ALMA

Atacama Large

Millimeter Array

Proposal for Phase 2 Construction

Volume 1

Executive Summary

22 December 2000

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Executive Summary

1. Introduction

The Atacama Large Millimeter Array (ALMA) is one of the highest priority projects in astronomy today, combining the aspirations of scientists in Europe, the U.S., and elsewhere around the globe. It will image the Universe with unprecedented sensitivity and angular resolution at millimeter and submillimeter wavelengths. It will be a major step for astronomy , making it possible to study the origins of galaxies, stars, and planets. With a capability of seeing star-forming galaxies across the Universe and star-forming regions across the Galaxy, it will open new horizons in science.

ALMA will provide images of galaxies as they were being formed twelve billion years ago, and will permit detailed study of the nearby dust-enshrouded regions in our Galaxy where stars and planets are being formed. It will be a millimeter/submillimeter counterpart of the VLT and HST, with similar angular resolution and sensitivity but unhindered by dust opacity. ALMA will be the largest ground-based astronomy project following the VLT/VLTI, and, together with the Next Generation Space Telescope (NGST), one of the two major new facilities for world astronomy coming into operation at the end of this decade.

ALMA will be comprised of 64 12-meter diameter antennas of very high precision, with baselines extending up to 12 km. Figure 1-1 shows an artist's impression of a portion of the array in a compact configuration.

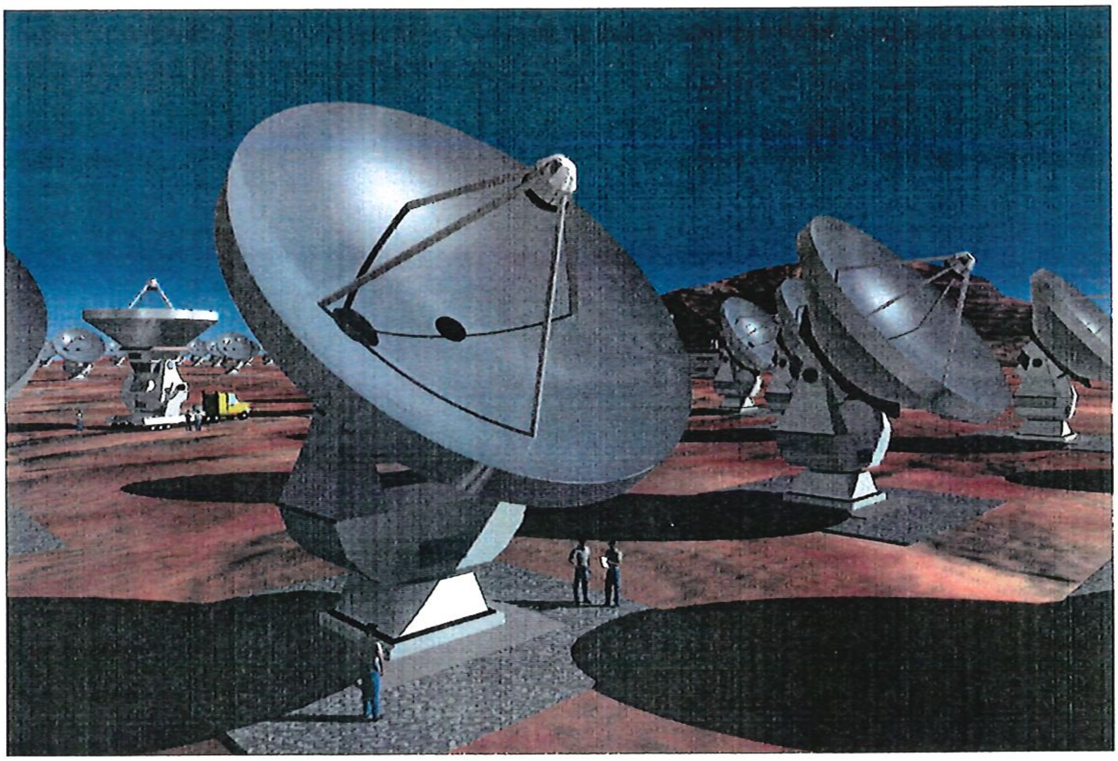


Figure 1-1. An artist's impression of several of ALMA's antennas in a compact configuration.

