4

Searching for a Site

"In Xanadu did Kubla Khan, a stately pleasure-dome decree."
Samuel Taylor Coleridge

Millimeter Array Site Requirements

The power of a radio telescope depends on its size, the quality of its electronics, and its location. The site requirements depend on the wavelength at which the telescope is to operate and on the nature of the telescope – whether it is a single dish or an interferometer. One of the most important considerations for the MMA site was the transparency of the atmosphere, the extent to which radio waves pass through without being substantially absorbed or diverted. While at the longest wavelengths applicable to radio astronomy this is less stringent, for the millimeter band it is critical. Longward of 1.3 cm wavelength, the atmosphere is clear until one reaches a wavelength of about 1 m, where the ionosphere reflects radio waves. (Amateur radio operators communicate around the globe by reflecting their signals off the ionosphere.) At 1.3 cm, corresponding to about 23 GHz in frequency, water vapor in the atmosphere absorbs radio waves, rendering the atmosphere slightly opaque. At increasingly higher frequencies and correspondingly shorter wavelengths, in the millimeter band, other atmospheric constituents come into play: oxygen, ozone, and again water. Between the broad, opaque spectral lines of these atmospheric constituents, the bands of transparency, shown in Figure 4.1, are the "windows" through the atmosphere in which millimeter/submillimeter astronomy can be conducted. The receiver bands implemented in ALMA were designed to match these windows.

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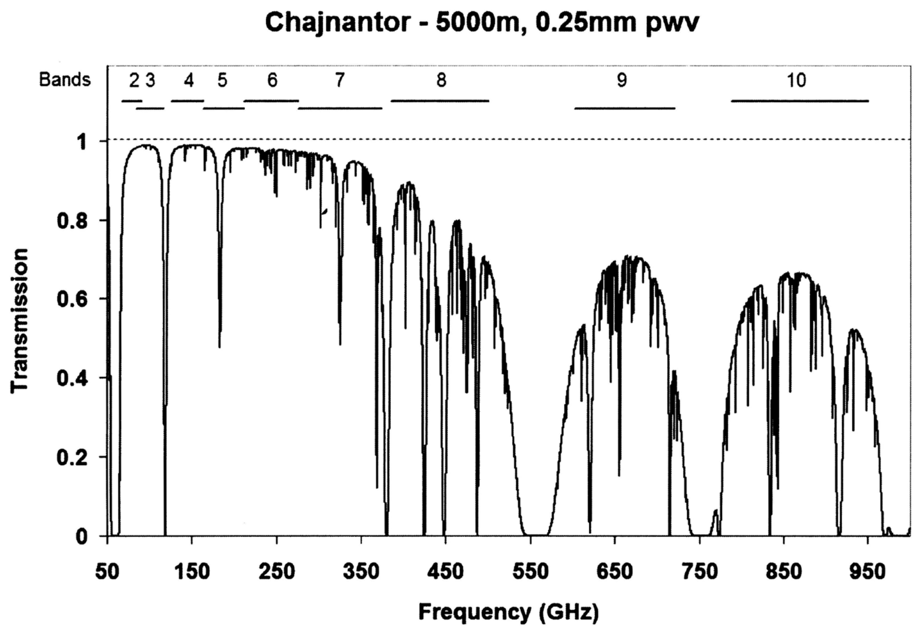

Figure 4.1 The transmission of radiation through the atmosphere as a function of observing frequency (GHz) for 0.25 mm of precipitable water vapor (PWV). The plot is from a model atmosphere for the Chajnantor ALMA site at an elevation of 5,000 m. The ALMA observing bands are indicated at the top for Bands 2–10. (Band 1 covers frequencies around 30 GHz, not shown in this plot.) A PWV column of 0.25 mm is typical of the best observing conditions on the ALMA site. Courtesy of Juan Ramón Pardo, reproduced by permission.

The windows become more transparent as site elevation increases and the concentrations of oxygen and water vapor decrease. Another consideration is that the atmosphere at the site should be stable, that is, should not vary in transparency from one interferometer antenna to another. The flow of air over the interferometer should be smooth, not turbulent. Windy sites are less desirable in this respect. Finally, the site should be sufficiently remote to minimize radio frequency interference. Radio observatories often use the catchy descriptor, “high, dry, and quiet” to describe the ideal site. In addition to a remote, high-elevation site, the MMA required an area sufficiently large and flat to accommodate the array and allow for repositioning the antennas. Ideally, there should be connections to electrical power and water, good access by road, a supportive local community, an available workforce, and a stable government. It took astronomers many years to find the location for their pleasure-dome at what is now the ALMA site in Chile.

United States Continental Sites

In his 1982 MMA concept proposal,[1] Frazer Owen characterized the VLA site as equal or superior to any of the existing millimeter observatory sites at that time, with the exceptions of Maunakea in Hawaii and White Mountain in California. Locating the MMA at the VLA site would also allow the project to benefit from the extensive infrastructure that had been built up there as well as from the considerable expertise in radio interferometry among the VLA staff. The choice of operating frequencies was also a factor and in the early 1980s, the array concept called for receivers operating at 70–120 GHz and over a band centered at 230 GHz, to allow for observations of emission in the two lowest frequency CO transitions. Observing the spectral lines of carbon monoxide was a prime interest of millimeter astronomers, as was discussed in Chapter 1. While this provided a first basis for site selection, over time the desired frequency range became more ambitious.

In June 1987, Mark McKinnon published a report[2] that presented the results of atmospheric opacity measurements at a frequency of 225 GHz with two different instruments on both the VLA site and the top of Mount Baldy in the nearby Magdalena Mountains. The measurements were made in late 1986 to early 1987. At an elevation of 3,500 m, Mt. Baldy is significantly higher than the 2,120 m elevation of the VLA site. With opacities close to 0.03, Mt. Baldy was superior to the VLA site where the lowest opacity was 0.1. These opacities correspond to transmissions through the atmosphere of 97 percent and 90 percent, respectively. However, since these values were seen only in the best months of winter indicating that observations of the CO line at 230 GHz at the VLA would be restricted to the coldest winter nights, with little or no wind; on Mt. Baldy, the times adequate for such observations were more frequent.

Although Mt. Baldy was the first MMA site to be seriously considered, there was motivation for the search to cast a much wider net, first in the continental United States, then in Hawaii, and finally in Chile. Cam Wade, a member of the NRAO scientific staff at the VLA, had evaluated prospective telescope sites for the VLA and was doing the same for the VLBA network of antenna stations. He took on the task for the MMA as well. Wade[3] began by studying topological maps for the southwestern United States looking for areas with an elevation above 2,700 m and south of 36 degrees N latitude. The latitude limitation was to ensure visibility by the MMA of the Galactic Center, and to avoid adverse winter weather conditions associated with more northern latitudes. Suitable candidate sites had to be relatively flat over an area of 3 km north–south by 2 km east–west to accommodate the planned configurations of the MMA. These principal criteria and considerations of accessibility and availability led to only two possibilities in the United States: the Magdalena Mountains (including Mt. Baldy) of New Mexico and the White Mountains of Arizona. The White Mountains have large flat areas above 2,700 m elevation, with good access by paved road from the towns of Springerville and Alpine. Five other initial candidate sites were too close to human activity with its accompanying radio frequency interference, or too remote, or had excessive snowfall: South Park, Colorado, near Colorado Springs; the Cannibal Plateau in the Gunnison National Forest, Colorado; the Grand Mesa, near Grand Junction, Colorado; the Aquarius Plateau, in the Dixie National Forest, Utah; and the Osier Plateau, near Chama, New Mexico.

South Baldy, the more western of Mt. Baldy's two peaks, is the site of the Langmuir Research Laboratory, a research arm of the New Mexico Institute of Mining and Technology that studies lightning. A dirt road leading to the Langmuir Lab provides access to the summit in summer, the season for thunderstorms. For year-round access to the MMA, the road would need to be improved and plowed to keep it free from snow. But that was a minor problem compared to those presented by the topography of the peak. Unlike the flat plain on which the VLA sits, the peak area has steep variations in elevation. Flat terrain existed that could accommodate the smaller configurations of the MMA, but moving the antennas to greater separations, especially to the north, would be daunting. A report[4] by an engineering consultant discussed the options and gave very roughly estimated costs. The problems were summarized in a memorandum[5] by Peter Napier to Brown on 16 May 1991, where he stated, "*If an array larger than 2 km in the N-S dimension is an absolute requirement for the MMA we should not commit to the Baldy site until we have done significant additional engineering and cost studies.*" For this reason and to make sure a better site had not been overlooked, studies of two sites in the White Mountains of Arizona, "Springerville" and "Alpine," were begun. The Alpine site was located just north of the town of Alpine on the south side of Escudilla Mountain. The Springerville site had a larger extended flat area just to the north of Big Lake, about a 30-minute drive from the towns of Springerville and Eager.

