CHARA TECHNICAL REPORT

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Site Selection for the CHARA Array

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1. INTRODUCTION

The selection of a site for the CHARA Array has been a long-standing challenge affected by the lengthy process of obtaining construction funds and a shifting perspective on what constitutes an appropriate site. Now that capital funds are in hand, CHARA must press forward with the selection in order to avoid adverse consequences to schedule and budget. This report provides an analysis of the information available for three specific sites (Kitt Peak, Mt. Palomar, and Mt. Wilson) as potential alternatives to a site in New Mexico. The report concludes that Mt. Wilson is the site of choice for the Array.

2. BACKGROUND

2.1. CHARA's Original Site Selection Process

Sites for the Array have been chosen on two previous occasions. Anderson Mesa, near Flagstaff, Arizona, was selected in 1988 and replaced in 1993 by Mesa Negra, near Grants, New Mexico. Anderson Mesa was picked from among ten sites in Arizona, California, Hawaii, New Mexico, and Texas following an extensive analysis reported in Appendix K of CHARA's final report to NSF Grant AST 84-21304. The criteria that led to the selection of Anderson Mesa were (without any priority assignment):

- TERRAIN – Emphasis was given to flatness to provide the best possible (u,v)-plane coverage, thereby eliminating most classical, developed sites.
- METEOROLOGY – Relative cloudcover was evaluated from heterogeneous data.
- DARKNESS – Although judged somewhat less important that other criteria, consideration of sky background was given for non-interferometric uses, particularly spectroscopy.
- GEOLOGY – Seismic and microseismic activity and access to bedrock were considered to be significant issues.

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- SEEING – Atmospherically-limited seeing conditions were judged to be of critical significance but very difficult to ascertain.
- LOGISTICS – Logistics and their relation to construction and operating costs were recognized as potentially dominating the selection process, and the baseline precept was that site infrastructure (roads, power, water, telecommunications, etc.) would already be in place.

Anderson Mesa rose to the top under these selection criteria. A seeing monitoring campaign showed a mean FWHM image profile of $1''.24$ and a median value of $1''.18$. Subarcsecond seeing was encountered in 15% of the 364 observations otained on 21 nights during May and June 1988 and displayed in Figure 1. The study of Anderson Mesa as an array site was undertaken largely by Dr. Wean-Shun Tsay, now at the National Central University of Taiwan, and was the subject of Georgia State's first astronomy PhD dissertation. The analysis was published by Tsay et al. (1990).

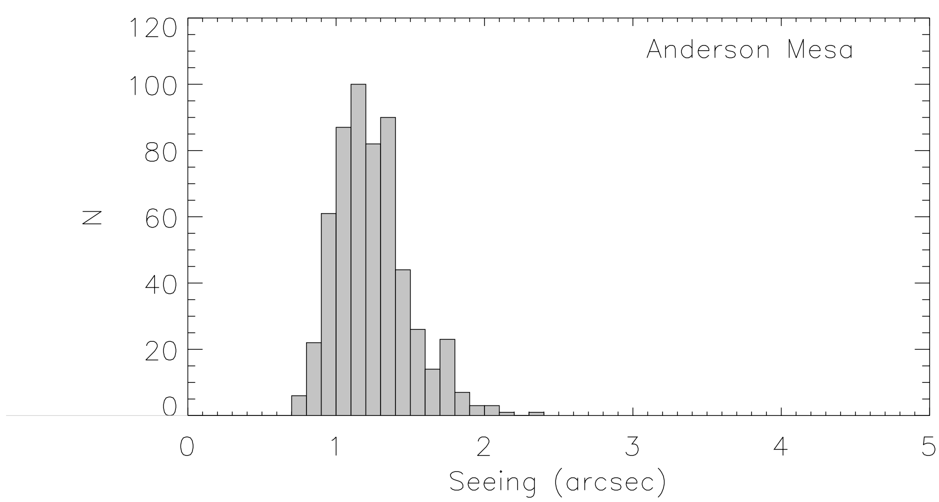

FIGURE 1. Seeing histogram for Anderson Mesa, from Tsay et al. (1990).

Although CHARA did not subsequently build on Anderson Mesa, the U.S. Naval Observatory has constructed the NPOI astrometric facility on the location we proposed. While this does not preclude CHARA from building adjacent to NPOI, the different scientific missions and operational requirements of NPOI and the CHARA Array make it unlikely that the two projects could achieve significant gains by merging operations to some degree. It is also disadvantageous for the nation's two largest optical interferometers to be subject to identical cloudcover and seeing conditions, especially if a potentially better site can be obtained.

2.2. Mesa Negra, New Mexico

The replacement of Anderson Mesa with Mesa Negra has been described in our most recent proposal to the NSF that led to grant AST 94-14449. The site, located within the Acoma Pueblo, was to have been developed by the Institute for Astronomy (IfA) at the University of New Mexico in its leadership role in "Cosmic Explora," a major science education effort now underway with federal and state support. CHARA carried out several site-specific studies that considered topographic, geotechnical, and construction issues on Mesa Negra. Unlike the original selection of Anderson Mesa involving an analysis of many alternative sites, Mesa Negra was selected following an overture to CHARA from the University of New Mexico.

Consistent with our original precept regarding terrain, the extensive flatness of the mesa offered unrestricted (u,v)-plane coverage as well as the potential for expansion to nearly arbitrarily long baselines. Satellite data showed the mesa to have excellent cloudcover characteristics, essentially free of orographic clouds often associated with higher mountain top sites. Prior to the invitation from the University of New Mexico, we looked extensively at potential sites in the Sacramento Mountains of southern New Mexico adjacent to the National Solar Observatory. While Sacramento Peak offered several potentially excellent sites, environmental issues (particularly spotted owl habitat) were seen to pose significant obstacles. Mesa Negra's lower elevation and its ownership by the Acoma Pueblo essentially eliminated any concerns over potential environmental problems.

