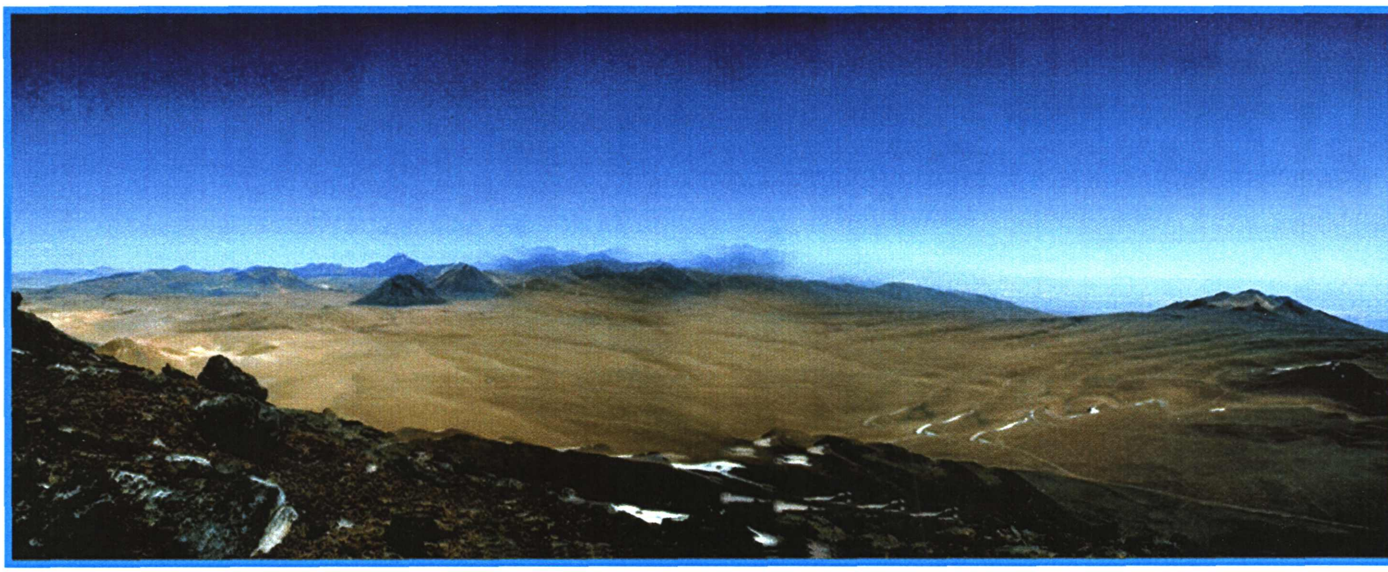
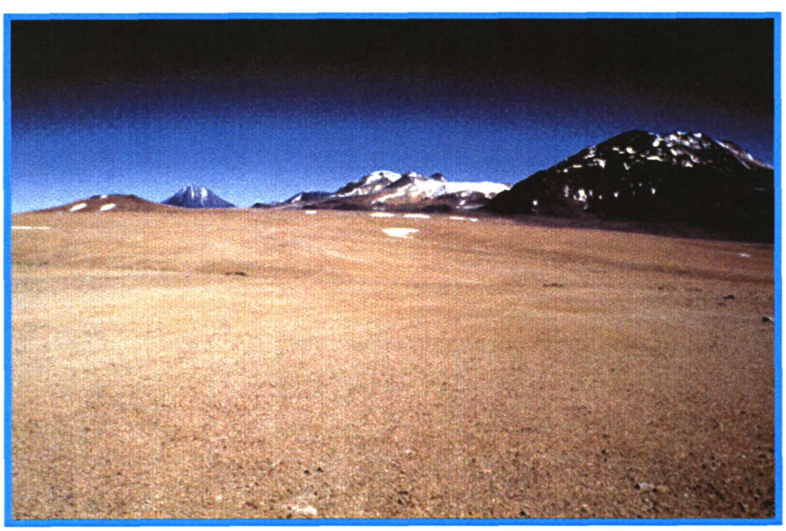
RECOMMENDED SITE





FOR THE

MILLIMETER ARRAY

NATIONAL RADIO ASTRONOMY OBSERVATORY
A facility of the National Science Foundation operated under
cooperative agreement by Associated Universities, Inc.

Upper panel: The highway leading to the recommended MMA site. The photo is taken from the MMA site looking north toward Bolivia.

Middle panel: The MMA site; the flat area shown here has an extent of approximately seven kilometers at a mean elevation of 5,000 meters (16,400 feet) above sea level.

Bottom panel: A photograph taken on the site itself.

Recommended Site for the Millimeter Array

National Radio Astronomy Observatory

May 1998

The National Radio Astronomy Observatory (NRAO) is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

EXECUTIVE SUMMARY

The Millimeter Array (MMA) will provide new and uniquely important capabilities for observational astronomy in the next century. It will extend the powerful, high-resolution imaging techniques of radio astronomy to millimeter wavelengths, where cosmic thermal objects illuminate the sky. However, unlike the situation in radio astronomy, imaging at millimeter wavelengths is greatly hindered by atmospheric water vapor and turbulence. To maximize the scientific productivity of the MMA it is therefore crucial that this facility be located where the atmosphere is extremely stable, dry, and transparent.

The MMA will achieve its goal of providing astronomical imaging with a clarity of detail comparable to that of the Hubble Space Telescope when its antennas are arranged over an area at least as large as three kilometers in extent. For the purpose of imaging a large part of the sky at low resolution, the antennas will need to be placed very close together. Thus, the site should be flat enough to allow routine reconfiguration of the many MMA antennas to provide it with this "zoom-lens" capability. It also should be located where operational infrastructure and logistical support can easily be provided. Over the past decade, candidate MMA sites in the continental U.S., in Hawaii, and in Chile have been investigated and atmospheric tests conducted.

No site in the continental U.S. meets the MMA requirements. The frequent passage of winter storms, combined with the summer incursion of moist, Gulf air, reduces to an unacceptable level the number of days on which observations are possible.

Mauna Kea on the island of Hawaii, and Llano de Chajnantor in the Altiplano of northern Chile, both meet the minimum requirements for the MMA. However, the extensive site-testing program clearly shows that Llano de Chajnantor is the superior location. The reasons are:

- The Chilean site's atmospheric transmission is so much better that four times as much science can be achieved there as can be accomplished in the same time at the Hawaiian site.

- The greater atmospheric stability of the Chilean site facilitates precision imaging; the combination of superior atmospheric transmission and stability allows the MMA to observe effectively at submillimeter wavelengths under median conditions on this site.

- Unlike the Hawaiian site, Llano de Chajnantor provides adequate space for expansion to larger MMA configurations for still higher resolution imaging in the future.

- The Chilean site can be accessed easily via a major international highway.

- The southerly latitude of the Chilean site provides a full view of the entire disk of the Milky Way Galaxy, the Galactic center, and the Magellanic Clouds (the galaxies nearest our own).

Construction and operating costs at the two sites are estimated to be comparable. Since the MMA's science may be done more rapidly, to higher precision, with greater possibility for future growth and with full access to the Milky Way if the MMA is sited in Chile, we recommend Llano de Chajnantor as the MMA site.

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1 INTRODUCTION

1.1 SITE REQUIREMENTS FOR THE MMA SCIENCE OBJECTIVES

The millimeter-wavelength range of the electromagnetic spectrum is a boundary where radio astronomy ends and infrared astronomy begins. The distinction is more than nomenclature: the richness of the radio sky is provided by non-thermal synchrotron emission from relativistic electrons, whereas the richness of the millimeter sky is produced by thermal emission from cool gas and dust, the same material that brightens the sky at infrared wavelengths. Fortunately, the aperture-synthesis techniques of radio astronomy which permit precision imaging on sub-arcsecond angular scales are directly extendible to millimeter and submillimeter astronomy. The principal scientific requirement for the Millimeter Array (MMA) is to apply radio astronomy's precision high-resolution technological tools to the imaging of celestial thermal objects. Presently, such objects can be studied only from space in the far infrared, and only with the coarse angular resolution and limited sensitivity that small orbiting telescopes provide.

As a scientific complement to the next generation of space optical and infrared telescopes, the Millimeter Array will provide images at 1-mm wavelength with the same $0''.1$ resolution achieved by the Hubble Space Telescope (HST) at visible wavelengths. This is accomplished with an MMA configuration as large as three kilometers in extent. Lower resolution imaging comes from more compact array configurations. With the MMA antennas packed closely together, astronomers will make high-fidelity images of astrophysical objects that are very much larger than the primary beam of the array antennas. The scientific goals required designing the MMA as such a complete imaging instrument. To realize this goal, the MMA site must allow easy rearrangement of the antennas.

Other principal MMA site requirements include the need for transparent and stable skies to minimize distortion of the astronomical images by the Earth's atmosphere. Water vapor in the atmosphere, which both absorbs and emits at millimeter and submillimeter wavelengths, attenuates signals from astronomical sources and creates a background of emission that limits the sensitivity achievable by the array. The only way to minimize this effect, and hence maximize the array sensitivity, is to locate the array where the air is exceptionally dry. Since water is trapped low in the atmosphere, very dry air may be found at high elevations. The search for an MMA site thus concentrated on characterizing very high-elevation, very dry sites.

1.2 DEVELOPMENT OF THE MMA PROJECT

Initial design work on a synthesis imaging telescope for millimeter wavelengths began at the NRAO in 1981. The effort was accelerated, and the community involvement broadened, in 1983 when the National Science Foundation (NSF) Astronomy Advisory Committee called for a design study for a national millimeter-wavelength synthesis array. A series of scientific workshops in the 1980s helped define the Millimeter Array from both a scientific and an instrumental perspective. Associated Universities Inc. proposed the MMA to the NSF in July, 1990.

The desired capabilities of the MMA build upon and extend those of the successful pioneering millimeter-wave synthesis telescopes—the Owens Valley Radio Observatory (OVRO) Millimeter Array and the Berkeley–Illinois–Maryland Association (BIMA) Array—in sensitivity, resolution, image quality, and frequency coverage. In particular, the MMA as proposed in 1990 provides precision, sub-arcsecond imaging at frequencies from 30 GHz to as high as 350 GHz and is fast enough to provide "snapshot" images of sufficiently high fidelity that wide-field mosaic images may be constructed.

Subsequent evolution of the MMA design was prompted by technical developments that brought dramatic increases in the MMA's scientific potential. In particular, development of niobium-based superconductor–insulator–superconductor (SIS) mixers led to wideband millimeter-wave receivers with receiver temperatures only a few times the quantum (photon) limit. Development of high-efficiency antennas with clean Cassegrain optics at BIMA led to the realization that with careful design the MMA antenna temperatures could be made extremely low. Both these technical innovations can increase the MMA's sensitivity, but the opportunity to exploit fully this design potential depends also on minimizing the MMA site's atmospheric opacity. This caused a further tightening of the MMA site requirements and led to the present realization that a site capable of allowing the MMA to exploit the potential sensitivity gains of quantum-limited electronics and clean optics at millimeter wavelengths also will support sensitive imaging at submillimeter wavelengths.

At an MMA science workshop in October 1995, the U.S. community advocated that submillimeter capability become part of the initial MMA project design. This group also emphasized that the spatial resolution improvement achieved by adding some baselines as long as 10 km would greatly enhance MMA science and should be added to the project. These two new goals put new pressure on the atmospheric quality and the physical extent of the site desired for the MMA.

1.3 SITE-TESTING PROGRAM

Developed sites for astronomical observations at millimeter wavelengths (frequencies greater than ~100 GHz) in the U.S. include the Boston area and western Massachusetts in the East, inland valleys in California and mountain peaks in southern Arizona in the West, and the summit of Mauna Kea on the island of Hawaii. The initial MMA site-selection criteria included the following: (1) latitude south of 36° N; (2) elevation greater than 9,000 feet (2743 m) above sea level; (3) area greater than 3 km in extent with a site gradient less than 10%; and (4) site potentially available. None of the existing astronomical sites met all these criteria.

From a thorough survey of U.S. topographical maps, a complete list of sites meeting the MMA criteria was established and a testing program was begun. Two potential sites in the continental U.S. appeared attractive, one in the Magdalena Mountains near the VLA/VLBA Operations Center in Socorro, NM, and the other in the White Mountains of eastern Arizona near the town of Springerville. Using a remote tipping radiometer, the atmospheric opacity at 225 GHz was measured on both sites every ten minutes over a period of a year or more. Also, the tipping radiometer made a periodic assessment of the atmospheric stability to produce a rapid time series of measurements of the zenith brightness temperature. Taken together, data from these tests were used to describe the fraction of time that it would have been possible to observe with the MMA at a given frequency and in a given array configuration (size of the array). Finally, as a point of reference, similar site-testing equipment was placed at the Caltech Submillimeter Observatory on Mauna Kea; these latter data were used to compare the potential MMA sites in the continental U.S. with a site where submillimeter astronomy is currently done effectively.

The body of site-testing data is presented in MMA Memo 79, and a comparison of the scientific utility of the two continental sites for the MMA is given in MMA Memo 68. The cumulative time of low atmospheric opacity, $\tau(225\,\mathrm{GHz}) < 0.10$, during the common year of testing on the two continental sites was greater on the site in the Magdalena Mountains than it was on the White Mountains site. The relative advantage of the Magdalena Mountains site was consistent with what would be expected because of its higher elevation (10,500 feet versus 9,100 feet). This means that high-frequency observing could be done more frequently, and more effectively, on the higher site. The atmospheric stability of the higher-elevation site also was superior, implying that long-baseline, high-resolution imaging was possible for more days each year on the Magdalena Mountains site.