In 1990, when the MMA proposal was written and submitted to the NSF, studies of the Springerville and Alpine sites were in the beginning stages. Array configurations for all three sites were illustrated in the proposal, and are shown here in Figure 4.2. The Springerville site allowed for a configuration similar to the ideal one in the artist's impression of the MMA that appeared on the proposal cover (shown in Figure 3.3). The Alpine site came close in this regard, while the Mt. Baldy site looked nothing like the ideal configuration. Even so, imaging simulations showed the Mt. Baldy configuration provided roughly comparable quality, provided the extensive site work required for access to the more distant antenna locations could be made. Given all this, Mt. Baldy was the

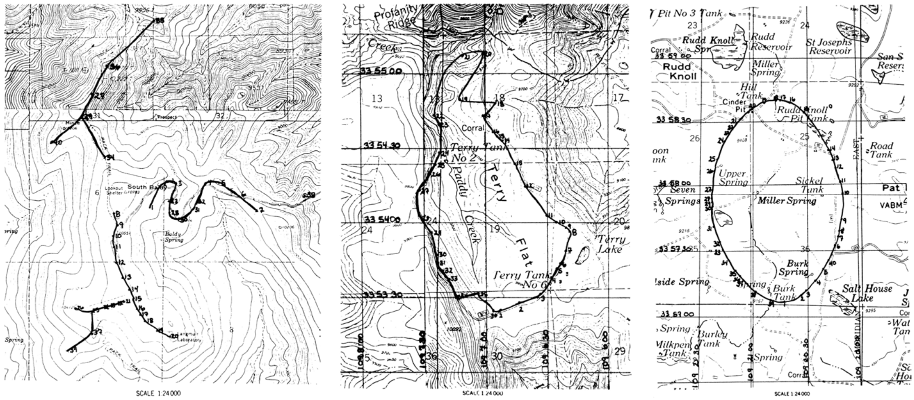

Figure 4.2 The MMA array configurations on the Mt. Baldy (left), Alpine (center), and Springerville (right) sites. The antenna locations are shown as black dots along tracks over which the antennas would be moved. The areas are approximately 3 km east–west by 5 km north–south. Credit: Adapted from topographic maps of the US Geological Survey; NRAO/AUI/NSF, CC BY 3.0.

leading contender for an MMA site in 1990 because atmospheric quality studies had already shown it to be an acceptable site, whereas such studies had not yet begun for the White Mountains sites.

The original MMA proposal did not specify a site. Rather, it only stated that the plan was to continue studying the three continental US sites, eventually pick one of them, and then get permission to begin construction. All of this was to be accomplished by 1994. Contacts with the National Forest Service and local government officials during the investigation of the Alpine and Springerville sites led to publicity in the Arizona media and interest in the nearby communities. A joint resolution[6] was passed in the Arizona Legislature endorsing the construction of the MMA in Apache County. Environmentalists worried about the impact the MMA would have on the Alpine site as it was a habitat for the Spotted Owl. Escudilla Mountain near the Alpine site had been the home of the last grizzly bear seen in Arizona. NRAO was urged to favor the Springerville site, if they chose Arizona.

Several environmental and geographic factors were at play now, and an overriding consideration continued to be the atmospheric transparency. Atmospheric testing was accomplished using radiometers that measured the sky transparency at various elevations above the horizon, tipping the line of sight from the zenith to near the horizon. The radiometers came to be called "tippers." Figure 4.3 shows an open tipper. They operated at a frequency of 225 GHz, near the frequency of the second lowest spectral line of CO. Eventually, four such tippers were constructed by the NRAO Central Development

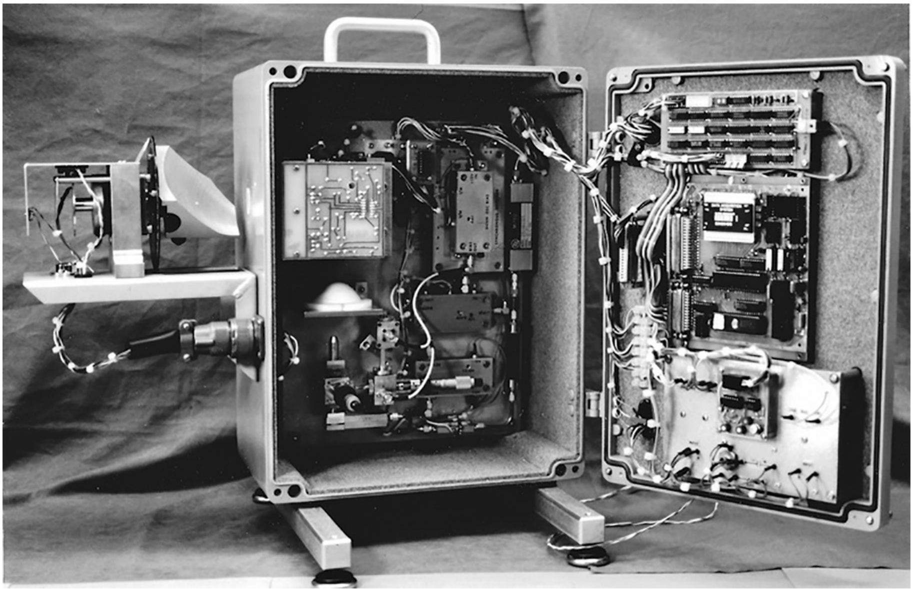

Figure 4.3 An open view of an MMA tipper showing the receiver electronics and computer control and communications circuits. The moving parabolic surface mounted on the side rotates (tips) in elevation to make the observations. The radiometer front end, or receiver, is in the left half of the box, and the intermediate frequency and digital sections are in the right half. The box can be closed for ease of shipment and to preserve temperature stability during operation. Credit: NRAO/AUI/NSF, CC BY 3.0.

Laboratory (CDL). Sandy Weinreb, the lead engineer of the CDL, designed and supervised the tipper construction,[7] along with Z.-Y. Liu, a visiting engineer, and Scott Foster, an NRAO summer student who greatly improved the software.

The first three tippers were successively placed at the NRAO 12 Meter Telescope on Kitt Peak near Tucson AZ, on Mt. Baldy, and at the Springerville site, shown in Figure 4.4. The latter tipper was later moved to the CSO on Maunakea in Hawaii. The tippers measured both atmospheric opacity at 225 GHz and atmospheric stability which could be inferred from the fluctuations in opacity versus time. The MMA proposal noted that the atmospheric stability on both Maunakea and Mt. Baldy were very good. An analysis of the tipper data for Mt. Baldy showed that for 25 percent of the time the opacity was less than 0.081 (92 percent transparency), meeting the specification for a good millimeter observing site of opacity less than 0.1 (90 percent transparency) for a reasonable amount of the time. An analysis of the duration of low opacity periods of time showed that the average was 24 hours, four times the expected typical observation of six hours.

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Figure 4.4 The weather station on the Springerville site. The shed held the tipping radiometer and recording equipment. Battery power was maintained by solar panels and a windmill. Credit: Frazer Owen, NRAO/AUI/NSF, CC BY 3.0.

The tipper data confirmed what was indicated by theoretical models of the atmosphere – the elevation of a site is the prime characteristic controlling the transparency. South Baldy at 3,240 m was better than the VLA at 2,120 m, the Springerville site at 2,800 m, and the 12 Meter Telescope site on Kitt Peak at 1,895 m. On Maunakea, the CSO site at 4,072 m was better than the VLBA site at 3,725 m, and both were better than South Baldy. As a result, the MMA Project had to give serious consideration to a non-continental site, namely Maunakea on the Big Island of Hawaii.

Hawaii

Maunakea, on the Big Island of Hawaii, is arguably the best astronomical observing site in the northern hemisphere. At the time of the MMA project's interest in Maunakea, it hosted a number of optical and infrared telescopes, the CSO, and the westernmost antenna of the VLBA. Use of the mountain top for astronomy was managed by the Institute for Astronomy (IfA) of the University of Hawaii, Manoa, under a lease agreement with the State of Hawaii. NRAO had

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been through the required negotiations, agreements, and permits for a VLBA antenna that had been placed on Maunakea. A sticking point for the MMA was the requirement the IfA imposed on all telescopes sited on Maunakea, namely that the IfA receive 15 percent of the observing time.[8] NRAO was opposed to the granting of a block of time to another organization that would control its use but, if necessary, might consider doing so for no more than 10 percent.

A negotiation with the IfA for an MMA site never occurred. It was not easy to fit the MMA onto the mountain. Don Hall, the IfA Director, thought it could be done and had indicated in broad brush how he would do it. Cam Wade thought it might barely fit onto a flat area stretching east from the VLBA antenna. Nevertheless, NRAO continued to discuss the possibilities with the IfA if only to keep open the possibility that the MMA might be merged with the Japanese Large Millimeter/Submillimeter Array (LMSA), a project[9] with similar science goals to the MMA. The Japanese astronomers already had a large optical/infrared telescope on Maunakea, the Subaru Telescope, and siting the LMSA there as well would offer economies of operation.

Atacama Desert of Chile

The Atacama Desert in northern Chile arguably has the best observational sites for ground-based astronomy in the world. It is to the southern hemisphere what Maunakea is to the northern. But in the Atacama, there are even fewer clouds. As shown in Figure 4.5, moisture from the Pacific Ocean is inhibited from coming onshore by the cold Humboldt Current, which condenses the moisture off-shore. The Andes mountain chain stops moisture from the Amazon Basin from flowing west. The result is a desert where rainfall is rare[10] and the landscape is arid. As such, it has attracted numerous astronomical observatories; among the most prominent optical telescopes at the time of the MMA site search were NSF's Cerro Tololo Inter-American Observatory (CTIO), the Carnegie Institution's Las Campanas Observatory (LCO), and ESO's La Silla and Paranal Observatories. It is also where the MMA, to become ALMA, would eventually be sited.

As was mentioned in Chapter 2, Mark Gordon was the first[11] to suggest locating the MMA in Chile, in his memorandum of 1 October 1984. The reasons for ignoring or dismissing this suggestion were several. Despite the fact that NOAO had, with NSF funding, successfully operated CTIO for many years, *radio* astronomers thought of Chile as being very far away, too far from the expertise required for the MMA. The first MMA Advisory Committee had even dismissed the idea as "*uninteresting*." In time there were exceptions: Pat Thaddeus installed a "Mini" telescope at Cerro Tololo to map CO in the southern hemisphere.