In February 1993, CHARA indicated in writing to the University of New Mexico our commitment to locating the Array on Mesa Negra "or a similarly situated site in its vicinity". Negotiations with the Acoma governor and tribal council were well underway at that time, but there was still a question as to whether Mesa Negra or a neighboring location known as Putney Mesa would emerge as the site of choice. Putney Mesa had a slight logistical advantage due to the existence of four-wheel drive roads while Mesa Negra remains accessible only by foot, horseback, or helicopter. UNM and CHARA considered Mesa Negra to be the better of the two sites due to its very flat terrain compared with Putney Mesa. Under the assumption of a favorable agreement with the Acoma, CHARA undertook aerial and ground topographic surveys of the specfic area on Mesa Negra desired for the Array. We also subcontracted for a preliminary geotechnical survey used as input for a site construction analysis. The results of these studies are given in Appendices W and X of the companion volume to the Array NSF proposal.

In late October 1994, we learned that negotiations between UNM and the Acoma leadership had encountered difficulties that led UNM to elevate a backup site to prime site status and relegate Mesa Negra to backup status. The prime site for Cosmic Explora is now Horace Mesa, a very extensive formation located north of I-40 and somewhat closer to the small town of Grants than is Mesa Negra. As a condition of the environmental assessment being conducted under the authority of the AFOSR, UNM is evaluating at least three sites as potentially suited to their needs. Horace Mesa is primarily federal land controlled by the Bureau of Land Management, and UNM is negotiating with BLM over access to the site. It is our understanding that UNM will initiate seeing testing at these sites and these measurements will become part of the environmental assessment for site selection. In late 1994, UNM estimated that final site selection will be completed and the permission for access will be obtained during the summer of 1995.

Following the apparent loss of Mesa Negra, we decided to pursue backup sites, and, in the fall of 1994, CHARA initiated discussions with the appropriate potential hosts for access to Kitt Peak, Mt. Palomar, and Mt. Wilson. We entered these discussions with the realization that these extensively developed sites may be preferable to a New Mexico site for our particular circumstances due to the possible impact on our planning of UNM's own schedule for the acquisition and development of a site for Cosmic Explora.

3. REVISED SITE SELECTION CRITERIA

Numerous personal and written exchanges of information have transpired to date with Drs. Sidney Wolff (Director of NOAO), Robert Jastrow (Director of the Mt. Wilson Institute), and Shri Kulkarni (Professor of Astronomy at Caltech). Each has been extremely forthcoming in their discussions and in providing information relevant to the site selection, and we are very grateful to them for their graciousness in considering hosting CHARA. They have provided extensive data regarding seeing, logistics, and operating costs, and the remainder of this report is an analysis of those data. A summary of site parameters is given in Table 1, where Anderson Mesa, AZ and Horace Mesa, NM are included for comparison.

TABLE 1. Alternative Site Parameters

Site	Longitude	Latitude	Elev. (m)	Land Ownership
Kitt Peak, AZ	111 36.9	+31 58	1920	Indian Reservation
Mt. Palomar, CA	116 51.8	+33 21	1710	Private Land
Mt. Wilson, CA	118 03.6	+34 13	1742	U.S. Forest Service
Anderson Mesa, AZ	111 32.2	+35 06	2200	U.S. Forest Service
Horace Mesa, NM	108 45.0	+35 12	2400	BLM

In growing older and hopefully wiser with this project, it is the author's opinion that there are three site selection criteria for this project that are of overriding importance. These criteria are atmospheric seeing, (u,v)-plane coverage, and logistics (including operating costs). The first two criteria are the essential performance limiting factors of an interferometric array and will heavily influence the scientific impact the project will have on astronomy. The last criterion boils down to money which, in the final analysis, may be the determining factor in chosing from among the potential sites. Each of these selection criteria is examined in the following sections.

4. ATMOSPHERIC SEEING

Atmospheric seeing characterized by Fried's turbulence scale size parameter $r_\circ$ and correlation time $\tau_\circ$ (or a related parameter) will determine the limiting magnitude for a given signal-to-noise ratio and integration time. The limiting magnitude of the fringe tracking servo is also strongly seeing dependent. Thus not only will $r_\circ$ and $\tau_\circ$ determine, for example, whether the CHARA Array plays any role in extragalactic astronomy, but the overall observing efficiency and throughput for brighter objects will be seeing limited. When all else is equal, seeing should drive site selection.

The obstacle to completing a seeing evaluation of these sites is the near impossibility of obtaining archival seeing data for different sites that can be meaningfully intercompared. Furthermore, we did not wish to embark on any new seeing monitoring due to schedule and resource considerations. Thus while seeing information exists for the three specific sites under consideration, it will be seen that one must force an arguable conclusion from these data.

4.1. Kitt Peak Seeing

Until recently, Kitt Peak has not been known for outstanding seeing. Our own experience during 100+ nights since 1975 at the 4-meter telescopes is that seeing conditions there are typically $1''.5$, and subarcsecond seeing is extremely rare. The 4-meter image quality has been improved significantly by eliminating heat sources in the telescope building. For example, in a report to the Kitt Peak Users' Committee in the fall of 1992, Bruce Bohannan showed image profile measures from September 1992 yielding a mean seeing disk diameter (FWHM) of $1''.14$ and a median seeing of $1''.11$ as evidence that steps being taken to improve 4-meter image quality were having a positive effect. It is likely that such steps have nearly reached their limiting payoff at that telescope.

More recently, seeing measurements from the new WIYN telescope on the Kitt Peak summit and the MDM telescope on the "southwest ridge" have shown that even better seeing can be obtained. Figures 2 and 3 show seeing histograms from these two telescopes.