While the atmospheric opacity measurements for the two continental sites differed in subtle but distinguishable ways from each other, both were found to be dramatically different from Mauna Kea. In particular, continental sites all suffer from a summer incursion of humid air from the Gulf of Mexico. This essentially precludes millimeter-wavelength astronomical observations for three months or so annually. No such effect is shown in the Mauna Kea data. Second, MMA Memo 79 points out that the "striking feature of the continental sites is the almost periodic fluctuation of the opacity on a time scale of a few days" in the winter season as storms follow the jet stream down from the Pacific Northwest. Favorable observing conditions are interrupted regularly by the passage of moist air on the continental sites. In contrast, the weather patterns in Hawaii are dictated by the comparatively steady trade winds, producing stable observing conditions lasting weeks at a time. Finally, the mean opacity of the CSO site on Mauna Kea was lower than that of the continental sites even in winter, when the continental sites provide their most favorable observing conditions. Much of this latter advantage could be expected from the higher elevation of the CSO (13,500 feet versus 10,500 feet).

The lessons of the initial MMA site-testing program were these: (1) Only a site with low mean opacity can exploit the potential scientific gain of quantum-limited electronics, and such sites are found at high elevation above the concentration of atmospheric water; and (2) Sites outside the continental U.S. provide a steady weather pattern where effective astronomical observations at millimeter wavelengths will be possible throughout the year. The sensitivity of the MMA depends exponentially on the product of the mean site opacity with a negative term; since the speed of the MMA in accomplishing a given scientific objective depends on the square of this exponential, there is an enormous advantage in locating the MMA at a truly superior site. Such sites exist only outside the continental U.S.

The second phase of the MMA site-testing program concentrated on identifying and evaluating exceptionally good, and operationally feasible, sites. Two sites generally appeared to meet these demanding criteria and received more detailed study.

1.4 CANDIDATE MMA SITES

1.4.1 General Site Descriptions

Two sites were identified that meet all the scientific and technical requirements of the MMA, and measurements of the atmospheric transparency and stability (the "seeing") at millimeter wavelengths were made at these sites. The testing program is described in Section 2 of this report. The two sites are: (1) Mauna Kea on the island of Hawaii and (2) a region in the Altiplano of northern Chile near Cerro Chajnantor which we will call "Llano de Chajnantor." Both sites are at high elevation, well above most of the atmospheric water vapor. Both are at equatorial latitudes, near the tropic of Cancer or the tropic of Capricorn, where seasonal variations are minimized.

1.4.2 Mauna Kea

Mauna Kea is a 13,796-foot-high volcanic shield located on the island of Hawaii. Since 1968, the University of Hawaii (UH) has managed the development of Mauna Kea as a resource for observational astronomy under the terms of a sixty-five-year lease from the State of Hawaii Board of Land and Natural Resources. The lease sets aside 11,200 acres of land above 12,000-foot elevation as the Mauna Kea Science Reserve (MKSR). The UH Board of Regents adopted a Research Development Plan for the MKSR in 1983 that projects construction of thirteen telescopes in the area of the summit by the year 2000. Among these are the Caltech Submillimeter Observatory (CSO); the James Clerk Maxwell Telescope (JCMT), a submillimeter instrument; and the Submillimeter Array (SMA), under construction by the Smithsonian Observatory.

In addition to these thirteen telescopes, all of which exist or are under construction, an antenna facility for the VLBA is located at the 12,200-foot level of the MKSR.

As a developed, high-altitude astronomical site that currently supports submillimeter observatories, Mauna Kea is, in principle, a very attractive site for the MMA. Although the summit area of the mountain is not large enough to accommodate the large three-kilometer configuration of the MMA, it is possible to locate this configuration within the MKSR at the 12,200-foot level on the shield directly east of the summit (Figure 2). This area is to the north of the VLBA antenna, and, for convenience, we refer to the area as Mauna Kea/VLBA (or MK/VLBA). The MMA site atmospheric testing equipment was located adjacent to the VLBA antenna.

The MMA is not among the thirteen telescopes included in the 1983 Research

Development Plan for the MKSR. Access to this site for the MMA thus would involve the project in the entire panoply of actions needed to develop a post- year-2000 Research Development Plan for the MKSR that would incorporate the MMA as one element of the Plan. The governing bodies of MKSR and the citizens of Hawaii would decide whether it was in their interest to include the MMA in the future MKSR development.

1.4.3 Llano de Chajnantor

Extending over thirty-eight degrees of latitude, from 18° S to 56° S (equivalent in the North to the range in latitude from Mexico City to Juneau, Alaska), Chile experiences the full range of climatic conditions. In particular, the northern region is dominated by the spectacularly dry Atacama Desert, while on the east the Andes bound the country. The Andes Mountains mark the zone of convergence where the Nazca oceanic plate is subducted beneath the South American plate. On this margin in the Andes of northern Chile lies the 4,000–5,000-m high Altiplano. The presence of such a high plateau adjacent to perhaps the driest area on Earth provides a uniquely suitable site for a synthesis telescope such as the Millimeter Array.

In selecting an area of the extensive Altiplano suitable for operating the telescope, our two principal concerns were access to the site and proximity to a community from which MMA operations could be supported. Such a site was located on the Altiplano at 16,400-foot (5,000-m) elevation 50 km east of the historic village of San Pedro de Atacama (see Figure 1). The site is accessible via the Paso de Jama, the main international highway connecting the Chilean port of Antofagasta and the northern provinces of Argentina. The site itself is at the highest point of the Altiplano in that region of Chile and is exposed to the unobstructed prevailing westerly winds; this should provide for a laminar airflow across the site. The MMA testing equipment is located near Cerro Chajnantor, on the plain which is called Llano de Chajnantor (Figure 3).

Llano de Chajnantor is Fiscal Land, public land held by the Republic of Chile under the stewardship of the Ministerio de Bienes Nacionales. Recognizing its potential as a site for scientific research, and after contacts with the NRAO, the Chilean National Scientific and Technical Research Commission (CONICYT) has requested a concession of the land from the Ministerio de Bienes Nacionales. Conditions under which the MMA may operate in Chile will be similar to those specified for other astronomical institutions, including respect for the site environmental-assessment process, compliance with labor laws, and allocation of observing time to Chilean scientists and students.

Locating a telescope site outside the United States is a new undertaking for the NRAO and would not be feasible were it not for the substantial encouragement and support given to the MMA project by the Chilean astronomical community. Radio and millimeter-wave astronomy is an active component of university research in Chile, and the people involved have been instrumental in promoting the MMA locally. The site-testing program is being done collaboratively with the University of Chile. Chilean atmospheric scientists share in the testing data; they will be partners in a program of radiosonde measurements on the site that will complement the ongoing opacity measurements. Chilean geophysicists are conducting long-term seismological studies, using

Figure 1: Northern Chile. Note Santiago at the bottom and Antofagasta near the top, on the coast. The MMA site (Llano de Chajnantor) is identified by the large black dot near the upper right of the figure. The road just to the north of the MMA site is the Paso de Jama international highway. Latitude grid lines at 24° S and 30° S are shown on the map. The air-travel distance between Santiago and Antofagasta is 660 miles.

precision accelerometers provided by the NRAO, to characterize the site and to provide a sound risk assessment. This involvement of the Chilean university community is an indispensable asset that makes real the possibility of a Chilean site for the MMA. This involvement is further detailed in Section 3.

2 CHARACTERISTICS OF PROSPECTIVE MMA SITES

2.1 INTRODUCTION

The site-testing program on Mauna Kea and Llano de Chajnantor used the same 225-GHz tipping radiometers as were employed earlier at the continental U.S. sites. These instruments were used to make opacity and stability measurements, as described in Section 1.3, at the offshore sites. These data, combined with standard atmospheric models, allow us to estimate the transparency across the millimeter and submillimeter spectrum. Wind velocity and ambient temperature also were recorded as before. In addition, a "seeing" interferometer with a 300-m baseline was stationed on each site. This interferometer looks continuously at a geo-stationary satellite and monitors the phase on this baseline at 11.5 GHz. These phase measurements, and to a lesser extent the stability measurements from the tipping radiometers, are used to assess the phase fluctuations expected at millimeter and submillimeter wavelengths.

Before we started, we expected the atmospheric opacity to be a factor of two lower on the Llano de Chajnantor than on the Mauna Kea site, based solely on the exponential decrease in water vapor with elevation. The phase stability was more of an unknown, since the atmospheric turbulence does not correlate very well with the amount of water vapor. The wind velocity expected on the Chilean site also was only poorly known.

The MMA site-testing program is being conducted in collaboration with the Chilean astronomical community, the Nobeyama Radio Observatory (NRO), and the European Southern Observatory (ESO). The NRO is studying possible sites in Chile for the Large Millimeter and Submillimeter Array (LMSA), including Pampa la Bola, near Llano de Chajnantor. ESO is evaluating sites in northern Chile for the Large Southern Array (LSA). By sharing the site-testing data, we and our colleagues can better characterize the possible observing conditions at high-elevation sites in northern Chile.

Since the statistics for both sites cover more than a year, all measured quantities have been averaged by month. For months sampled more than once, the median values for the different years observed have been averaged to determine the best estimate for the conditions during that month. All other statistics, e.g., diurnal and yearly statistics, are averages or medians of results that were first calculated by month.

2.2 TOPOGRAPHY

Figures 2 and 3 are 30-km-scale contour images of each site with 100-m elevation contours. Also superimposed is a 3-km ellipse representing the proposed array configuration. Layout of a 3-km configuration clearly is possible on both sites. However, Figures 2 and 3 show two important differences: First, the elevation change across a 3-km ellipse on the Mauna Kea site is much larger than on Llano de Chajnantor. Second, the maximum possible baselines within the Mauna Kea Science Reserve (above 3,550 m) are much less than 10 km. In fact, given the steep slopes, the maximum baseline does not

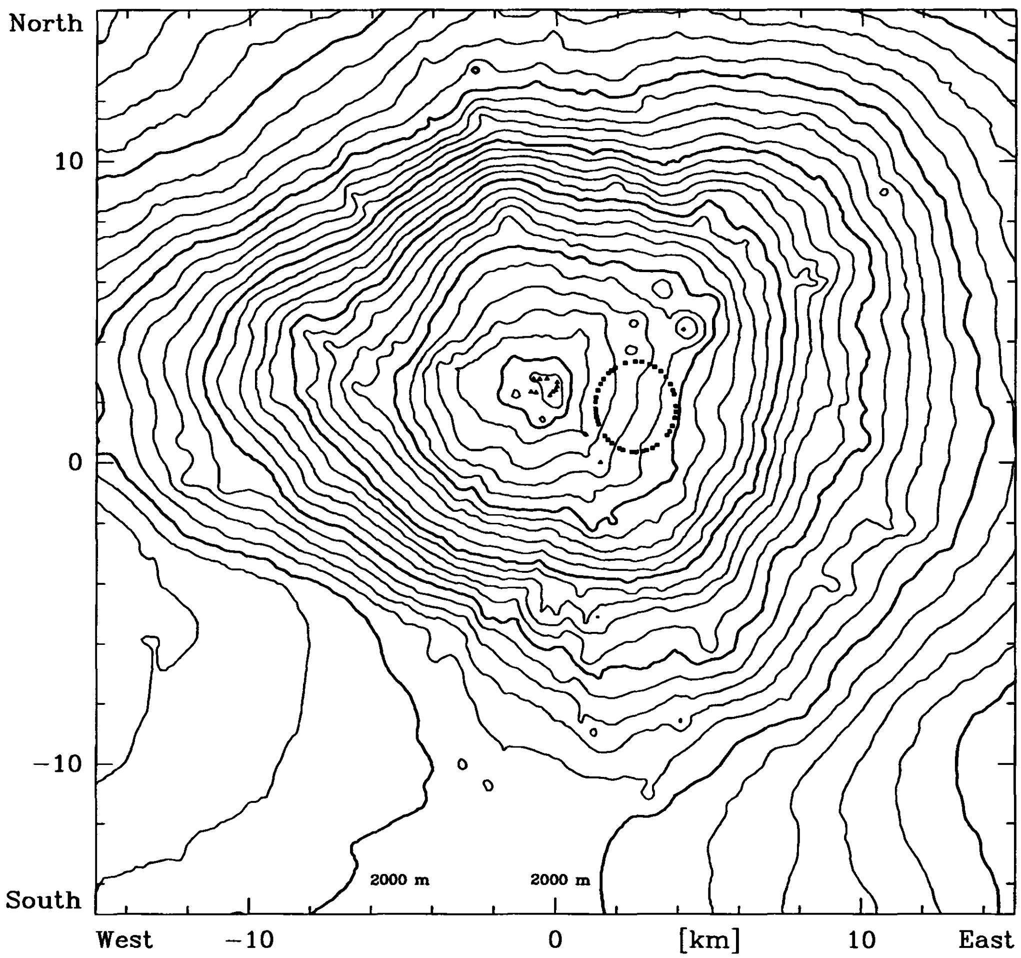

Figure 2: Summit area of Mauna Kea, showing a possible layout for a 3-km array (the ellipse of squares) and the approximate positions of existing telescopes (the clump of triangles near the summit and the lone triangle, the VLBA antenna, southwest of the ellipse). The contour interval is 100 m.