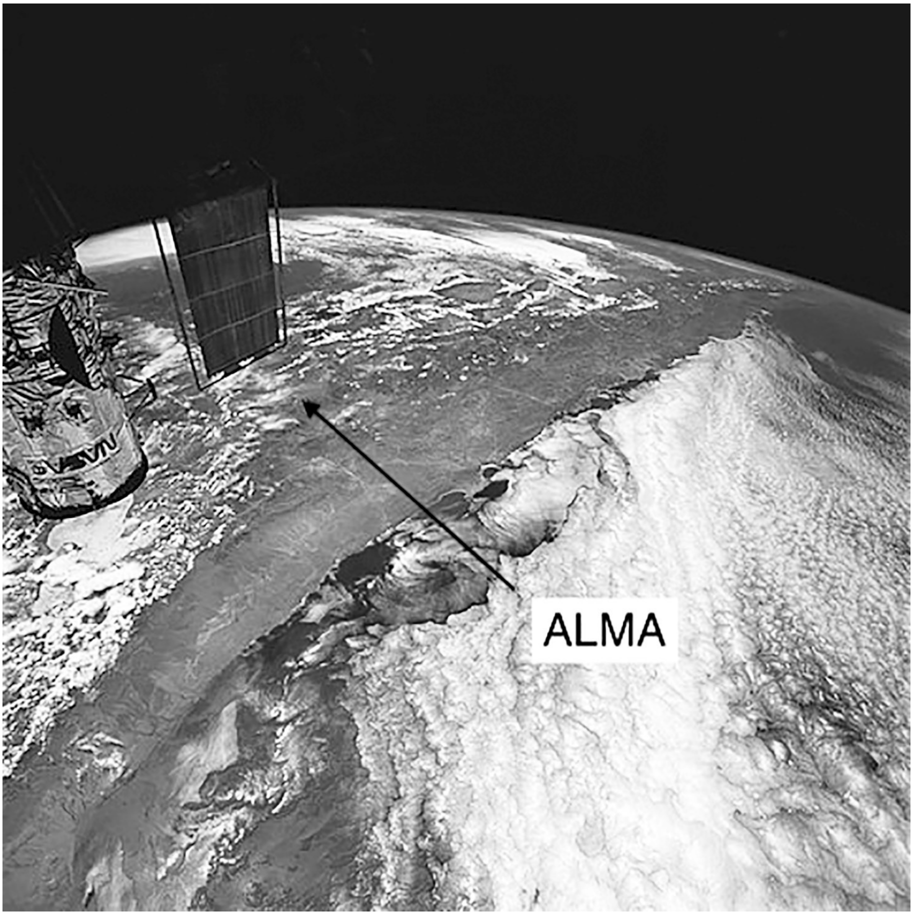

Figure 4.5 A picture looking south at the Atacama Desert in northern Chile, one of the most arid places on Earth, taken from the International Space Station by Swiss astronaut Claude Nicollier, showing the location of the site selected for the MMA, and in time ALMA. The moisture trapped in off-shore clouds by the cold Humboldt Current are clearly seen from this perspective, as are the clouds in the Amazon Basin blocked by the Andes. The swath of gray that crosses the image diagonally is the Atacama Desert. Credit: Claude Nicollier; ESO, CC BY 4.0.

And, under the leadership of Roy Booth, the Onsala Space Observatory in Sweden built and successfully operated a submillimeter telescope, the Sweden-ESO Submillimetre Telescope (SEST) at ESO's La Silla Observatory. Thaddeus and Booth reported the observing conditions for millimeter astronomy to be superb. By February of 1994, it had become clear that Chile deserved a look. Importantly, Dickman at NSF was strongly encouraging consideration of a Chilean site for the MMA. Vanden Bout and Brown decided to make an exploratory trip, scheduled for May 1994.

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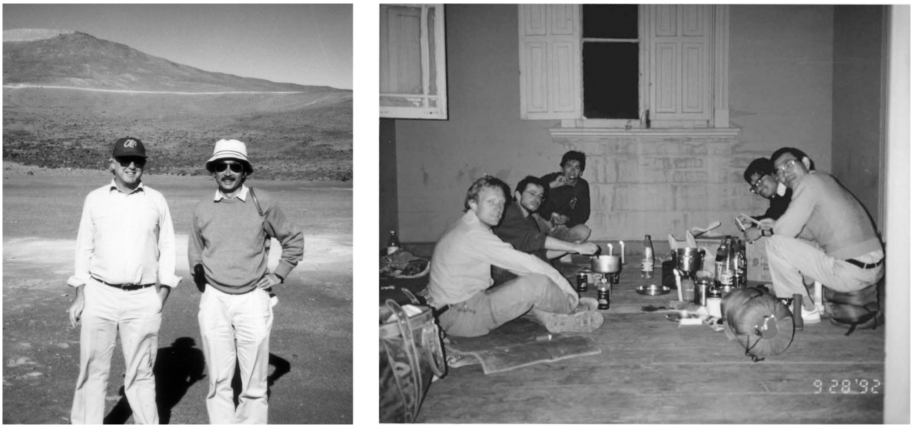

Figure 4.6 Left panel: Roy Booth and Masato Ishiguro on a visit to the Vega Valley near Paranal in February 1992. Courtesy of M. Ishiguro, used by permission. Right panel: The LMSA site search team enjoying a meal. They appear to be camping out. (left to right) Nick Whyborn, Wolfgang Wild, Angel Otárola, Kimiaki Kawara, and Naomasa Nakai. Courtesy of Nagayoshi Ohashi, reproduced by permission.

NRAO was by no means the first to search for a site in Chile for a millimeter/submillimeter array. As early as 1991, Roy Booth and Lars Bååth searched the Atacama Desert to identify possible sites for a millimeter array.[12] Before selecting Maunakea for the SMA, the SAO had searched for possible sites in Chile. Using topographic maps, Phillippe Raffin and Alan Kusonuki picked out 22 high elevation places which they visited. They identified a site near the town of Ollagüe, at 4,650 m elevation as the most promising. Their list did not include the high plateau above San Pedro de Atacama that was to become the ALMA site. A team[13] from ESO and Japan, shown in Figure 4.6, visited 20 potential sites[14] for the LMSA in 1992, including some of the sites identified by Raffin and Kusonuki in their 14 May 1992 report.[15] In May 1993, three[16] from the team, led by Angel Otárola, went to the high country east of San Pedro where they were able to view from the side of Cerro Toco the plateau below that was to become the ALMA site. By bad luck they were prevented from descending to the plateau due to snow and penitentes,[17] the icy snow formations found at high altitudes.

The visits by Brown and Vanden Bout to observatories in Chile went smoothly, facilitated by the gracious hospitality of their hosts and the considerable help they gave in making travel arrangements. Peter Shaver, an ESO scientist, was observing at La Silla and gave them a tour of the telescopes, introducing them to the La Silla Director, Daniel Hofstadt. The New

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Technology Telescope was particularly impressive, as was the cafeteria, a first-class eatery managed by Herr Shumann, the most famous executive chef in astronomy. Miguel Roth welcomed them to the nearby LCO, which looked to Vanden Bout to be run much like McDonald Observatory in Texas. The chief conclusion from the visits was that these three major observatories had operated successfully in Chile for many years with little trouble, despite political upheavals. Malcolm Smith, the CTIO Director, made time available for a discussion of what it is like to operate in Chile, and he offered a tour of the telescopes even though the groundbreaking ceremony for Gemini South was about to happen. Vanden Bout recalls asking the contractors removing the top of Cerro Pachón for the new telescope what permits were required for such work. A man put a hand on a bulldozer and said, "*This is my permit*." (The statement gave a totally false impression of the environmental consciousness in Chile; ALMA would undergo a rigorous environmental review and permitting process.) Dick Malow, of AURA, the research management corporation that operates the NOAO, had arrived early for the ceremony and took Brown and Vanden Bout to dinner in La Serena. He was to follow the ensuing development of the MMA and ALMA in Chile with keen interest, making sure no missteps were made that might adversely impact AURA's interests.

The NRAO team was expanded for the trip to the high sites. Hernán Quintana had been an NRAO postdoctoral fellow after graduating from Cambridge University, and was now on the faculty of the Pontificia Universidad Católica de Chile (U. Católica). Brown welcomed Quintana, as a former colleague to the team. Riccardo Giovanelli of Cornell University was invited as a trusted friend and US colleague who was fluent in Spanish and understood South American culture, having grown up in Argentina and Bolivia; Vanden Bout spoke no Spanish, and Brown's high school Spanish was very rusty. Finally, and most important, Leo Bronfman, an astronomer at the Universidad de Chile (U. Chile), asked for the help of Angel Otárola, an expert on telescope site requirements in general. Roy Booth, the director of the SEST where Otárola was working, graciously agreed to the request. Otárola knew the high Atacama Desert exceedingly well, having explored it at length. He also knew people in the many villages and larger towns throughout the desert. His knowledge would prove to be crucial to the MMA site selection.

The expedition began in the coastal city of Antofagasta, with a tour of ESO's Paranal Observatory about two hours south of the city. The Very Large Telescope (VLT) and its support facilities, especially the staff and visitor hotel, were a stunning example of the successful construction in Chile of a truly major astronomical installation. It was encouraging to see, and at the same time provoked a bit of jealousy among the Americans.

One unfortunate turn of events was that it was not possible to rent any Toyota HiLux® 4-wheel-drive trucks from the Hertz rental agency. These short-bed super-cab models, equipped with extra gas, water cans, and spare tires, were favored by the geologists prowling the desert for minerals, as well as by personnel of the mining industry that dominates the region. Instead, only a Chevrolet sport utility vehicle and a more conventional Toyota pickup were available, both more suited to urban use rather than the poorly maintained roads of the desert.

