ALMA in Chile

A Plan for Operations and Site Construction

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Foreword

This report deals with plans for developing the Chilean sites for ALMA. "ALMA" is the acronym for the Atacama Large Millimeter Array, to be constructed on a high altitude site in the Andes east of San Pedro de Atacama.

Much of the material presented here has been drawn from many reports, spreadsheets, and memoranda I have either written or contributed to over the last several years. The basis of this material is the NRAO's experience operating radio telescopes – particularly the Very Large Array – and the experience of observatories operating in Chile for decades.

I have not included a discussion of the Chilean Environmental Review Process. This will be the responsibility of ESO and AUI representatives in Chile. Chilean law requires a detailed plan for construction and operations before applying to their environmental review agency, CONAMA. The procedure is similar to – but simpler than – that of the United States' Environmental Protection Agency.

Many people educated me regarding operating astronomical telescopes in Chile. I thank Ana Maria Báron, Glen Blevins, Leonardo Bronfman, Hernán Bustos, M. J. (Peter) Dejonge, Guillermo Delgado, Clark Enterline, Jörg Eschwey, E. Enrique Figueroa, Robert D. Gould, Karen Gross, Eduardo Hardy, Jan Hellebuyck, Daniel Hofstadt, Jorge May, José Maza, Lars-Åke Nyman, Patrick Osmer, Angel Otárola, Gerardo Palma, Teobaldo Ponce, Hernán Quintana, Víctor Realini, Miguel Roth, Frank Ruseler, Malcolm Smith, Juan Soler, Elaine Williams, Robert Williams, Julia Zoffoli, and Remo Zoffoli. I am especially indebted to Peter Dejonge and Hernán Bustos who went to great effort to make certain I understood the nuances of working in Chile.

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I. Introduction

This report describes plans for operating the ALMA radio telescope proposed for construction in northern Chile. It also describes a physical plant necessary to support these operations. These two topics are the two views of ALMA in Chile. The operations plan determines the design of the physical plant; the physical plant determines how ALMA can be operated.

For operations and construction of the physical plant, I've tried to estimate costs. These estimates derive from the NRAO experience operating observatories in the United States, from the mitigations suggested by other observatories who operated for many years in Chile, and from specific cost estimates provided by commercial companies in Chile.

The reader knows that these plans unavoidably contain some fiction. Yet what will be fiction and what will be fact? Only the future will tell. Despite the thinking described here, ALMA in Chile will evolve along necessity. The early years will determine the most effective staffing and the best usage of the physical plant. As ALMA moves from construction through partial operation through full operation and into maturity, these things will change. ALMA management must be flexible.

To allow the reader to judge my reasoning, I have included sections on what ALMA will do and how it will do it. I've included information on Chile's history, government, and present politics. I've also described the geography of northern Chile and the characteristics of ALMA's environment.

II. ALMA

A. What ALMA will do

The Atacama Large Millimeter Array (ALMA) makes astronomical pictures. It will be a "synthesis radio telescope" imaging regions of the sky at very short wavelengths. Known as the millimeter and sub-millimeter regime, these wavelengths lie between radio and infra-red.

These will be wonderful pictures. They will be quite sharp. The angular resolution will be as high as $0\farcs1$, or about ten times sharper than optical images produced by the Hubble Space Telescope. They'll be deep images, that is, sensitive images. ALMA's geometric collecting area will be about 7,000 m^2. Compare this with the 200 m^2 of the Very Large Telescope of European Southern Observatory now under construction in northern Chile. ALMA will need this big collecting area. The photons it will receive contain 1,000 times less energy than optical photons

These wavelengths allow astronomers to acquire important astronomical information otherwise unobtainable.

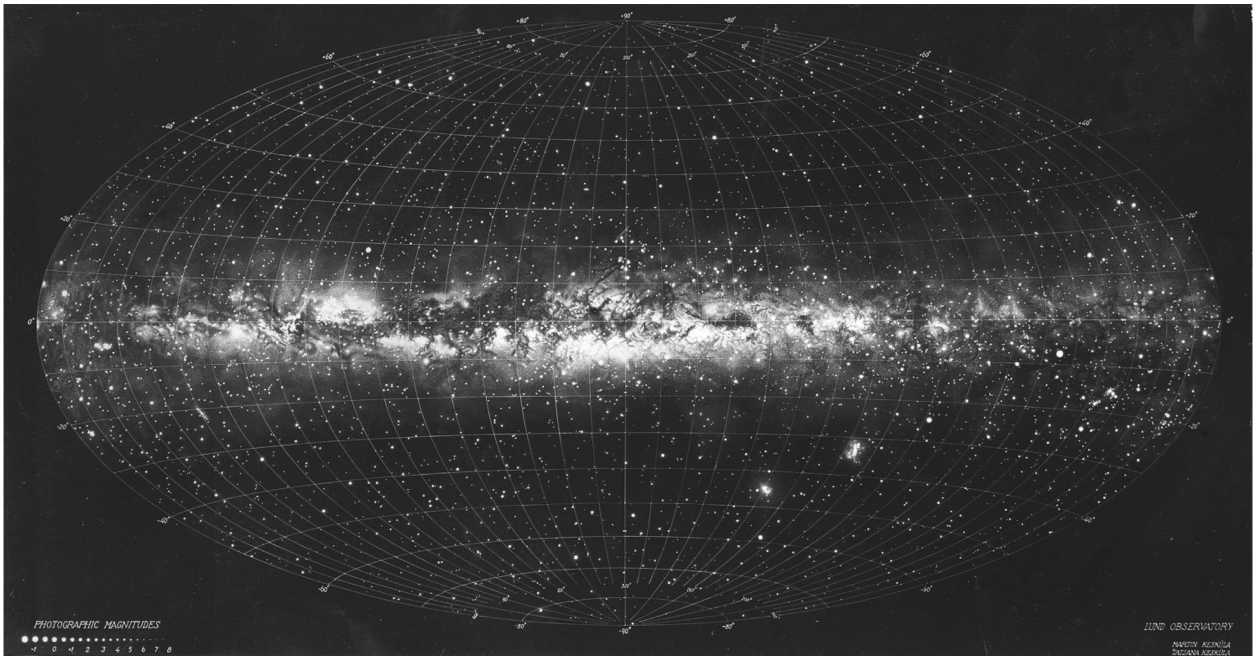

Figure 1 Our own galaxy – the Milky Way – seen edge on. The dark areas running obscuring the background stars are cold dust clouds in which stars form. The horizontal dark lane called Great Rift, left of center, is a prominent feature of northern skies. ALMA will be able to image these dark regions as bright objects, facilitating the study of star-forming processes. Composite image made by Knut Lundmark, Lund Observatory.

ALMA will teach us more about how stars form. Figures 1 and 2 show us black lanes that are conspicuous features of most spiral galaxies. This material is invisible to optical astronomers. These lanes are gas and dust with temperatures ranging from 10 to 60K[1]. This material is usually called the Interstellar Medium or ISM. Stars form from this material. The internal nuclear processes that make stars shine consume this material as fuel, enriching it in the process. When the stars die, the enriched material returns to the ISM. Astronomers call this overall process “astration.” It is a biological analogy for stars breathing in and then exhaling, enriching the ISM in the process.

ALMA can image these dark regions with great sharpness. The cold material may absorb background starlight at the wavelengths the eye sees but it radiates brightly in the wavelengths that ALMA sees.

Astration affects all of us. The nucleosynthesis processes that generate the starlight in our Milky Way galaxy refined the ISM, creating all the heavier atoms and isotopes we find on Earth . Except hydrogen and helium, all of the atoms in our human bodies were produced in this way.

Chemical processes also occur in the interstellar gases. One type is called “gas-phase” chemistry in which the atoms and molecules interact within the gas itself. Another type is a catalytic chemistry in which the atoms and molecules momentarily stick to the surfaces of interstellar dust grains where they form new molecules. These processes take place in conditions difficult to duplicate in terrestrial laboratories, that is,

[1] Gordon, M. A. and Musser, G. S. 1997, “Cold Heart of the Cosmos,” Mercury, 26:No. 1,15

at temperatures near absolute zero, at low densities, and on dust grains with surfaces of unknown characteristics. Interstellar chemistry is a unique, new area of astrophysical research.

Figure 2 Messier 51 composed of a large spiral galaxy (NGC 5194) and a small, irregular companion galaxy (NGC 5195). Seen face on, this large spiral galaxy shows many dark dust lanes where stars are forming. ALMA will be able to image these regions as bright objects. These galaxies lie about 2 Mpc (6.5 million light years) from Earth. Photo from Alan Sandage, Hubble Atlas of Galaxies.

The molecules and atoms of the ISM give astronomers powerful tools. They radiate at discrete wavelengths – known as emission lines – that provide a unique "signature" for each constituent. Small changes in the wavelengths measured for these lines show the line of sight velocity of the material with respect to us through the Doppler Effect. The width of these lines gives information regarding motion and temperature internal to the material. The intensity tells us about the amount of material along the line of sight.

At millimeter and submillimeter wavelengths, the most intense and ubiquitous line emission from galaxies is that of carbon monoxide (CO). ALMA will be able to image galaxies in these emission lines, allowing astronomers to study star formation even in extremely distant galaxies.

Millimeter and sub-millimeter observations also facilitate the study of galaxies at the "edge" of our universe. A characteristic of the cosmos is that the wavelengths of radiation are shifted to longer wavelengths with increasing distance – a phenomenon known as "the redshift" and discovered years ago by

Edwin Hubble. This too is a Doppler Effect. Emission from galaxies at great distances – "primordial" galaxies because we are looking very far back in time – should come from interstellar gas similar to that found in our Milky Way. The peak emission from 100K gas occurs in the far infrared. At a redshift of 10, that peak emission would fall in the sub-millimeter range where it could be easily imaged by ALMA.

For these reasons and many more, ALMA will be a powerful new telescope for studying the universe. It will give new information about how stars form and galaxies evolve, and insights into chemical processes in a cosmic environment. And, it will complement observations being made with other telescopes at the Xray, ultraviolet, optical, infra-red, and radio wavelengths.

B. How ALMA works

ALMA will be a "synthesis radio telescope." It will consist of 64 12-m diameter, parabolic antennas acting together to synthesize a single large telescope with "holes" in its mirror. All antennas or "elements" will operate up to 800GHz or 375µm. To reflect radiation at these wavelengths efficiently, the shape of each antenna must conform to a perfect paraboloid within an error of 25µm (0.001in) and maintain this accuracy while the antenna changes its direction of pointing – up or down, day (sunshine) or night (no sunshine), winter (colder) or summer (warmer). Figure 1 shows an artist's rendition of how the telescope will look from the ground.

ALMA will be a virtual single antenna. The 64 antennas synthesize a huge single parabolic reflector with missing sections. If the antennas lay randomly within a 1 km circle, a view from space would show them to form a circular paraboloid made of sixty-four 12-m disks – like a circular jigsaw puzzle with only a few pieces in place. All of the antenna elements would point in the same direction while, that is, at the same celestial object. As the earth turns, an observer on the star would see the individual disks appear to shift position over time, as if they were sweeping out arcs within the circle and thereby filling missing spaces. During this time, the signals arriving at each antenna are correlated with each other and mathematically manipulated to form a single image – one that could have been made with a single antenna with a 1-km diameter but one with some significant holes in its surface.

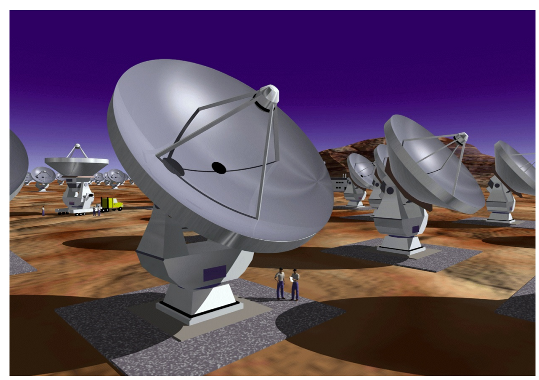

Figure 3. Artist's rendition of the ALMA synthesis telescope. Courtesy of ESO.

The sharpness of the resulting image results from the overall diameter of the circle. A synthesis telescope is a "diffraction-limited" device. Its angular resolution corresponds to the diameter of the central lobe of the Airy function of optics. This width in radians is $\Delta \vartheta = 1.2\lambda / D$ where λ is the wavelength of the observations and D is the diameter of ALMA. At $\lambda = 1.2$mm and an ALMA diameter of 1km, then the resolution would be about $0''.3$. At the full ALMA diameter of 10 km, the resolution would be $0''.03$ at the same wavelength.

Because of the holes in the surface of the synthetic telescope, the image will not be perfect. Perhaps it is more accurate to say it's because of the small amounts of surface in the telescope – the virtual telescope surface being mostly holes. The theoretical Airy function produced by this instrument will be flawed. Optical astronomers would call this function the "point spread function." It would have lots of strange peaks and valleys produced by the holes in the telescope surface.

Not to worry. Astronomers have developed tools to fix these flaws and improve the image quality. Most of these work by guessing at the missing information based on what has been observed, upon the shape of the synthesized beam (point spread function), and what is physically possible. For example, a negative intensity in the image would be physically impossible. The names of two common techniques are “Clean” and “ Maximum Entropy Method.” Clean works by repeatedly subtracting the synthesized beam shape from each point observed in the image. MEM works by guessing at the missing data in the observations using the theory of electrical noise. Other powerful techniques are available.

Superb electronics are essential to successful to a synthesis radio telescope. The weak cosmic signals at millimeter- and sub-millimeter wavelengths require that the radio receivers be cooled to as low temperature as possible to prevent their own electrical noise from swamping the incoming cosmic noise. ALMA’s refrigerators using helium as a refrigerant will cool each radio receiver to about 4K (-270C). Each antenna will have its own refrigerator and compressor.