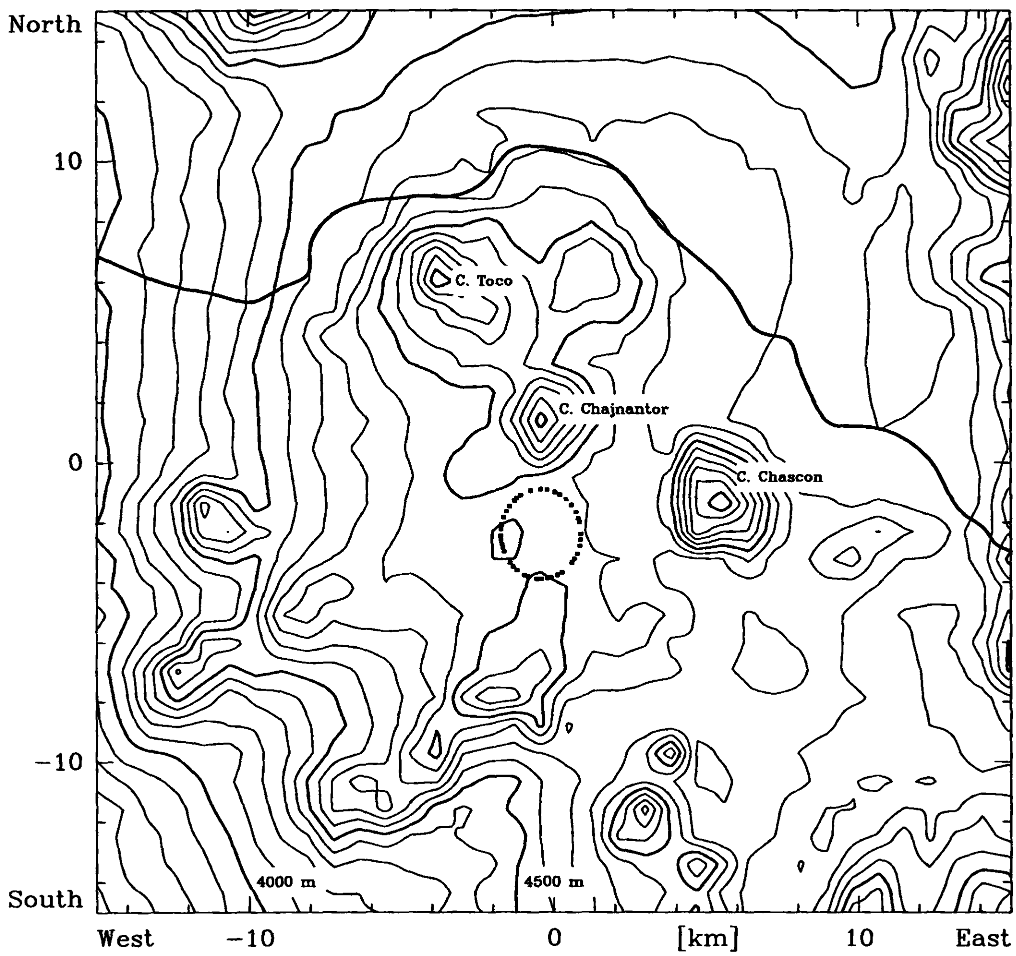

Figure 3: Environs of Cerro Chajnantor, Chile, showing approximate positions of a possible layout of a 3-km array (squares). The contour interval is 100 m. The Paso de Jama highway, shown as a dark line running north of Cerro Toco, runs approximately East–West just north of Cerro Toco.

Table 1: Site Characteristics

	Mauna Kea Hawaii	Llano de Chajnantor Chile
Longitude	155°28′ W	67°45′ W
Latitude	19°48′ N	23° 1′ S
Altitude	3720 m	5000 m
Survey Period:		
start	1995 March	1995 April
stop	1996 June	1996 October
Temperature:		
minimum	− 2° C	−21° C
median	+ 6° C	− 4° C
maximum	+17° C	+22° C
Wind:		
25th percentile	$3\,m\,s^{-1}$	$3\,m\,s^{-1}$
50th percentile	$5\,m\,s^{-1}$	$6\,m\,s^{-1}$
75th percentile	$7\,m\,s^{-1}$	$10\,m\,s^{-1}$
maximum	$30\,m\,s^{-1}$	$35\,m\,s^{-1}$

exceed the extent of the 3-km ellipse by much. Conversely, the maximum baselines on flat land near 5,000 m on the Llano de Chajnantor are measured in tens of kilometers. Thus only Llano de Chajnantor could provide the much higher resolution imaging that was recommended by the 1995 MMA Science Workshop.

Figure 3 shows that Llano de Chajnantor is not the highest ground in this region. Three peaks reach 5500 m. One of these, Cerro Toco, is accessible to these elevations by automobile now. Other, slightly higher, sites are reachable by road within 50 km of San Pedro de Atacama. Thus, location of the MMA on Llano de Chajnantor could provide a base for future astronomical sites at still higher elevation.

2.3 CLIMATE

Overall, Llano de Chajnantor is colder than Mauna Kea (Table 1), as expected from its higher altitude. However, neither site has particularly extreme temperatures, so this is not seen as an issue. The estimated precipitation on Llano de Chajnantor is 10 cm per year (SAO Submillimeter Array Memo 59). For the Mauna Kea site the average precipitation is 51 cm per year (MMA Memo 113).

The wind velocity statistics for the two sites are not strikingly dissimilar (Table 1). Figure 4 shows that the wind speed on Llano de Chajnantor is higher after noon, while Mauna Kea's median winds are almost constant. Strong winds may hinder accurate antenna pointing, delay array reconfigurations, and potentially damage equipment. However, the normal winds are fairly mild on both sites—although on Llano de Chajnantor they may require scheduling reconfigurations to avoid the mid-afternoon peak

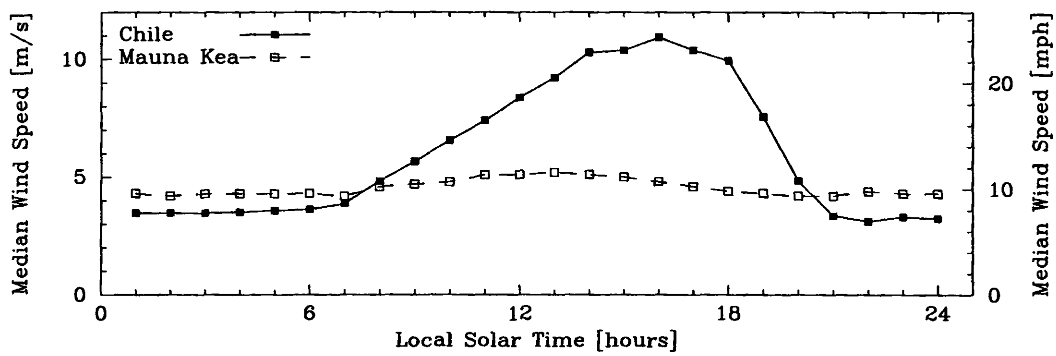

Figure 4: Diurnal variation of median wind speed on Llano de Chajnantor *(solid)* and Mauna Kea *(dashed)*. Local solar time is UT minus $4^h.5$ on Llano de Chajnantor and UT minus $10^h.4$ on Mauna Kea.

winds. The winds on both sites should allow the highest-precision pointing planned for the MMA (~1 arcsecond) more than half of the time (MMA Memos 145 and 159). Exceptional winds are probably higher on Mauna Kea than on Llano de Chajnantor, because hurricanes sometimes cross the Hawaiian Islands. Wind speeds greater than $50\,\mathrm{m\,s^{-1}}$ (110 mph) are not uncommon at the Mauna Kea summit. During the survey period, however, the highest measured wind speeds at the two sites were of about the same magnitude (Table 1).

2.4 TRANSPARENCY

The cumulative distributions of opacities measured on Llano de Chajnantor and on the Mauna Kea site during our survey are shown in Figure 5. As expected from the altitude difference, opacity quartiles on Mauna Kea are 2 to $2\frac{1}{2}$ times higher than for Llano de Chajnantor. This difference has a profound effect on the sensitivity of the array. In millimeter bands where we expect the system temperature to be dominated by the atmosphere, the measured difference corresponds to a factor of $1\frac{1}{2}$ to $2\frac{1}{2}$ improvement in sensitivity of the array in the most transparent submillimeter windows. The relative speed of the array to accomplish a given scientific objective is the square of this ratio. Thus, a program of scientific observations that would take the MMA twelve months to do on Mauna Kea could be done in about three months on the Llano de Chajnantor site.

The expected performance in the submillimeter is shown in Figure 6 for the best 25% of the time on each site. The combination of the lower water vapor and the lower atmospheric pressure should open up large windows above 350 GHz which are available rarely on Mauna Kea. Thus the Chajnantor site offers a substantial advantage for submillimeter observations.

Also, on Mauna Kea there is a prominent, and well known, diurnal variation in transparency (Figure 7). The median optical depth on Mauna Kea rises to twice as high during the day as at night. This effect is caused by the inversion layer, which traps

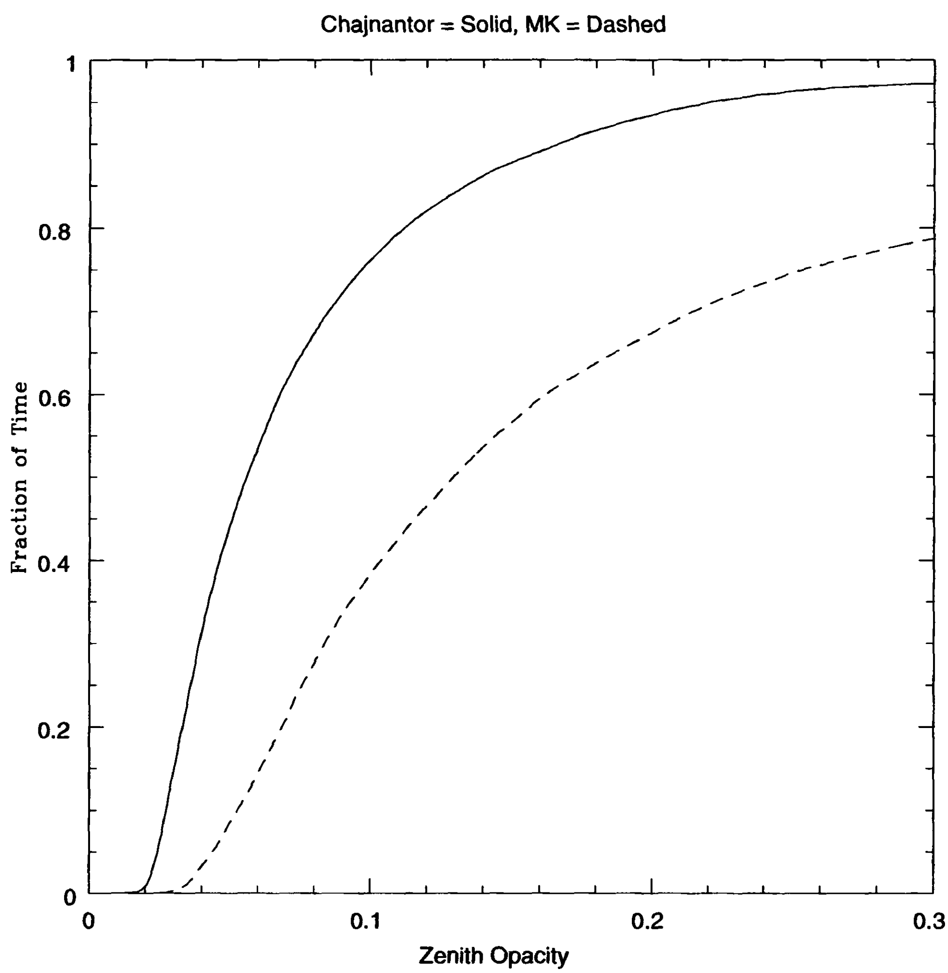

Figure 5: Cumulative distributions of 225-GHz zenith optical depth, τ_{225}, on Llano de Chajnantor *(solid)* and Mauna Kea *(dashed)*. The distributions were first averaged by month, and then the distributions for each of the twelve months were averaged to produce the final curve.

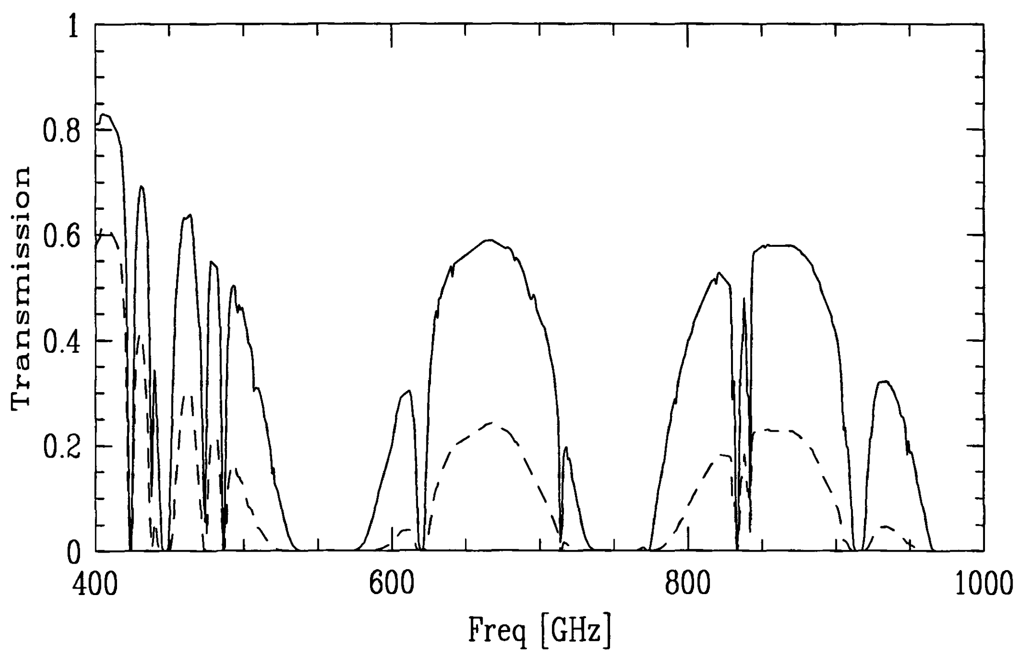

Figure 6: Atmospheric transmission at submillimeter wavelengths for the best 25% of the time on Llano de Chajnantor *(solid line)* and on the Mauna Kea site *(dotted line)*, from the model of Grossman (AT Program Ver. 1.5, 1989). For clarity, some minor atmospheric lines have been omitted from the plot.

atmospheric water: as the daytime air is heated, the inversion rises above the mountain summit; and when the air cools at night the inversion descends, carrying the water with it. This diurnal effect would significantly limit the daytime productivity of the MMA on Mauna Kea. This effect is much smaller on Chajnantor and almost non-existent there during the winter. The lack of significant diurnal variation in the transparency suggests the MMA would be usable both day and night on Llano de Chajnantor.