After an overnight stay at the Park Hotel in the mid-sized city of Calama, the team drove to the town of Ollagüe, on the border with Bolivia. Ollagüe is where a railroad line from Antofagasta crosses into Bolivia and on to La Paz, carrying freight and passengers. It is near sites previously visited by the SAO group, and the team was headed to the highest of those sites. The town offered a school, medical clinic, restaurant, and, most significantly for this trip, a police station. Otárola forgot that protocol requires checking in immediately with the Chilean national police, or Carabineros, upon entering a border town. It had been a rough drive on a poor dirt road with the inadequate rental vehicles and the hungry team went to the restaurant first. Upon leaving the restaurant, they were accosted by an officer who asked why they had not checked in with him on arrival. At the station, they presented passports, driver's licenses, and rental agreements. The officer in charge falsely claimed that the truck insurance had expired and that the group would be held at his station, along with the vehicles, until the matter was sorted out. Otárola suspected a bribe was expected. After what seemed like a very long time, another officer entered the station and greeted Otárola warmly. He was a friend. Suddenly, all was in order and the team was free to go. The experience was an insight on the darker side of the tight security procedures that lingered for a while after the dictatorship of Augusto Pinochet had passed.

After visiting the Ollagüe school and medical clinic, the team went to the site that Raffin and Kusonuki had listed as their first choice for the SMA. It was a gentle climb out of the village. The site was spectacular, with a large level of extent. The sky was unbelievably blue. A tipping radiometer was too bulky and complex in its operation for this initial search. Instead, the team used a handheld water vapor meter,[18] provided by Mark Gordon of NRAO Tucson. One pointed it at the Sun to measure the precipitable water vapor (PWV) column in millimeters. The readings indicated very low values, which was encouraging, but the device also seemed erratic and its reliability was questioned. The site near Ollagüe is shown in Figure 4.7.

It had been a long day. The group, tired and reluctant to spend a night in Ollagüe, at its elevation of nearly 5,000 m, decided to drive back to the Park Hotel in Calama. On the way, they were treated to a spectacular view of the full

Figure 4.7 The site identified by SAO's Raffin and Kusonoki as "Ollagüe Area, #19/20" elevation 4,650 m near Cerro Aucanquilcha. It was their top choice for the SMA. Left to right: Hernán Quintana, Angel Otárola, Paul Vanden Bout, and Bob Brown. Credit: Riccardo Giovanelli; NRAO/AUI/NSF, CC BY 3.0.

Moon rising over the Salar Ascotán. The long day, wretched road condition, and high altitude left them with blinding headaches on arrival at the Park Hotel. These were cured by Quintana's therapy of one or more Pisco Sours, a national mixed drink specialty. He suggested making San Pedro de Atacama the next stop. He said the small village was charming, and that he had frequently vacationed there. Furthermore, he knew there was high, flat terrain above the village toward Argentina. As it turned out, Brown also knew of the high, extended terrain above San Pedro based on his recent studies of topographical maps. He had purchased a number of such maps for the general area while in Santiago at the start of the trip. Leo Bronfman had taken him to the Instituto Geográfico Militar, which sold the maps to the public. It was suspected that in border regions the maps had deliberately been made incorrect, but even so, there was obviously high ground at the top of the Jama Pass above and to the east of San Pedro. Most important, Otárola had actually seen the spot on a previous trip. As has been mentioned, in May 1993 with a group from ESO and Japan, he had looked down at the plateau that was to become the MMA site from the south side of Cerro Toco. It was quickly decided to head to San Pedro.

The group arrived in San Pedro late the next day and checked into the Hostería, at that time just about the only decent place to stay in the village other than hostels where one could spread a sleeping bag on the floor. The Hostería had a restaurant and, most significantly, a gas station, the only one in the area. Good use was made of both. The village of 2,500 inhabitants was delightful and enchanting, as Quintana had claimed. The streets were unpaved and electricity was only available between the hours of seven to ten in the evening. Underground runoff from the Andes range provided a stream that flows through the village and drains in a delta, feeding the lagoons of the Salar de Atacama, the third-largest salt flat in the world. San Pedro de Atacama had been a farming village for centuries. A Spanish-built church sits next to the town square. A local priest, Father Gustavo Le Paige, had founded an archeological museum and built a collection of artifacts including well-preserved mummies. But the museum had to wait for later trips; the team was off to the high country east of town.

A national highway, Route 23, runs from Tocopilla, on the Pacific Coast, past the largest open-pit copper mine in the world, Chuquicamata, through Calama to San Pedro and points south. From San Pedro, Route 27 goes over the Jama Pass to Argentina. The team followed this route, past the customs and immigration checkpoint just outside of San Pedro and the military airstrip nearby, up into the Andes. The highway was unpaved at the time and deeply rutted in places as a result of traffic and poor maintenance. About halfway to the top of the pass, the vehicle carrying Vanden Bout and Otárola died. It had a carburetor rather than a fuel injection system, and the carburetor mixture had been tuned to run at sea level. It was surprising that it had not already failed in Ollagüe. Brown, Quintana, and Giovanelli went on to the top of the pass, where they could catch a view of the iconic Laguna Verde in Bolivia. At a high point, an attempt was made to measure the water vapor with the water vapor meter. It would not work, even after installing new batteries and giving it a few sharp raps. But the sky was an astoundingly deep blue and it felt like the area might pass Frank Low's informal test for a good infrared site – a tendency for nose bleeds. Brown chose not to follow Otárola's directions to Cerro Toco in view of the late afternoon hour and concern for the broken vehicle.[19] The team convened again in San Pedro greatly encouraged. In their review of the last two days and the visits to the two high sites, the group clearly favored a site near San Pedro. The next step was to visit the site identified by Otárola on his May 1993 trip. But that would not happen for another five months.

Before returning to the United States, Brown, Giovanelli, and Vanden Bout flew to Mendoza, Argentina, to meet with Raúl Colomb, director of the Argentine Institute of Radioastronomy, and Hugo Levato, the Director of the

Astronomical Complex El Leoncito. They visited the El Leoncito site and spent the night before returning to Santiago and the United States. It was clear that the low elevation of the Argentina site ruled out any possibility of developing the MMA there. In 1995, Felix Mirabel proposed siting the MMA in northern Argentina, near Salta and due east of the Chajnantor site, but the elevation of the area, although higher than El Leoncito, was inferior to Chajnantor for submillimeter observing.

Llano de Chajnantor

The MMA Design and Development Plan that NRAO had submitted to the NSF in 1992 required approvals up through the management structure at NSF, including the National Science Board, in order for the MMA Project to receive funding. Bill Harris, NSF Assistant Director for Mathematics and Physical Sciences (MPS), was key to getting this approval. Informed of the potential site near San Pedro, Dickman thought that Harris might be convinced to promote the MMA by a visit to the Chilean altiplano region. With the stunning vistas as a backdrop, he might warm to the idea of building a millimeter instrument there. On 24 October 1994, Vanden Bout, Harris, and Hugh van Horn, AST Director, arrived in San Pedro. Leo Bronfman joined them. Brown had preceded them to San Pedro. Otárola was unable to guide Brown on this trip as he was needed at SEST for the scheduled maintenance of the telescope. Instead, Geraldo Valladares went with Brown. He had been hired by Bronfman to accompany Otárola on trips to high elevations. Following Otárola's directions Brown and Valladares spent two days exploring the top of the Jama Pass and the side road to Cerro Toco, where Otárola had been able to see the Chajnantor Plateau. They also found a place on Highway 27 to impress the NSF delegation with the surroundings. On 25 October 1994, the group drove up Highway 27 to the spot Brown and Otárola had chosen, near the turnoff to Bolivia and the Laguna Verde. The scenery was as dazzling as expected based on the previous scouting visit – bone dry land, volcano peaks, the green lakes, and endless distant vistas. From the deep blue sky and thin air Harris could see the potential for millimeter observing. Brown told Harris that he was sure that a flat expanse nearby could accommodate the MMA. Harris, in his typical "I want action" style told Brown to find it. On the drive back to San Pedro, Harris ordered van Horn to make the MMA happen, something that van Horn was only too willing to attempt.

The next day Brown and Valladares, following the route they had taken two days earlier, arrived at the lookout point on Cerro Toco and saw the site shown in Figure 4.8. Brown's recollection of seeing the site was given to Vanden Bout in an email message[20]:

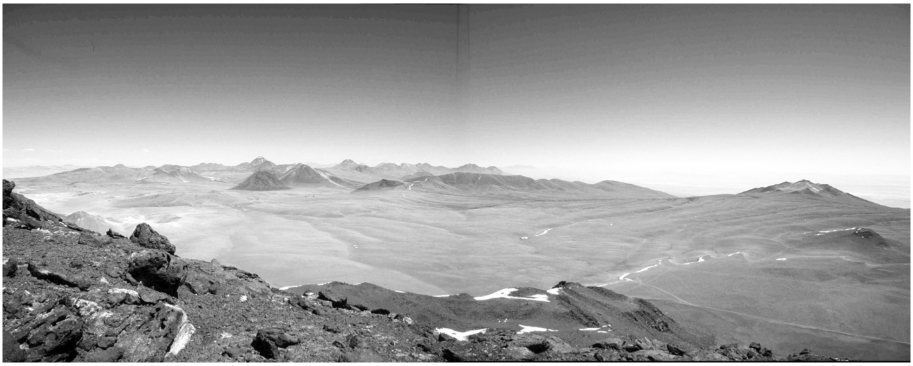

Figure 4.8 The 5,000 m (16,400 ft) elevation site as seen from a point on Cerro Toco. M. Gordon named it the Llano de Chajnantor, after a neighboring peak, Cerro Chajnantor. In general usage, the site name is usually shortened to "Chajnantor," a word that means "place of departure" in the Kunza language of the Atacameños. Credit: Simon Radford; NRAO/AUI/NSF, CC BY 3.0.