The electrical path length, that is, the distance in wavelengths, between each receiver (antenna) and the correlator must be known *and* maintained to a small fraction of a wavelength. Measuring these distances is easy. Astronomers simply image a calibration source to decide the locations of each antenna. Maintaining these distances is more difficult. The inter-antenna cables (fiber) must be buried for stability and their electrical length continuously monitored and adjusted.

The extremely short wavelengths (high frequencies) are a big problem with a simple solution. They cannot travel well through conventional cables or waveguides. Accordingly, the receivers are designed to strip information from the incoming cosmic signals and transfer it to a longer wavelength signal generated internally. This “intermediate frequency” or IF travels easily through cables and waveguides and carries all of the information of the cosmic signal. This kind of receiver is known as a superheterodyne type, with the adjective referring to the technique of mixing two high-frequency radio signals together so that information on one is transferred to two new radio signals corresponding to the sum and the difference of the two frequencies. The man-made radio signal mixed with the cosmic signal is called the “local oscillator” or LO.

The LO itself will be generated through a new technique. ALMA designers plan to generate the LO by beating together two high-purity laser signals at each telescope. Buried fiber-optic cables will carry the laser signals to each telescope.

C. When do astronomers see their observations?

Seeing images will be difficult for ALMA astronomers while observing. Unlike observations made with a single radio or optical telescope, the observations made with a synthesis telescope are in the form of a three dimensional correlation function (known as a UV data cube) that must be mathematically converted into an image of the sky. The conversion process (Fourier Transform) requires powerful computers – after careful inspection and calibration of the raw data. Consequently, the astronomical images could be unavailable for weeks or months after the observations. Consequently most observations made with a synthesis telescope are preplanned and automatically performed.

The presence of an astronomer not only is not required, it can be disruptive to the actual observing process. What array operator needs someone continually asking, “What’s happening now?” The answer to such a question can only be functional and not astronomical, that is, “We’re now looking at the calibration source.” This kind of observing is often called “service observing,” that is, a professional telescope operator makes the observations for the astronomers(s) according to preplanned instructions.

D. How ALMA came about

Radio astronomers pioneered the technique of synthesis observing[2]. More correctly, radar operators discovered the technique that some of them later exploited when they went into radio astronomy. The principle was discovered during World War II by building radar transmitters on high bluffs overlooking the sea. Combining echoes reflected from the sea with those directly entering the antenna formed an interference pattern in elevation that located the radar target more precisely than a single beam radar ever could. Since then, synthesis telescopes have become powerful tools for astronomers.

At millimeter and sub-millimeter wavelengths, the University of California (now with the Universities of Illinois and Maryland), the California Institute of Technology, and the Institut de Radioastronomie Millimetrique (IRAM) have operated powerful synthesis telescopes for astronomy for years. These instruments have contributed greatly to our understanding of star formation.

In 1983, the US National Science Foundation convened a committee chaired by Prof. Alan Barrett of MIT that recommended[3] construction of a *national* large millimeter-wave array that would have a resolution of 1″at 115 GHz (λ2.6mm), a collecting area of 1,000-2,000m^2, and good imaging at 300 GHz (λ1mm). Funded by the National Science Foundation, such an instrument would be open to all astronomers on the basis of merit.

Responding to this proposal, in 1990 the US National Radio Astronomy Observatory submitted a proposal[4] to the NSF to build a 40-element synthesis telescope to be called the Millimeter-wave Array or MMA. The design was tailored to the recommendations of the Barrett Committee. Each antenna element would be 8m, giving a combined collecting area of 2,010m^2. The instrument would operate from 30-366GHz, giving a maximum resolution of 0.07″for an array diameter of 3km. The site was unspecified except that only US sites were discussed in detail. The price was a very preliminary estimate of US$120M 1990 dollars.

By 1994, the NRAO found an accessible, high-altitude site in the Andes mountains east of Antofagasta, Chile. This site is a geologic bench at an elevation of 5,000m in the Atacama Desert, a region known for extreme aridity. The latitude is about 20°, giving access to much of the northern sky as well. Best of all, the Llano de Chajnantor site lies less than 20km from a paved, international highway and about 70km from a small Chilean town at much lower altitude. Subsequent site testing showed the atmospheric transmission to be so good that the MMA specifications were revised to include operation in the 650GHz atmospheric window. The diameters of the elements were increased to 10m to increase the sensitivity of the MMA.

In 1995, a consortium of European astronomers began to investigate construction of a similar telescope, the Large Southern Array or LSA, in northern Chile. Because they represented many individual observatories, they used as an affinity group the European Southern Observatory (ESO) that operated optical telescopes in Chile for European astronomers.

Meanwhile, Japanese astronomers associated with the Nobeyama Radio Observatory were looking for a site

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[2] Sir Martin Ryle won the Nobel Prize in Physics in part through his development of aperture synthesis for radio astronomy.

[3] Barrett, A. H. *et al.*, 1983, "Report of the Subcommittee on Millimeter- and Submillimeter-Wavelength Astronomy," NSF Astronomy Advisory Committee

[4] Brown, R. L., *et al.*, 1990, "The Millimeter Array," NRAO internal report

in Chile for their own proposed array, known as the Large Millimeterwave and Submillimeter Array or LMSA.

On June 26, 1997, the European Southern Observatory (ESO) and the NRAO signed an agreement to cooperate by exploring the possibility of combining the LSA and the MMA into a single instrument. Combining these instrument would produce a much more powerful telescope. The agreement noted that the Japanese might enter the combined project later.

In 1997, the NSF awarded the NRAO a $26M grant for Design and Development of the MMA for the Chilean site. The objective is to produce a detailed design, accurate costs, and a Gantt chart for construction of the MMA. The time for the D&D phase is three years plus a one-year extension. A mid-course cost estimate[5] gave the cost of the MMA – then called The U. S. Reference Project – to be $292M 1999 dollars, including a contingency. The higher cost resulted from increasing the antenna diameters from 10m to 12m, and from extending the frequency range from 366 to ~650GHz to take advantage of the Chilean site.

Midway through the D&D work, the Europeans and the US agreed to commit to a combined instrument to be called the Atacama Large Millimeter-wave Array or ALMA, a Spanish word for "soul."

The design effort now divided across the Atlantic. Some electronics would be designed in the US; others, in Europe. The story is the same with the software. Two prototype antennas were ordered, the U. S. one from Vertex Corporation and the European one from EIE in Italy. The plan is to erect these two antennas on the VLA site in New Mexico, test them individually and also together as a test interferometer. Presumably, the better design will become the official ALMA antenna.

Development of the Chilean sites would be the joint responsibility of the NRAO and ESO. NRAO has experience operating synthesis radio telescopes, and ESO knows about operating observatories in Chile.

Recently, the European and U. S. representatives capped the non-recurring costs of ALMA at $552M in 2000 dollars.

Construction is scheduled to begin in January 2002, with the first antenna components arriving in Chile in October 2004.

III. Chile

A. The Republic

Like the United States, Chile is a constitutional democracy with three branches: executive, legislative, and judicial. The president of the republic heads the executive branch and is elected by direct vote every six years. The president forms the executive branch by appointing a cabinet of ministers of his own choice. The legislative branch consists of a two-chambered Congress with an upper house called the Senate, whose members serve six-year terms, and a lower house called the Chamber of Deputies, whose members are elected every two years. The judicial branch is organized hierarchically, with the Supreme Court ultimately responsible for the activities of all lower courts.

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[5] Brown, R. L. 1999, "Millimeter Array. Construction Costs of the U. S. Reference Project." NRAO internal report

Unlike the United States, the Republic of Chile is highly centralized administratively. It consists of thirteen “regions,” numbered I to XII from north to south plus the metropolitan region (Región Metropolitana) of Santiago. Region XII includes the wedge of Antarctica claimed by Chile and on which they maintain a few scientific stations. These regions function differently than the “states” of Argentina, Brazil, Germany, or the United States of America – to give a few examples. Chile is not a federation of quasi-independent governments. The regions have virtually no political independence and no possibility of acting (legally) in any manner not dictated by the national government. In particular, they have no taxing power. The highest political authority in each region is the intendente, who is appointed by and serves at the pleasure of the president of the republic. Consequently, the election of a new president results in a new government for each region of Chile.

Decentralization has been an objective for many years but is proceeding slowly. One of the first measures adopted was to place in each region (including the Metropolitan) a representative of each national ministry (SEREMI[6]) who has certain discretionary powers regarding the implementation of ministerial policies. Thus the SEREMI of the Ministry of Public Properties (Bienes Nacionales) in a particular region handles the details of transactions involving public lands in that region.

Communities are governed by locally elected Mayors and Councils. Nonetheless, their freedom of action is circumscribed by national policies, and they have no independent taxing power.

Coalitions of political parties nominate candidates for the presidency of the republic. Citizens then vote directly for their choice. A successful candidate must receive the majority vote, that is, 50% plus one. A simple plurality is insufficient for election. If a candidate receives less than a majority vote, then there is a run-off election between the two leading candidates. This procedure ensures that the president will represent the political philosophy of a majority of the citizenry. The most recent presidential election required a run-off election in which Ricardo Lagos defeated Joaquín Lavin.

The intent of the majority rule is to avoid the 1970 situation when the socialist candidate Salvador Allende was elected president with only 36% of the vote in a three-candidate election. The other two candidates split the conservative vote. Thus, Allende became president without representing the political preference of the majority of the population. He also lacked a majority in the new Congress. The result was internal chaos, resulting in a 1973 military coup headed by General Augusto Pinochet.

In the three administrations since the end of the military regime in1990, the president of the republic has been elected by a coalition of political parties of the center-left: the Christian Democrat Party (DC), the Socialist Party (PS), the Party for Democracy (PPD), and the Radical Socialist Party. Before the 1999 presidential election, nominees from the Christian Democrats and the Socialists ran against each other in a primary election similar in principle to a U.S. party convention, in which the Socialist nominee Ricardo Lagos won the preference although the Christian Democrats have the largest membership. On the right there are National Renovation (RN) and the Independent Democratic Union (UDI), which have always coordinated their actions but have only recently celebrated a formal alliance. There is also a Communist party, but it is quite small.

B. History

[6]Secretario Regional Ministerial (SEREMI).

According to Nurse's handbook[7] than, Chile was of little interest to Spain during the colonial period of the 16th , 17th, and the early 18th centuries. Toward the south, the Mapuche indians discouraged European settlements. Furthermore, early expeditions by conquistadores – like that of Pedro de Valdivia in 1535-37 – failed to reveal significant gold or silver. Nevertheless, small European settlements took root in the fertile middle areas of the country near what is now Santiago. The South remains sparsely settled.

During this period, Chile was part of what was known as the Viceroyalty of Peru. Lima was the official capital. Most policy decisions came from Spain. All trade went through Lima until 1740 when direct trade was allowed between Chile and Spain. In 1750, Chile issued its own currency.

Napoleon's invasion of Spain in 1808 provided an opportunity for Spain's colonies to revolt. Battle after battle alternatively established a local rule then a return to the colonial government. In 1830, local rule was finally established. In 1833, a constitution was adopted, and Chile became an example of political stability throughout Latin America – interrupted by brief civil wars in 1851, 1859, and 1891. While Chile was governed by an elected President and a Congress, Nurse notes that up to 1924 the Congress actually controlled the government.

The Great Depression in the 1930s stimulated several changes in government with interludes of political stability. Notably, in 1970, socialist Salvador Allende barely won the election. Because of his concern for the poor, he nationalized many industries, from banking to copper mining. In 1973, because of the resulting political unrest, General Augusto Pinochet and the army took over the government. The brutality of the new military regime shocked not only Chileans but also the world. The result was an exodus of tens of thousands of Chileans.

The military regime remained in power from 1973 until 1990, with Pinochet at its head from 1973 to 1988. Under this regime with advice from the University of Chicago department of economics, the government privatized assets previously nationalized and adopted a free-market policy. Today, Chile's financial health is sound.

C. Astronomy

For many decades, Chile has supported astronomy and hosted foreign observatories. The University of Chile and the Pontifical Catholic University have excellent astronomy programs. There are now a few astronomers at the University of Concepción and at some of the regional universities, such as the Pontifical Catholic University of Northern Chile in Antofagasta.

D. Atmospheric transparency

[7] Nurse, C. 1997, "Chile Handbook," Chicago: Passport Books.