Both sites showed seasonal transparency variations (Figure 8). On Chajnantor, the best conditions were during the winter (April–October), when the median optical depth was 0.042. During the summer (November–March), the median optical depth, 0.087, was roughly twice as large as in the winter. In both seasons, the transparency at Chajnantor was superior to that measured on Mauna Kea during its best months.

Are these results typical, or did we just sample a bad year on Mauna Kea and/or a good one in Chile? For Mauna Kea, we have five years of data from the tipping radiometers which show that the seasonal variation during our survey was somewhat unusual but that the overall yearly median was typical (Figure 9). For Llano de Chajnantor, we have only $1\frac{1}{2}$ years of data with the tipping radiometer, but a detailed comparison with opacities estimated during the same period using the radiosonde data from Antofagasta shows a good correlation. Thus, we can use the radiosonde data available back to 1988 to evaluate the long-term trend. These data, and the opacities for 1995–96 measured with the tipping radiometer on Llano de Chajnantor, are shown in Figure 10. These results suggest the overall conditions on both sites were representative of the recent past and thus are probably a good indication of what we can expect in the future.

2.5 PHASE STABILITY

The remaining issue is the atmospheric phase stability, or "seeing." Because radio waves travel more slowly in wet air than in dry air, fluctuations in the water-vapor content above the MMA will cause variations in the electrical path length through the atmosphere. Path-length variations across the array aperture will degrade both image quality and array sensitivity. Path-length fluctuations, which are almost independent of observing frequency at millimeter wavelengths, correspond to phase fluctuations that scale linearly with frequency. Numerical simulations of MMA data with a realistic model atmosphere show that phase fluctuations of less than 10° rms at the observing wavelength will have little impact upon most imaging. Phase errors of 30° rms will permit imaging with up to 200:1 dynamic range, at somewhat reduced sensitivity. Image reconstruction becomes all but impossible with phase errors higher than 60° rms. We expect either fast switching or phase calibration from total-power or line observations to allow imaging when conditions are worse than this; however, the better the absolute stability is, the easier it will be to make use of these correction schemes (MMA Memos 139 and 144).

Atmospheric phase stability was measured with a 300-m baseline, 11.5-GHz interferometer observing geo-stationary communications satellites (Radford, Reiland, & Shillue 1996, PASP, 108, p. 441). Because the atmosphere is non-dispersive away from line centers, these measurements can be extrapolated to characterize the atmospheric

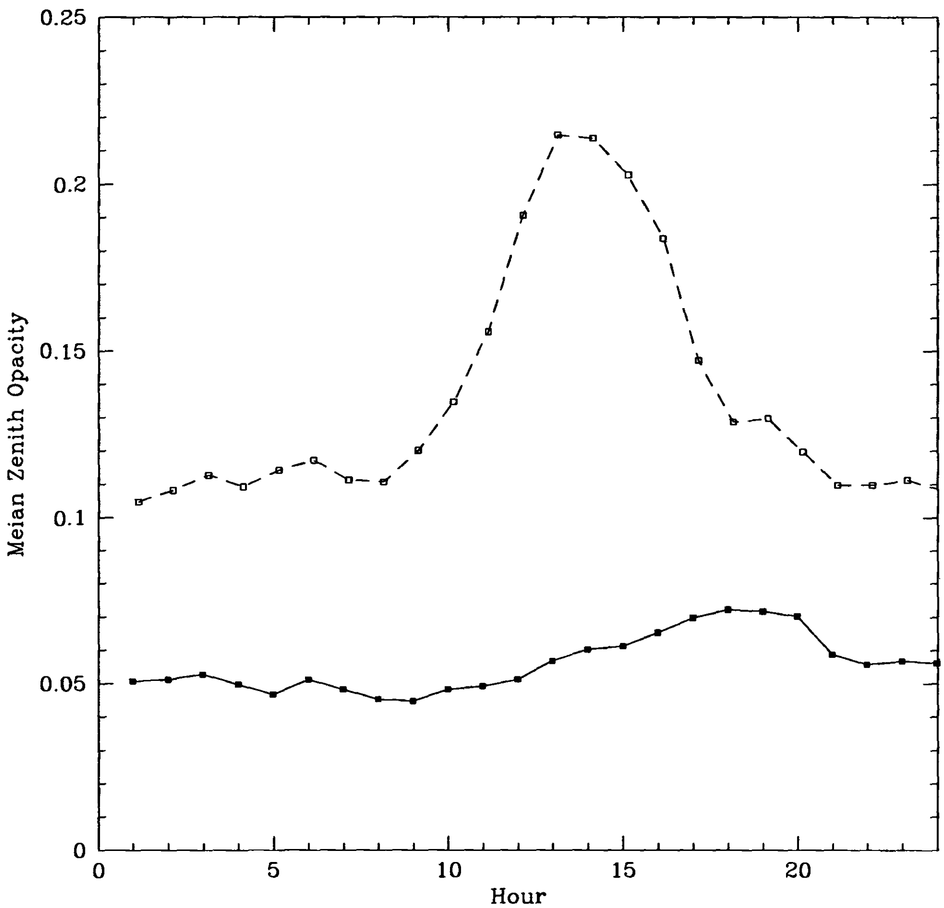

Figure 7: Diurnal variation of median 225-GHz zenith optical depth, τ_{225}, on the Mauna Kea site *(dashed)* and Llano de Chajnantor *(solid)*. Local solar time is UT minus $4^{\rm h}\!.5$ on the Chajnantor site and UT minus $10^{\rm h}\!.4$ on Mauna Kea.

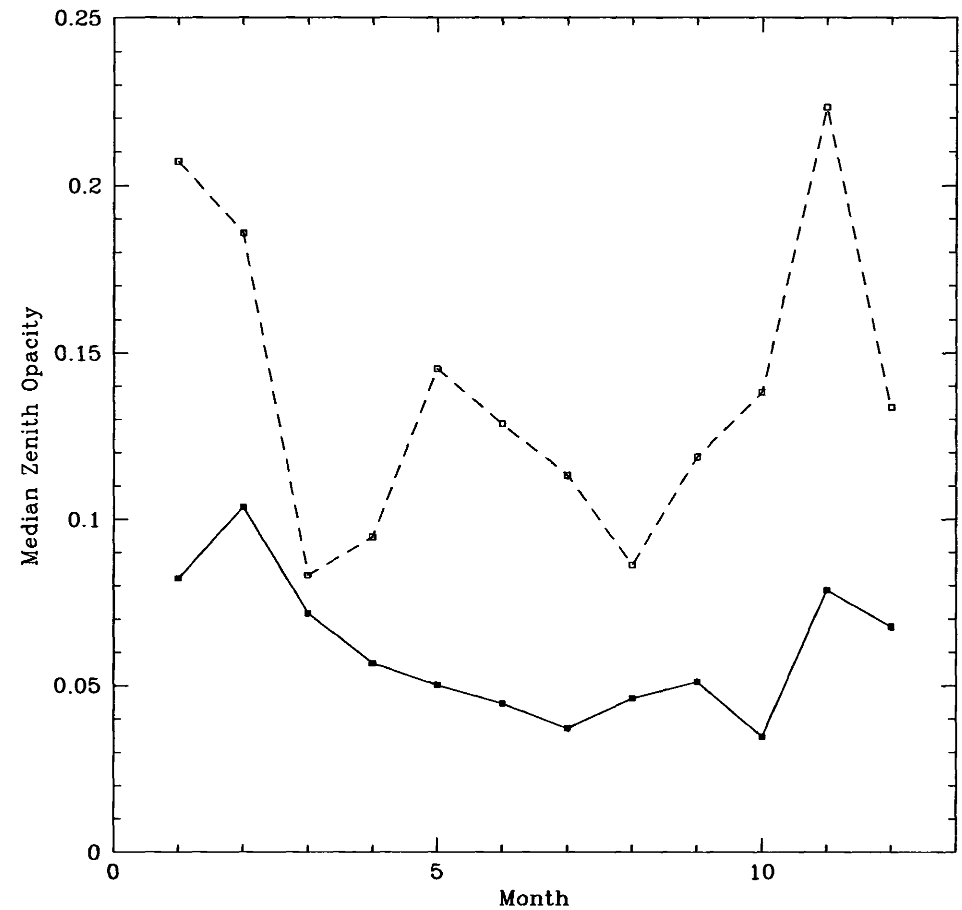

Figure 8: Seasonal variation of median 225-GHz zenith optical depth, τ_{225}, on the Mauna Kea site *(dashed)* and on Llano de Chajnantor *(solid)*.

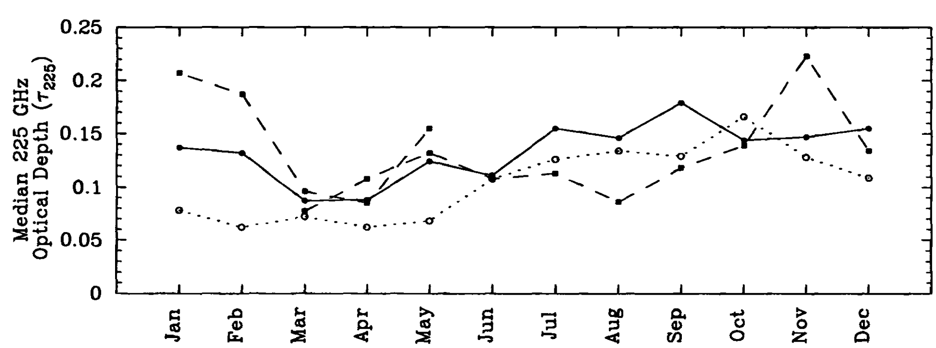

Figure 9: Seasonal variation of median 225-GHz zenith optical depth, τ_{225}, on Mauna Kea for 1995–96 at the VLBA site *(dashed)*, several years at the CSO *(dotted)*, and several years, including 1995–96, at the VLBA site *(solid)*.

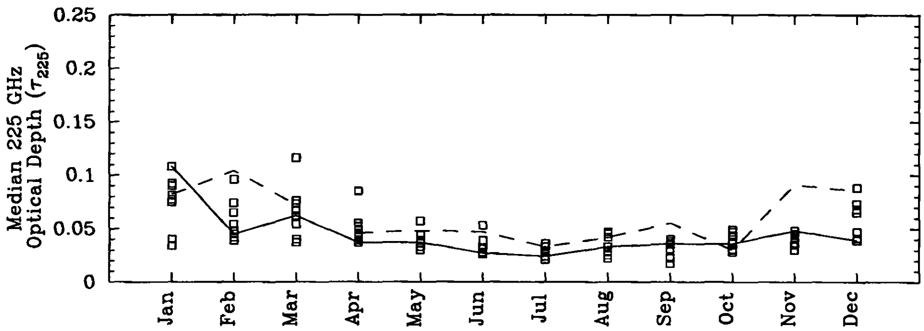

Figure 10: Seasonal variation of median 225-GHz zenith optical depth, τ_{225}, on Llano de Chajnantor for 1995–96 *(dashed)* compared with optical depth deduced from 1988–95 Antofagasta radiosonde data. The 1995 radiosonde data are connected *(solid)*.

phase stability up to at least 350 GHz. These interferometers sense atmospheric structures of about 300-m and smaller scales. To compensate for the different elevation angles of the satellites observed from the two sites, we corrected the phase fluctuations to the zenith (MMA Memo 127). We characterize the phase stability by the rms phase fluctuations calculated over 10-minute intervals. This interval is twenty times longer than the time it takes an atmospheric feature to move the length of the baseline at $10\,\mathrm{m\,s^{-1}}$, which is the median wind speed aloft. Thermal instrumental phase noise is on the order of $0\overset{\circ}{.}1$ rms at 11.5 GHz, while the smallest rms phase fluctuation seen to date—after correcting for instrumental noise—is $0\overset{\circ}{.}3$ rms at 11.5 GHz (MMA Memo 139).