The next day … I drove with Geraldo Valladares back up the Paso de Jama to find a "real" site for the MMA. It was at that time that Geraldo and I ventured down the road to Bolivia only to be turned around by a guy pointing a rifle at us (Geraldo says 'I do not like his face'). We then drove the opposite way, south, found the western entrance to the plateau by following the switchback road that goes to the sulfur mine on Cerro Toco and continued onto the Chajnantor Plateau. The plateau was perfect. I climbed up on a rock and excitedly took some panoramic pictures with Geraldo watching me perhaps wondering if I had lost my mind. I said to Geraldo, 'Isn't this a beautiful place? Can't you just see it with the MMA antennas spread out in the distance?' Geraldo was very serious. He said, "Yes, but it is a beautiful place without the antennas." … That was October 26, 1994.

Who "discovered" the ALMA site? As with many discoveries, the answer is nuanced. Quintana knew there was flat land at the top of the Jama Pass from family vacations taken in San Pedro and topo maps of the area. Otárola was the first to identify the site on his May 1993 scouting expedition for the LMSA, and he provided Brown with the directions to the Cerro Toco lookout. Brown and Valladares were the first to drive down from Cerro Toco and actually explore the site itself. It is a little like asking who discovered America: the prehistoric people who crossed the Bering Strait to settle the Americas, the Vikings, or Christopher Columbus? A fair statement is that Otárola and the ESO team were the first to *see and identify* the site and that Brown and Valladares were the first science team to *explore* the site.

Chajnantor Site Studies

In November 1994, the NSF National Science Board approved the MMA Design and Development Plan, after a presentation by Dickman. In principle, funding would follow. But, although the Chajnantor Plateau might seem promising as a site for the MMA, NSF expected to see extensive studies to characterize the site before it could be approved as the site of choice. Those studies had just begun.

On 27 October 1994, an NRAO team composed of Peter Napier, Frazer Owen, Simon Radford, and Juan Uson arrived in Chile from Socorro, New Mexico, with a tipping radiometer for measuring atmospheric transparency and the gear necessary to operate it. Their expedition had been organized months earlier by Brown on his return from the first site search in May of that year. On 14 July 1994, Napier had sent Brown an email message[21] listing the places near San Pedro that had sufficiently high elevations to be of interest for transparency measurements with a tipping radiometer, including Chajnantor. By coincidence, they arrived the day after Brown had visited the Chajnantor site. The survey team crossed paths in the Santiago airport with Vanden Bout and the NSF group, who were returning to the United States. Following a discussion with Brown, the arriving team's attention was immediately focused on Chajnantor. After flying to Antofagasta and connecting with Otárola, the site-testing team drove the next day to San Pedro and unpacked the tipper. It was giving problems and working to fix these occupied the following day. On 30 October 1994, the team, guided by Otárola, explored the Chajnantor site looking for a location where they could install the tipper. A boulder was located that offered shelter from the wind and this is where they chose to set up camp. The next day Radford drove Uson, who had become ill, to Antofagasta for his return to the United States. The rest of the team took the tipper to the high site and commenced its operation. This first monitoring station on the Chajnantor site is shown in Figure 4.9.

On 1 November 1994, Otárola left to work with a Japanese team in the area, who were running a radiometer at Paranal. The others stayed in San Pedro where they met a German graduate student working on a meteorology degree. He educated them on the Altiplanic Winter, known colloquially as the "Bolivian Winter," an annual phenomenon in (austral) mid-summer whereby moisture from the Amazon Basin is pushed west over the Andes. In severe events, there can be heavy snowfall on the high plateaus. As the snow melts and runs off the mountains, deep ravines are cut, which are visible everywhere on the mountain slopes. The next day, after checking on the tipper, the group, now Napier, Owen, and Radford, decided to drive to an even more extreme site at an elevation of 5,700 m on the Bolivian border. A dirt road to the site existed by virtue of a sulfur mine, now abandoned. Years later Radford would return to this site and install a submillimeter spectrometer built by Ray Blundell of the SAO. One of the authors (Plunkett)

Figure 4.9 The first MMA site survey team and their equipment: tipping radiometer in the entrance to the tent and solar panels for charging the batteries that powered the tipper in front. Left to right: Peter Napier, Frazer Owen, and Angel Otárola. Credit: Simon Radford; NRAO/AUI/NSF, CC BY 3.0

recalls visiting this site several times while she was a graduate student to make observations using the spectrometer. It was so high and remote that they always drove two trucks and kept both running throughout the night as a precaution.

A total eclipse of the Sun occurred on 3 November 1994. The path of totality passed through the border town of Arica in the far north of Chile, but the team chose to stay in San Pedro, where the event was 92 percent total; their priority was to tend the tipper. After doing so, they decided to climb Cerro Chajnantor, the extinct volcano for which the ALMA site was named by Mark Gordon, as the Llano de Chajnantor. The elevation of 5,635 m proved to be a challenge but Napier and Radford made the summit. The next day the team brought the tipper and equipment back from the Chajnantor Plateau site to San Pedro, and packed up to leave. It was a full day of getting to know the area: a visit to the archeological museum in the village, then a drive of several hundred kilometers to Paranal to compare measurements made there with those of a Japanese instrument,[22] and to Antofagasta for the night. The next day, after picking up the tipper from Paranal, the team flew back to the United States. The tipper measurements made at Paranal agreed with those of the Japanese radiometer to within five percent, so both teams felt their data could be trusted.

For the most part, the PWV measurements recorded on the Chajnantor site were comparable to those on Maunakea. This was encouraging. All the more so, as the readings had been taken at the start of the Altiplanic Winter. Because the tipper had developed some operating problems, it was decided to return it to the United States, overhaul the tipper, and come back and set up a permanent monitoring station.

The Container

Sustained and reliable monitoring of the weather and the atmospheric transparency and stability required a small laboratory that could be deployed on site. Ideally, the laboratory would house test equipment and the tipper, as well as serve as a base to control an instrument to measure the atmosphere stability and record data from the weather station. Gerry Petencin, an engineer on the staff at NRAO based in Socorro, designed and built this laboratory in a shipping container. In April 1995, Petencin, Ramón Gutiérrez, a VLA antenna mechanic, and Otárola installed the container at a location on the Chajnantor site that was thought to be approximately where the center of the MMA would be placed, shown in Figure 4.10. An array of solar panels and a windmill generator supplied power to a bank of batteries. An inverter then supplied AC

Figure 4.10 The atmospheric monitoring laboratory in the center of the Chajnantor site. It was built into a standard shipping container. The array of solar panels leaning on the back side of the container provided power. The tipping mirror mechanism of the 225 GHz radiometer can be seen mounted on the top right-hand side of the container. The small antenna on the end of the container provided a data connection via SatPhone. Credit: Paul Vanden Bout; NRAO/AUI/NSF, CC BY 3.0.

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power to the instruments and to the computer that was used to control and record their data. The tipper was mounted inside the container with its tipping antenna poking out through an opening in the wall. It measured the atmospheric transparency at 225 GHz and was later equipped to do so at 325 GHz. The station was brought into operation by Radford, and the tending of the station became the responsibility of Otárola, who was a wizard at fixing problems.

The phase stability of the atmosphere was measured using an interferometer designed by NRAO staff members Darrel Emerson, John Payne, and Dick Thompson, and then installed by Radford. It used two small 1 m diameter antennas separated by about 200 m, to receive the 12 GHz carrier signal from a geostationary satellite. Atmospheric studies on the ALMA site continued for many years. Otárola has curated all the data and results of those studies.[23] In 2005, the temperature variations of atmosphere across the site were measured using radiosonde balloons. The difference of 2 C between two spots 7 km apart was judged to have minimal effect on the pointing of the array.[24] Figure 4.11 shows a balloon launch.

Figure 4.11 Launching a radiosonde balloon during an August 2005 study of the variation of atmospheric temperature across the ALMA site. Left to right: Rubén Bravo (behind balloon), Roberto Rivera, Angel Otárola, Jorge Riquelme. Courtesy of Alison Stirling, reproduced by permission.

The container laboratory, which came to be referred to simply as the "Container," became a destination for those visiting the Chajnantor site. Jim Moran of Harvard University was the first to sign his name on the wall of the Container. He inspired dozens of others to do the same over the years that followed. Figure 4.12 shows a portion of the wall. It is rumored that the wall is now in storage waiting for a suitable place for display.

It must be noted that the effort to measure the atmospheric quality of sites in the Atacama was one of extraordinary cooperation between ESO, NAOJ, and NRAO. Otárola was an employee of ESO who was made available to work with the other two groups by the SEST director, Roy Booth, at the request of Leo Bronfman at U. Chile. The NAOJ was looking for a site for the LMSA and for a single-dish submillimeter wavelength telescope. ESO was searching for a site for their Large Southern Array and NRAO was doing the same for the MMA. All the groups worked together to ensure success, with Otárola at the center. In the end, as will be described in the next chapter, the three projects were merged into one with Chajnantor for its site.