The array of antennas will be reconfigurable, giving ALMA a zoom-lens capability. The highest resolution images will come from the most extended configuration, and lower resolution images of high surface brightness sensitivity will be provided by a compact configuration in which all antennas are placed close to each other. The instrument thus combines the imaging clarity of detail provided by a large interferometric array together with the brightness sensitivity of a large single dish. The large number of antennas provides over 2000 independent interferometer baselines, making possible excellent imaging quality with "snapshot" observations of very high fidelity. The receivers will cover the atmospheric windows at wavelengths from 0.3 to 10 millimeters. ALMA will be located on the high-altitude (5000 meter) Llano de Chajnantor, east of the village of San Pedro de Atacama in northern Chile. This is an exceptional site for millimeter astronomy, possibly unique in the world.

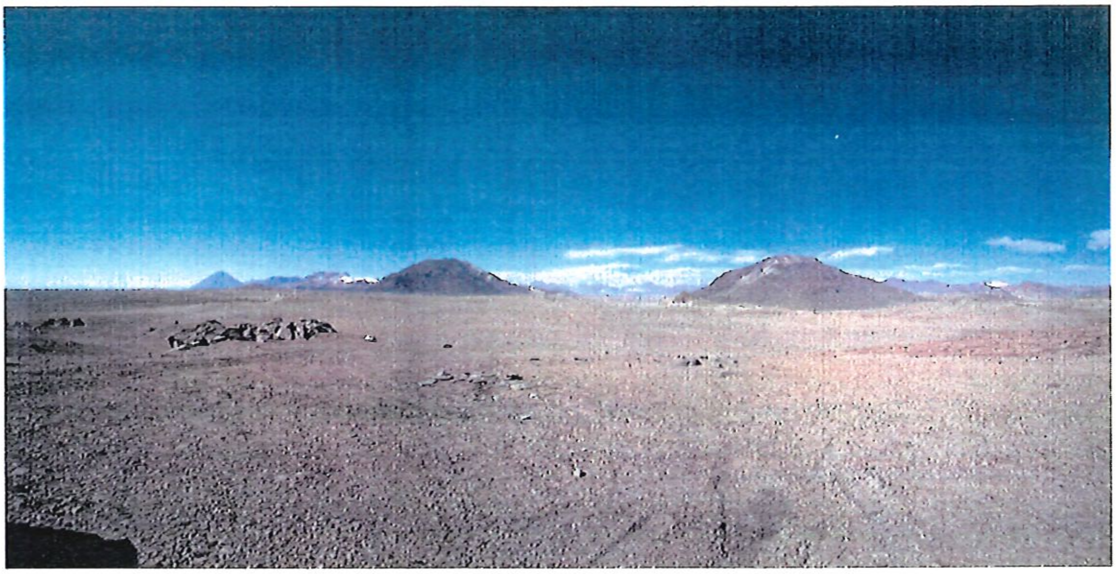


Figure 1-2. A panoramic view of the 5000 meter high Llano de Chajnantor in the Atacama desert of northern Chile.

To make such an ambitious project possible, ALMA has become a joint endeavour involving several nations and many scientific institutions, and it is likely that it will become the first global project in ground-based astronomy – an essential development in view of the ever-increasing complexity and cost of front-line astronomical facilities.

For years Europe has had a major involvement in millimeter astronomy, with several of the leading facilities in the world. Many institutions throughout Europe have active research programmes in this field, and a number of them have developed technical expertise in this area together with European industry, so it is natural that a European collaboration should be looking to the future.