Astronomical observations at millimeter and sub-millimeter wavelengths require a thin, dry atmosphere. Atmospheric water vapor and molecular oxygen absorb these wavelengths absorb this radiation, leaving only narrow wavelength “windows” through which cosmic radiation can reach the ground. Choosing an arid site with little rainfall minimizes the water vapor. Selecting a high-altitude location reduces the O_2

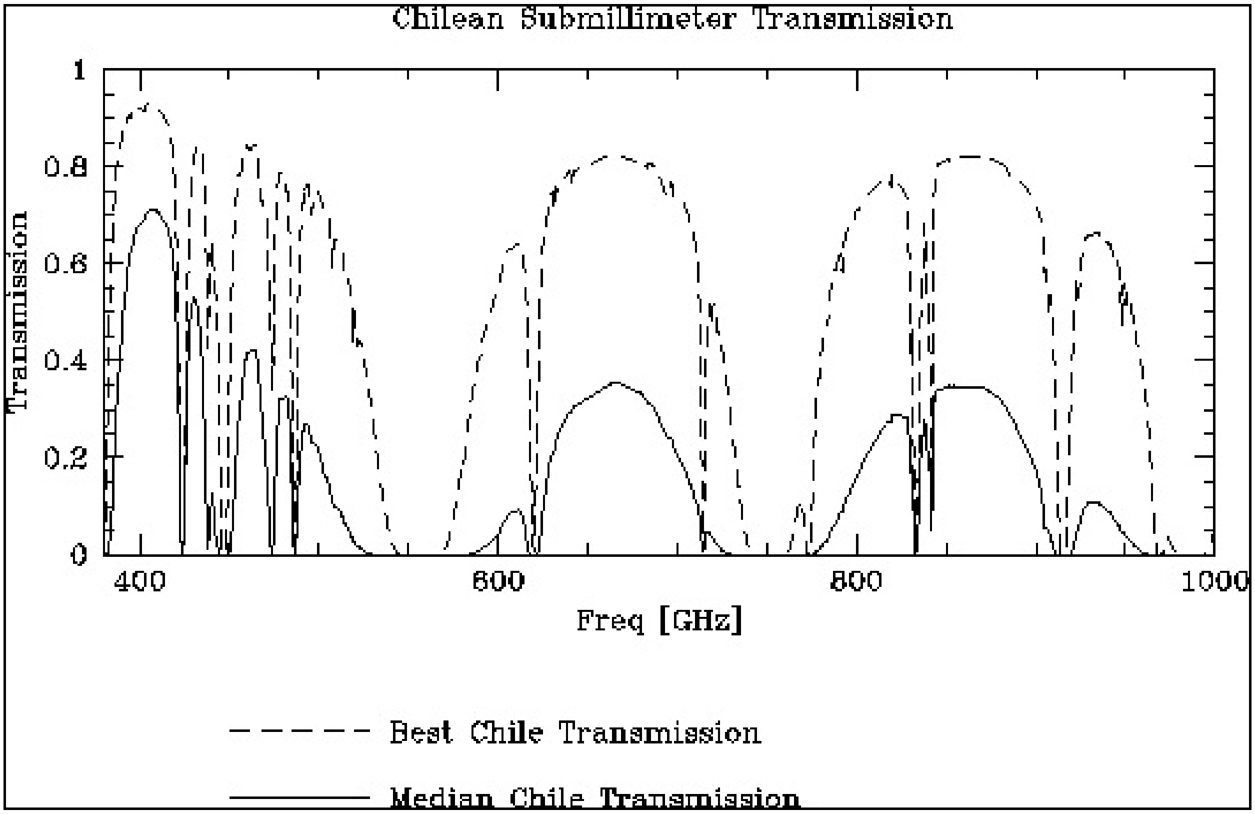

Figure 4. The vertical transmission of the atmosphere over the ALMA site in Chile. The thin dry air creates “windows” through which cosmic radiation can reach the antennas. In the best conditions, the windows are extremely transparent even to rather high frequencies as shown by the broken line.

absorption. The lower pressure of a high altitude also narrows the absorption features of both constituents. Figure 5 shows the remarkable transmission of the atmosphere over the ALMA site produce by the combination of thin and dry air.

E. Geography

Figure 5 shows the geographical extent of Chile with respect to the continent of South America. Chile is smaller than any other South American republic except Ecuador, Paraguay, Uruguay, and the Gianas. The country is 4,330km long, extending from 18°S to 56°S, not counting its claimed Antarctic territory. Its average breadth is only about 180km. Its eastern boundary is the Andes’ mountain range; its western, the Pacific Ocean.

These geographic barriers isolate the country politically. Although it borders Peru, Bolivia, and Argentina, the great heights of the Andes, the extreme aridity of the north, and the rugged fiords of the south historically made commerce difficult with its neighbors. The capital city of Santiago lies near the middle of the country, toward the Argentine border. The largest port, Valparaiso, lies immediately to the west.

The ALMA site, which I named Llano de Chajnantor, lies to the north of the country near intersection of the borders of Bolivia, Argentina, and Chile at the latitude 23° S. Figure 5 shows its location.

Figure 5. The South American continent with Chile marked in black. Labels indicate the location of the ALMA site and of the capital, Santiago.

F. Climate

Because of the large latitude extent of Chile excluding its Antarctic territory, the climate range is great. The Atacama Desert in the north, in which the ALMA site lies, is one of the most arid regions on Earth. In many areas there is no visible vegetation. Annual rainfall in the Atacama Desert averages less than 5mm (0.2 in). Some meteorological stations near the coast have *never* reported precipitation. In the south, there is some of the most miserable weather on earth – as ancient seamen reported in their trips around "The Horn."

The northern aridity is due to a circulation phenomenon. An anticyclone high pressure region on the coast, seen as "A" in Figure 6, excludes moisture from northern Chile. The Andes mountains serve as barriers to weather fronts that might move in from the eastern region of South America. These two barriers prevent moisture from moving between them, creating the Atacama Desert. This desert is among the most arid regions in the world.

The result is that the ALMA site, the Llano de Chajnantor in the Atacama Desert, is an ideal site for a large, synthesis telescope operating in the millimeter range. An added benefit is access to the southern celestial sky, creating an opportunity to augment observations of the northern sky being made by BIMA, OVRO, and IRAM.

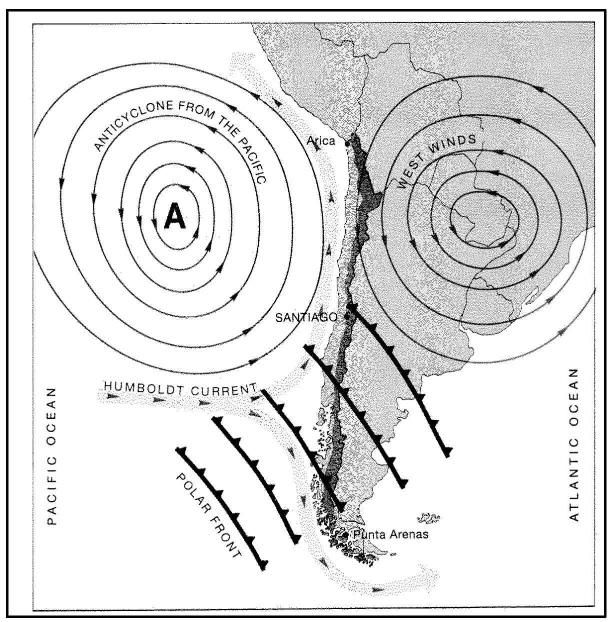

Figure 6. Air and water circulation near Chile.

G. Access to ALMA

Figure 7 shows a conceptual East-West cross-section of Chile at the 23° latitude of the ALMA site. Note that the land generally rises from the ocean toward the Andes. There are three North-South mountain ranges: the coastal range, the Domeyko range, and the Andes. The valley between the first two ranges is a rich source of nitrates that, in the later part of the 19th century, formed an important part of the Chilean economy before chemists learned how to synthesize nitrates.

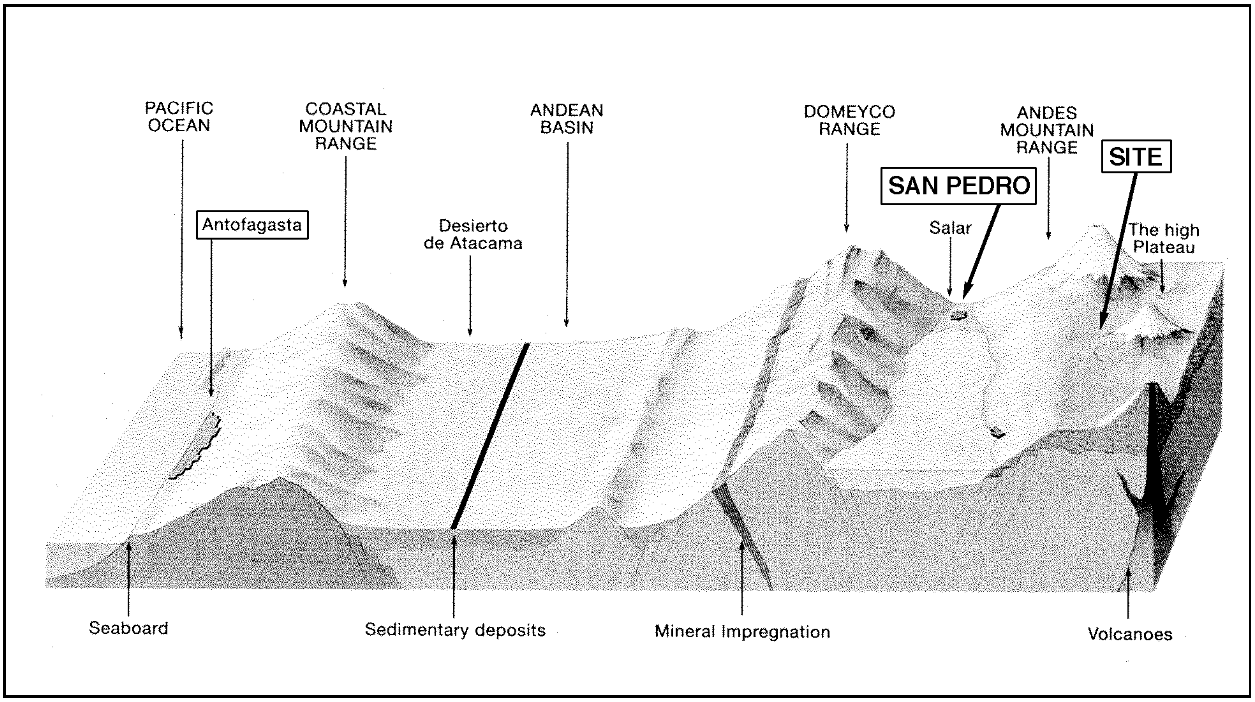

Figure 7. West-east cross-section of Chile at Antofagasta. The approximate locations of San Pedro de Atacama and the proposed MMA site at Llano de Chajnantor are shown.

The soils of the eastern valley contains high concentrations of mineral salts leached over aeons from the volcanic formations. Lithium is being obtained by evaporating the water seeping from the salar (brackish marsh).

Approximate locations of the village of San Pedro de Atacama at the upper end of a salt flat (salar) and of the proposed ALMA site at 5,040m (16,500ft) are also shown. The high volcano at the far right could correspond to Volcán Licancabur, an isolated cone 5916m (19,400ft) high near San Pedro that is sacred to the Atacameños people who live in and around the village. On its summit, on the rim of its lake-filled vent, is a stone altar erected by the Incas during their short 200-year reign.

H. Regional Roads

Figure 8 shows a road map of northern Chile between -21.8 to -23.8° latitude and 67 to 70.5° west longitude. Notable points are the ports of Antofagasta (pop. 228,500) and Tocopilla (pop. 22,000), the mining support town of Calama (pop. 106,000) in the central region, the tourist village of San Pedro de Atacama (pop. 900) toward the eastern boundary with Bolivia, and the road to Paso de Jama leading eastward from San Pedro to Argentina. The ✚ on the Paso de Jama road marks the Llano de Chajnantor, the region of the altiplano at an altitude of 5,040m (16,500ft) where the site test equipment for the MMA is located.

National Route 5 and, subsequently, Route 25, connect Antofagasta with Calama over a distance of 215km

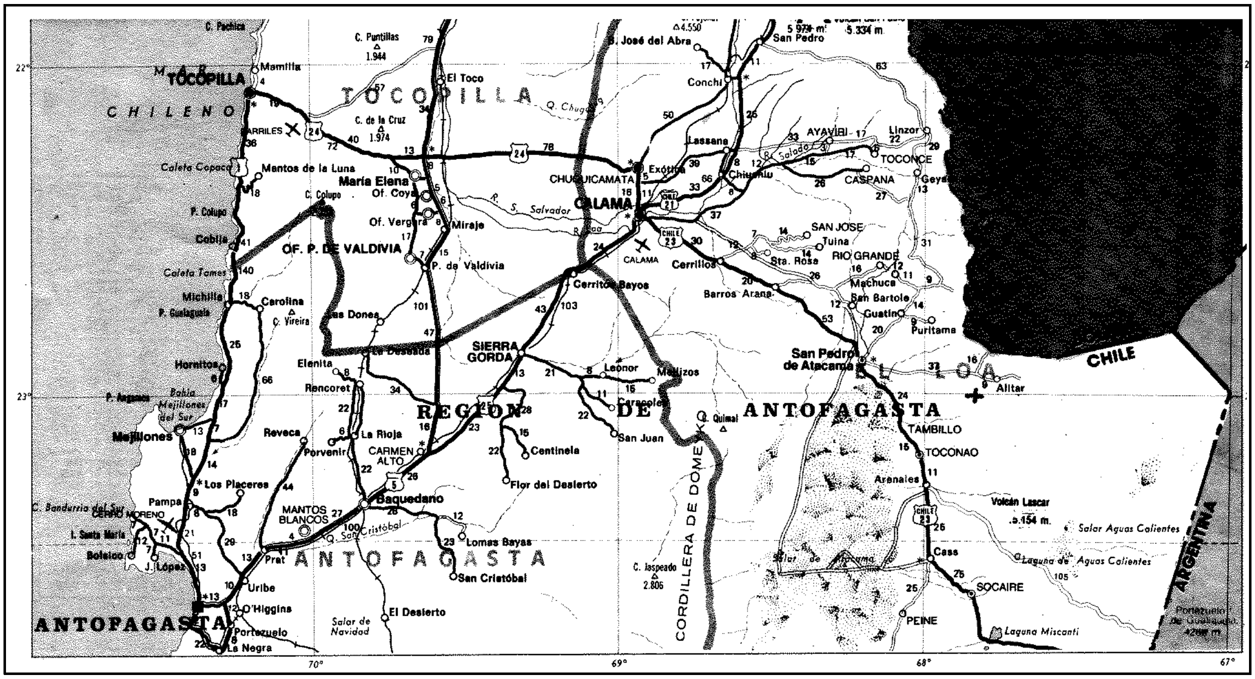

Figure 8. Atacama Desert east of Antofagasta, Chile. The cross near San Pedro de Atacama marks the ALMA site.