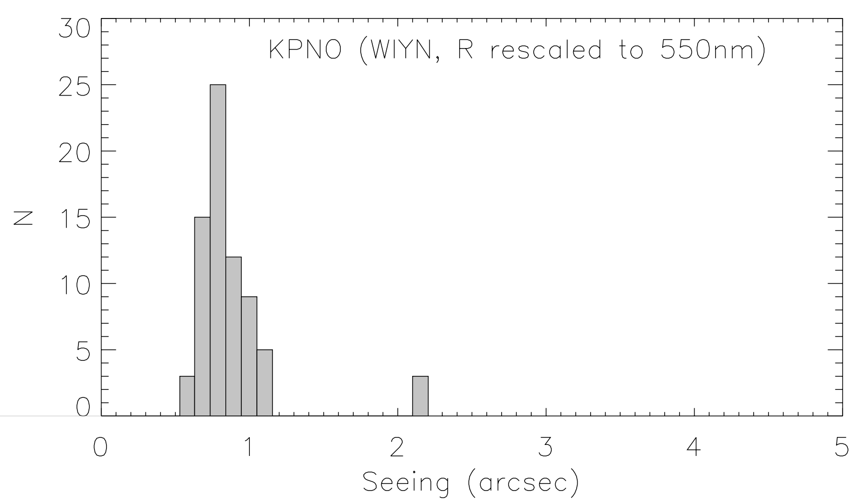

FIGURE 2. Seeing histogram from the WIYN Telescope on Kitt Peak

The WIYN 3.5-meter telescope data in Figure 2 were originally obtained using an R filter and have been rebinned here according to a $\lambda^{-0.2}$ dependency to correspond with expectations at the V wavelength. The WIYN measurements were usually taken immediately after making a wavefront measurement and tuning the WIYN active optics system if the measurement indicated that the latter was necessary. The measurements were not guided and show effects of image trailing and small deviations from ideal focus. It is estimated that when tracking and guiding are brought under better control the median image quality will improve by perhaps as much as $0''.1$ FWHM.

From many years of observing at the "No. 1 36-inch telescope" (since decommissioned from KPNO service and relocated to another site), the WIYN site has long been regarded as a "sweet spot" on Kitt Peak due to its situation on a topographic peninsula, with excellent air drainage, thrusting into the prevailing wind. The WIYN dome and telescope structure have been designed to minimize local seeing effects. This, coupled with the use of active optics to tweak the image quality, implies that the WIYN seeing measurements are probably at the atmospheric limit of seeing quality intrinsic to Kitt Peak.

With that last conclusion in mind, one wonders whether or not WIYN seeing could be assumed to be representative of what the CHARA Array might encounter on the picnic ground site upwind and 200 meters lower in elevation than WIYN or whether the WIYN site is anomalous due to the channelling of air by the local topography. One could not assume that the lower elevation site on less favorable terrain would experience such fine seeing. Fortunately, data from a location adjacent to the potential Array site at the same elevation do exist.

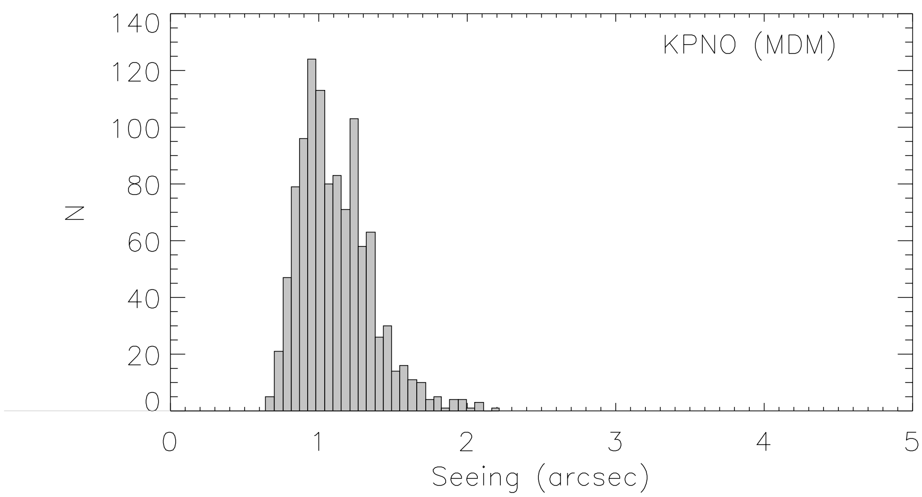

FIGURE 3. Seeing histogram from the MDM Telescope on the Kitt Peak southwest ridge

Seeing data from the Michigan-Dartmouth-MIT (MDM) 2.4-meter telescope are shown in Figure 3. These data were obtained by John Tonry during observing runs in April and August, 1992; April, May and October, 1993; and February 1994. The majority of the measures were 10-minute exposures taken with an I filter except for the most recent run which employed a V filter. Dr. Tonry has very kindly provided us with the individual data sets, and Figure 3 is a composite of the results from these six observing runs. The I-filter data were summed and rebinned to V-band performance in order to then add the February 1994 V-filter results. Transforming from I to V gives 10% larger image profiles.

Dr. Tonry has pointed out that there is a modest bias in that no measurements are taken under non-photometric conditions and conditions of very bad seeing (FWHM worse than $\sim 2''$). He estimates that such conditions occur about 5% of the time (in addition to completely cloudy nights of course!) He also noted that the very best seeing is not well represented due to the coarse pixelation of the data and that their mirror suffers from $0''.4 - 0''.5$ of astigmatism which is not removed from these data. The 2.4-meter mirror is actively cooled to minimize mirror seeing effects, and considerable care has been taken in dome thermal management. Finally, Dr Tonry indicated that the McGraw-Hill 1.3-meter telescope adjacent to the MDM produces images that are "definitely worse" than the MDM with the poorer performance of the smaller telescope attributed to dome-generated seeing.