The idea of a large European southern millimeter array ("Large Southern Array", LSA) has been discussed since 1991. In 1995 a LSA project collaboration was formally established to explore the possibility in a two-year study which included site surveys in Chile and critical technical studies. A report published in April 1997 concluded this first phase.

An important step was taken in June 1997. A similar project had also been under study in the U.S. since 1984, the "Millimeter Array" (MMA), and an agreement was

made to explore the possibility of merging the two projects into one. The basic principle was that of a 50-50 partnership between Europe and the U.S., with joint overall direction. Three aspects were studied in detail – scientific, technical and management – and a feasibility study was published in April 1998.

The framework for the formal European collaboration in Phase 1 of this project (the 3-year design and development phase) was established in December 1998. An European Co-ordination Committee (ECC) was created to direct the European effort, with participation and funding from the European Southern Observatory (ESO), the Centre National de la Reserche Scientifique (CNRS), the Max-Planck-Gesellschaft (MPG), the Netherlands Foundation for Research in Astronomy (NFRA) and Nederlandse Onderzoekschool Voor Astronomie (NOVA), the United Kingdom Particle Physics and Astronomy Research Council (PPARC), the Natural Science Research Council (NFR) of Sweden, the Instituto Geográfico Nacional (IGN) and the Ministerio de Ciencia y Technología (MCYT) of Spain.

In June 1999 a formal agreement between Europe and the U.S. regarding collaboration on Phase 1 of the project, now called the Atacama Large Millimeter Array (ALMA), was signed. The U.S. side of the partnership is led by the National Radio Astronomy Observatory (NRAO), operated by Associated Universities, Inc. (AUI) under a cooperative agreement with the National Science Foundation (NSF). Recently, Canada has formally joined the U.S. in the North American collaboration. The overall direction for the project is provided by an ALMA Co-ordination Committee (ACC), which oversees the activities of an ALMA Executive Committee (AEC) and several technical project teams, with advice from international Scientific and Management Advisory Committees.

Phase 1 of the project extends from 1999 through 2001, with the objective to completely define a joint program to construct and operate ALMA. The total resources available are US$ 32 million from the North American side and € 22 million from Europe.

Japan has also been working towards a project of this kind, the Large Millimetre and Submillimetre Array (LMSA). The Japanese astronomical community has decided that it would be best to fully merge this project with the European and U.S. projects. As all three are comparable in scale, it was natural to consider an equal three-way partnership. Japanese participation would provide significant scientific enhancements to the current Europe-U.S. project, and this possibility is currently being actively pursued. If it is realized, ALMA will become a truly global project, the first ever in ground-based astronomy.

The design and development Phase 1 of the project will be completed at the end of 2001. The construction phase (Phase 2) is planned to begin in 2002, with completion foreseen in 2010. The total Phase 2 cost is 552 million (in year 2000 US$), to be shared equally between Europe and North America. The U.S. budget request for initial Phase 2 funding in fiscal year 2002 has already been submitted. Approval for European funding will be required in 2001 in order for the joint project to move ahead in 2002.

This proposal presents the scientific case for the project, a detailed technical description, the proposed management plan, and detailed cost breakdown. These different aspects are summarized in this Executive Summary, and elaborated in the accompanying four volumes of this proposal.

2. Science with ALMA

The scientific case for ALMA is overwhelming. The main science drivers are the origins of galaxies, stars and planets: the epoch of first galaxy formation and the evolution of galaxies at later stages including the dust-obscured star-forming galaxies that the VLT and HST cannot see, and all phases of star and planet formation hidden away in dusty cocoons and protoplanetary disks. But ALMA will go far beyond these main science drivers – it will have a major impact on virtually all areas of astronomy. An extensive overview of the science possible with ALMA is given in Volume 2 of this proposal, and a brief summary is given below.