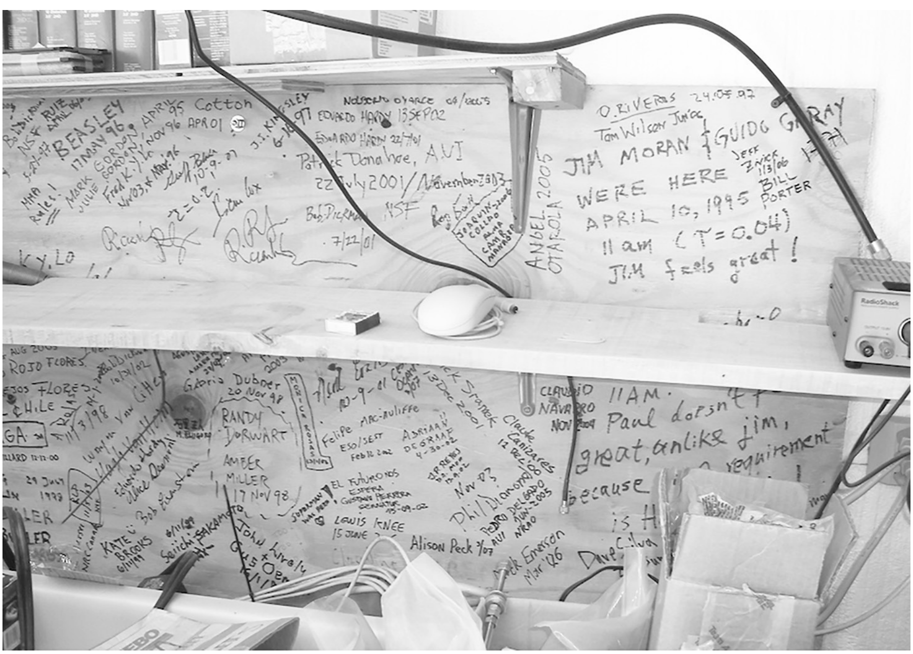

Figure 4.12 A portion of the "signature wall" in the monitoring station, a modified shipping container on the Chajnantor site. Note that on 10 April 1995 when Moran and Guido Garay (U. Chile) visited, the atmospheric opacity was 0.04, or an atmospheric transparency at 225 GHz of 96 percent. Courtesy of James Moran, reproduced by permission.

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Searching for the ALMA Site

My involvement in the search for a location in northern Chile for a radio interferometer with a large collecting area and long baselines is one of the highlights of my personal and professional life. I owe a debt of gratitude to my former supervisors and collaborators at ESO for entrusting me to join colleagues from Europe, Japan, and the United States for the exploration of suitable sites in the Atacama Desert. I also contributed to studies to better characterize their conditions in terms of local weather, atmospheric PWV, and atmospheric stability. In all of this work, I was not alone. I was a member of a great team. There were too many to mention, but I must acknowledge the friendship and great collaboration I had with my colleagues Guillermo Delgado and Roberto Rivera, both of whom, sadly, did not live long enough to see the ALMA come to full operation and deliver great science for the scientific community. I think of them often. I am convinced ALMA was the product of a great collaboration that included various organizations with leaders who supported and stimulated all of us to do our best. Believe me, we had a lot of fun working together.

In the beginning of the 1990s, scientists from ESO and Onsala Space Observatory of Sweden, including staff from the Swedish-ESO Submillimetre Telescope (SEST), started to explore the Atacama Desert to identify a possible location for a European radio-interferometer facility (later called the Large Southern Array, LSA). My first exploration trips were with the radio astronomer Lars Bååth, with whom I had a good collaboration at the time for this purpose. A few years later (1995), the European community expressed interest to build a 10,000 m^2 collecting area interferometer array using 15 m diameter parabolic antennas with up to 10 km baselines for sub-arcsecond spatial resolution. We explored several sites: the Vega Valley by the Paranal area, Pampa Loyoques and Pampa Herrera (east of the town of Toconao into the Andes mountains), Pampa El Chino, Pampa San Eulogio and Pampa de Pajonales, located south of Salar de Punta Negra and in the vicinity of the Llullaillaco Volcano. The Llullaillaco area, with its natural beauty and pristine views, later became a national park in Chile. This effort counted on the support from Roy Booth, Lars-Åke Nyman, Peter Shaver, Daniel Hofstadt, and colleagues at OSO and SEST.

Simultaneously, in 1992, a group from the Smithsonian Astrophysical Observatory visited northern Chile, around the west slope of the Andes mountains, to identify potential spaces for the observatory's Submillimeter

Array, which was ultimately built on the Maunakea Science Reserve in Hawaii.

Not long after, an extended exploration campaign along the Atacama Desert was conducted by the Nobeyama Radio Observatory (NRO) of Japan, with help from our local collaboration between the SEST team and academics from the Astronomy Department at the University of Chile. The NRO group wanted to identify a place for their LMSA project. The colleagues from Japan studied in detail two potential sites: Pampa de Río Frío, near the Llullaillaco Volcano, and Pampa La Bola, just east of the Chajnantor Plateau. This exploration effort was led and supported, on the field, by Masato Ishiguro and Naomasa Nakai.

This effort gained major momentum with the arrival in May 1994 of Paul Vanden Bout and Robert Brown from NRAO in the United States. Together with some of their guests and my participation, we visited several sites. They were convinced to come back and look more closely at the high- elevation sites by the Chajnantor Plateau as potential opportunities for their Millimeter Array. Soon after the first visits, we started monitoring the optical depth at 225 GHz and also the atmospheric stability using a 12 GHz, 300 m baseline radio interferometer. In the period from 1996 to 1998, the LMSA and LSA teams also joined NRAO at Chajnantor for a collaborative effort to monitor conditions in the Chajnantor/Pampa La Bola area.

All the teams acknowledged the superior atmospheric qualities of the Chajnantor Plateau to support radio astronomy in the millimeter/submillimeter spectral bands. This opinion was supported by the results from our collaborative studies. The friendly collaboration to identify the best place for what we now call ALMA had a perfect ending. It included people from many countries, organizations, and professional backgrounds and was a great opportunity for my own professional development. My family and I owe a great debt of gratitude to all who made that opportunity possible.

Angel Otárola
European Southern Observatory
Santiago, Chile

Cost Considerations

The Chajnantor site was deemed superior to Maunakea, but was it affordable? To answer this question, Mark Gordon was given the task of studying the operations of the optical observatories in Chile and constructing a strawman construction and operating budget for the MMA. To give Gordon credibility with Chilean contacts, Brown made him Head of MMA Site Development, Chile. After taking an intensive course in Spanish, Gordon made many visits to Chile gathering the relevant data. Using a mathematical estimation technique called "fuzzy logic" he came up with costs. Gordon also investigated means to counter the effects of working at an elevation of 5,000 m; with Eduardo Hardy, he visited facilities in La Paz, Bolivia, where oxygen enrichment was in use. His report,[25] *ALMA in Chile: A Plan for Operations and Site Construction,* is a comprehensive document covering the history of Chile, its geography and geology, climate, and details on the area around the proposed MMA on the Llano de Chajnantor. The report also laid out detailed plans for operations and site construction. Although Chile would be more expensive than Maunakea as an MMA site, the premium was considered good value. These plans were later captured in the chapters he wrote for the MMA Project Book on site development and operations. The report was an important input to the decision by NRAO management to place the MMA in Chile. After the MMA entered ALMA, a much larger project, the site development and operations costs increased accordingly, but Gordon's analysis of the issues and his advice provided valuable guidance beyond the MMA.

Site Proposal

As the data from the NRAO container came in and were analyzed, it became obvious that the site was the best that had been studied. The MMA project came to assume that it was the site of choice. Dickman, NRAO's NSF program officer, was keenly aware of NSF requirements and told NRAO it would need to follow proper protocol. He asked for an official proposal requesting approval of Chajnantor as the MMA site. The first draft of the site proposal was available for comment on 9 October 1996. In 33 pages, the report[26] presented the science requirements, the site testing program, and the two candidate sites, Maunakea and the Llano de Chajnantor. The characteristics of the two candidate sites were given, concluding that the Chile site was best. The report went on to argue the feasibility of locating the MMA on the Chajnantor site with respect to volcanism, earthquakes, high altitude considerations, and logistics. The issue of lightning on the site was not mentioned, even though it was potentially a serious threat. (Six years later a study[27] showed that lightning was rarely observed on Chajnantor.) Nor was the matter of exposure to cosmic ray radiation discussed. (Five years later a study[28] showed that the radiation dosage for an ALMA employee splitting his/her time between the high and mid-level ALMA sites was approximately double that at sea level.) Strawman plans for construction, commissioning, and operations were presented. The conclusion of the report was that Chajnantor was the site with the best atmosphere, could accommodate the longest anticipated separations of antennas, and was operationally feasible.

The data supporting the selection of the Llano de Chajnantor for the MMA were clear. Figure 4.13 shows how a potential array 3 km in extent could be accommodated on it and Maunakea. But it is obvious that Chajnantor offers a much large flat area with the possibility of much larger arrays, while on Maunakea the 3 km array barely fits on sloping terrain. Figure 4.14 shows the high-frequency transparency on Maunakea and the Chajnantor site.

The proposal to site the MMA in Chile was not officially submitted to the NSF until 18 May 1998. The cover letter to Dickman, signed by Brown, was accompanied by an endorsement from the AUI Board, and signed by Martha Haynes, Interim AUI President. On 31 December 1998, Aaron Asrael, the Grants and Agreements Officer for the NSF, sent Haynes a letter approving the choice of the Llano de Chajnantor as the site for the construction of the MMA. He took pains to point out that actual construction would require the approval of the National Science Board.