4.2. Mt. Palomar Seeing

Dr. Xiaopei Pan of Caltech provided CHARA with a report entitled "Seeing Statistics from 200-inch Temperature Log Books" by Tadashi Nakajima in which data from 1990 to 1993 have been analyzed in an attempt "to characterize seeing at the 200-inch." The seeing measurements were taken with an instrument known as "four shooter" which is judged as the only instrument capable of providing objective estimates of the seeing disk. The report utilizes extensive temperature data collected inside and outside the dome as well as at the mirror to find thermal relationships coincident with good and bad seeing. It was found that good seeing occurs when $T_{dome} > T_{mirror}$ and subarcsecond seeing tends to occur only when $(T_{dome} - T_{mirror}) < 2$ C. Under conditions of low wind speeds, good seeing is encountered when $T_{outside} > T_{dome}$, and subarcsecond seeing is not encountered when $V_{wind} > 13$ km/s. These temperature relations are consistent with conventional wisdom. The best seeing measures are limited by the pixel scale of 0.4 arcsec/pixel and contain an aberration induced contribution of 0.4 arcsec.

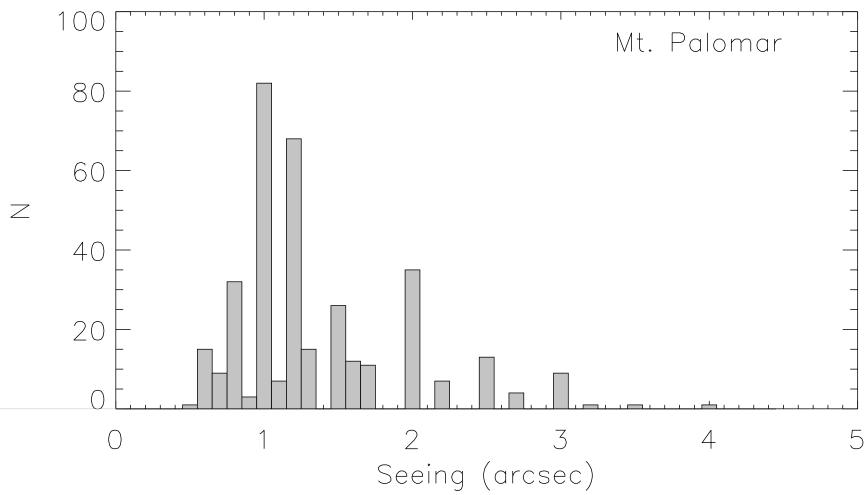

FIGURE 4. Seeing histogram from the 200-inch Telescope on Mt. Palomar

The seeing histogram of these data is shown in Figure 4. The report by Dr. Nakajima has a month-by-month breakdown of the frequency of subarcsecond seeing at the 200-inch. Such fine seeing conditions occur with an annual average frequency of 15% but are strongly seasonally dependent. The finest seeing occurs throughout the summer when subarcsecond images are encountered at least 30% of the time. By contrast, in the sample contributing to this analysis, no instances of subarcsecond seeing were recorded during the months of October and December. The report has an estimate that $\tau_\circ$'s ranging from 5 to 10 msec accompany the best seeing. The correlation time is here defined as $\tau_\circ = 0.314 \times r_\circ / V_{wind}$ where V_{wind} is the wind speed at the dominant turbulence layer.

4.3. Mt. Wilson Seeing

Mt. Wilson has a near legendary reputation for its seeing. For example, Babcock (1990) states that "beginning about 1936, I have made visually many hundreds of incidental knifeedge observations of primary mirrors in the course of research programs at Mount Hamilton, Mount Locke (McDonald Observatory), Mount Wilson, Palomar Mountain, and Cerro Las Campanas. It is easy to detect the direction and rate of flow of the changing pattern of turbulence as influenced by air movements in the optical path and to estimate the average dimension of the Fried coherence cell size ($r_\circ$). Typically $r_\circ$ lies in a range from a few centimeters to a few decimeters, but, with the very best natural seeing, in calm conditions at the 100-inch Hooker telescope on Mount Wilson, $r_\circ$ has been observed to attain the extraordinary value of 1 m. At such times, which are extremely rare, the boundaries of the coherent areas are of low contrast and they change slowly, on a time scale of several seconds. Coherent patterns of this high quality were correlated with a measured diameter of 0.25 arcsec for the seeing disk at the coudé (250-foot) focus of the 100-inch telescope. The image was not only very small and sharp, but it was remarkably stable. Such superlative seeing has been observed to last for several hours. It can be stated with a high degree of confidence that Mount Wilson offers the best seeing of any North American observatory." Under the conditions discribed by Babcock, our telescopes would realize their full aperture capability. Among the three sites, only Mt. Wilson has documentation supporting such superb seeing conditions.

The site has also been advanced by Nisenson et al. (1984) who, in the title to their paper, asked the question "Is Mt. Wilson the Best Interferometric Site in the World?" From speckle data, they claimed that the site has "exceptionally good seeing and uniquely long correlation times, the two critical parameters for maximizing the rate of convergence of the speckle process and for the continued implementation of an astrometric or long baseline amplitude interferometer." They presented temporal correlation data for four series of observations made during a night when $r_\circ \sim 10$ cm in which $\sim$50% correlation existed after 50 milliseconds and state that during four nights in August 1983 they encountered seeing of approximately 1/3 arcsec. They concluded that Mt. Wilson is "probably the ideal site for interferometric experiments." Buscher et al. (1995) have recently discussed the outer scale length of turbulence as measured with the Mark III interferometer on Mt. Wilson and coincidentally presented some limited but favorable data for $r_\circ$.

Dr. Jastrow has passed along to CHARA several collections and samples of actual seeing measurements. The first of these is a histogram of seeing disk sizes obtained by Dr. Geoff Marcy at the 100-inch coudé focus during 44 nights between August 1983 and August 1984. Marcy's data are shown in Figure 5. The seeing was better than $1''\!.0$ on 10 of these nights. In subsequent correspondence, Dr. Marcy has told the author that "the Mt. Wilson seeing measurements were obtained simply as a matter of practice during each of my nights on the 100-inch at coudé. All the measurements were simply eyeball estimates of the 'diameter' of the seeing disk as seen on the guiding TV, using the slit as the reference size scale. My runs were distributed uniformly throughout the year (mostly bright time) and I always logged the seeing, independent of its value. The tail of bad seeing at Mt. Wilson occurs primarily when the winds shift to the east, the so-called Santa Ana winds. On the other hand, as the data show, the seeing is often near an arcsec, as viewed from coudé. I strongly agree [with the author's suggestion] that the optics and air path down to the 100-inch coudé focus certainly degrade the seeing. We see this effect at the Lick coudé too. I also do not know how to correct the Mt. Wilson coudé seeing measurements to something less dependent on those coudé effects."