2.1 Galaxies and Cosmology

Three dramatic events over the last decade have spectacularly opened up the mm/submm wavebands to the distant Universe: the discovery of CO emission in a $z = 2.3$ ultraluminous infrared galaxy, the discovery of the far-infrared background radiation, and the discovery of a large population of star-forming galaxies that probably dominate the luminosity of the Universe at high redshift. The most remarkable discovery is that large amounts of dust and molecules are present already at $z = 4.7$. This redshift corresponds to a look-back time of 92% of the age of the Universe and shows that enrichment of the interstellar medium occured at very early epochs.

It is now clear that the mm/submm wavebands are exceptionally well suited for the study of the distant Universe. Whereas the broadband flux from distant galaxies is diminished in the UV and optical both due to the redshift and obscuration by internal dust, the same dust produces a large peak in the rest-frame far-infrared, which, when redshifted, greatly enhances the millimeter and submilleter emission from these objects. Thus, ALMA may provide one of the best ways to find the first galaxies that formed after the "dark ages".

Current studies are limited to the very brightest objects. ALMA will make it possible to detect objects one hundred times fainter, and will make a decisive contribution to one of the key questions in current astronomy: the origin of the infrared background and the star formation history of the Universe. The "ladder" of molecular transitions essentially guarantees that a redshifted spectral line will appear in one of the observing bands. ALMA will thus be able to obtain the redshifts of distant galaxies, and study their detailed morphology and kinematics. It will be able to detect not only molecular lines from these objects, but potentially also the atomic fine-structure lines of carbon, oxygen, and nitrogen, which, at high-z, are redshifted into the submm bands.

At present, even the strongest submillimeter sources are very difficult to identify. Most of them are not associated with previously known bright objects, yet this population probably dominates the luminosity of the distant Universe. With ALMA's high angular resolution, precision and sensitivity, it will be possible to accurately locate such sources in minutes, and measure their redshifts through the detection of CO lines in less than an hour. ALMA may also find a population of more distant, optically obscured, objects which would escape detection at other wavelengths.

The study of the early epochs of galaxy formation is one of the main goals of ALMA, and one of the main reasons for a very large collecting area.