While the best phase conditions at the two sites are similar (Figure 11), the median phase stability on 300-m baselines at Llano de Chajnantor is about 25% better than on Mauna Kea. In practice, we are interested in observing on much longer baselines than 300 m, on which the phase stability will be worse. However, we can accurately model the use of fast switching under the power spectrum of fluctuations determined by the interferometers. This analysis shows that we can expect to be able to image coherently at 230 GHz on baselines longer than 300 m about 65% of the time on Mauna Kea and about 75% of the time on Llano de Chajnantor (MMA Memo 139). The Chilean site thus offers somewhat better stability, but not by as large a factor as the difference in opacity.

Both sites show a significant diurnal variation in phase stability (Figure 12). On Mauna Kea, there is a dramatic, and well known (e.g., Masson 1994, IAU Colloquium 140, p. 87), increase in phase fluctuations during the day that parallels the increase in opacity. At local noon, the median phase stability is about seven times worse than at midnight. On the Chajnantor site, the same pattern can be seen, but the peak effect occurs at a lower level. This will limit the observations which are possible on either site during the day; the exact details depend on frequency, array configuration, and the phase-calibration technique employed.

However, if we divide the year into the best and worst halves for phase stability, a different pattern occurs on the two sites (Figure 13). On Mauna Kea, the phase

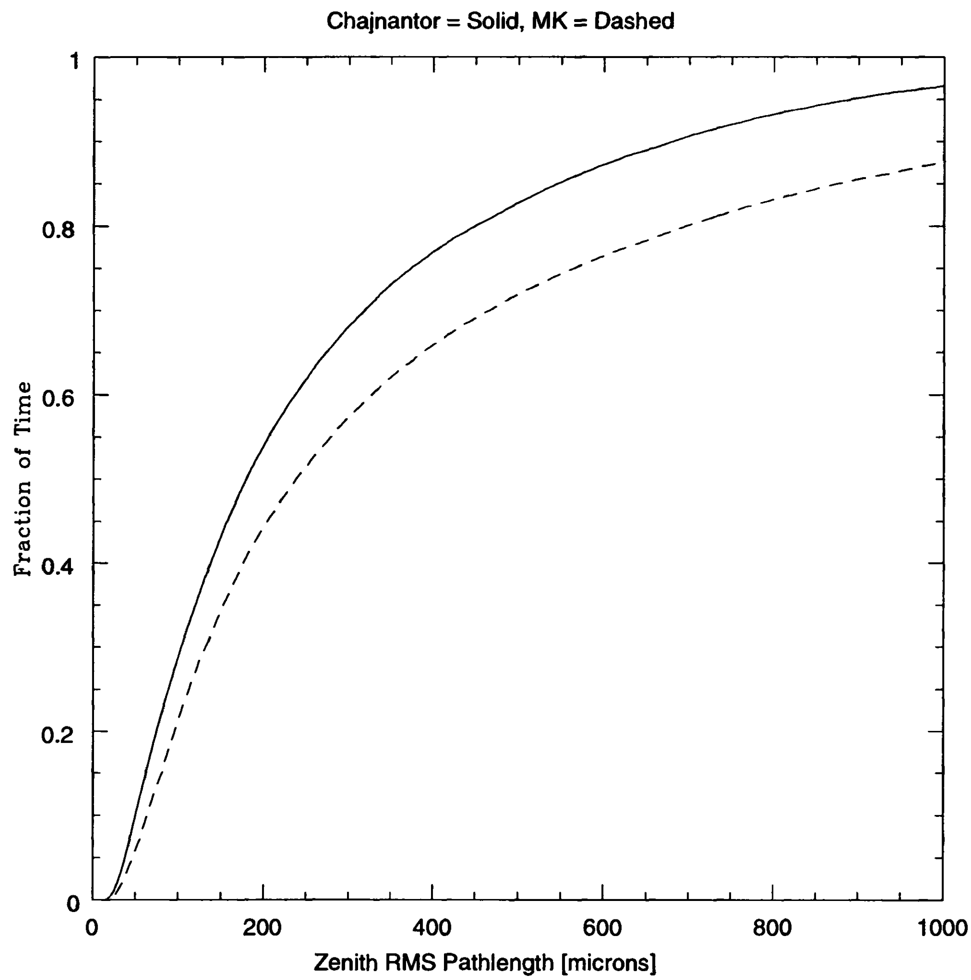

Figure 11: Cumulative distributions of rms path-length fluctuations on a 300-m baseline on Llano de Chajnantor *(solid)* and Mauna Kea *(dashed)*.

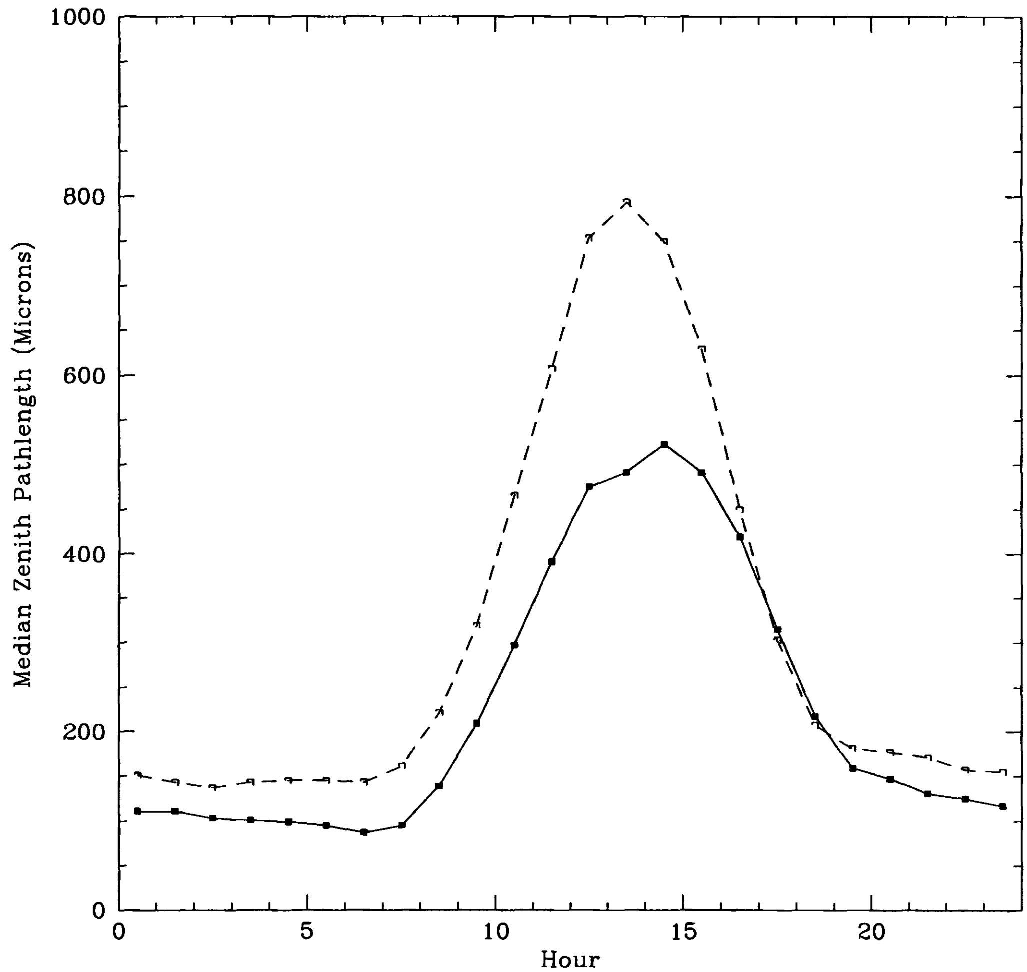

Figure 12: Diurnal variation of median rms path-length fluctuations on Llano de Chajnantor *(solid)* and Mauna Kea *(dashed)*. Local solar time is UT minus $4^{h}.5$ on Llano de Chajnantor and UT minus $10^{h}.4$ on Mauna Kea.

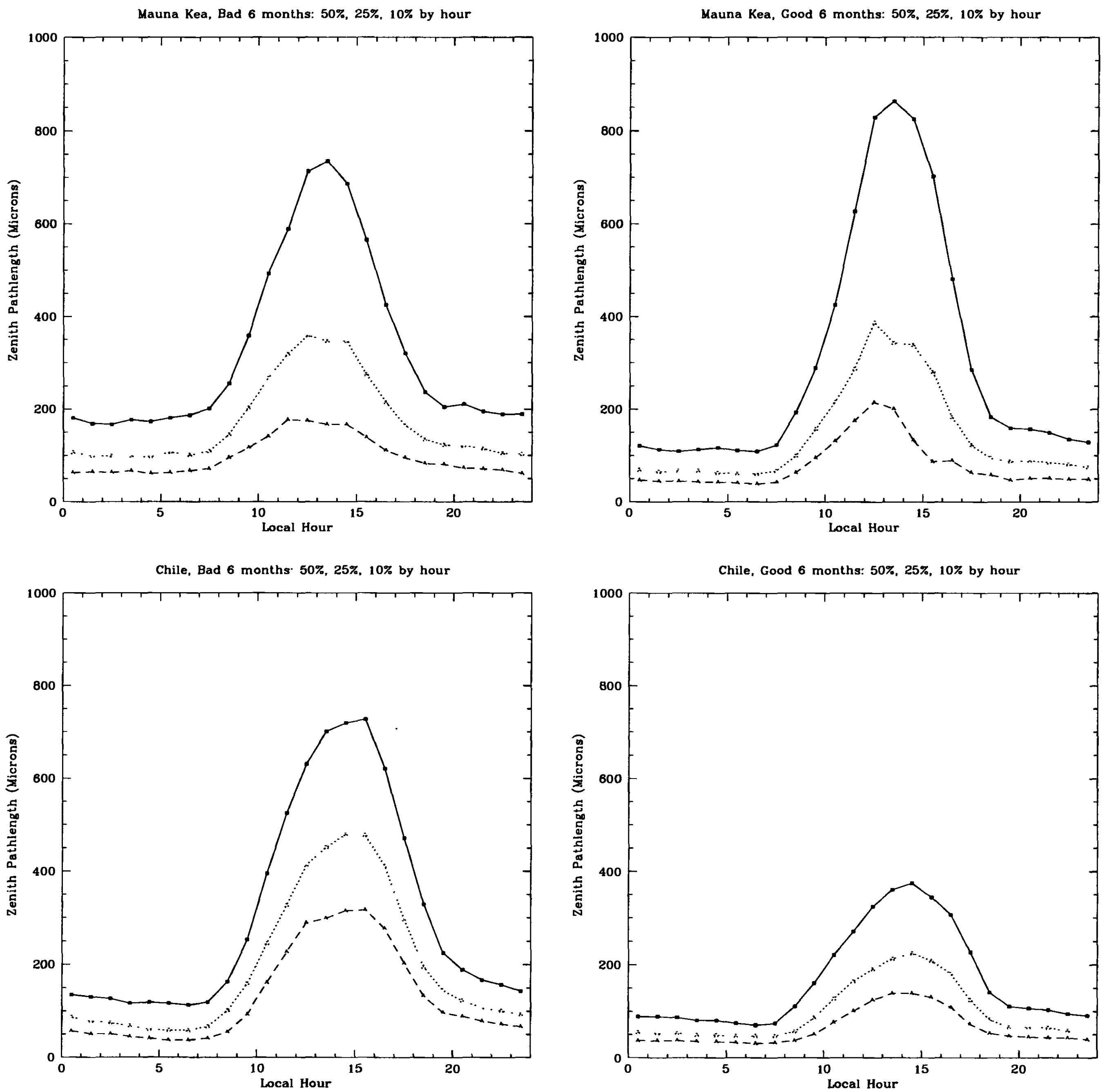

Figure 13: Diurnal path-length fluctuations for the best and the worst six months on each site: *(solid)* — 50^{th} percentile; *(dotted)* — 25^{th} percentile; *(dashed)* — 10^{th} percentile.