Protecting and Securing the Site

Mining has been the principal, and at times only, industry besides tourism in northern Chile, and it has a long, important legacy for the country's identity and economy. It began with the extraction of saltpeter (sodium nitrate, colloquially known as "white gold"), but it is copper that came to dominate mining in modern-day Chile, with lithium recently rising in importance. The Chuquicamata mine is the largest open-pit copper mine in the world, towering above Calama from the north. Another major mining operation, Mina Escondida, is located midway between the Pacific coast and the southern end of the Salar de Atacama. Other mines pepper the region's higher elevations, and geologists are often seen scouring the areas in between for mineral deposits. Even a tourist can understand why they come here, based on the infinite shades that make up any rock formation in sight. The region seems geologically unparalleled.

The economic importance of mining to the Chilean economy is enormous and mining claims take legal precedence over land ownership. It was vital that the MMA project protect the Llano de Chajnantor, which was

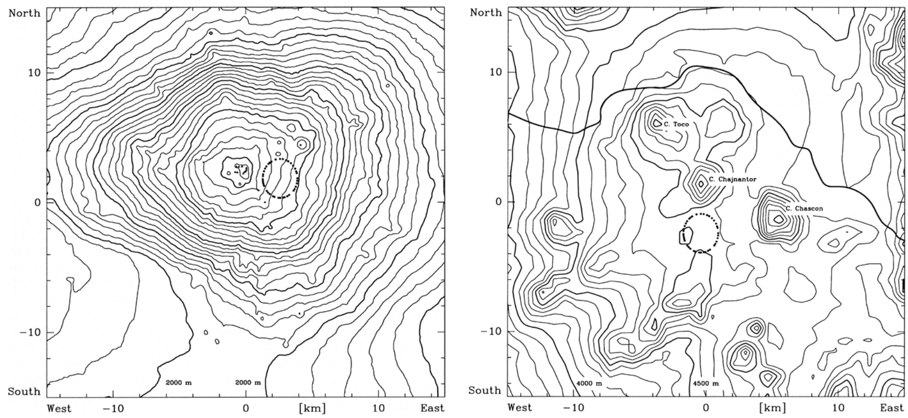

Figure 4.13 Contour maps of the two candidate sites, Maunakea (left panel) and Chajnantor (right panel). A small dotted oval in each map shows the possible locations and extents of a nominal 3 km array. The Chajnantor site clearly offers much more level ground for more extended baselines. Credits: Left panel –Adapted from a topographic map of the US Geological Survey; NRAO/AUI/NSF, CC BY 3.0; Right panel –Adapted from a topographic map of the Instituto Geográfico Militar, NRAO/AUI/NSF, CC BY 3.0.

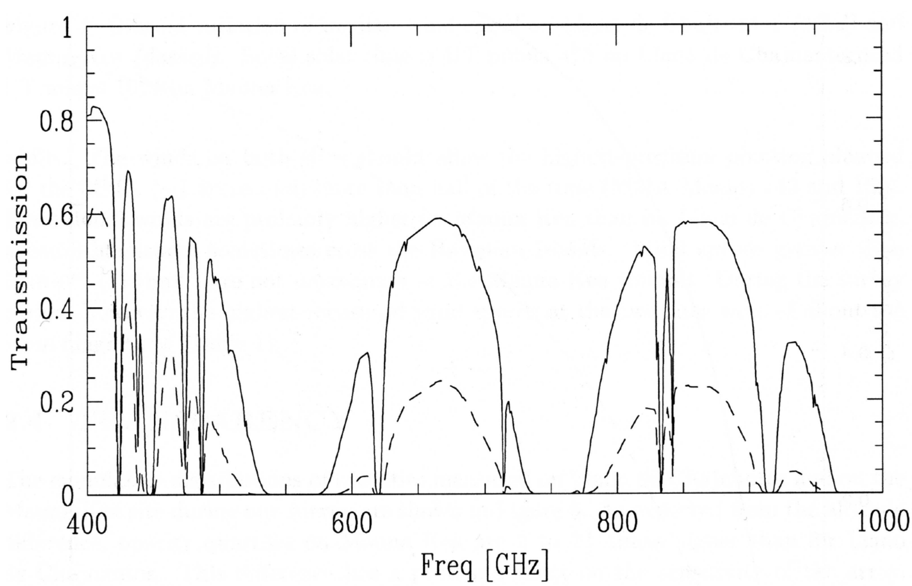

Figure 4.14 A plot comparing atmospheric quality on the two candidate sites in the submillimeter band. The dark line shows that Chajnantor has two to three times better transparency than Maunakea (dashed line) for the best observing conditions. Credit: Simon Radford; NRAO/AUI/NSF, CC BY 3.0.

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government land held by the Ministerio de Bienes Nacionales (BN), from mining interests. The array could not be built there if there was even the slightest chance the site would become an open-pit mine. The question was: had any mining claims been filed on the site? If not, how could the MMA project file a claim before anyone else? As rumors of the MMA project spread, there was a danger that some party would file a mining claim on the site, if only to demand a ransom to relinquish the claim.

NRAO was assisted in filing the mining claim by Leo Bronfman. To build and operate an astronomical observatory in Chile requires an agreement with U. Chile regarding the sharing of observing time. This is a legal requirement, under Chilean Law 15172. (ESO, as an international treaty organization, did not need to satisfy this law but rather dealt directly with the Ministry of Foreign Affairs.) It was clear that NRAO would follow the conventional route with the University, and a good working relationship was established in time with the National Astronomical Observatory of U. Chile. The first AUI offices in Chile were located at the observatory on Cerro Calán in Santiago, where the U. Chile astronomy department was also located. Bronfman put NRAO in touch with an attorney who could take care of the necessary land rights.

From the Southern Mini to ALMA

Millimeter wave astronomy in Chile began with the 1.2 m Southern Millimeter-wave Telescope, known as the "Southern Mini," which was brought in 1982 to CTIO by Columbia University and Universidad de Chile (U. Chile), to complete the first CO survey of the Galaxy. The telescope demonstrated the high quality of the atmosphere for mm observing, further demonstrated in the sub-mm by the SEST 15 m telescope installed at La Silla Observatory in 1986/87 by ESO and OSO.

By 1993/94 Europe, North America, and East Asia were working on separate arrays, searching for sites near San Pedro de Atacama. NAOJ characterized several sites, with U. Chile help. The data obtained near Cerro Toco were shared with NRAO. In October 1994, NRAO and U. Chile personnel explored the nearby Chajnantor Plateau, which became the future ALMA site. In 1995 and 1996, permits were obtained from Ministerio de Bienes Nationales (BN) by U. Chile to test the Chajnantor site and Pampa La Bola. In 1998, the whole area was protected for astronomy by CONICYT as a Science Preserve, in a five-year concession from BN. In 1997 and 2001, AUI/NRAO, and in 2004 NAOJ, signed collaboration agreements with U. Chile, officializing their status as international organizations, allowing 10 percent of its future observing time in ALMA for Chilean astronomy. Similarly, ESO signed an ALMA agreement with the Chilean government in 2002.

The transition to a long-term BN concession for the ALMA consortium, in 2003, was marked by an accord between ALMA and the Chilean government establishing an ALMA-CONICYT fund for the development of Chilean astronomy, and an ALMA Region II fund promoting social and economic development in the local community. The area surrounding the ALMA site, including Cerro Chajnantor, has excellent mid-infrared conditions. It was protected by CONICYT in 2005 by the creation of the "Atacama Astronomical Park." After a long-term concession from BN was given, the park was inaugurated in 2014 further shielding ALMA.

Together with the progress of submillimeter astronomy in Chile, an important consequence of the ALMA installation was the opportunity to participate in state-of-the-art astronomical instrumentation projects. The U. Chile Millimeter-wave Laboratory (MWL) obtained funding from CONICYT to develop in 2008–2013 an ALMA Band 1 receiver prototype, within the new Basal Center for Astrophysics and Associated Technologies, with support from ALMA and Caltech. The MWL was staffed by PhD students and engineers, some trained at the Caltech Cosmic Background Interferometer. Collaborations were further established with NRC/HIAA (Canada), ASIAA (Taiwan), NRAO, U. Manchester (UK), and the Centro de Astronómico de Yebes (Spain). The MWL participated in the development of six ALMA Band 5 prototype receivers, within an ESO-led consortium. The Southern Mini was relocated from CTIO to Cerro Calán Observatory in 2010, close to the MWL. The Band 1 optics design (horns and lenses) was further optimized and prototyped in 2014–2018, in collaboration with NAOJ. Production for the ALMA Band 1 receiver suite took place at the MWL in 2019–2021. Work with NAOJ is underway for the optics of the new ALMA Band 2. Having ALMA in Chile has been crucial for the establishment of new technological capabilities, and a great example of international partnership. Personally, it has been a privilege to be involved.

Leonardo Bronfman,
Professor, Universidad de Chile
Santiago, Chile

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The lawyer, Carlos Ruíz Bourgeois, had a distinguished career with clients in the mining industry. He had been a professor at the U. Chile law school and had held high-level administrative positions there. He was at the time retired, but still consulting on matters of mining law. His son, Juan E. Ruíz was also an attorney, working for the Center for Space Studies at U. Chile. All of the dealings with Ruíz senior were conducted through the son. It was clear that the well-connected father would pave the way for the son, who would do all the work. Brown and James Desmond, the NRAO Associate Director for Administration, were given powers of attorney to represent AUI in Chile. The powers of attorney were crafted after those used by AURA and the Carnegie Institution of Washington (CIW). In July/August 1996, a contract for the legal services of C. Ruíz was signed. The mining claim to be filed covered 20,050 hectares (almost 50,000 acres), the largest mining claim in the history of Chile. It would cost AUI approximately $50,000 in filing fees and approximately $25,000 in annual patent fees, plus the fees and expenses of the Ruíz lawyers. On 14 October 1996, notice of the claim was published in the official Chilean mining periodical, the Boletín Oficial de Minería, Volume 26.508, pp. 76–79. The fees were due in 30 days. After paying the fees, Brown made a trip to Santiago where J. Ruíz transferred the claim, which had been filed in his name, to Brown on behalf of AUI.