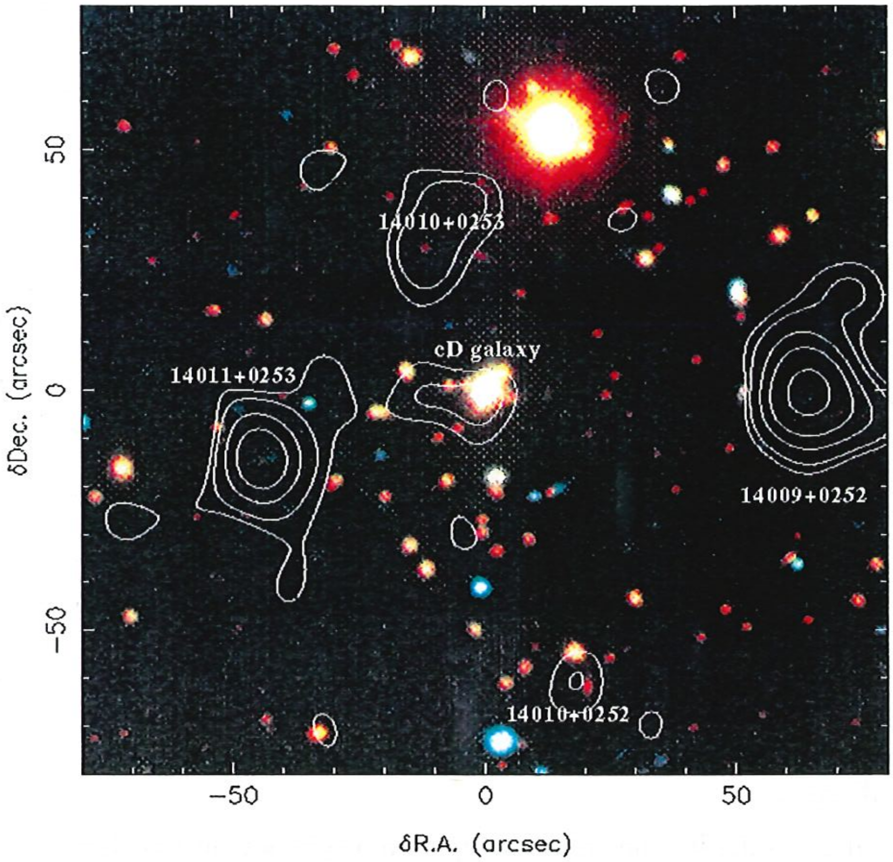


Figure 2-1. The submillimeter and optical wavebands provide complementary views of the Universe. This figure shows submillimeter contours superimposed on an optical image of the galaxy cluster A1835 (Ivison et al., 2000). It is clear that the submillimeter sources are very faint optical objects, while the red cluster galaxies are not prominent submillimeter sources. The mm/submm wavebands are particularly sensitive to the most distant galaxies; the source 14011+0253 is at a redshift of 2.55, as determined directly from CO line observations. ALMA will provide submillimeter images with much finer resolution than the optical image.

Many gravitational lenses will be found by ALMA – possibly more numerous and at higher redshifts than in the optical or radio wavebands because of the very steep source count. Gravitational arcs will be mapped in molecular lines.

Molecular absorption lines will be observed in the spectra of many quasars. This is a new field with great potential. Already, in the few sources bright enough, over 30 transitions from 18 different molecules have been observed in absorption systems up to $z = 0.9$. This opens up the study of detailed chemistry at cosmological distances, and makes possible direct measurement of the cosmic background temperature at high redshifts. Thousands of sources will be accessible to ALMA.

ALMA will be a unique tracer of microwave background anisotropies on small angular scales – no other planned instrument will be capable of making these observations. It will provide detailed images of the Sunyaev-Zel'dovich effect in clusters, and may detect the anisotropies associated with the reionization of the Universe.

Active galactic nuclei can be studied in depth at millimeter wavelengths because of the low synchrotron and dust opacity and the unprecedented angular resolution of millimeter VLBI. The optically-obscured molecular tori and the circumnuclear starbursts of nearby galaxies can be resolved with linear resolutions of a few parsec. ALMA will be able to map both the gas and the dust that obscure the nuclei. The presence of central black holes can be studied kinematically in a large number of galaxies. The center of our own Galaxy can be observed free of obscuration, in particular the gas dynamics of the 1-pc circumnuclear disk around the galactic center source Sgr A*.

ALMA will make observations of normal galaxies at z = 1-2 with the same detail as is presently possible in nearby galaxies. The main dynamical features of nearby spirals will be observed with enough resolution and sensitivity to constrain theoretical scenarios of galaxy evolution. The mass spectrum of molecular clouds in galaxies of different types will be determined. Detailed studies of nearby mergers and IR luminous galaxies will be important to serve as templates for objects found at high redshifts. In the Magellanic Clouds, star formation processes can be compared with those in our Galaxy. This would be highly interesting, because star formation is closely related to the ambient radiation field, dust content, and metallicity.

2.2 The Formation of Stars and Planets

A major astronomical goal of the 21st century is an understanding of how stars and planets form. Studying star and planetary system formation requires very high angular resolution, because proto-planetary disks are small (10-500 AU) and the nearest star formation regions are ~100 pc away. ALMA will provide a linear resolution as fine as 1 AU at these distances.

ALMA will be the premier instrument for studying how gas and dust evolve from a collapsing cloud core into a circumstellar disk that can form planets. The array will be able to directly observe astrophysical phenomena that have until now only been conjectured in theoretical models of the early stages of star formation. ALMA will yield new unique information on the gravitational contraction of protostellar cloud cores, with accurate kinematics and mass distributions inside the cores and their envelopes. It will give new clues to the role of the magnetic field in the cloud cores, the circumstellar envelopes, and the accretion disk. Observations of high excitation submm lines of various molecules will allow us to study the physics and chemistry of the shocks in the ubiquitous outflow jets that carry away the original angular momentum.