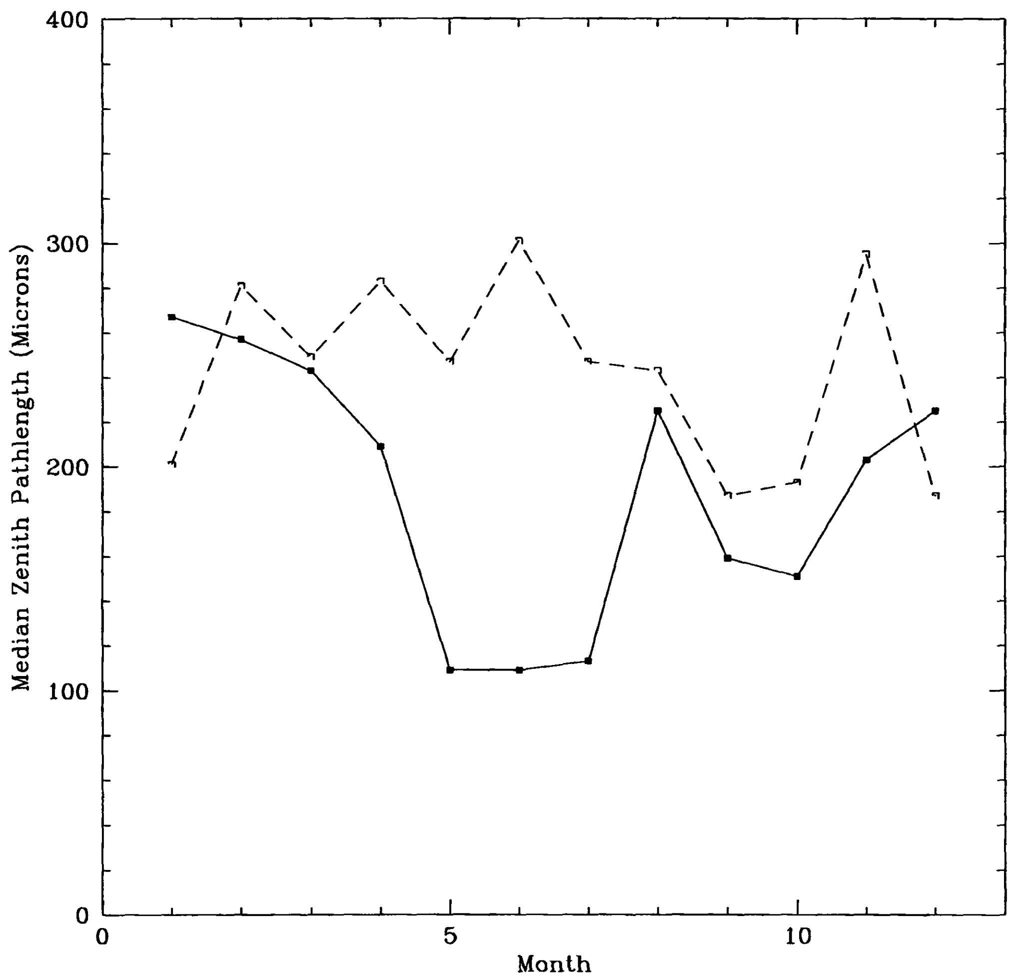

Figure 14: Seasonal variation of median rms path length fluctuations *(left scale)* and equivalent 230 GHz phase fluctuations *(right scale)* on Llano de Chajnantor *(solid)* and Mauna Kea *(dashed)*.

stability is very similar for the two halves of the year. On Llano de Chajnantor, the stability during the worst six months is similar to that found year-round on Mauna Kea. However, during the best six months, conditions are much better on the Chilean site. This period is during the Chilean winter, when the best opacities also occur. This winter period of exceptionally good atmospheric stability and transparency sets the Chajnantor site apart from Mauna Kea and provides suitable conditions for the most demanding scientific observations.

On both sites, seasonal variations in phase stability (Figure 14) are less pronounced than diurnal variations. The best conditions are in the winter. On Llano de Chajnantor, the diurnal variation in phase stability is also much less extreme in winter than in summer. Thus, during the Chilean winter, high-resolution observations are possible around-the-clock much of the time, while daytime observations would only rarely be possible on Mauna Kea.

2.6 CONCLUSION

The results of the site-testing program show clearly that Llano de Chajnantor is superior to Mauna Kea as the site for the MMA. Both sites would meet the minimum MMA goals for millimeter-wave operation and three-kilometer baselines. However, atmospheric transparency and phase stability on Llano de Chajnantor will allow the array to operate more of the time and with better sensitivity than would be possible on Mauna Kea. Furthermore:

- The transparency at the Chajnantor site will allow the array to operate much more effectively at submillimeter wavelengths;

- The extensive Altiplano on which the Chajnantor site is located permits future expansion to baselines longer than ten kilometers, with a corresponding increase in angular resolution; there is no room for such expansion on Mauna Kea;

- The Chajnantor site includes accessible mountain peaks at elevations above 5500 m, for future astronomical instruments that will be limited by atmospheric water vapor;

- At latitude 23° S at Chajnantor, the MMA will have unfettered access to the center of the Milky Way, the entire plane of the galaxy, including both of the inner quadrants and the rich molecular clouds present therein, the Magellanic Clouds, and the nearest radio galaxy, Centaurus A;

- The Chajnantor site provides visibility of 90% of the sky, including all declinations from $-90°$ to $+57°$.

Based on the testing data and the physical attributes of the sites, we recommend Llano de Chajnantor as the site for the MMA. The remaining question is whether it is feasible for NRAO to develop and operate a new site at 5000-m elevation on the Chilean Altiplano. In the next section of this report, we consider this question and compare the costs of building and operating the MMA in Chile and Hawaii.

3 FEASIBILITY OF THE MMA ON LLANO DE CHAJNANTOR

3.1 INTRODUCTION

Questions about the feasibility of operation in Chile can be grouped into two classes. First are questions about the safety and practicality of operating on such a high, dry site surrounded by volcanic peaks: How do we deal with the physiological problems of operating on a site at 5,000 m? Is there significant danger of geophysical damage to the array on this site? Second are questions of logistics and organization: Is sufficient logistical support available within Chile to build a complex instrument in the Altiplano? Can we organize and staff a major observatory in this relatively undeveloped location?

To help answer these questions we consulted experts on each subject. For geophysical questions, we drew on the expertise of the geophysicists at the University of Chile. For physiological issues, we worked with several medical experts, especially John West, M.D., Ph. D., from UCSD, who specializes in high-altitude medicine in general and as applied to northern Chile in particular. We also consulted with people at the observatories on Mauna Kea. We discussed operational questions with two former directors of CTIO, as well as with a number of other individuals who are experts on various aspects of operating astronomical and other facilities in Chile. We also have begun to build our own expertise in Chile by operating an atmospheric testing system on Llano de Chajnantor. Below, we summarize our findings and how we plan to address the problems. More detailed discussions of some of these issues are available in the reports of the consultants we engaged as referenced below.

3.2 GEOPHYSICAL CONSIDERATIONS

Chile's geological activity is well known. Earthquakes are a regular feature of Chilean life, and Llano de Chajnantor is surrounded by volcanic cones. To assess the geological risks at the Chajnantor site, we commissioned two reports by the University of Chile geophysics department in Santiago: one on volcanism and one on seismicity. Below we summarize this material.

3.2.1 Volcanism

This section is a summary of the report, "MMA Site East of San Pedro de Atacama, North Chile—Volcanic Hazards Assessment and Geologic Setting," by Dr. Moyra G. Gardeweg P., Department of Geology, University of Chile.

Normally, a volcano is considered active if it has erupted in historic times. However, in Chile historic time is only 400 years. Thus a volcano there is considered active if it has shown out-gassing or smoking during historic times. Under this definition, there are three active volcanos within about 60 km of Llano de Chajnantor. Two of these are Putana (55 km NW) and Sairecabur (37 km NW). Neither has erupted in historic times. Putana continues to smoke, but Sairecabur is considered active only on the basis of altered ground material. Lascar (40 km S), on the other hand, had a major explosive eruption in 1993, and strong activity dates back to 1848.

The risk to Llano de Chajnantor from these volcanos is considered minimal. First, the most extreme events associated with eruptions in this part of the Andes—e.g., lava flows and ejecta from eruptions—are not known to affect areas more than 30 km from the volcano. The fine ash associated with an eruption can affect areas much further away. However, the prevailing wind pattern from Lascar has a very high probability of directing this fallout to the southeast, away from the site. The biggest risk to the site would be if Sairecabur, or to a lesser extent, Putana, had a big eruption. The prevailing winds could bring their plumes of fine ash over the site. Such an event, which has very low probability, would mainly affect unprotected machinery and possibly electrical transmission lines.

Of course, it is always possible that one of the other apparently dormant cones nearer the site could become active, but this process has a geological timescale; there is no evidence this will occur in the near future.

Thus while there is some risk due to volcanism, the greatest risk is from three volcanoes many tens of kilometers from the site, none of which is directly upwind. Should one of these volcanoes erupt, we could expect some ash fallout and some site cleanup work to be needed, but no major interruption of MMA operations.

3.2.2 Earthquakes

This section is a summary of a report entitled, "Seismicity and Seismic Hazard at the MMA Site, Antofagasta, Chile," by Dr. Sergio E. Barrientos, Department of Geophysics, University of Chile.

Earthquakes take place regularly all along the Chilean coast, because the oceanic Nazca plate is sliding under the South American plate. Earthquakes caused by this interaction can exceed magnitude eight. However, this interaction begins offshore about 300 km west of Llano de Chajnantor. The activity directly under the site occurs at a depth of 120 km and thus, even though it can be quite strong at the source, the shaking on the surface is relatively mild. Both the regular thrust earthquakes offshore and the fracturing of the Nazca plate just below the site can have an important effect on the Chajnantor site. The risk of occurrence of shallow crustal earthquakes, which could cause more localized shaking, is negligible.

Estimates of the earthquake risk are based on a probabilistic formalism employing historical data. Even though the offshore thrust events can be stronger, the tensional events under the site have the most effect on Llano de Chajnantor. However, the attenuation and geometric spreading of seismic waves due to the depth reduces the effects greatly. The largest historical earthquake ($M_w = 8$), which took place in 1950, is estimated to have produced an acceleration of 23% g on the site. Recently, the large ($M_s = 7.3$) Antofagasta earthquake of 1995 is estimated to have produced only a 7% g acceleration. Over a one-hundred-year timescale, there is a ninety percent chance that the acceleration due to earthquakes will not exceed 25% g. This acceleration is less than the standard NRAO has designed to on other sites such as Mauna Kea, where the VLBA antenna was designed for 30% g. Seismic effects should not be a problem in designing the array.

In summary, in spite of the geophysical activity in the region, Llano de Chajnantor does not appear to present an unreasonable risk. As long as we design the array with consideration for the minimal risk of some fine ash falling on the site and the accelerations which are likely due to earthquakes, this activity should present no significant problem to location of the MMA on Llano de Chajnantor.

3.3 MEDICAL AND PHYSIOLOGICAL CONSIDERATIONS FOR A HIGH-ALTITUDE SITE

At 5,000-m (16,400-ft) altitude, the proposed MMA site in Chile is higher than Mauna Kea Observatory (MKO) which, at 4,215-m (13,800-ft), is the highest astronomical observatory currently in full time operation. Since the effects of altitude are noticeable in MKO workers, it is important to include planning for these effects in the MMA operation. Here we summarize the results of a study of the potential high-altitude problems to be expected for workers on the MMA site and the measures proposed to address these problems. Details of the study are contained in MMA Memo 162. This study was performed in consultation with Prof. J. B. West, a specialist in high-altitude medicine and physiology at the School of Medicine, UCSD.

3.3.1 Human Response to High Altitude

The two principal concerns in having personnel working at an altitude of 5,000 m are illness and reduction in work ability. Both of these problems are caused fundamentally by the reduced partial pressure of oxygen in the atmosphere at high altitude. On the Chilean MMA site, the partial pressure of oxygen in the inspired air inside the lung is 53% of its sea-level value (compared to 59% of sea-level at MKO). The human body responds to this reduction in available oxygen, and, by a complex process called acclimatization, adjusts functions such as breathing and heart rate, and blood properties such as pressure, volume, pH, and red cell count, in an attempt to keep the oxygen levels in the tissues at as close to their sea-level values as possible. Acclimatization begins in minutes after exposure to altitude and is mostly complete in a few days, although the slowest processes can continue for many weeks. The extent to which and the speed with which an individual is able to acclimatize determines how well that individual will feel and function at altitude, and, for reasons that are not well understood, this can be quite variable among different individuals. The only reasonably sound predictor that a person will function well at altitude is that that individual has previously done so, although even this is not a complete guarantee.

High-altitude sickness is caused by the reduced oxygen at altitude. Usually its symptoms are minor discomfort such as headache, fatigue, insomnia, loss of appetite, and dizziness and/or nausea. These symptoms begin a few hours after ascent and typically disappear after a day or two, as acclimatization progresses. About 50% of MMA workers could be expected to exhibit some of these symptoms on the first day of work without taking any medication. However, acetazolamide, now accepted as the standard treatment for these symptoms, is very effective in reducing or eliminating these problems. More serious altitude sickness is much rarer, occurring less than 0.1% of the time at 5,000 m. Although it is rare, we must watch for it and know how to treat it. Luckily, in our situation the preferred treatment is just to take the patient to lower altitude. This can be accomplished quickly and easily by taking the patient down to San Pedro by car.

Reduction in the ability to perform work at high altitude includes both physical and mental work. We must deal with this problem. The ability of MMA workers to perform hard physical labor will be reduced by about 25% compared to sea-level. Loss of mental work ability is difficult to quantify, but the few available studies suggest that, in the absence of supplemental oxygen, functions such as attention span, short-term memory, arithmetic ability, and decision-making ability will all be reduced by about 10% to 30% compared to sea-level performance. Workers will be much more prone to mistakes such as arithmetic errors.

3.3.2 An MMA Operational Scenario for High Altitude

Our proposed MMA high-altitude operating scenario is based on three key points:

(1) Minimize the amount of work which must be done on the 5,000-m site.

(2) Allow workers to sleep at an altitude where they can sleep soundly, but not so low that they lose their acclimatization.

(3) Provide supplemental oxygen for workers on the high site.

Items (1) and (2) will be achieved by the construction of an Operations Support Facility (OSF) near San Pedro de Atacama at about 2,500 m (8,000 ft). Workers will live and sleep at the OSF and will make the one-hour drive to the MMA site only when required. To the maximum extent possible, we will design the MMA so that equipment can be repaired by swapping a "module" rather than by repair in place. For example, a "module" might be a complete cryogenic receiver, a correlator circuit board, an antenna drive motor, or a building air-conditioning unit. Modules will be repaired in workshops at the OSF rather than on the high site. This concept of maintenance by module swapping has proven effective for both the VLA and VLBA. Several techniques will be used during the construction phase to minimize the amount of work at 5,000 m. A small test array will be built on a convenient site in the continental U.S. and as many problems as possible, both hardware and software, will be identified and solved there before the system is used at 5,000 m. We will investigate the feasibility of completely assembling, outfitting, and testing antennas at the OSF and then transporting them up to the MMA site on the antenna transporter. Once routine operation is achieved, the array operator will be located at the OSF. A medical clinic equipped and staffed to handle high-altitude problems will be provided either at the OSF or by enhancing, if necessary, the capabilities of the medical clinic which already exists in San Pedro.