Legal Status in Chile for AUI

From this point on, AUI's affairs in Chile were handled by Eduardo Hardy, who was appointed Gerente General (General Manager) for AUI in Chile. He had been recruited on the suggestion of Riccardo Giovanelli when he learned that NRAO was seeking a representative to conduct MMA affairs in Santiago. Hardy was fluent in Spanish, having grown up in Santiago from the age of 10, and was fluent in English and French as well. He was a research astronomer with a degree from the University of Indiana; his doctoral thesis had been supervised by Alan Sandage of the Carnegie Observatories. At the time he was recruited by AUI, he was a tenured professor at Laval University in Quebec City, Canada. But he was apparently ready for a change, and returning to Chile was an attractive prospect. His appointment became official on 1 January 1998. He would prove to be a significant asset in future negotiations with the Chilean government at all levels.

In particular, in the early days of NRAO/AUI activities in Chile, Hardy was the point of contact in securing legal status for AUI in Chile. The procedure for gaining legal status was the same as that followed by AURA and the CIW decades earlier, so at least there was precedent. To begin, a cooperative

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Figure 4.15 Left to right: Eduardo Hardy, President Eduardo Frei, Martha Haynes, who was interim AUI president at the time. The framed map was constructed from satellite images by a group at Cornell University. Credit: Paul Vanden Bout; NRAO/AUI/NSF, CC BY 3.0.

agreement was concluded in 1997, granting the astronomers at U. Chile 10 percent of the observing time on the MMA, in accordance with the Chilean Law 15172. Recognizing the agreement, the Ministry of Foreign Affairs asked President Eduardo Frei to issue a decree granting AUI the same rights and privileges as ESO, and conceding the site to the Comisión Nacional de Investigación Scientifica y Tecnológica (CONICYT). That occurred on 15 June 1998. In recognition of this decree, in 1999, the Chilean Treasury Department issued a decree granting AUI exemption from import duty and value-added taxes. (In 2002, both the agreement with U. Chile and the Treasury Department decree were amended, changing the name MMA to ALMA.) At a press conference on 21 August 1998, President Frei declared the area around the site as the Chajnantor Scientific Preserve, which gave it a further degree of protection from interfering activities such as mining. The declaration was also signed by Sergio Jiménez (Minister of Mining), Adriana Delpiano (Minister of National Assets), and Mauricio Sarrazin (President of CONICYT). The declaration was welcome, but AUI continued to maintain its mining claims, as a precaution in case the designation could be reversed by a later president, however unlikely a prospect that might have been. Figure 4.15 is a photograph taken at the press conference for signing the declaration. On 7 July 1999, NRAO/AUI received permission from CONICYT to conduct *official* site studies on Chajnantor. ESO's permission came on 25 January 2000 and NAOJ's in July 2001, for the LSA and LMSA, respectively.

Radio Frequency Interference

The Chajnantor site needed more than protection from mining interests. It needed protection from interference from radio transmitters in the area. What the MMA needed was a so-called "quiet zone," such as those in place for the NRAO Green Bank, West Virginia, site and for the Arecibo Observatory. The Telecommunications Subsecretary of Chile, known as SUBTEL, created a quiet zone of radius 30 km around the center of the site, specifically, for frequencies in the range 31–275 GHz. In addition, it created a coordination zone of radius 120 km, within which applications for the installation of a fixed location transmitter at these frequencies was subject to review. The quiet zone and its local protections do not have any official *regulatory* recognition at the International Telecommunication Union Radiocommunication Sector (ITU-R) but the telescope's frequency use was recorded in the Master International Frequency Register. The relevant decrees were issued in 2003 and 2004, and the ALMA site was registered with the ITU-R. The team that gained this protection for the MMA included Benjamin Jacard (U. Chile), Harvey Liszt (NRAO), Darrel Emerson (NRAO), and Tom Gergely (NSF). The effects of vehicular radar from traffic on the highway over the Jama Pass, a major connection between Chile and Argentina, remained a concern. Nothing could be done to stop potential interference from satellites. Their transmissions had not yet reached millimeter wavelengths, but their centimeter band transmissions could potentially interfere with the MMA's electronics.

NRAO had found and secured a site for the MMA, protected it from intrusion by the mining industry, and obtained a degree of protection for the site from radio frequency interference. But the proposal to actually design, develop, and build the MMA was still waiting to be funded. In the next chapter, we tell the story of how MMA funding became a reality as the result of a breakthrough, one that would make it an international project eventually called ALMA.

Notes

1 Owen, F. 1982, *The Concept of a Millimeter Array*, MMA Memo #1. https://library.nrao.edu/public/memos/alma/main/memo001.pdf.

2 McKinnon, M. June 1987, *Measurement of Atmospheric Opacity Due to Water Vapor at 225 GHz*, MMA Memo #40. https://library.nrao.edu/public/memos/alma/main/memo040.pdf.

3 Wade, C. July 1993, *Search for Possible Millimeter Array Sites on the U.S. Mainland*, NAA-NRAO, MMA, MMA Site Selection, Box 1.
4 Warnock, G.,18 November 1991, NAA-NRAO, MMA, MMA Site Selection, Box 1.
5 Napier to Brown, 16 May 1991, NAA-NRAO, MMA, MMA Site Selection, Box 1.
6 NAA-NRAO, MMA, MMA Bahcall Site Selection, Box 1.
7 Liu, Z.-Y. 1987, *225 GHz Atmospheric User's Manual* (Electronics Division Internal Memo #271) MMA Memo #41. https://library.nrao.edu/public/memos/alma/main/memo041.pdf.
8 For the VLBA antenna on Maunakea NRAO agreed to give IfA 15 percent of the *single-dish* observing time. IfA had no intention of requesting such time, but the agreement avoided breaking the rule.
9 An early description of the LMSA was presented by Ishiguro (1997), of European plans for a large mm array by Booth (1997), and of the MMA by Brown (1997).
10 At high elevations rain and snow occur more frequently than on the desert floor. The evidence for this is clear in the many ravines that run down the mountainsides, created by erosion from snowmelt runoff.
11 Nearly a decade prior to Gordon advocating Chile as the place to site the MMA, Ken Kellermann had suggested to NRAO director Heeschen that were a millimeter array to be built by NRAO, it should be put in Bolivia. This idea came to him on a trip via taxi from Lima, Peru, to La Paz, Bolivia, where he saw the vast, flat expanses of high-altitude land. The trip was an adventure shared with Ron Ekers and Radakrishnan following the 18th General Assembly of URSI in 1975. (Kellermann to Vanden Bout, private communication.) Much later, George Wallerstein made the same suggestion to Vanden Bout in a letter but he noted that Bolivia did not enjoy stable government.
12 A report of their searches was given by Otárola, Delgado, and Bååth (1995).
13 The survey team included Naomasa Nakai (NAOJ), Kimiaki Kawara (NAOJ), Nagayoshi Ohashi (NAOJ), Nick Whyborn (ESO), and Wolfgang Wild (ESO), in addition to the team leader Angel Otárola (SEST/ESO).
14 Records of the LMSA site searches have been published by Kono et al. (1995) and Sakamoto (2001).
15 Raffin, Phillippe and Kusonuki, A, *Searching for Submm Sites in Chile*, [SAO] Submillimeter Array Technical Memorandum 59, 14 May 1992. NAA-RLB, Box 2. https://science.nrao.edu/about/publications/alma.
16 Illness forced Nakai and Wild to remain in San Pedro. (Otárola to Vanden Bout, private communication.)
17 Whyborn to Vanden Bout, private communication.
18 The water vapor meter, more properly, an infrared hygrometer, has an interesting history that has been described by Gordon (2005), p. 177.
19 Quintana to Vanden Bout, private communication.
20 Bob Brown *Reminiscence of 1994 Chile Trip*, Brown to Vanden Bout (undated, ca. 2004). NAA-RLB, MMA. https://science.nrao.edu/about/publications/alma.
21 Napier to Brown, NAA-NRAO, MMA, MMA Site Selection, Box 1.
22 The Japanese radiometer was being prepared by Naomasa Nakai (Kwansei Gakuin University) for measurements of atmospheric transparency at Río Frío, a site being considered for the LMSA.

23 The data and results of the Chajnantor atmospheric studies can be found at: https://science.nrao.edu/facilities/alma/site-characterization; https://alma.sc.eso.org/; https://researchers.alma-telescope.jp/e/report/site/.

24 ALMA Memo No. 541 – *Horizontal Temperature Variations at Chajnantor*. https://library.nrao.edu/public/memos/alma/main/memo541.pdf.

25 Gordon's final report, written for the record, is dated 30 May 2000 (revised 3 August 2000) but the report material was available to NRAO management much earlier in a series of draft reports sent to Brown. The final report can be found at NAA, Papers of Mark A. Gordon, ALMA, Box 2. https://science.nrao.edu/about/publications/alma.

26 *Recommended Site for the MMA*, May 1998 NAA-NRAO, MMA, MMA Site Selection. https://science.nrao.edu/about/publications/alma.

27 ALMA Memo No. 487 – *Lightning Near Cerro Chascón*. https://library.nrao.edu/public/memos/alma/main/memo487.pdf.

28 ALMA Memo No. 466 – *Levels of radiation exposure near AOS and OSF*. https://library.nrao.edu/public/memos/alma/main/memo446.pdf.

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