Dr. Marcy stated that the 100-inch coudé rarely delivered seeing better than $0''\!.7$ because of the optical path. He attributes the lack of a fall off in the good seeing regime to the inability of the telescope to produce images better than this value.

Dr. Jastrow has also provided output of a seeing monitor used by D. Walters of the Naval Post-Graduate School on Mt. Wilson during the night of 7 August 1986 which Walters had characterized as a fairly typical night, neither the best nor the worst. This output, which is not reproduced in this report, shows a nearly continuous monitoring of $r_\circ$ throughout the night starting at 10 cm during the first two hours of the night, improving to nearly 20 cm for the next six hours before dropping back down to ∼12 cm and finally climbing to ∼30 cm for the two hours before dawn. Thus, the night started with $1''\!.0$ seeing which quickly improved to $0''\!.6$ and culminated for the last two hours with $0''\!.3$ seeing.

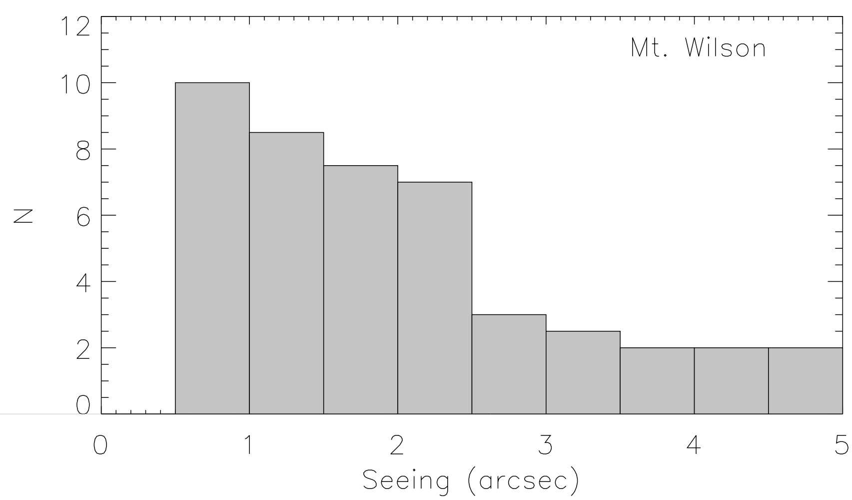

FIGURE 5. Seeing histogram from the 100-inch Telescope on Mt. Wilson

There is considerable information regarding atmospheric correlation times on Mt. Wilson. The earliest example of such data appears to be the measurements of $T_\circ$ made by Colavita and Shao (1988) using the Mark II interferometer in 1983. During several nights in August and September of that year, mean values for $r_\circ$ and $T_\circ$ of 25 cm and 24 msec were measured. The most extensive seeing data for Mt. Wilson are from the recent paper by Buscher (1994) who presents correlation time measures from more than 450 nights during the three-year period 1989–91 as measured by the Mark III interferometer. Buscher defines a quantity $t_\circ$ as the time lag during which the temporal structure function of the phase at a point on the wavefront has a value of 1 radian^2. Buscher carefully distinguishes this definition from a coherence time defined as the inverse of the Greenwood frequency f_G and another approach based upon the rms difference between the phase at any point during an interval $T_\circ$ and the mean phase for that interval. For Kolmogorov seeing at a given λ, these quantities scale according to $(1/f_G : T_\circ : t_\circ) = (7.5 : 2.6 : 1.0)$. The quantity referred to as $\tau_\circ$ in the Mt. Palomar study of Nakajima is identical to Buscher's quantity $t_\circ$. Buscher's (1994) histogram of $t_\circ$ shows an instrumental cutoff around 4 msec with median values over the three years of 7.0, 6.9, and 6.7 msec.

4.4. Seeing/Imaging Intercomparison

A comparison of the image qualities measured from the above-described data samples, including Anderson Mesa, is given in Table 2. One must make a careful distinction between "seeing quality" and "image quality" because there clearly are known biases among the samples even though they cannot be accurately evaluated.

TABLE 2. Frequency of Subarcsecond Images

Parameter	Mt. Pal.	Mt. Wil.	KP - WIYN	KP - MDM	And. Mesa
mean	1″.36	2″.00	0″.88	1″.13	1″.24
median	1″.19	1″.75	0″.81	1″.07	1″.21
%-age $\leq$ 1″.0	28.7	22.5	82.9	39.0	15.6

In comparing what superficially appear to be the "best" and "worst" sites among the three under consideration one should note the following:

- Kitt Peak–WIYN data were taken at a "sweet spot" on the mountain.
- Kitt Peak–WIYN telescope has an actively controlled primary mirror tweaked when necessary before each measure.
- Kitt Peak–WIYN enclosure is carefully designed to minimize dome seeing.
- Kitt Peak–MDM mirror is actively cooled.
- Kitt Peak–MDM dome seeing is minimized.
- Kitt Peak–MDM measures were not taken during bad seeing conditions.
- Kitt Peak image quality data based on CCD measures.
- Mt. Wilson–Marcy data are "eyeball" estimates.
- Mt. Wilson–Marcy data were obtained at coudé focus of ~80 year-old optical system.
- Mt. Wilson–Marcy data do not turn over at good seeing end implying that telescope cannot deliver images consistent with the best seeing.
- Mt. Wilson–Marcy data were taken even during bad seeing conditions.