The problem of reduced ability for mental and physical work at 5,000-m altitude will be solved by providing supplemental oxygen. Increasing the oxygen concentration inside MMA buildings from its natural 21% up to 26% will provide a partial pressure of oxygen equivalent to an altitude of 3,500 m (11,500 ft). At this altitude, the loss of mental ability is minimal and there should be little loss of acclimatization. A 26% oxygen atmosphere will be provided in those work areas, such as the main control room and electronics and computer areas, where difficult problem-solving is required. Enclosed areas away from the main buildings, such as the antenna assembly building, the antenna receiver cabins, and the antenna transporter's operator cabin, will be designed to allow oxygen enrichment if it proves necessary. This technique of oxygen enhancement now is in use at high-altitude mines in Chile, such as the El Tambo mine at 4,300 m, in order to increase the efficiency of workers who must operate the sophisticated, high-technology mining equipment. The technique is made economically feasible by the use of modern, molecular-sieve oxygen concentrators. For the MMA, the oxygen-enhancing equipment is estimated to require a capital expenditure of $5,000 per worker on the high site and an annual operating cost of $500 per worker.

A concern that often is raised about oxygen enrichment is the possibility of increased fire risk. At an oxygen concentration of 26%, the partial pressure of oxygen still is only 68% of its sea-level value. Published tests show that the burning rates of solids such as paper are lower than sea-level burning rates, so the fire risk for these kinds of materials is acceptable. The low barometric pressure does decrease the flash point of volatile liquids, so it will be necessary to avoid the use of such liquids in oxygen-enriched work spaces. Workers who work primarily outdoors probably will achieve sufficient acclimatization to perform most tasks adequately without supplemental oxygen. This has been our experience to date on the site. However, for those outdoor tasks which are particularly demanding, either mentally or physically, workers will be provided with convenient portable oxygen systems which increase the effective concentration to 26% through an unobtrusive nasal cannula.

Thus, from the advice of medical experts and through our own personal experience on Llano de Chajnantor, we believe that, by taking a few prudent steps beyond the normal practice at MKO and taking advantage of the ease of access to the 5,000-m site, we can adequately deal with the physiological effects of working at such a high altitude.

3.4 LOGISTICS IN CHILE

The Republic of Chile has hosted international astronomical observatories for longer than thirty years. These include the Cerro Tololo Interamerican Observatory in La Serena, the European Southern Observatory (ESO) at La Silla, and the Carnegie Southern Observatory at Las Campanas. New optical telescopes are being constructed at Las Campanas (the Magellan Telescope), at Cerro Pachón (the Gemini southern Telescope), and at Cerro Paranal (the ESO Very Large Telescope). Chile has granted duty-free and tax-free status to the observatories, which facilitates low-cost operations.

Chile is a constitutional republic of more than fourteen million people, five million located in the Santiago region. There is a large middle class. The literacy rate exceeds ninety-eight percent. University education in Chile is respected throughout South America. The principal universities are the Universidad de Chile, the Universidad Católica, the Universidad de Santiago, the Universidad de Concepción, the Universidad Católica de Valparaiso, the Universidad del Norte (Antofagasta), and the Universidad Austral de Chile (Valdivia). Chile has a one-hundred-seventy-year tradition of democracy, which was interrupted in the 1970s. A democratic government has been in power since 1990.

The economy is based principally upon the export of mining and agricultural products, particularly copper. Currently, Chile is enjoying great economic growth. Recent governments have privatized many federal monopolies. This action stimulated investments that produced state-of-the-art technical improvements to the national infrastructure, and it created a competitive marketplace. To reduce government and enhance efficiency, Chile has privatized social services such as the national pension and health-care programs.

The MMA site lies at 23° S in the sparsely populated Atacama Desert of northern Chile. Mining is the principal industry in the region, supported by the coastal port of Antofagasta (population 200,000) and the inland city of Calama (population 100,000). The nearest community to the MMA is the historic, pre-Columbian village of San Pedro de Atacama (population about 1,000), on an international road connecting Chile with Argentina.

A skilled work force is available in northern Chile due to the importance of mining in the region and to Chile's economy as a whole. Calama, located about one hour by car from San Pedro, is the support center for the region's mining industry and can provide a great variety of services needed by the MMA. The Chilean national university community also can provide highly skilled people in most, if not all, the specialties needed for the MMA.

Generally, the infrastructure in this region is good and improving. Hard-surfaced roads and frequent bus service connect these communities. Telephone service is good, with improvements such as fiber-optics links and E1 circuits now being installed. The Chilean portion of the international road from San Pedro to Argentina is now being paved; international buses and eighteen-wheel trucks use it regularly. The port at Antofagasta is large enough to support the operations of the enormous copper mine at Chuquicamata.

While San Pedro presently generates its own electricity, copious electric power is available at Calama and Chuquicamata, 100 km to the north, where it is used for the electrolytic stage of copper refining. It is expected that power transmission lines will be extended to San Pedro in the next few years. The MMA could build a transmission line to bring electricity from San Pedro to the site and to the OSF. Alternatively, electrical power to the high site might come from gas turbine generators. A pipeline carrying natural gas from the production fields in Argentina to the coastal city of Mejillones is being built near the MMA site. A tap to this line and local power generation would solve the needs of the MMA. The costs and practicality of these solutions are being studied. We expect the net cost of power will not exceed that on Mauna Kea.

The scarcity of water in San Pedro, as everywhere in the Atacama desert, is a problem faced by every enterprise in the region. In an attempt to assess its implications for the MMA, and to seek solutions, we commissioned a study by Dr. Francisco Townsend G, a geologist at the University of Chile. His report, "Preliminary Report on Water Supply, Millimeter Array Project, National Radio Astronomy Observatory" provides the following options. The MMA could buy water from a nearby well (Pozo Tres, for example), truck it to the OSF and to the site, and recycle as much of it as possible. Bottled drinking water would be trucked to San Pedro from Calama as needed. Such practices are widely used in mining communities in Chile and at many astronomical observatories world-wide. Dr. Townsend advises us that ground water is likely to be available under the high site and that we should drill a well to explore this possibility. We need to evaluate the long-term costs before making a decision. Water is available.

3.5 CONSTRUCTION

Antennas will provide significant milestones within the context of the MMA construction plan. The first phase of the MMA project will be the antenna design; the second, construction and testing of the prototype antenna; the third, assembly of the test interferometer; the fourth, erection of the antennas at the MMA site; and the fifth, the commissioning and testing of the array itself. A key part of this plan will be to develop and test all major systems in the U.S. before we try to use them on Llano de Chajnantor.

3.5.1 Prototyping and Development

The first stage of the project will be the development and prototyping of the antenna and associated electronics. The most important part of this effort will be the construction of a prototype antenna to test the concepts and tolerances before a commitment is made to the quantity procurement. Prototypes of all the major electronics systems also will be designed and tested before being mass produced. This will be done at existing NRAO and university sites in the U.S.

In the two-phase structure imposed by the NSF on the MMA project, the construction phase follows three years of a design and development phase. If we commit to design decisions in the first year of the MMA project, we risk producing in 2008 an instrument with 1998 technology. To avoid this, the MMA development will be done collaboratively and in parallel with the university groups presently engaged in millimeter-wave interferometry. For each area in which some significant technological development appears necessary, two approaches will be taken simultaneously: one based on "mature" technology, and another based on a more innovative approach. The work will be parceled out to groups at the NRAO or groups at the universities, under the guidance of the MDC Steering Committee. A future date will be set for a choice between the two approaches. This way, the MMA will end up with the "best" technology. In addition, the university instrumental and software groups will be fully engaged in the MMA project and will gain knowledge that can be applied to their own instruments or to a possible future merger of those two arrays into a single university-based array.

3.5.2 The Test Interferometer

The next stage will be construction of an engineering test interferometer at the VLA site. The engineering test interferometer will have all the subsystems included in the finished MMA. We will develop the online software, the correlator interface, and major observing modes of the MMA before they are implemented on Llano de Chajnantor. This is a continuing effort that will overlap with construction in Chile. Once a stage of engineering development is complete at the test interferometer, we will implement its features on the Chilean site. The production suite of antennas and other subsystems will be shipped directly to Chile. However, the first version of each component of the array will be checked out at the test interferometer and its associated software developed. This will maximize the effectiveness of the MMA personnel in a familiar environment and minimize development and testing necessary on the 5,000-m site.

The test instrument also will be used to train the permanent staff of the MMA: those individuals, including Chilean nationals, who will be assigned to operations in Chile.

3.5.3 Construction in Chile

Work in Chile will begin with construction of the OSF near San Pedro de Atacama and preparatory work at the array site. Work at the OSF will include erecting the buildings and installing the technical components appropriate to that site. Site work includes installing the concrete antenna pads, trenching between these pads, connecting the power and signal cables from the pads to the control building, building the roads connecting the pads, erecting buildings to house the on-site electronics and the antenna maintenance operations, erecting and aligning the antennas, constructing the communications and power links to the OSF near San Pedro, and improving the access road between the site and the Paso de Jama international highway.

As the project progresses, these efforts would shift to implementing the development completed on the test array. Finally, the antennas and electronics from the engineering test interferometer will be packed up and shipped to Chile to complete the MMA.

3.5.4 Commissioning

As construction ends, and for several years after construction is complete, the project will be in its commissioning stage. During this phase, all the array's capabilities are tested and made to work. On previous NRAO instruments, this period lasted about five years after construction. Personnel requirements peak during commissioning, then settle into a steady state.

During construction and commissioning, MMA and contract employees probably will live at the OSF near San Pedro. Based upon ESO's experience at Cerro Paranal and Gemini's experience at Cerro Pachón, we expect most of them to commute on a Turno system, as discussed in the next section. These workers will be accommodated in temporary buildings, which will be dismantled and removed when construction ends.

During commissioning, the percentage of foreign workers, from the U.S. and other partner countries, working on the MMA in Chile will be higher than during the operations phase. In addition, the foreign workers may stay at the OSF for longer periods to offset their longer commutes.

We expect the MMA construction to evolve much like previous major NRAO construction projects. The main difference between the MMA and earlier projects is that we will do more of the debugging and testing in the U.S. instead of at the instrument site.

3.6 OPERATIONS

3.6.1 Introduction

Operation of a visitor-oriented telescope in Chile will be a new experience for the NRAO. While large astronomical observatories have operated successfully in Chile for decades, rural northern Chile does not have sophisticated technical resources nor extensive amenities. We have discussed operations with two former directors of Cerro Tololo Interamerican Observatory (CTIO) and several ESO administrators, and drawn from our own experience in operating visitor-oriented telescopes. We conclude that operation of the MMA on Llano de Chajnantor is practical, although some details of our operations plan may change as we gain more experience.

The MMA will operate similarly to the VLBA, principally as a "service instrument"—that is, observing without requiring that the astronomer be at the telescope. Interaction between the MMA staff and astronomers will occur most often via telephone or the Internet. This will not preclude astronomers from going to Chile if the experiment requires it. Rather, it will free them from *having* to travel to Chile to observe with the MMA.

3.6.2 Operating Locations

The MMA will consist of limited facilities for on-site maintenance at the 5,000-m observing site, the operations and support center near the village of San Pedro de Atacama, a small business office near the port facilities at Antofagasta, an office for governmental affairs in Santiago, and some additional support staff at existing NRAO sites in the United States.

MMA Site. Because of the altitude, only essential maintenance facilities will be located at the telescope site. "Essential" means whatever is necessary to maintain the array, its antennas, and its site-based electronic systems. This includes buildings to house the electronics systems common to the array—such as the local-oscillator system, the IF control circuitry, the correlator, and a small laboratory with test equipment. It also includes buildings such as an antenna erection building, a small warehouse, a mechanical shop, and a garage for transporter repairs. As discussed earlier, the laboratory areas will feature equipment to increase the partial pressure of oxygen.

Operations Support Facility (OSF). The operations support facility near San Pedro de Atacama is the heart of the MMA. It will provide and coordinate all technical and logistic support in Chile. Its personnel will operate the MMA remotely via fiber-optic and/or microwave links to the observing site. This center will consist of laboratories and offices, computing facilities, libraries, dining facilities, dormitories, recreation facilities, and mechanical, electrical, and automotive shops. During the construction phase, the OSF will have extra buildings to accommodate the installation crews. After construction, these buildings will be removed to reduce maintenance requirements.

Antofagasta Business Office. As with the ESO/VLT operation, an MMA business office will be located near the seaport in downtown Antofagasta. This office will process the paperwork associated with the import and export of international cargo, purchase supplies unavailable in San Pedro, and represent the observatories in dealing with local Chilean officials.

Santiago Office. Irrespective of the port through which materials are imported, Chilean permission for the duty-free import of those materials is authorized by the Foreign Ministry in Santiago. For this reason all international observatories in Chile maintain a business and legal affairs office in Santiago. This will be equally necessary for the MMA.

U.S.-based Support. All MMA personnel responsible for array operations will be based in Chile. Support functions including development of new receivers and off-line software, support of U.S.-based observers, and some business functions, will be performed in the U.S. This will draw on expertise within the NRAO, from personnel located at the principal NRAO sites.

3.6.3 Staffing Plan—Operations

Staffing methods will differ from location to location. Employees based in the United States, in Santiago, or in Antofagasta will commute daily from home to work on standard working hours.