(133.5mi). From Calama, Route 23 leads to San Pedro de Atacama over a distance of 113km (70.2mi). International Route 27, now paved, connects San Pedro to the turnoff to Llano de Chajnantor over a distance of 36km (22mi). The unpaved access road is 18km (11.2mi). Presently, driving times are about 3.5h from Antofagasta to San Pedro, and 1.2h from San Pedro to Llano de Chajnantor

Calama is the principal support town for a huge open-pit copper mine at Chuquicamata (pop. 15,000), reportedly the world's largest. Consequently, the Chilean airlines Lanchile and Ladeco operate Boeing 737 airliners between Calama and Santiago, and between Calama and Antofagasta daily at listed fares of US$460 and US$56, respectively, and flight times of 3 and 0.5h, respectively. Several buses per day connect Antofagasta with Calama, and Calama with San Pedro de Atacama at fares of approximately C$3,000 (US$8). Twice weekly, international busses run from Antofagasta to Calama to San Pedro to Argentina via Route 5, Route 25, Route 23, and Route 27.

Figure 8 also shows the road leading from the town of San Pedro to the Llano de Chajnantor site.   This international highway, just paved, is designated as International Route 27, or the "Paso de Jama" road. It leaves the east side of the village of San Pedro de Atacama, passes by a Customs office, goes by the airstrip, then steadily climbs upwards to the altiplano, eventually wending its way down the eastern slope of the Andes into Argentina. At a distance of 36km (22mi) from San Pedro, there is a junction with a unpaved mining road that used to service an now-defunct sulfur mine at Cerro Toco. From this junction to the Llano de Chajnantor site (marked with a white circle) is approximately 18km (11.2mi).

I.	San Pedro de Atacama

The village of San Pedro de Atacama will serve as the support center. The Operations Support Facility (OSF) will be constructed outside of this community. It is the nearest settlement to the ALMA site at Llano de Chajnantor. Its modest altitude of 2,425m (7,950ft) is much more hospitable than the 5,000m ALMA site. It is the last settlement on the newly paved Paso de Jama highway to Argentina, the road ALMA personnel will use to get to the site.

San Pedro de Atacama is a pre-Columbian community of about 1,400. Settled by the Atacamañan people, it was "conquered" by the Incas and treated by them as a protectorate in the late 15th century. In the mid 1500s, the conquistadores Diego de Almagro and Pedro de Valdivia followed the "Inca highway" from Cusco, Peru, to explore what is now Chile. The Amagro expedition took place from 1535-7 and quickly returned to Peru because they found no gold. The Valdivia expedition conquered the southern region of Chile and, in 1541, founded the city of Santiago as well as other communities on their route.

The town exists because of water. Two rivers, the tiny Rio Vilama and the larger Rio San Pedro, merge into a wide marsh area. This water drains from the high Andes, where snow accumulates during the winter. The water has a high mineral content, including arsenic salts, and is generally unpotable without treatment like distillation or reverse osmosis filtering. However, the water makes farming possible in the green riparian areas known as "ayllos." Some Atacamañan families have owned specific ayllos for generations.

Its principal industry is tourism. Chilean and international visitors visit SpdA to enjoy spectacular views of the Andes to the east, to explore the extreme aridity of the high Atacama desert, to visit its archeological museum, and to enjoy the ambience of its ancient adobe buildings and dirt streets. There are many places to stay, ranging from modest rooms to modern motels to the luxurious Hotel Explora.

Currently, two OSF sites hold interest for us. Figure 9 shows both of them. One is Vilama, an area about 3km from the village to the NNE on the banks of the tiny Rio Vilama. The other is on the Jama highway, at an elevation of about 3,000m and about 20km from the village. The Vilama area lies within bicycling – if not walking – distance of SPdA and has a riparian character due to its proximity of the Rio Vilama. Its disadvantage is that a new 2-4km road must connect the antenna assembly building with the Paso de Jama highway. The Paso de Jama site lies near the high-pressure gas line, has easy access to the Paso de Jama highway, and lies closer to the ALMA site. Either site work well.

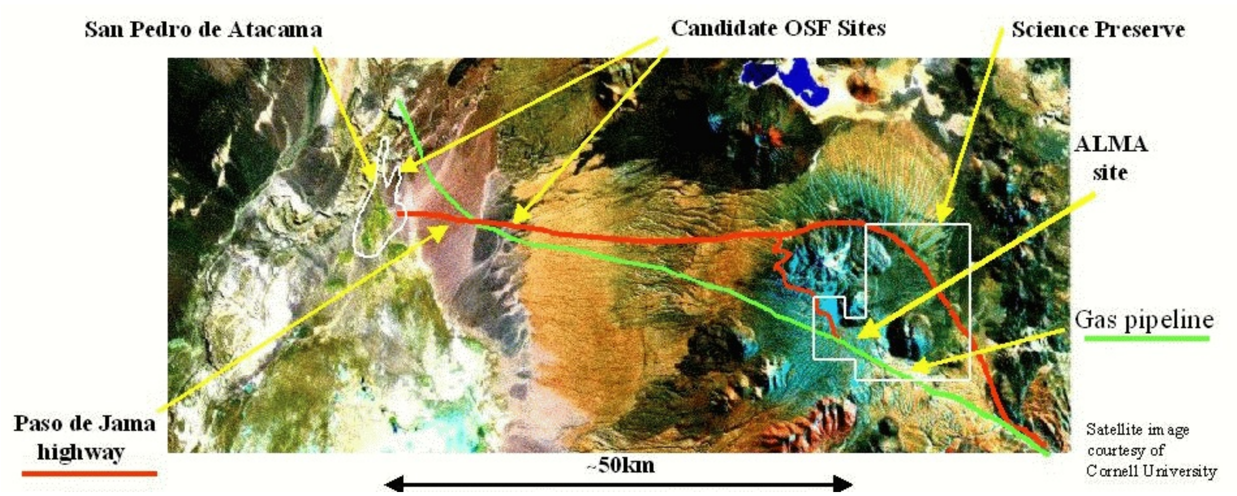

Figure 9   Satellite map of San Pedro de Atacama (left) and the ALMA site (right). The lines indicate the access routes and the high-pressure gas pipeline. Courtesy of Cornell University.

IV.   ALMA Operations

Site development and operations are closely linked . The physical development of an observatory affects how it operates. Yet, we need to know how an observatory will operate to build an effective physical plant. The plan for site development described below is a consequence of our present ideas for operations in Chile. This plan will surely evolve as we gain experience operating in Chile. Moreover, the Chilean custom of using high-quality prefabricated buildings in remote areas will allow us to make substantive changes in the physical plant easily as we discover what works and what does not.

A. Preliminary plan

Operating a complex, synthesis radio telescope in Chile will be a new experience. Large optical astronomical observatories have successfully operated in Chile for decades, and the new Very Large Telescope (VLT) is now under construction in Region II. Our operating plan results from the collective experience of these optical observatories and from the experience of synthesis radio telescopes in the United States and Europe.

The plan described below is necessarily tentative. It presumes an operating mode that will take time to perfect. It presumes that ALMA can find employees willing to live and work in northern Chile, which depends upon the Chilean economy there at the time the ALMA is hiring and in the ambience of the ALMA work environment. To succeed, the ALMA operations management must be analytical, flexible, creative, and willing to build on the experience of the optical observatories. *We believe it essential that the ALMA staff in Chile -- that is, the local staff -- should schedule, manage, and operate the radio telescope rather than officials located far away in the United States or Europe.*

The ALMA will operate somewhat like the Very Long Baseline Array (VLBA) headquartered in Socorro, New Mexico. It will be a “service” instrument, observing without astronomers present at the operations center. Astronomers need not travel to Chile to observe, although they may choose to do so. This observing mode will free them from *having* to travel to the ALMA to observe. In addition, service observing will give the local staff the freedom to juggle observing programs to match the current receiver status and atmospheric transparency. Such a mode requires the ALMA to provide astronomers with the capability to monitor the observing over the Internet, so as to make program changes when necessary.

B. Operating Centers

ALMA operations will require three locales in Chile, supplemented by several in the United States and Europe. The instrument itself will be situated on the Llano de Chajnantor, a geologic “bench” at an altitude of 5,000 m (16,500 ft) in the Andes mountains east of the village of San Pedro de Atacama. The operations center will be located near this village because of its proximity and its lower altitude of 2,450 m (8,040 ft). Finally, a small administrative and business office must be located in the capitol of Chile, Santiago, to process duty-free imports, to accommodate high-level administration, to maintain contacts with the national government, and to provide a research environment for the scientific support staff. Sites in the United States and Europe will oversee long-term technical development and offer high-level technical support when necessary.

Similar to the Very Large Array (VLA) in New Mexico, the principal operating center of the ALMA may change with time. San Pedro de Atacama is a small village (population 1,000) with few amenities other than those required to support its tourist industry. Few employees’ families will want to live there for a long term, especially those with school-age children. As the ALMA evolves into stable operations, we believe it likely that some aspects of its operations will move to a larger community -- probably, Santiago -- with more amenities. Such changes could make long-term employment attractive to skilled professionals. The modern fiber-optic telephone network now being installed in Chile should easily facilitate this relocation. In this case, the San Pedro de Atacama facilities will become principally a maintenance facility similar to the VLA facilities on the Plains of San Augustin in New Mexico.

C. High altitude

Workers will experience some hypoxia at the ALMA site. The atmosphere at the 5,000m (16,400ft) elevation of the ALMA site has about half (53%) the oxygen at sea level. Consequently, workers will be less effective at that site, and sleep can be quite difficult. To facilitate ALMA operations, the NRAO has a consultant, a specialist[8] in high altitude medicine. We have also consulted with the management of several high-altitude mines in Chile regarding effective methods of accommodating this environment.

Hypoxia refers to the body's reaction to inadequate oxygen. At altitude, the body increases the breathing rate to provide more oxygen. This correspondingly increases the loss rate of CO_2, changing the pH of the blood as carbonic acid is reduced. The kidneys respond by increasing bicarbonate excretion to return the blood pH toward its normal value. Mild headaches are common. Acclimatization occurs over days by increasing the number of oxygen-bearing red blood cells. This process proceeds at different rates in different individuals.

Sleep can be difficult at altitude. The slower breathing occurring in sleep decreases oxygen intake further. The degree of hypoxia then increases.

Mitigations are possible. Placing the OSF at the altitude of San Pedro de Atacama (2,450m) or slightly higher will help acclimatization to some extent. This altitude is low enough that most visitors will be able to sleep well when they arrive. Increasing the partial pressure of oxygen in the ALMA buildings to that of a 3,200m altitude will help enormously. Those working outside at the ALMA site will have oxygen bottles available to them. Drinking lots of water is helpful. Recently, a Caltech scientific expedition working at the Llano de Chanantor have shown these procedures to be effective.

At higher altitudes, these mechanisms cannot bring the oxygenation/chemistry into equilibrium. Mental performance, productivity, and general well-being deteriorate. Acute cases of these symptoms are known as Acute Mountain Sickness (AMS). In severe cases, pulmonary or cerebral edemas can develop – fluid accumulation in the lungs or brain.

The ultimate mitigation is that most ALMA employees will work in the OSF near San Pedro. Few will go to the telescope site.

Finally, the drive from the ALMA site to the OSF takes only about 30 minutes, allowing rapid evacuation of affected personnel.

We are confident that altitude will be a manageable factor in the operation of ALMA.

D. Medical care

As in most countries, the quality of available medical care decreases in rural areas. Fortunately, the mining companies have solved this problem for ALMA. By contracting for medical services, these companies have stimulated the creation of two large, health services companies in Chile. These are Asociación Chilena de Seguridad (ACHS) and Mutual de Securidad (Mutual). While they are other companies as well, these two companies have installations all over Chile. Moreover, these two companies have a mutual assistance agreement. A contract with one of them can mean that the other will provide services in an emergency.

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[8] John B. West, M.D., Ph.D, Professor of Physiology at the School of Medicine, the University of California at San Diego.

The usual procedure is to contract with one of them to supply medical services. The level of services is negotiated as a function of price. I suggest that ALMA execute a contract with one of these companies to oversee the safety environment of our sites on a periodic basis and to provide all auxiliary medical services including first aid. They can even provide a physician full time if necessary.

E. General operations concept

ALMA will be operated by a staff working from the OSF near San Pedro de Atacama. The staff will include telescope operators, technical support personnel, and a maintenance crew.

ALMA will be operated through a fiber-optics link from the site at Llano de Chajnantor to the OSF in SpdA.

Observing will normally be “service observing;” that is, guest astronomers will not come to the OSF to observe. Scheduling will probably be dynamic depending upon weather and the technical condition of ALMA. We expect that local staff will decide which and when observing programs will be carried out. This is another reason why astronomers should not need to come to SpdA. It will be difficult to tell them exactly when their observations will be made. Of course, there will be exceptions – certainly during the earlier stages of ALMA operations.

Most of this operations staff will commute from their homes to work on some kind of Turno basis. We expect, however, that a few high-level managers and their families will live in SpdA for extended periods. ALMA will provide dormitories, food service, and recreational facilities for all personnel working from SPdA.

The support astronomers will surely live in Santiago and commute to SPdA, dividing their working time between supporting ALMA observing and conducting their own research in the Santiago facilities.

Only those personnel involved with the antennas will commute to the ALMA site. These will be daily trips; no-one will spend the night there. These personnel will service and reposition the antennas, remove and replace defective electronics modules, and maintain the access roads.