How does one then assess the available seeing information? The above biases seem impossible to quantify. For example, the WIYN data are closest to measuring the free atmosphere above Kitt Peak, while the Mt. Wilson data are convolved with a strong telescope optics contribution. Although the 100-inch dome is apparently more benign than many modern domes in its contributions to image degradation, it is nonetheless a dome and must cause some dome seeing. But what numerical corrections should be applied? It seems likely that the WIYN data may include a bias as do the MDM data in not taking measurements during times of seeing worse than about 2″.0. Truncating the Mt. Wilson sample of Marcy at 2″.0 produces a mean image size of 1″.20 and an apparent frequency of subarcsecond seeing of 38%. This has also not been corrected for any differences in optical quality. Nor do we know what systematic effects lie in Marcy's "eyeball" estimates compared with the more objective measures from CCD images.

Walker (1971) asserts that sites with the best seeing are situated such that a cold ocean current offshore lowers the height of the inversion layer above which the laminar airflow set up over the ocean still persists. This model certainly holds for Mt. Wilson and to a somewhat lesser extent for Mt. Palomar. As one approaches inland from such a cold current, surface heating drives the inversion layer to higher elevations. Walker reasoned that inland sites on isolated peaks offer the next most preferable locations, and Kitt Peak fits that model. Under both circumstances (coastal and inland), elevation improves seeing conditions.

The conclusion drawn here is that Mt. Wilson and Kitt Peak probably have similar seeing conditions with Mt. Palomar somewhat poorer. Mt. Wilson may have the edge, and may be the only site that occasionally provides coherence volumes that will permit the Array to reach extragalactic objects. That capability alone could be sufficient justification to select such a site over its competitors. Finally, we note that a mesa site with only modest elevation above the dominant terrain is less likely to provide access to good seeing, a conclusion consistent with all three of the sites under consideration appearing to have better seeing conditions than does Anderson Mesa.

5. (U,V)-PLANE COVERAGE

The ability of each of the three sites to attain optimal (u,v)-plane coverage has been carefully considered in CHARA Technical Report Nos. 11 and 12, and the reader is referred to those publications for details. It was found that the index of (u,v)-plane coverage decreases slightly in the order of Mt. Palomar, Kitt Peak, and Mt. Wilson for both 5- and 7-telescope arrays and that the attainable values are not significantly less than what an unrestricted flat terrain would offer. TR 12 concluded that Mt. Wilson has the advantage of an easy upgrade from a 5- to 7-telescope array, because none of the original telescopes need be moved. Simulations of reconstructed images from all three arrays appear very similar.

One concludes, somewhat surprisingly perhaps, that the traditional mountain sites do offer opportunities to distributed arrays, contrary to our original precept calling for an essentially flat site. With the use of extra reflections to allow "bent" light pipes, considerable flexibility can be realized in locating telescopes for (u,v)-plane optimization and filling. Even without such increased flexibility, there is not sufficient variation in (u,v)-plane coverage performance among the three sites to contribute meaningfully to the selection process other than to indicate that all are satisfactory approximations to flat terrain. This conclusion coupled with Walker's (1971) discussion about what leads to inherent good seeing at a particular site, argues against locating the Array on an inland mesa. Acting upon this realization and the unknown schedule for developing Horace Mesa, we decided to opt against locating in New Mexico.

The final step in this process is thus the selection from among the three remaining sites according to an overall evaluation of the three selection criteria. The remaining criterion, logistics, is discussed in the next section.

6. LOGISTICS AND OPERATING COSTS

When all else is equal, logistics and especially their relation to cost emerge as the determining influence in site selection. Many factors contribute to the logistical evaluation of a potential site; those considered here are:

6.1. Accessibility

In terms of accessibility from Atlanta, the California sites are served by several non-stop flights per day while, at the present time, there are no non-stop or even direct flights into Tucson. Current state contract airfares are $474 for Atl/Tuc/Atl on United (generally through Chicago) and $558 for Atl/LA/Atl on Delta (non-stops available) representing a cost differential of $84 per person-trip. All three sites have excellent road access from their serving airports with Mt Palomar requiring the longest automobile commute. In simple terms of getting to the site from Atlanta, Mt. Wilson has the edge. Mt. Wilson is also closest to the nearest populated area, being only a 45-minute drive from downtown Pasadena. Los Angeles is obviously an area that has high potential for supplying potentially exotic electronic and mechanical items that may be needed on an occasional emergency basis as well as providing a deep pool of technically qualified manpower. Tucson has a significant aerospace and university community and may not be far behind LA in this regard. Finally, the fact that CHARA is already committed to continuing our speckle observing on the 100-inch telescope means that we will be sending people there anyway, a number of whom will also be participating in the Array project. Overall, Mt. Wilson leads in this category.

6.2. Basic Infrastructure

All sites have the basic infrastructure of roads, power, water, and living accomodations present to varying degrees of depth and breadth. While Kitt Peak has extensive on-site facilities for providing and maintaining this infrastructure, they may exceed the needs of CHARA and require costs in excess of those at other sites.

6.3. Emergency Services

All sites are within essentially equal helicopter commutes of nearby hospitals. Kitt Peak is the only site with a fully trained EMT on duty and thus leads in this category.

6.4. Living Environment

LA and Tucson are contrasting in size and life styles, but both offer a great deal to satisfy most people. It is not clear which area has the highest cost of living in our case, but such factors as housing costs will drive salary requirements. The few FTE's we have permanently on site, particularly the site superintendent, are likely to live in the vicinity of the site itself (if not on it). Transients from Atlanta will live in quarters provided by our hosts or built especially for us (and by us). All three sites pose special problems in arriving at sleeping, eating and lounging accomodations that are pleasant and affordable. It is likely that all three sites will cost CHARA money to provide the kind of living quarters we would like. Mt. Wilson may be the most cost-effective site for living while Mt. Palomar (where there are no on-site accomodations with guaranteed access by us) is perhaps the least cost-effective.