A different system will be required for employees at the OSF. The village of San Pedro de Atacama is too small to accommodate the permanent residence of the additional hundred or more workers, and it does not offer an adequate infrastructure of shops, schools, libraries, other logistics, and amenities to attract the employees' families. Some employees probably will commute daily from San Pedro or Calama (population 100,000—about one hour away on a good road). However, we expect a significant fraction of the staff to live too far away to make a daily commute practical.

Sistema de Turno. To operate the MMA, ***all*** consultants recommend a rotating shift system called the "Sistema de Turno" for staffing the San Pedro OSF. In Chile, the Turno system is used by all international observatories and most mining operations. It complies with Chilean labor laws. It consists of one week "on" and one week "off" to provide eighty-eight work hours in a two-week period. Customarily, the employer provides room, board, and a transportation subsidy to the employees. To ensure continuity, we will design the schedule to provide more employee overlap than is typical under this system.

A Turno-like system is not new to the NRAO. Telescope operators on Kitt Peak, in Arizona, have worked under a similar system, called the "Fixed Salary, Fluctuating Work Week" and described by Regulation 778.114 of the U.S. Labor Department.

To staff the the high-altitude MMA observing site, rotating shift crews will commute daily from the OSF near San Pedro during their "on week." No personnel will sleep or live at the array site itself.

To accommodate the Turno system, dormitories at the OSF will be sized to permit overlap between arriving and departing crews. Additional accommodations will house astronomers and engineers visiting the OSF on a non-scheduled, temporary basis. The dining facilities, kitchens, and recreational facilities will be sized accordingly.

MMA support staff on the Turno system might choose to live in Antofagasta—population 200,000, and 200 mi (330 km) from San Pedro. Roads to San Pedro are excellent, and commercial buses run several times daily. Antofagasta would provide a larger range of amenities, particularly the opportunity of mixing with the staff of ESO's Very Large Telescope, now under construction at Cerro Paranal. However, the commute is $3\frac{1}{2}$ hours. Some Turno employees probably will choose to commute from Santiago, as is the case for many of the scientific and technical staff of the VLT. This is easily accomplished via regularly-scheduled commercial airline flights to get as far as Calama. These and other communities would offer more cosmopolitan schools than San Pedro, the range of choice varying with the size of the town. We expect to learn operational staffing issues from our experience and that of other observatories operating in Chile. We will be prepared to modify our plans according to the needs of the MMA staff.

Resident Management. MMA operations would benefit from a few senior employees living in San Pedro near the OSF and the array itself. These might include an operations director and a technical manager who would be available at any time, and who could provide continuity from one Turno crew to the next. This will require building a small number of houses for these people and their families, probably near the OSF.

If desirable, such employees also could work on a Turno system, but on a scale of months rather than weeks. For example, a senior ESO construction manager commutes to Antofagasta from his home in Minnesota; and a Carnegie Observatories project manager, from his home in California. Experience has shown that even these commutes are practical and not without precedent. Indeed, they could have a salutary effect on the U.S.-based NRAO staff were such periodic responsibility shared among several individuals.

Based on our experience in operating radio telescopes and that of the existing observatories in Chile, we believe an operations plan such as this will succeed. We will need to remain flexible about the details of the operation as we gain experience operating on Llano de Chajnantor. The most important conclusion is that we will be able to build and operate the array in Chile thanks to the access a major highway provides to the site at 5,000-m elevation and thanks also to the support available from the nearby, tourist-oriented village of San Pedro de Atacama. But, as is the case in both Green Bank and New Mexico, we expect that the operation must be tailored to the realities of the people and the place involved.

3.7 COST DIFFERENTIAL BETWEEN CHILE AND HAWAII

3.7.1 Construction and Operation of the MMA on an Offshore site

Regardless of whether the MMA is located on Mauna Kea or Llano de Chajnantor, construction will involve maritime shipment of materials. As long as such materials can be packaged in standard ocean shipping containers, the shipping cost is determined by the number of containers shipped. The shipping cost is dominated by the loading and unloading of the containers, not by the distance the ship travels. We may decide either to accumulate and ship construction materials for assembly at the array site or to fabricate and test large sub-assemblies in the continental U.S. and ship them as modular units that are as large as will fit in a shipping container. The first approach would minimize the number of containers shipped, at the expense of requiring most instrument fabrication to be done at the offshore site; in the second case, most instrument assembly would be done at the NRAO and large integrated assemblies shipped. Recognizing that testing and debugging the MMA hardware will be a demanding task best done in as controlled an environment as possible, we intend to build major parts of the MMA at the NRAO, test them as thoroughly as possible, and then ship the fully functional instruments to the site. Ideally, the work on-site can be reduced to that of connecting major subsystems and testing. Precisely this approach is being implemented by the Smithsonian Astrophysical Observatory in the construction of the Submillimeter Array on Mauna Kea; it is an appropriate model for the MMA in Chile. Since the same construction plan applies to the two sites, we have a common basis for a cost comparison.

Operation of the MMA at any high-altitude site—on the Chajnantor site or on Mauna Kea—would be functionally similar. In either case, the array support staff would have laboratories and repair facilities at a low-elevation support facility, either in San Pedro de Atacama or in Hilo. Only a few individuals would be required to commute daily to the array site; the work day for the remainder would be at the low-elevation support facility.

3.7.2 Differential Site Cost Estimates

Detailed cost estimates for construction of the MMA in Hawaii and in Chile have been made and updated as the instrument design has evolved. Because of the similar construction and operational models for Hawaii and Chile, we can make a valid comparison of the relative costs for these two sites. We are aided greatly in this process by the experience of the SAO in constructing the SMA on Mauna Kea; since many of the cost

Table 2: Fractional Breakdown of MMA Construction Costs

Antennas and Transporters	35 %
Site Development and Buildings	20 %
Electronics at the Antennas	25 %
Central Electronics, Correlator	6 %
Monitor & Control, Computing	6 %
Management, Spares, Commissioning	8 %
TOTAL	100 %

areas are identical for the SMA and the MMA it is possible to anchor the MMA estimates to actual expenses incurred by the SMA. Table 2 shows the current construction cost estimate of the MMA in broad spending categories. This cost breakdown applies nearly equally to both sites.

For an MMA assembled incrementally on a continental site and then shipped to an offshore site, the cost differences appear principally in the "Site Development and Buildings" category. This is twenty percent of the whole project. There also is some cost difference in the Management and Commissioning aspect of the construction, but principally the cost differences are in site development.

Using budgetary figures provided by contractors, we estimate that the cost of roads and trenching for power and signal-distribution cables, and the cost of concrete at the site, are higher on Mauna Kea than on Llano de Chajnantor. There also are some infrastructure "buy-in" expenses that are unique to Mauna Kea. On the other hand, the Chajnantor site is wholly undeveloped and will require us to provide all services ourselves, including electrical power. We estimate that the total costs are about the same on the two sites.

Since the site development costs appear to be approximately the same between Chile and Mauna Kea, and since the remaining cost areas are the same, given the way in which the MMA will be prepared for any offshore site, construction cost is not a discriminator between the sites.

Operationally, the MMA is an adjunct to existing NRAO facilities, and as such its operational costs are incremental to the cost of operating the NRAO. The MMA will benefit, for example, from the NRAO infrastructure that exists in support of device development and antenna design at the NRAO Central Development Laboratory, and it will build upon Observatory activities in support of imaging techniques. The ability to graft MMA operations onto existing NRAO support will help minimize the MMA operational costs.

The MMA will involve creating two new operations centers for either offshore site. These two are the array site itself—Mauna Kea or Llano de Chajnantor—and an MMA Operations Support Facility (OSF) local to the site. In Hawaii, the OSF logically would be located in Hilo, whereas in Chile the OSF would be near San Pedro de Atacama. In either case, there will be some additional MMA activities at mainland NRAO sites; the emphasis here is on administration, electronics and imaging R & D, and on user support.

The cost of MMA activity at the NRAO mainland site is essentially identical regardless of the offshore site chosen.

The operational cost of the MMA on the offshore site is the sum of personnel costs and the cost of materials, utilities, communication, and transportation. NRAO's experience in operating the VLA and VLBA—both synthesis array telescopes, comparable in scale, if not in detail to the MMA—indicates that personnel costs are approximately seventy percent of the total operational expense. Assuming that this would apply to the MMA if it were located in the continental U.S., we can assess the expected operational cost differences between Mauna Kea and Llano de Chajnantor by looking at the respective cost differences of these sites from the U.S. mainland.

Observatories on Mauna Kea are accustomed to paying their employees premium salaries compared to observatories on the mainland, in recognition of Hawaii's higher cost of living. The salary increment is approximately one-third: the employee working on Mauna Kea may receive 1.3 times the salary that individual would receive at a mainland observatory. In Chile, salaries of technically trained people have been increasing rapidly in real terms, and we assume that the MMA Chilean staff will be paid at U.S. mainland rates for comparable job skills. However, at a Chilean MMA site, as with the mines in the Chilean Altiplano, the personnel will be recruited from cities in some cases many hundreds of kilometers from the site. These workers commonly work rotating week-on/week-off shifts. The cost increase which would be due to the inefficiency of this system of operation is not entirely clear. Also, in Chile it is customary for personnel working in remote places to receive some extra compensation. We estimate that, in the worst case, personnel costs may be fifty percent higher than on the U.S. mainland or fifteen percent higher than on Mauna Kea. We consider this an upper limit.

In summary, if the array materials, utilities, communications, and travel costs are identical on the sites in Hawaii and Chile, then the cost of operating in Chile will be no more than ten percent higher because of the possible increment in personnel costs.

3.8 PURCHASING POWER OF U.S. DOLLARS IN CHILE

MMA operations will be funded in U.S. dollars, but the services purchased with Chilean pesos. It is thus prudent to assess the potential risk involved in future currency exchanges. Since the purchasing power of the U.S. dollar in Chile is driven by market forces, one cannot expect to forecast risk with precision. However, it is possible to examine the past effect of the principal market forces in order to guide future expectations.

If we concentrate on searching for trends in the purchasing power of the U.S. dollar in Chile, rather than trying to understand the ratio of the dollar to Chilean peso at a snapshot in time, then the trend will depend on: (1) the appreciation or depreciation of the dollar in the U.S., as measured by the Consumer Price Index (CPI), for example; (2) the appreciation or depreciation of the peso in Chile, as measured by the Indice de Precios al Consumidor (IPC), for example; and (3) how much Chilean banks are willing to pay, in pesos, for each U.S. dollar. There are several ways to measure the latter, which represents the actual exchange rate. For personal dealings—i.e., other than bank-to-bank transactions—the most common is the Dólar Informal. Therefore, to assess the trends in the purchasing power of the dollar in Chile, the prescription is this: For each past year, compare the Chilean peso corrected by the IPC to the Dólar Informal. Over the past five years, this comparison shows the purchasing power of the U.S. dollar in Chile to have eroded at approximately six percent per year, with little year-to-year variation and no clear sign of a second derivative.

A prudent estimate of future trends is therefore to budget for an increase in MMA operation costs in Chile at six percent per year. This is commensurate with the estimate CTIO makes of an approximately eight percent per year increase. Clearly, market forces in either country can cause this expectation to change.

4 CONCLUSIONS

The arduous search for the most suitable MMA site now is ended, and our recommendation is Llano de Chajnantor. From all of the site-testing studies, Llano de Chajnantor clearly is the superior site from the point of view of the transparency and stability of the atmosphere. Indeed, the atmospheric conditions of the Chilean site are so good that, in a given period of time, four times as much millimeter-wave science can be accomplished with the MMA on that site as in the same time on Hawaii. At submillimeter wavelengths, the advantage of the Chilean site is greater still. Llano de Chajnantor also will allow the longest antenna baselines, and hence the highest resolution, of any site seriously considered for the MMA. The conditions on Llano de Chajnantor will allow us to exceed even our loftiest science goals for the MMA as they stood only a few years ago. Furthermore, the site invites the opportunity for a sharing of facilities and the possible future combining of the MMA with the LMSA, the LSA, or whatever other instruments eventually are located in the same area.

Construction on Llano de Chajnantor will be no more expensive than construction on Mauna Kea, and the operations cost in Chile will be no more than ten percent higher than it would be in Hawaii. With the MMA in Chile, we can expect a significant scientific gain for a very modest cost increment over a Hawaiian site. Geophysically, the site is stable and practical to build on. With a few prudent and practical adjustments to operational procedures, the physiological problems associated with this or any other high-altitude site are manageable.

Based on the general experience at the NRAO and elsewhere with other major astronomical facilities, and on the specific experience gained by the astronomical observatories presently operating in Chile, construction of the MMA is entirely feasible. MMA planning will need to remain flexible so that we may accommodate properly to the realities of the ambitious and exciting undertaking that is the Millimeter Array.

5 REFERENCES

The Millimeter Array Memorandum Series is the primary repository of documentation for all aspects of the MMA project. Several very detailed studies related to site selection are included in this series. A complete list of the memoranda most pertinent to site selection is given below.

Recent memoranda are directly accessible at the NRAO World Wide Web site (`http://www.nrao.edu`), by following links to the MMA project, where a complete list of MMA memoranda can be found. Copies of earlier memoranda, not available on the Web, can be requested by e-mail.

A list of special reports which were prepared by paid consultants, dealing with environmental conditions at Llano de Chajnantor, is also given below. These reports are not available on the Web, except as noted. An MMA Memorandum which was prepared in consultation with Prof. J. B. West is included here as well.

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