F. Character of Chilean Operations

1. Management

Management decisions should be local ones. The ALMA director in Chile should make all decisions involving operations in Chile. All employees in Chile should report to the ALMA director, regardless of whether they are “permanent” Chilean hires or ones “borrowed” from related organizations. The sponsoring organizations, the NRAO, ESO, and others, should confine their involvement with the ALMA in an oversight role such as financial support, selection (but not scheduling) of observing proposals, and general policies.

2. Salaries and benefits

As far as possible, employee salaries and benefits should be “consistent” among all ALMA employees regardless of their place of hire. By the time the ALMA moves into full operation, we expect that Chilean professional salaries will be competitive with the world market. This salary consistency would include the job classifications and the salary steps within them. Exceptions would be temporary employees “borrowed” from other organizations. Because of continuing financial commitments at home, these temporary employees would require larger compensation.

"Benefits" would include medical insurance, pension contributions, educational allowances, housing, and travel allowances where appropriate. Such benefits and work rules should be in strict accordance with Chilean law whatever the eventual diplomatic or international status of the ALMA organization.

3. Contracting support services

As customary in the Chilean mining industry, the ALMA should contract for commercial services when they are available. For example, Chile has several large companies that provide food service to remote locations. The employer needs only supply a kitchen and dining room, and specifies the variety and quality of the food to be served. This situation also applies to medical services, housekeeping services, payroll, security, and vehicle leasing and maintenance. The ALMA should hire only those employees unavailable or inappropriate to obtain from commercial service companies, such as management and administrative personnel, support scientists, engineers, programmers, and telescope mechanics. Not only is this system flexible and cost-effective through competition, but it also frees the ALMA management to expand or contract services as needed without affecting long-term ALMA employees.

G. Staffing

1. Sistema de Turno employment for the ALMA and its Operations Center

To operate the ALMA in Chile, *all* consultants recommend a rotating shift system known in Chile as the "Sistema de Turno" for staffing the operations center and the maintenance of the ALMA itself. In Chile the Turno system is used by all international observatories and most mining operations. It complies with Chilean labor laws.

Turno work arrangements include a range of schedules. Variations are common. A construction project in a remote area east of Iquique operates on a two-week "on" and a 10-days "off" system. ESO uses two schedules: known as "5/2" and "8/6." The "5/2" schedule is appropriate for office staff. The work begins at 3PM Monday, consists of 9.5-hour days Tuesday through Thursday, and ends at 1PM Friday. The "8/6" schedule is more appropriate for skills needed every day. It provides approximately 88 work hours over a two-week period. It begins at 3PM on day one, consists of 9.5 hours each on days two through seven, and ends at 1PM on day eight. Sunday is compensated at 1.75 times the basic rate. Replacement personnel overlap on days one and eight. Customarily, the employer provides room, board and transportation to and from an urban assembly point.

An effective Turno system must be appropriate to the specific operation of the ALMA. This system is not appropriate for highest level management people who need to be continually available. It is also inappropriate for employees responsible for creating new systems or equipment. However, it works well for many office positions and for "interchangeable" personnel like telescope operators and maintenance people who must be available seven days a week, 24 hours a day. There is extra cost involved. ESO statistics show that the "8/6" arrangement requires about 2.4 employees for every Turno position to ensure overlap and continuity.

Given the difficulties of staffing a location like San Pedro de Atacama, the Turno system may be the only practical solution.

To accommodate a Turno system, the ALMA would need to provide dormitories at its operations center near San Pedro de Atacama. Our advisors recommend that the dormitories be sized so that each Turno-employee could have the same room and the same bed each visit. In this way, that employee could leave personal effects in the room and could decorate the room to suit his or her preferences.

The ALMA should establish pickup points for Turno employees only in Calama and Antofagasta, at first. Region II has a network of modern, commercial buses linking its cities. Some of these buses serve San Pedro de Atacama more than once daily and, of these, a few continue on the Paso de Jama road into Argentina. The principle would be that commuting employees need to get themselves to the collection points by the most appropriate means and at their own expense.

Professional employees would either live in San Pedro and take substantial holidays as compensation for long hours on the job, or commute from elsewhere in Chile with some of the commuting time being considered working time.

2. Support offices in Santiago

The Santiago offices will not require a Turno system, nor would one be appropriate to their function. Because of the added expense and inefficiency of commuting to and from San Pedro de Atacama, all positions not required in SpdA should be located in Santiago. These would include certain senior administrative management, contract and procurement personnel, accounting functions, and an import/export office.

Effective supply for ALMA will require an import/export office in Santiago. The Chilean Foreign Ministry (Ministerio de Relaciones Exteriores) in Santiago must process all papers for duty-free imports regardless of which Chilean port is used. Furthermore, even after 30 years of operating in Chile from La Serena, the CTIO has chosen to use only ports of entry near Santiago even though the city of La Serena is contiguous with the port of Coquimbo. The CTIO has found that the high traffic levels at the Valparaiso seaport and the Santiago International Airport give the widest opportunities for shipping. Equally important, they have found that, in most cases, these ports are less expensive to use than the port of Coquimbo even though the Santiago goods must be trucked to and from La Serena. The same situation may apply to Antofagasta – the closest port to ALMA.

The Santiago facilities would also include offices for support astronomers. ESO experience has shown that their support scientists had little success conducting research while at the ESO observatory at La Silla. Yet, opportunities to conduct research is essential to retaining quality astronomers. Therefore, ESO instituted schedules for their support astronomers of a week at La Silla, a week in Santiago, and a week off – or some variation on this theme. This system has worked well, and ALMA should adopt it.

The roles of the Santiago office may change with time. As ALMA operations mature, it may be possible to withdraw all but essential operations support from San Pedro de Atacama to Santiago. Specialized support staff would then fly to SpdA (Calama) when needed. This could save money without impacting the reliability of ALMA.

H. Organization chart

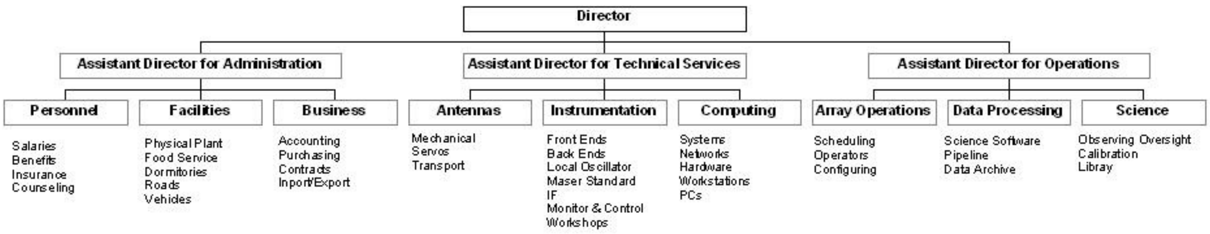


Figure 10. Preliminary organization chart suggested for ALMA operations.

Based upon the NRAO's experience operating the VLA in New Mexico, we propose an organization chart for operating ALMA in Chile. Figure 9 shows the chart. Note that the scientific aspects of operations are separate from other departments. Also, we have separated computer and software into those areas closely linked to observing and analysis, and those areas involved only with the routine support of the facility.

I. Number of employees

To estimate the number of employees, we analyzed what was required to operate the VLA. Experienced ESO managers then amended this list to adapt it to conditions appropriate to Chile and, specifically, to operation of the ALMA in Region II. We considered four phases of the ALMA project:

-- "Start-up," where the staff is adequate to assemble antennas from the incoming modules, to equip them with electronics, test them, and transport them to the observing site at a rate of approximately one per month;

– "Intermediate," where 32 antennas are in operation but the remaining 32 are still to be built;

– "Final," where all 64 antennas are in operations, and

– "Mature," where ALMA operation has become so routine that many of its employees are now based in Santiago.

The appendix contains the detailed estimates of personnel based upon the VLA analysis and upon a discussion between Robert Brown (NRAO), Guillermo Delgado (ESO), Daniel Hoftstadt (ESO), Angel Otárola (ESO), and me (NRAO) in Santiago in January, 2000. The spreadsheets are complicated because they multiply the number of employees by an inefficiency factor due to Turno scheduling and round upwards from that number.

The table below gives a summary.

Table 1: Adjusted Number of Employees					
Epoch	*Total Positions Needed*	*Direct San Pedro*	*Direct Santiago*	*Contracted*	*Total*
Start-up	114	66	8	86	160
Intermediate	139	83	10	97	190
Final	170	101	16	113	230
Mature	?	?	?	?	?

Nota bene: “Contract” means personnel on site hired through contracts for services; they are not direct employees of ALMA. These employees are fictitious because the contacts are actually for services and not for a specific number of employees. We include this column because of possible impact on food services and upon space requirements.

“Total” is a smaller number than the sum of rows C, D, and E because of rounding the number of employees in those columns. Within the columns, fractional employees were rounded upward to the nearest integer.

These numbers should be considered upper limits. Experience shows that *fewer* employees can often accomplish the work of *more* through efficient organization. Also, our model is just that – a model. The personnel need for actual operation may be quite different from the categories we considered. For example, Daniel Hoftstadt of ESO has estimated smaller numbers based upon ESO’s experience managing an optical observatory at La Silla and their projections for operating the new VLT on Cerro Paranal. Nonetheless, our numbers should be considered carefully because they have been derived from the proven operation of a telescope similar to ALMA – the VLA.

J. Annual operating (recurring) costs

Traditional, the annual recurring expenses for an observatory can be estimated in two ways, which I call the “bottom-up” and “top-down” methods.

The bottom-up method derives from considering the average cost of employees – including those provided through service contracts – in terms of a target ratio of employee costs to total operating expense. If the averaged total employee cost is US$70k (2000)and the target ratio of labor costs to total expense is 0.6, then the staff levels in Table 1imply annual recurring costs of ALMA to be US$16.3k, 24.0k, and 29.5k in 2000 dollars if we inflate wages by 3% per year.

The top-down method uses the historical guideline that the operating cost of an observatory is approximately 6% of its replacement cost. Using the non-recurring cap of US$552M in Y2000 dollars to build and equip ALMA, we calculate the annual operating costs to be US$33M.

This section discusses the cost of operating in Chile. Section A describes estimates of these costs in US dollars from data from different epochs; Section B, historical variations in the purchasing power of US dollars in Chile; and finally, Section C, the estimate for operations in Chile in terms of 1999 dollars.

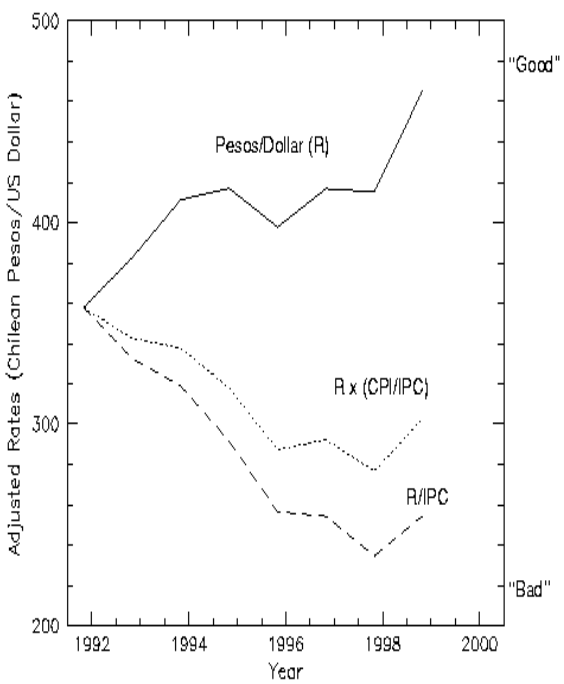
K. Purchasing Power of US Dollars in Chile

The purchasing power of the US dollar in Chile is driven by market forces. These include how much Chilean banks are willing to pay for US dollars on the international market, how much Chileans are willing to pay for foreign-made goods, and the cost of living in Chile. At this writing, Chile has no national debt. Its economy is expanding. It has a favorable trade balance with the US and, consequently, more dollars than it needs.

Variations in the purchasing power of dollars in Chile also involve the relative price inflation of both countries. Consistent with economic practice, both countries track inflation through a variety of consumer and wholesale price indices. A principal US index —there are many — is the seasonally adjusted Consumer Price Index or " CPI", published by the US Federal Reserve Data Bank (FRED) and available on the World Wide Web. For Chile, the approximate equivalent is the Indice de Precio de Consumador or "IPC". Both indices are model dependent, they are calculated from a hypothetical "market basket" of a typical family that may or may not apply to the ALMA situation.

Until recently, Chile has experienced high rates of inflation. It has become common practice for Chilean companies to write contracts, and in some cases pay salaries, in units of the Unidad de Fomento (promoted unit) or UF. The Chilean government adjusts the UF to compensate for variations in the internal buying power of the Chilean peso.

Specific exchange rates between the US dollar and the Chilean peso are the Dolar Acuerdo (agreed rate), the Dolar Informal (informal rate), and the Dolar Interbancario (interbank rate). The Dolar Acuerdo reflects the number of pesos per dollar in contracted transactions. The Dolar Interbancario applies to mercantile and financial transactions within the banking industry. The Dolar Informal is the rate that results from tourists and foreign companies exchanging pesos for dollars as needed.



R ≡ Dolar Informal exchange rate
CPI ≡ seasonally–adjusted, urban, US consumer price index
IPC ≡ Indice de Precio de Consumador (Chilean CPI)

The figure below shows the buying power of US dollars in Chile. The parameter R shows the number of pesos per dollar -- the Dolar Informal -- experienced by the consortium that operates CTIO in Chile, the Associated Universities for Research in Astronomy (AURA) The broken line shows R/IPC, the exchange rate corrected by the Chilean inflation index, IPC. In essence, this line shows the buying power of US dollars in Chile as a function of time since 1992. Note that the buying power has fallen about 6% per year but has stabilized in the last two years.