Mt. Wilson leads in this category except for the very special consideration that Tucson is the hometown of a Co-Investigator on this project.

6.5. Environmental Issues and Permitting

From our discussions with the potential hosts, there appear to be no environmental issues of a critical nature at any of these sites. Caltech and MWI must get permission from the Forest Service for developments and tree cutting. Caltech had some difficulty with San Diego County in obtaining permits for construction of the JPL interferometer testbed. That situation appears to have been a special case of an accumulation of inappropriate permits and is presumably no longer an issue. KPNO must obtain permission from the Tohono O'odum tribal council, but Dr. Wolff does not foresee any difficulties in that regard. CHARA will be required to do an environmental assessment as a result of our spending federal dollars on construction, but such assessments are probably quite minimal. With the knowledge now available to us, no site stands out as particularly favorable or unfavorable in this category. The New Mexico site could be sensitive to potential environmental problems simply because it is not yet developed even though heavy grazing has been on-going for many years.

6.6. On-Site Technical Facilities

All three sites have shop and electronic repair facilities ranging from adequate to nearly spectacular. We originally planned on having our own machine and electronic shops, but those facilities were dropped from our program plan. It would seem likely that we will make regular use of a basic machine shop during the installation and integration phases of the project. On the other hand, SUSI made essentially no use of its host's shop facilities but relied heavily upon the host's heavy equipment in the form of lifts and cranes during construction. Kitt Peak is outstanding in this area.

6.7. On-Site Human Resources

All three sites have permanent staffs, with Mt. Wilson being the most limited and Mt. Palomar being midway in size between Mt. Wilson and Kitt Peak. At the two California sites, our site fee would entitle us to some amount (5–10%) of the respective superintendent's time. Access to other technical support is probably very limited on Palomar while such support is potentially available on Kitt Peak on a cost-reimbursable basis. We must expect to pay for any use of KPNO personnel. We must also be realistic about the budgetary future of NOAO with the advent of Gemini and the trend towards smaller federal budgets. On Mt. Wilson, it is more likely that access to MWI staff will be relatively informal and limited by the small on-site staff. From the perspective of having technical manpower available on a special case need, Kitt Peak appears to stand out, and we could be back "on the air" sooner at Kitt Peak under certain failure scenarios. However, CHARA should strive to be as self-reliant as possible. Our operating budget currently includes 3.5 FTE's (a superintendent, two operator/technicians, and 0.5 additional technician). Under normal circumstances, an appropriately hired on-site staff supplemented by transient staff, should be able to handle most contingencies. Overall, this category appears to favor Kitt Peak under certain circumstances, especially during construction, but is judged to be site neutral under most circumstances.

6.8. Operating Costs

CHARA currently plans on having a resident staff of 3.5 FTE's significantly supplemented by transients from Atlanta. This number could be reduced through potential sharing of positions with site hosts or purchasing of services from the host. Because the FTE's are intended for the operation and maintenance of the Array, it is not likely that we would cut this staff back and rely on occasional purchase of human resources.

The non-personal services operating costs of the site are related to the elements summarized in Table 3. Kitt Peak has a number of items that are not charged by the other sites. A cost summary is given in Table 4 in which utilities costs are based upon electric power, water and telephone costs. Telephone expenses are considered to be the same regardless of site and should be nominal due to our likely heavy use of Internet. The Kitt Peak utililty fee includes a relatively large cost for Internet access not found at the other sites. A standard telephone cost at each site of $1,500 per year is included to which the greatest contribution is likely to be long-distance faxes. Kitt Peak charges for water, and the very nominal amount of $25 per month is a reasonable estimate there. Electric power consumption is difficult to estimate at this time. The approach taken here was to scale the writer's home power annual power consumption by the increase in square footage and then multiply by 1.5 to reach what is intended to be a conservative estimate. It is estimated that the delay line building (31 ft$\times$196 ft), beam combining laboratory (30$\times$50), a potential office building (25$\times$28), control building (50$\times$28), and a miscellaneous building (30$\times$50) lead to a total square footage of $\sim$12,000 ft^2. The use basis is 5.18 kwh/yr/ft^2 or 95,150 kwh/yr (including the 50% contingency).

TABLE 3. Site Cost Elements

Category	Kitt Peak	Mt. Palomar	Mt. Wilson
Site Fee[1]	$25,700[2]	$10,000±	$11,000[3]
Electricity	$0.07/KWH	$0.08/KWH	$0.05/KWH
Water	$0.01/Gal	N/C?	N/C
Telephone Buy-In[4]	~$15,000	N/C	N/C
Internet via T-1[1]	~$5,000	N/C	N/C
Transient Lodging	$50/day	?	$6/day
2-Bedroom House	$550/month	$700/month±	$50/month
Office/Lab Space[5]	$9.60/sqft/yr	N/C	N/C for 100-in grnd floor
Office/Lab Space[6]	$20.10/sqft/yr	N/A	N/A

[1]Annually recurring expenditure.

[2]Includes: road maintenance; snow removal; security; emergency medical; fire prevention and fighting; sewage maintenance; rubbish removal; servicing high voltage lines; shuttle service (Tucson/Kitt Peak/Tucson); cargo and mail delivery; mountain library access.

[3]Includes: fraction of Superintendent's salary; snow removal; maintenance of roads, water system, power, and phone lines. Calculation based on the fraction of 35 "site units" CHARA occupies according to $-share = [(2.0 + FTE's)/35]×$130,000. It assumes 1.5 FTE's and there is no additional charge for transients.

[4]One-time expenditure [5]On-site [6]"Downtown"

The recurring costs may be significantly affected by the arrangements for any on-site rentals of residences unless this cost is passed along to the occupant. The maximum difference in annual recurring costs, excluding housing, is $23,400 for Kitt Peak – Mt. Wilson. Even with the higher site fee, the difference is also only 8% of the current estimated operating cost, which must be considered as having an even larger error bar, and is therefore not a strong driver in site selection.