For the later stages, when the newly-formed stars are surrounded by protoplanetary disks, imaging the gas and dust on scales of several AU will be the only way to study the earliest stages of planet formation. Current mm arrays have revealed large (hundreds of AU) rotating disks around single T Tauri stars, but the angular resolution necessary to resolve the inner regions, where planets are expected to form, will only be provided by ALMA. ALMA will be able to reveal, within proto-planetary disks, the gaps that are tidally cleared by Jovian sized planets at distances of a few AU from their young, central stars. Multi-wavelength studies of such objects will be powerful tools for analyzing the dust and gas properties on the scale of the Solar System. Maps of dust and optically thin molecular lines with 0.1" to 0.05" beams will provide crucial data on the chemistry, the reservoirs of the biogenic elements, and the timescales on which planets form. ALMA will provide the masses of the pre-main-sequence stars through the measurement of the Keplerian motion in the protoplanetary disks.

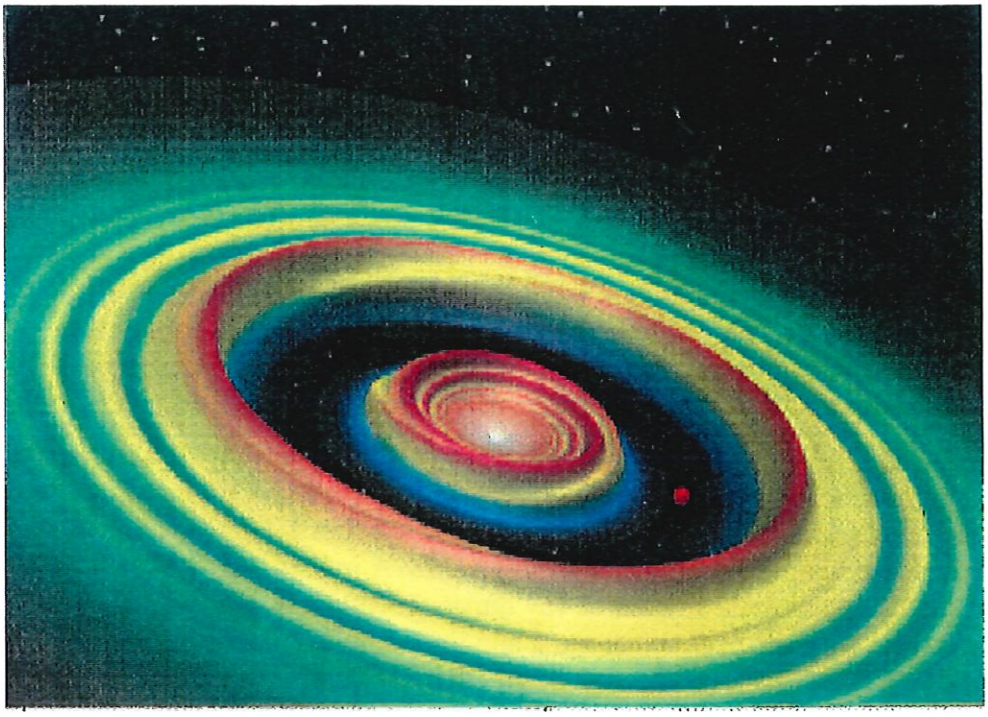


Figure 2-2. ALMA will reveal the details of planet formation. The figure shows a hydrodynamic model of a protostellar accretion disk in which a giant protoplanet is forming (Bryden et al., 1999). The newly formed protostar resides (invisibly) at the center of the accretion disk and a Jupiter-mass protoplanet orbits around it at the Jupiter-sun distance. A gap in the disk is cleared out by the protoplanet. Using ALMA it will be easy to image such gaps in protostellar disks in nearby star-forming regions. In this plot surface density is coded as "height".