The third line, marked R x (CPI/IPC) shows the buying power also corrected for US inflation, that is, this line shows what 1992 dollars would have purchased in Chile over succeeding years. This is of academic interest only because ALMA will not have the luxury of using 1992 dollars for construction.

Scaling budgets to future years is difficult. Despite more than thirty years of experience, AURA has found it impossible to predict the variation in the buying power of the US dollar in Chile. Market forces affecting the dollar/peso exchange rate and the US and Chilean inflation rates are too complex to predict. AURA recommends that projections be limited to only one year in the future.

We hope that the stable trend continues.

L. Construction needs

Large, sophisticated optical observatories have operated in remote areas of Chile for decades. Indeed, perhaps the most sophisticated observatory of all, the Very Large Telescope (VLT) of the European Southern Observatory (ESO) is now under construction at a remote site approximately 96 km (60 miles) south of Antofagasta. Our development plan results from inspections of these observatories, extensive discussions with their directors past and present, and our own experience operating radio telescopes in the United States for forty years. To succeed with the ALMA, we will need to be flexible and creative.

A principal feature of the ALMA operation will be remote or "service" observing. The local operations staff will make observations for astronomers. During these observations, these astronomers will be able to oversee the observing via an Internet connection and, when necessary, modify the instructions. This mode is now common for the NRAO's VLA and 12-m telescopes. This situation is similar at many other astronomical observatories. There will be exceptions, of course, especially during the early years of operations. Data will be transported to the astronomers probably in the form of magnetic tapes.

The ALMA "site" in Chile will involve several locations. The observing site is the location of the instrument itself, the Llano de Chajnantor in the Andes mountains. The nearby village of San Pedro de Atacama will serve initially as the construction office and, with a scope that may change with time, the local operations center. The ALMA will require an office in Santiago because Chile's head Foreign Office is the only place to process shipping documents associated with duty-free imports, no matter which Chilean port is used. A Santiago office will also house senior administrative functions. Each of these Chilean sites will need to be developed. Each of these sites will evolve differently because of changing requirements as the ALMA moves from construction through interim operations into normal operations. Finally, the ALMA will rely heavily upon NRAO sites in the United States and upon European laboratories and observatories for sophisticated technical leadership.

1. Llano de Chajnantor.

The telescope site lies at an elevation of 5,000 m (16,400 ft) in Region II of Chile, at a latitude of 23°S. Geologically, the site is a "bench" on the western side of the Andes range, with excellent drainage and a line-of-sight to a nearby community.

Logistically, this site has three important advantages: easy access, proximity to developed communities, and a gas pipeline. It lies near an international highway (Camino de Paso de Jama or International Route 27) connecting Chile with Argentina and now being paved. It lies within a 1-hour drive (approximately 55 km or 34 miles) east of the tourist village of San Pedro de Atacama (population 1,000); within a 2-hour drive (approximately 180 km or 110 miles) southeast of the mining support city of Calama (population 120,000) serviced daily by major Chilean airlines; and within a 5-hour drive (approximately 390 km or 240 miles) east of the port city of Antofagasta (population 300,000) also serviced daily by Chilean airlines. Finally, a new high-pressure gas line will pass by the periphery of the site, providing reliable and inexpensive energy to power gas-turbine electric generators.

Additionally, Chilean telephone companies are now installing broadband, fiber-optic cables and modern switching systems to link Chilean cities to accommodate the rapidly expanding economy. We can easily connect the ALMA at Llano de Chajnantor into this network either by fiber-optic cable or state-of-the-art microwave links.

To make this site viable for the ALMA, we will need to improve an 18-km (11-mile) existing mining road (with switchbacks) connecting the Paso de Jama highway with the site. It is likely that we might also want to improve an existing, straighter, 32-km (20-mile) mining road connecting the site to the Paso de Jama highway via the eastern side of the nearby hills Cerro Toco, Cerro Chascon, and Cerro Chajnantor.

Gas Atacama, an international consortium that built the gas pipeline between gas-rich Argentina and energy-thirsty northern Chile, has routed the pipeline near the edge of the ALMA site. They will provide a gas tap at a place of our choosing, to allow us to site a gas turbine electric generating plant to power the ALMA itself and the site support facilities. Energy provided to the site in this form should be reliable, inexpensive, and visually unobtrusive compared with the option of a high-voltage transmission line between Calama and the Llano de Chajnantor.

Potable water is a more difficult but solvable problem for the site. The Atacama desert receives little moisture, although higher elevations in the Andes mountains receive more because of the cooler temperatures associated with their altitude and their proximity to the wetter, eastern side of the range. The small, known accumulations of water on the western slopes of the Andes have already been committed to providing water for desert communities. For example, Antofagasta's water is piped about 320 km (200 miles) from the Andes to the coast. However, Andes water also collects into underground aquifers in the valley (Salar de Atacama) where San Pedro de Atacama lies. The new 4-star Explora Hotel in San Pedro de Atacama found good water approximately 180 m (590 ft) below the surface, accessed through a well. The simplest way to supply the ALMA site would be to process this water through a treatment plant at the ALMA support facility near San Pedro de Atacama and truck the water to the site as needed. Alternatively, it may be possible to drill a well at the ALMA site itself. Environmentally, it would be prudent to use this water sparingly at the site by installing low-water toilets and reprocessing grey water, if any. In effect, European Southern Observatory now does this to supply their VLT site at Cerro Paranal, approximately 96 km (60 miles) south of Antofagasta.

2. Operations Support

The remaining locations in Chile will serve to support operation of the ALMA. Their functional aspects will change as the ALMA moves from construction into operations and, correspondingly, so will the site characteristics. Largely, these changes will depend upon the individual preferences of the first few Chilean hires, on the Chilean economy at the time of their hiring, on the cash flow from the funding agencies, and what we learn is necessary to support the array.

a. San Pedro de Atacama

Initially, this village will surely be the center of construction operations. It is the closest community to the ALMA site. Built to support its tourist industry, its few modern hotels could house temporary visitors to the construction operations. The highway connecting it with Calama is excellent. The runway of its small airport has just been paved and, possibly, commercial feeder flights may begin to use it in support of the tourist trade.

Land needed for the operations center and for off-site private housing may have limited availability. San Pedro de Atacama is a village of privately-owned land surrounded by government or "fiscal" land. Chilean law prevents foreign nationals from owning land within 10 km of an international border. The ALMA should purchase fiscal or private land for the OSF.

The extent of the ALMA development in San Pedro de Atacama will depend upon how construction proceeds. We are planning to send antennas to Antofagasta, Chile, by ship and to San Pedro de Atacama by road in the largest practical modules, so that a minimum of assembly will be required. If possible, we will assemble the antennas at the 2,425 m (7,960 ft) altitude of San Pedro, equip the antennas with cabling and electronics, and truck the completed antennas to the much higher-altitude ALMA site. Such an operation would require a 2-storey assembly building, a machine shop, an electronics workshop, offices, a library, dormitories, a dining facility, a water treatment plant, and some recreational facilities like tennis courts and a swimming pool. The extent of these facilities will depend upon how quickly we procure the antennas, that is, ultimately upon the cash flow from the funding agencies.

The ALMA should plan to buy power from the local public utility if possible. However, it should also be able to generate its own electric power. At this time, the village provides electric power by a generator operated only during the early evening hours. There is no electric power during the day. The better hotels generate their own electricity. The GasAtacama pipeline will run a few kilometers east of the village. They have agreed to install a separate side tap to provide natural gas to the ALMA operations support facility (OSF) near the village. Still to be decided is whether to generate electric power at the tap and bring it to the OSF by high voltage lines, or to install approximately 3 kilometers of 6 inch gas pipe between the tap and the OSF to allow electric power to be generated at the ALMA support facilities. Economic and aesthetic considerations will influence this decision.

After three antennas have been delivered to the site, limited observing can and should begin to test the array and to produce astronomical data. Such operations will require high-level support staff like computer programmers, electronics engineers, and support scientists generally unavailable locally. These employees, although temporary, may insist upon bringing their families to Chile and require the ALMA project to provide family housing as well, some of which will surely be in San Pedro de Atacama.

As operation increases and construction wanes, the character of the work and of the support staff in San Pedro will change. Those remaining will tend to be "permanent" ALMA employees, largely Chilean nationals, who will operate and maintain the array. Buildings suitable for construction will become unnecessary, and they should be removed. On the other hand, additional office and laboratory space will be required. Given the widespread use of high-quality prefabricated buildings in the Chilean mining industry, the ALMA should also use such buildings in San Pedro de Atacama. Prefabricated buildings make it easy to change the physical plant to adapt to its changing function.

Eventually, ALMA operations should become routine. Only a small staff may be required in San Pedro de Atacama, and most of the support staff could be moved to a Chilean city with more amenities where employee recruitment and retention will be easier. At this stage, the physical plant in San Pedro could be further reduced if prefabricated buildings are used.

Whatever the evolution of ALMA operations based in San Pedro de Atacama, the ALMA management needs to be sensitive to the character of the village. It is an international tourist destination because of its 16th century architecture, its geothermal areas, its pre-Columbian archeological sites, its indigenous Atacamañan residents, and its unique charisma. The village itself has strict architectural codes. Our location with respect to the village and the architecture of our buildings will affect our being accepted as desirable members of the community.

3. Santiago

Chile is a country of about 14 million inhabitants. About 50% live in the Santiago-Valparaiso area, and five million live in Santiago itself. Santiago's environs while smog-impaired during part of the year are exceedingly pleasant. It is an international city with lots of amenities. It has foreign-language schools that can prepare students adequately for admission to foreign universities, such as scoring well on the US SAT and achievement examinations, or the German Arbitur exam, or the French Baccalauréat exam. Two of its universities, the University of Chile and the Catholic University are among the best in South America. Most substantive Chilean companies maintain offices there. It is the entry point for most international flights. It is where you have to be to make and maintain important political and economic connections. Chileans and foreigners enjoy living there.

The ALMA operations will need a presence in Santiago. Shipping documents for duty-free imports can be processed only by the Foreign Office in Santiago. Specific goods are more available in Santiago than elsewhere in Chile. Visitors to the ALMA will arrive first in Santiago.

Other business functions should be located in Santiago. Accounting, purchasing, personnel/payroll can operate more efficiently from Santiago than from San Pedro de Atacama. Employment in Region II always carries a premium owing to a shortage of skilled workers and the high wages paid by the mining industry and subsidiaries. To minimize operating costs, only employees essential to site activities should be posted in San Pedro de Atacama.

Finally, ESO, CARSO, and CTIO experience has shown that support astronomers can be best retained if provided with research offices away from the interruptions intrinsic to support work at the observing sites. Accordingly, ESO gives its support scientists a schedule allowing them to spend every third week in their Santiago headquarters where it maintains an excellent science library. ALMA should do the same.

Based upon the advantages of maintaining some business and administrative functions in Santiago and the importance of providing a research environment away from the hustle and bustle of the observatory sites, I recommend the construction of ad hoc ALMA facilities in Santiago. Especially useful would be the construction of an ALMA building immediately adjacent to the present ESO headquarters building, with auditorium and library facilities shared by the two organizations.
The sophisticated support resources of the NRAO in the USA and of similar observatories in Europe will be difficult to duplicate in Chile. While the ALMA management will maintain its equipment as much as possible in Chile, the ultimate technical support will be the NRAO and European facilities. I would expect technical development of new sophisticated equipment and software to occur there, as well as the identification and correction of subtle flaws in hardware and software, and support of ALMA users located outside of Chile.

4. United States and Europe

Through continuing development of new technology as well as evolving requirements for observing, I suspect that various laboratories, associated with ALMA, in the United States and Europe will contribute new designs and techniques to ALMA. In a sense, these relationships will be symbiotic because the new contributions will also enhance the research possibilities being used by astronomers in these continents. Such a relationship would also apply to the Japanese if or when they join ALMA.

A consequence of this relationship is that from time to time experts will be making extended visits to Chile to oversee the implementation of these improvements, training the local operating staff, and, inevitably, diagnosing any problems with the improvements.

V. Electric Power

A. Continuous demand

Providing electricity to ALMA could be a challenge. Expanding on consumption estimates[9] made very early for the MMA at a United States location, I prepared an estimate[10] of power needed for the MMA in Chile. This has been revised for ALMA utilizing estimate for the power consumption of the Vertex antennas. A Quattro Pro spreadsheet contains the detailed calculations that are excerpted below.

Table 2: Estimated Consumption of Electrical Power by ALMA

Item	*Estimated Sea Level Load (kW)*	*Correction Factor for Altitude (%)*	*Estimated Load at Altitude (kW)*	*RMS Uncertainty (kW)*	*Total Load (%)*
Llano de Chajnantor Site					
Antennas (64), Vertex	4,480.0	35	6,048.0	0.5	74.0
Cryogenics compressors (64)	614.4	35	829.4	0.5	10.1
Antenna heating/cooling (64)	384.0	35	518.4	0.5	6.3
Antenna electronics (64)	128.0	70	217.6	1.2	2.7
Correlator (1)	150.0	70	255.0	1.2	3.1
Control electronics	32.0	70	54.4	1.2	0.7
On-site computers	3.5	70	6.0	1.2	0.1
Cntrl Bldg H/C	46.4	70	78.8	1.2	0.9
Mechanical shops	100.0	70	170.0	1.2	2.1
Total (seal level):	5,938.3	*Total (5,000m):*	8,177.6		100.0
Operations Support Facility near San Pedro de Atacama (2,450 m)					
OSF computers	30.0	36	40.8	0.5	5.7
Other OSF support	200.0	36	272.0	0.5	37.6

9 Wade, C. M. 1992, "Millimeter Array Operating Costs, Electric Power, Telephone Service, and Water," NRAO internal memorandum.