TABLE 4. Site Cost Summary

Category	Kitt Peak	Mt. Palomar	Mt. Wilson
Buy-In Fee[1]	$55,000[1]	N/C	$15,000[2]
Annual Utilities	$13,460	$7,600	$4,760
Annual Site Fee	$25,700	$10,000	$11,000
Total Annual	$39,160	$17,600	$15,760

[1]Includes telephone system and 50% of dorm renovation.
[2]Covers 50% of Kapteyn House renovation.

6.9. Host Access

In addition to real operating costs, there is the effective loss to CHARA of any observing time allocated to the site host as a condition of access. While such shares are in certain cases highly appropriate and scientifically effective, they do represent a loss to CHARA of Array time. In effect, such time adds to the site fee and increases the operating costs to CHARA in terms of dollars per unit science obtained by CHARA astronomers.

Mt. Palomar anticipates an assignment of time to the host as being part of the memorandum of understanding. Although the amount is unsettled, it is likely to be in the vicinity of 15%. Dr. Wolff has expressed interest in NOAO having guaranteed access to some amount of Array time with the goal of distributing this time in some fashion to enable community access to the facility. This is consistent with the broad desire of NSF to have a degree of community access to facilities they sponsor, and NOAO has unparalleled experience in the allocation of time based on scientific merit. Mt. Wilson would not require any guaranteed time from CHARA. From the narrow perspective of CHARA's self interest, Mt. Wilson leads in this category.

6.10. Logistics and Costs Intercomparison

The various categories under this major selection criterion boil down to the following "winners":

- Accessibility – Mt. Wilson.
- Basic Infrastructure – Site neutral.
- Emergency Services – Kitt Peak.
- Living Environment – Probably site neutral except that Mt. Wilson appears to be the most cost-effective.

- Environmental Issues and Permitting – Probably site neutral.
- On-Site Technical Facilities – Kitt Peak.
- On-Site Human Resources – Probably site neutral.
- Operating Costs – Although Kitt Peak may cost ∼$25K per year more than Mt. Wilson, this represents only ∼8% of the anticipated base operating budget. Therefore, this category is considered site neutral.
- Host Access – Mt. Wilson.

Depending upon one's philosophy and judgement of possibilities and risks involved, either Kitt Peak or Mt. Wilson can emerge as the leader in this category. Under circumstances in which CHARA has not properly planned for and accomodated its technical manpower needs and under emergency situations that cannot be anticipated, Kitt Peak has the depth and breadth of technical and engineering expertise on site to bail us out. On the other hand, the California sites are located in a region that probably possesses the greatest concentration of technical talent in the nation. In any case, it should be CHARA's goal to be independent of any reliance upon other than occasional outside assistance. With this in mind, the possible advantages that Kitt Peak could have over Mt. Wilson tend to be diminished.

7. CONCLUSION

To summarize the intermediate conclusions for the three selection criteria applied to the potential sites, we have:

- **Seeing** – From its situation near a cold ocean current, Mt. Wilson is likely to possess the best intrinsic seeing conditions with Kitt Peak perhaps a close second. The data do not strongly support, nor do they refute, this assertion.
- **(u,v)-Plane Coverage** – All three sites present acceptable coverage nearly equivalent to that offered by an arbitrarily flat mesa. Mt. Palomar has some advantage in that if can provide longer baselines. However, the consensus within CHARA is that filling in the (u,v) plane is more desirable than are longer baselines.
- **Logistics and Operating Costs** – Mt. Wilson leads in this category under certain assumptions and operating goals.

Evaluation of the selection criteria defined in Section 3 points to Mt. Wilson as the most desirable site for the CHARA Array. Another way to intercompare the three sites is to point to their principle pros and cons:

Kitt Peak pros –

- The world-class infrastructure in both people and facilities could permit CHARA to tap into resources not available as other sites. The most important resource is the technical staff whose services could significantly fill out our own limited staff.

- Location at the national observatory could enhance community's recognition of CHARA and quicken the national acceptance of optical interferometry as an important tool for the next century.
- The Array would be located near the home town of a principle member of the CHARA team.

Kitt Peak cons –

- Extent to which infrastructure is available is problematic, a situation likely to be worsened by federal funding trends.
- Kitt Peak is likely to be the windiest site with deleterious effects on telescope stability.
- Buy-in and recurring costs are somewhat higher than other sites.

Mt. Palomar pros –

- A potentially powerful collaboration opportunity exists with S. Kulkarni and his students.
- The JPL ASEPS-0 testbed could be merged with the Array.
- Longer baselines and most flexible (u,v)-plane coverage are available than at other sites.

Mt. Palomar cons –

- CHARA would be first real tenant on the mountain and our impact on Caltech staff and facilities is generally uncertain.
- JPL testbed future is uncertain.
- Existing dorms are probably not sufficient to serve us.

Mt. Wilson pros –

- The best seeing conditions are probably found here.
- Optimum site overall in terms of logistics and costs.
- CHARA already operates its speckle program from here.
- 60-inch and 100-inch telescopes are potentially available to support Array science and even possibly to be incorporated into the Array.
- Berkeley interferometer, Illinois laser beacon AO, and MWI natural guide star AO projects provide complementary science and technology opportunities.

- Probably is most conducive to fund raising efforts due to location and the public knowledge of the site.
- Closest proximity to JPL where delay line work is being done.
- Space available at cost of renovation in 100-inch building.

Mt. Wilson cons –

- (u,v)-plane coverage somewhat more restricted than other sites due to terrain and existing structures.

Any of the three sites considered here would provide a very suitable home for the Array. In the balance, the potential for utilizing the extraordinary seeing encountered on Mt. Wilson gives occasional access to qualitatively different science than is likely to be reachable at the other two sites. Thus, the scales are tipped towards Mt. Wilson where the CHARA Array will play a major role in preserving an historically important observatory site and provide closure to the pioneering experiments of Michelson, Anderson, Merrill, and Pease.

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