (d) to create a large triangle for basic closure phase data.

## 9. NEXT STEPS

The main conclusion of the meeting is that there are a number of very appealing options to expand the Array that would vastly increase its imaging power and provide remarkable opportunities to explore processes on stellar surfaces and in their immediate environments. We will need to build a consensus in the CHARA collaboration and wider community about the options that are most promising and practical to implement over the next five to ten years. We would then need to share our vision with the stakeholders at Mount Wilson and garner support for fund raising and detailed planning activities. The expanded Array will be central to our scientific exploration of the stars in the next decade.