10 Gordon, M. A. 1996, "Electric Power for MMA Operations in Chile," memo to file. Available with QP spreadsheets as the file "ElectricPowerEstimate.pdf" from Gordon.

Dormitories & kitchen	100.0	36	136.0	0.5	18.9
Shops	100.0	36	136.0	0.5	18.9
Cooling/Heating	100.2	36	136.3	0.5	18.9
Total (seal level):	530.2	*Total(SPdA):*	721.1		100.0

Table 2 shows the power demand for the installation at altitude and for the OSF near San Pedro de Atacama. Columns one and two list each component of the load at sea level; column three, the correction factor for bringing that load to the specified altitude; column four, the power load corrected to altitude; column, five, the RMS uncertainty in that load; and column six, the percentage of the site load. Note that the Vertex antennas and cryogenic compressors will consume 74% and 10% of the load at the observing site, respectively. The total steady-state load (see the discussion below) for operating the telescope will be about 8MW.

B. Complications because of the "fast-switching" calibration technique

Analysis shows that the "fast-switching" calibration technique can increase the antenna demand by as much as 50%. To compensate for variations in the phase path of the atmosphere between the antennas and the astronomical target, the *all* of the antennas will switch pointing from the target to a calibration source every 30 seconds. In a stiff wind, the load can momentarily increase the power demand of the antennas by as much as 50%, or by 4MW. Few companies or communities have experience accommodating a fluctuating load of this size.

C. Design and analysis of a power network

In August 1999, ESO and the NRAO commissioned a study[11] of the power distribution system to ALMA – exclusive of the actual power supply itself. Based upon the specifications for the MMA, the report recommended voltages, cable sizes, switch-boxes, and a distribution system that would satisfy the instrument demand at 5,000m altitude. A essential consideration is insulators. The dielectric constant of dry air at that altitude is only 65% of sea level, facilitating arcing between terminals with standard connection boxes designed for sea level. The report designed and analyzed a distribution system that would accommodate the current flow associated fast-switching. However, it made no recommendations regarding the power supply itself.

D. Supplies of electrical power

In principle, there are three options to supply electricity to ALMA: diesel, natural gas, and a connection to the nearest high-voltage line. Each option has its own strengths and weaknesses.

1. Diesel

A common method of supplying electrical power to remote parts of Chile is through diesel generators. The mines and the astronomical observatories often use this. Contracts with Chilean companies can provide electricity to any site by using diesel generators mounted on large, "lo-boy" trucks. The contractor worries about the details. When a generator needs repair, the contractor simply hauls in and connects a replacement unit. There is no interruption in the electrical service. The consumer simply writes checks.

[11] M3 Engineering& Technology Corp., 1999, "Electrical Study for Load Flow and Voltage Drop Report for ALMA Telescope Project," available as the file M3ElectricalReport.pdf" from M. A. Gordon.

These checks can be big ones! First, diesel fuel is a derivative of oil that must be imported into Chile. It's costly. Diesel generators are reciprocating engines that require significant maintenance. That's costly. In 1995, optical observatories in Chile advised me that diesel-produced electricity would cost from 13 to 16¢ per kilowatt hour.

On the other hand, diesel generators are a known technology in remote areas of Chile. Parts are readily available for a wide variety of brands. A combination of turbo-charging and controlling the radiated heat optimizes them for use at high altitudes.

Even if the costs were not sufficiently daunting, there is the problem of how well the diesels would cope with the fluctuating power demand.

2. Natural gas

The ALMA site – Llano de Chajnantor – is crossed by a high-pressure pipe carrying natural gas from central and southern Argentina to the Chilean coast. A gas tap is already in place. Inexpensive energy is already at the ALMA site. It would be a shame not to use it.

The usual method of generating electricity from natural gas – certainly at sea-level – is to power high-speed turbines that, in turn, drive electric generators. In essence, turbine generators are modifications of aircraft jet engines connected to rotary generators. The technology is known, the turbines require remarkably little maintenance, and lubricant changes can be made without stopping the turbines. Major suppliers of moderately-sized turbines are Solar Turbines, a division of Caterpillar; GPT, a division of the General Electric Company; and Yanmar. Solar Turbines claims it supplies more than 50% of the world's turbine generator sets in the size needed for ALMA.

Turbine generator sets are not efficient at altitude. Unlike reciprocating diesel engines, the thin air can be compensated only by a special design of a series of compressor stages for the turbine. This could be prohibitedly expensive. And, ALMA would be in the unfortunate position of testing an unproven design when it really needs an extremely reliable source of electricity. Fortunately, calculations show that the production cost of electricity at the ALMA site would be about 5¢ per kilowatt hour without equipment amortization or 7¢ per kilowatt hour with amortization using a standard Solar Turbines generator set.

In principle, ALMA could consider generator sets using reciprocating engines burning natural gas. The gas blowing by the piston rings would be much cleaner, the interval between oil changes would be longer, and wear-and-tear on the mechanical parts could lead to greater reliability. In addition, it might be possible to tune such an engine to altitude by adding a super-charger and controlling the heat transfer.

In either case, the problem of accommodating a significantly fluctuating load needs to be investigated.

3. High-voltage line

Rumor has it that a new high voltage transmission line will soon cross the Andes from Argentina to northern Chile. Typical voltages for such lines exceed 200kV to facilitate low-loss transfer of electrical energy. ALMA could benefit from this supply by building a substation and a connecting line at, say, 110kV.

Tucson Electric Power estimated a cost of a long-distance transmission line to be about $55k per kilometer. Elecda, a Chilean company based in Region II, quoted a price of $100 per kilometer to build a 110kV line where they would recoup some of their construction costs by selling us electricity. Even if ALMA were to bear the entire cost of construction, a 100km transmission line would cost less than $10M – comparable to the costs of the turbine generators.

The attractive feature is that the enormous reservoir of electrical power in the trans-Andes line might easily accommodate the load fluctuations produced by the fast-switching calibration.

ESO's power engineer, Canio Dichico, is currently (pun intended) investigating all of these options.

E. Costly Chilean electrical code

The Chilean electrical code (norma) reportedly requires subterranean power lines (at 10 kV or so) to be protected by a concrete cover. This is not only contrary to techniques now used in Europe and the United States but carries a huge cost premium. This premium could be especially large at the ALMA site where concrete is expensive owing to a shortage of water and suitable aggregate. Europe and US techniques merely require the burial of a warning tape halfway between the surface and the buried high-voltage line. It is important to determine if this norma is still in effect at the time the ALMA site is developed and, if so, whether an exemption would be possible.

F. Power for the OSF

Presently, electric power is available in San Pedro de Atacama only between dusk and midnight. The capacity is inadequate for the OSF.

ALMA should plan on being self-sufficient with respect to OSF electric power. The new high-pressure natural gas line passes through the valley. It lies 2 km from the Vilama site and tens of meters from the Paso de Jama site. GasAtacama told me that a tap can be made into this line for about US$10k without shutting down the main line.

When and if San Pedro de Atacama community power becomes available and reliable, then the OSF could use it for its principal supply.

VI. Construction specifications

A. Llano de Chajnantor

1. Peripheral development

a. Access road from Paso de Jama to the site, 18 km (11 miles) with a double-asphalt surface, 1.6 km (1 mile) of guard rails on the switchback turns. Capable of supporting a transporter with antenna.

b. Gas taps on GasAtacama high pressure gas line, connecting pipe to gas turbine generator

c. Fiber-optics link from site to San Pedro de Atacama, approximately 56 km (35 miles) , Or, broadband microwave link (E-1 links) from site to San Pedro de Atacama

d. Water well, if economically feasible. Or, storage tank for potable water brought from SPdA.

2. Actual site development

a. Gas Turbine generator, 4-5 MW minimum (rated to produce 8-10 MW at sea level).

b. Diesel or gasoline emergency generators, 2 MW minimum at altitude, to power cryogenics during a lapse in main power

c. Transformer station to switch between generators and alter voltages as required.

d. On-site roads, approximately 7 m wide, compacted, salted, but unpaved, to connect pads with service buildings. (We need a specific configuration layout to estimate this number accurately.)

e. Approximately 145 antenna pads, reinforced concrete, with signal and power connections.

f. Intra-pad signal (fiber-optic and coax) and power connections. (We need a specific layout to estimate this number accurately.)

g. Water storage and distribution system to accommodate up to 20 workers.

h. Sewage disposal system.

i. Internal telephone system, data compatible

j. Internal power distribution system

k. Antenna barn with 3 bays, each 40 ft x 50 ft (6,000 ft^2 or 557 m^2), includes transporter repair station, perhaps with elevated partial pressure of oxygen

l. Warehouse, 1,000 ft^2 (93 m^2), prefab

m. Control building & first-aid station, 15,000 ft^2 (1,393 m^2), with elevated partial pressure of oxygen, prefab

n. Emergency dormitory, 2,000 ft^2 (186 m^2), with elevated partial pressure of oxygen, prefab

o. Generator building, 2,000 ft^2 (186 m^2), prefab (?)

B. San Pedro de Atacama

1. Peripheral development

a. Electrical generation plant, 500 kW maximum, powered by natural gas. It is possible that the municipality of SpdA could supply the electrical needs of the OSF but we should have a backup.

b. Access road from the OSF to the Paso de Jama highway, capable of supporting a transporter and antenna, 1-4 km, depending upon the OSF site selected.

c. Either approximately 3 km of 6 inch gas pipe to connect OSF generators with the GasAtacama gas tap, or 3 km of high voltage lines to connect our generators at the gas tap to the OSF. The connection length depends on the site of the OSF.

d. Well, probably 180 m (590 ft) deep based upon the experience of the new Explora Hotel. Or, it is possible that the new municipal water system of SpdA could supply the OSF effectively.

e. Water treatment/ recovery plant. This facility depends upon the source of potable water.

f. Sewage treatment

2. Actual site development

a. Laboratory, auditorium, & library building(s), 12,000 ft^2 (1,115 m^2), 12 small offices, 12 double offices, 5 moderately-sized offices, 3 large offices, reception area, librarian office, library (several thousand books) with a reading area and compact shelving, 2 meeting rooms (appropriate for teleconferencing), 3 laboratories with movable walls between them, prefab where possible. Auditorium should have outside entrance to permit its occasional use by citizens of SPdA

b. Dining area, kitchen, pantry to feed up to 200 people in a cafeteria style. Pantry and cold storage area should be sized to hold up to one week of supplies.

c. Antenna barn for assembling antennas, 18m high, 2,000 ft^2 (186 m^2), equipped with overhead 50-ton crane, prefab. (This 2-storey structure may conflict with local zoning laws.)

d. Antenna pads, 2, for equipping antennas prior to moving them to the Chajnantor site

e. Warehouse, 4,000 ft^2 (372 m^2), loading dock, near assembly building, prefab if possible

f. Control & first aid, building(s), ~8,000 ft^2 (743 m^2), control area to be partitioned with modern moveable office dividers, first-aid room well-equipped as a clinic, prefab. Unlike a single telescope, the control room will benefit from close proximity to software and engineering support.

g. Welding, carpentry, mechanical shop, 3,000 ft^2 (279 m^2), 3 shops in all, prefab

h. Dormitory, 100 rooms, 30 of these double, *masonry* for acoustic isolation; windows equipped with opaque shades

i. Recreational building (s), 8,000 ft^2 (743 m^2), prefab to contain basketball courts, racquetball courts, "work-out" room, showers, 3 television areas, 2 reading rooms, pool/table tennis room, 1 classroom, area with public telephones, prefab if possible.

j. Museum/Visitor area, ~100m^2, to display information of interest to visitors to SpdA and to the ALMA telescope.

k. Fiber-optics or microwave link terminal to Chajnantor site

l. Generator building to house 2 standby natural-gas electric generators, soundproof

m. Electric power distribution system.

n. Telephone system, internal, data compatible (can accommodate PC modems)

o. Sophisticated communications facilities such as LAN, facsimile, connection to Internet

p. Houses, 3 @ 2,000 ft^2 (~190 m^2), prefab, perhaps scattered through community if possible

q. Outdoor recreational facilities like "baby" soccer field, tennis courts, barbeque area, swimming pool

r. Fueling station for diesel, gasoline, and perhaps propane vehicles.

s. Parking lot for 40 vehicles

t. Security wall, adobe/steel, to surround the compound with guarded access gates.

C. Santiago

1. Actual Site Development

a. Offices, 3 large, 7 medium, 5 double, small canteen, reception area, ~6,000 ft^2 (~558 m^2) with meeting room,

b. Meeting rooms, 2 suitable for teleconferencing, auditorium for 100 people, and library (2,000 ft^2 or 186 m^2). These facilities should be shared with the ESO administration building.

c. Sophisticated communications facilities such as LAN, wide-band telephone, facsimile, and connection to Internet

d. Parking for, say, 20 vehicles

VII. Estimated construction (non-recurring) costs

Based upon the specifications listed above, we estimated the costing of building and equipping the OSF and ALMA itself *exclusive of the antennas, electronics, and special-purpose software and computers*. The estimates described below were first made for the Millimeterwave Array (MMA) and later amended for ALMA.

A. MMA costing

Although an initial estimate[12] for the non-recurring costs of the MMA existed as early as 1995, the we needed new estimates reflecting the detail of its most recent plans. This new estimate would also serve as a check on the accuracy of our earlier cost estimates, especially if made by a commercial engineering firm in Chile.

Accordingly we prepared a document describing the scope of the estimating work, spreadsheet pages listing the size and characteristics of each item, and a description of each in both English and Spanish.

We chose the engineering firm Ocegtel S.A., Ltda., to make the new estimate. Located in Calama, its business involves special engineering projects for mining enterprises in northern Chile where the MMA will be built. This company has considerable experience with high altitude sites. It installed the site-test equipment on the MMA site for both the NRAO and the ESO. Its managing director, Víctor Realini S., has visited the radio interferometer sites of the California Institute of Technology in the Owens Valley, of the University of California in Hat Creek, and of the NRAO on the Plains of San Augustin. We have confidence in the firm's judgement, engineering abilities, knowledge of local costs, and interest in seeing the MMA built in Chile.

On 9 November 1998, Eduardo Hardy (MMA managing director for Chile) and I met with Víctor Realini at the Ocegtel offices in Calama, Chile, to review our requirements. We spent approximately eight hours discussing each item in the spreadsheet. Sr. Realini focused our attention on details that we had not considered, thereby making the design for site development more realistic and, we believe, ensuring more accurate cost estimates. The Ocegtel report[13] arrived in late December. The reference section of this report includes it in both English and Spanish.

Meanwhile, Ellen Bouton (NRAO head librarian), Jeff Kingsley (former site manager for the 12m mm-wave telescope), Pat Lewis (a maintenance supervisor for the VLA), Antonio Perfetto (electronic engineer at NRAO Tucson), Dale Webb (NRAO business manager in Tucson), and I (a former NRAO site director) prepared a list of equipment and furnishings that would be needed for each site in Chile. This list contains furniture for the buildings, books for the library, kitchen equipment, audiovisual equipment, machines and tools for the shops, vehicles, earthmoving machines, electronic test equipment needed to diagnose and maintain the MMA, office equipment, and an initial stocking of shop and office supplies. The reference

[12] "Non-recurring Cost Estimates for the Millimeter Wave Array," M. A. Gordon, 17 March 1995 (narrowly circulated)

[13] Gordon, M. A. 1999, "Estimated Site Development Costs of the MMA Project in Chile," version 2.0, MMA199902-010

section of this report contains a listing of this spreadsheet for each site.

We include electric generators and distribution systems for the site and for the OSF. Investigation showed the most appropriate generator for the MMA site to be a natural gas-powered turbine to produce 2MW at that altitude. Natural gas will be available from a new gas line on the periphery of the MMA site. We include a cost summary in the reference section.

The same gas line will pass near San Pedro de Atacama. For the OSF, we plan to use two natural gas-powered reciprocating generators for the OSF, which we've acquired from government surplus. These units are designed for continuous operation and will produce up to 400kW at 50Hz at the 2,425m (7,960ft) altitude of San Pedro de Atacama. Unlike the MMA site, we expect the electrical load at the OSF to vary considerably during construction. Large variations in load is normally a problem for diesel generators, causing "coking" of the engines. We hope that the natural gas fuel should prevent this condition.

Table 3 below summarizes our estimate for site development of the MMA, including revisions mad

Table 3: Summary of Non-recurring Costs for Chilean MMA Sites Revision 24 June 1999:MAG

Site	*Category*	*Amount (US$)*	*Site Total (US$)*	*Contingency (included)*
Antofagasta	Buildings (lease)	0		
	Office Equipment	81,292		$3,000
	Vehicles (new)	57,500		
		Subtotal	$138,792	
Llano de Chajnantor	Development	26,336,907		20%
	Turbine Generators	6,244,500		15%
	Fiber-Optic Link to OSF	4,662,665		20%
	Emergency Dorm Furniture	7,360		15%
	Electronics Test Equipment	1,222,264		15%
	Office Equipment	136,358		15%
	Safety Equipment	115,000		15%
	Shop Equipment	218,845		15%
	Vehicles (new & used)	1,514,550		15%
		Subtotal	$35,795,784	
San Pedro de Atacama	Development	17,218,817		20%
	Const. Camp & Support	4,607,143		15%
	Dormitory Furnishings	169,050		15%
	Electronics Test Equipment	3,757,932		15%
	Food Service Equipment	117,897		15%
	Office Equipment	738,696		15%

	Recreation Equipment	5,750		15%
	Shop Equipment	222,300		15%
	Supplies	57,500		15%
	Vehicles	11,500		15%
		Subtotal	$26,906,584	
Santiago	Building (lease)	0		
	Office Equipment	88,115		15%
	Vehicles (new)	$51,750		15%
		Subtotal	$139,865	
		Total	$62,981,025	

These costs were modified further for inclusion in a report[14] containing the complete cost of the MMA as of May 1999. This report refers to the MMA as the "U. S. Reference Project" because agreements with ESO were then in place, and the report gave costs for a project that would not be build. Its principal purpose was to accommodate an intensive audit by the NSF of the NRAO's planning and methodology.

In this report, the costs of site development were altered. Some costs were deferred to operating funds, and some were arbitrarily reduced to lower the overall cost of the MMA.

B. Modification for ALMA

To update the 24 June table for ALMA, I modified it in the following way.

All activities in Antofagasta are eliminated. ALMA facilities will consist of the telescope on the Llano de Chajnantor, the Operations Support Facility near San Pedro de Atacama, and a small facility in Santiago.

The following describes changes made to the older table of MMA Non-recurring Costs.

Antofagasta No office. Delete $0.14

Llano de Chajnantor
Development Increased the cost of the 116 antenna pads by 50% because of the larger antennas. I assume the same number of stations for the 64 antennas of ALMA. This factor is midway between a square and cube function of the diameter, or about $3M.

Double the cost of the fiber-optics links connecting the pads to account for the tripled lengths involved with the 10km configuration. The terminals costs remain unchanged. This amounts to approximately $4M.

Increased the length of the infra-site roads by 3 to account for the larger array size. The increase is about $2.5M.

Increased the power network by about 50% to account for the larger array size. This increase is approximately $1.8M.

[14] Brown, R. L., 1999 "Millimeter Array, Construction Cost of the U. S. Reference Project," May, 1999

	Increased the size of the antenna maintenance building because the antennas have, roughly, doubled. This 50% cost increase is about $1.4M.
	The total increase for this item is then approximately $12.7M
Generators	Increase this by 50% to account for the doubled number of antennas by adding approximately $3.1M
Link	Unchanged
Furniture	Unchanged
Test Equip.	Doubled by adding $1.2M because of double the number of antennas.
Office Equip.	Unchanged
Safety Equip.	Unchanged
Shop Equip.	Doubled by adding $0.2M
Vehicles	Doubled because of the 64 antennas and the much larger array. Added $1.5M

Subtotal increase: $18.7M

San Pedro de Atacama

Development	Increase by 40% according to 60% increase in personnel, better quality architecture, 4km access road. Decrease family houses to 3. Added about $6.8M
Const. Camp	Unchanged
Dorm. Furn.	Rooms increase from 60 to 100. Add about $0.1M
Test Equip.	Unchanged. Additional personnel are not all technical and we've increased the site budget
Kitch. Equip.	Unchanged. Adequate to feed a lot of people.
Office Equip:	Unchanged (Overestimated offices originally)
Rec. Equip	Unchanged
Shop Equip.	Unchanged
Supplies	Increase by 60% according to increased number of workers by adding $0.03M
Vehicles	Increase by 60% according to increase in workers. $0.007M

Subtotal increase: $6.9M

Santiago

Building	Add $3M for new building of 1,000m^2 on ESO campus.
Office Equip.	Estimated to be 7% of above.
Vehicles	Unchanged

Subtotal increase: $3.2M

Table 4: Summary of Estimated Non-recurring Costs for Chilean ALMA Sites Revision 10 Feb 2000:MAG

Site	*Category*	*Amount (US$)*	*Site Total (US$)*	*Contingency (included)*
Llano de Chajnantor	Development	39,505,361		20%
	Turbine Generators	7,644,500		15%
	Fiber-Optic Link to OSF	4,662,665		20%
	Emergency Dorm Furniture	7,360		15%
	Electronics Test Equipment	2,444,527		15%
	Office Equipment	136,358		15%
	Safety Equipment	115,000		15%
	Shop Equipment	437,690		15%
	Vehicles (new & used)	3,029,100		15%
		Subtotal	$53,319,896	
San Pedro de Atacama	Development	24,106,344		20%
	Const. Camp & Support	4,607,143		15%
	Dormitory Furnishings	270,480		15%
	Electronics Test Equipment	3,757,932		15%
	Food Service Equipment	117,897		15%
	Office Equipment	738,696		15%
	Recreation Equipment	5,750		15%
	Shop Equipment	222,300		15%
	Supplies	92,000		15%
	Vehicles	18,400		15%
		Subtotal	$33,936,941	
Santiago	Building (1,000m^2)	3,000,000		20%
	Office Equipment(7%)	210,000		15%
	Vehicles (new)	$51,750		15%
		Subtotal	$3,261,750	
		Total	$90,518,587	

C. Modifications

The cost estimate contained in Table 4 will need some revision as the specifications for ALMA become clearer.

VIII. Special concerns

A. OSF design

Architects for the OSF should recognize that is will be a unique facility. It will *not* be a larger version of any existing observatory. When observing is routine, astronomers won't go there. When astronomer are there, they probably won't be able to see the results of their observing until after considerable editing and processing of the autocorrelation function (the U-V data cube).

Much of what we've learned from existing observatories won't apply. The OSF will surely be a facility for service observing. Visiting astronomers won't be necessary or welcome in the array control room; they'll just be in the way. The control room should have immediate access to people who repair the software and fix the hardware.

It is essential that the OSF have as pleasant an ambience as possible – consistent with the available funds. This means, among other considerations, acoustically isolated dormitory rooms and good food. Retaining excellent employees is *essential* to ALMA's success.

To design an effective facility, the architects will need to understand how ALMA will really function. Adapting the design of an existing astronomical observatory would be a mistake.

B. Quality of construction

New construction in locations outside of Santiago can be of poor quality. Traveling through Chile, I have seen many new hotels and buildings with exquisite design. There can be no doubt than Chilean architects are imaginative and well-trained. Chilean architects surely compete with the world's best.

Unfortunately, too many of these new buildings suffer from poor workmanship. Compounding these problems are the use of inadequate hardware, marginal quality plumbing installations, and inappropriate construction materials. Perhaps the reasons are a combination of limited funds for investment and inexperienced construction crews.

Poor construction quality could consume a significant fraction of ALMA's annual operating funds. The costs of maintaining a large maintenance crew and a stock of replacement parts would be expensive. San Pedro de Atacama is a community remote from a comprehensive source of supplies.

To control long-term costs, ALMA planners should demand quality in design, materials, and workmanship. If construction funds prove limited, it would be wise to maintain quality but reduce the scope of the construction. For example, if an architecturally pleasing, permanent OSF complex is too expensive, planners should reduce the size of the buildings and, where logical, choose *high-quality* prefabricated structures. (The dormitory is an exception; employees need an excellent environment for sleeping.) If the initial budget cannot accommodate all the desirable antenna stations, then planners should reduce the number of stations rather than compromise the quality of what will be built.

Furnishings should also be durable and easy to maintain. The purchase of high-quality furniture from reliable companies like Steelcase (www.steelcase.com), Herman Miller (www. hermanmiller.com), and European equivalents will save money over the lifetime of ALMA. These companies have offices in Santiago. The situation is similar with regard to tools and machinery but, in this case, carries the added benefit of worker safety.

C. Turnkey planning

The key milestone for construction planning is the arrival of the modules for the first antenna. Currently, this date is October, 2004.

ALMA must adopt a "just-in-time" approach to the local assembly process. Current plans for the OSF envision minimal warehousing facilities. Therefore, by October 2004, enough of the OSF must be finished, staffed, *and equipped* to facilitate the assembly and commissioning of that first antenna. Furthermore, the level of completion of this facility must be adequate to accommodate the planned arrival rate of subsequent antenna modules, which could be 1 per month initially.

Similarly, construction on the ALMA site must be adequately completed to accept the new antennas at the same arrival rate.

D. A campus for the Operations Support Facility

Acquisition of OSF land must be completed well before architects can begin work of the OSF design. I believe outright ownership would be far preferable to a lease.

Sufficient OSF land should be acquired to accommodate the headquarters buildings of other observatories installing telescopes on the ALMA site, that is, sufficient land to create a “campus” like the one in Hilo for supporting Mauna Kea observatories in Hawaii, and the science campus at Garching bei München in Germany containing some Max-Planck institutes and the headquarters of the European Southern Observatory. Interactions between support staffs could be mutually beneficial.

IX. Appendix

A. Spreadsheets estimating employees needed for ALMA operations.

As described in the text, these three spreadsheets estimate the number of employees needed for the three stages of ALMA. The stages are (1) when the parts for the first antenna arrive, (2) when half the array is finished and in operation, and (3) when the array has been completed and is in full operation.

The numbers shown won’t always add correctly. The spreadsheet calculations involve rounding of fractional employees owing to the inefficiencies of the Turno work schedules.

Also as described in the text, these estimates represent upper limits. ALMA assembly and operations may function well with fewer employees as shortcuts are discovered.

B. Original list of equipment for the MMA Reference Project

This estimate lists equipment needed for the MMA in Chile. The estimators were Ellen Bouton (NRAO Librarian), Jeffrey Kingsley (mechanical engineer and former manager of the 12m telescope on Kitt Peak), Antonio Perfetto (electronic engineer for the 12m telescope in Tucson), Dale Webb (business manager for NRAO Tucson), and me (former director of Arizona Operations for the NRAO).

This list needs to be expanded greatly for ALMA. I include it as a starting point for building a new list.

The equipment listed for Antofagasta should now be considered for the expanded Santiago facility, along with support equipment for astronomers.

C. Gantt Chart for Site Development

This chart shows the work breakdown structure (WBS) for developing the Chilean sites as of March 28, 2000. Planning continually evolves. The reader should consult the latest chart.