The high sensitivity of the array will allow us to make unbiased surveys of pre-main sequence stars to obtain the statistics of disk properties and frequency of protoplanetary systems in different star-forming regions. Comparison between isolated star formation and dense clusters will become possible. ALMA will also address the high mass star formation problem. Dense, hot cores are known to exist around massive (proto)-stars, but the existence of circumstellar disks analogous to those found around low mass star remains uncertain.

The study of star and planet formation is another major goal of ALMA, and one of the drivers for the highest angular resolution.

2.3 Stars and their Evolution

With its coverage of the millimeter and submillimeter ranges, ALMA will greatly expand the field of stellar astronomy. It will detect tens of thousands of stars over the entire H-R diagram. It will cover the full life cycle of stars. It will provide unique information on the winds of hot stars, novae, the photospheres of giants and supergiants, and non-thermal processes in flare stars, Be stars, and dust formation in supernovae and in the outflows of planetary nebulae. It will resolve the photospheres and chromospheres of giant and supergiant stars within a few hundred parsec.

ALMA has been designed so that it will be able to observe the nearest star, our sun. It will be the largest ground-based instrument for solar research built in this decade. It will address two of the most interesting solar physics problems: the acceleration of the highest energy electrons in flares, and the thermal response of the low chromosphere to waves and shocks from the interior.

ALMA will yield fundamental knowledge for our understanding of the dynamics and chemistry of the envelopes of evolved, oxygen-rich and carbon-rich stars, where important scientific goals are the understanding of dust formation and the enrichment of the interstellar medium with heavy elements. The winds of these red giant stars rapidly remove the outer layers, terminating further evolution. The winds have low outflow speeds and high densities, so that matter easily condenses into dust grains. ALMA will image the distribution of matter in the outflows at distances of a few stellar radii, to solve the long-standing problem of dust formation and study the interaction between stellar pulsations and wind acceleration. It will be possible to study such objects across the Galaxy.

Supernovae and gamma-ray bursts will both be important targets for ALMA. In both cases mm and submm observations provide unique and important information. Radio supernovae first appear at these wavelengths, where the flux is relatively unaffected by free-free and synchrotron self absorption. SN 1987A in the LMC will be a prime target for ALMA. In the case of gamma-ray bursts, mm/submm observations provide unique information on the peak of the burst and important constraints on the physical parameters. ALMA will allow detection of all GRBs detectable in the optical.

2.4 The Solar System

Because of its high angular resolution, its fast imaging capabilities, and its wide instantaneous bandwidth, ALMA will represent a major step forward in the study of comets, asteroids and planets. ALMA's highest angular resolution at a distance of 1 AU corresponds to a linear resolution of less than ten kilometers.

Observations of comets with ALMA will greatly increase our understanding of their nature and origin, and complement the planned space probes that will be able to sample only a few comets. Over 20 molecular species have so far been discovered in comets. ALMA will make it possible to search for less abundant molecules, radicals, and new ions, and to investigate isotopic ratios in several species. Such studies will provide key information on the origin of comets and the formation of the Solar System. It will be possible to detect molecules in distant comets and study the evolution of their outgassing as they approach the Sun. The fast, high resolution imaging capability of ALMA will allow us to study structures in the inner coma of comets, and maps of the distribution of rotational temperatures of different molecular species will help us study the thermodynamics, excitation processes, and physical conditions in these objects.

Asteroids and cometary nuclei of small sizes, and even distant objects such as Centaurs and trans-Neptunian objects, will be detectable in the mm and sub-mm continuum. Together with observations in other wavebands, ALMA will allow us to probe the temperature of these objects at various depths and to measure their albedo and size. Imaging thermal emission from the planetary satellites, the Pluto/Charon system, and the largest asteroids will provide clues to their thermal properties and the degree of heterogeneity of their surface.

ALMA will be able to map planetary atmospheres on short timescales. Maps of CO and HDO in Mars and Venus will give data on wind, temperature, CO and water distribution, and atmospheric dynamics on spatial scales comparable to regional weather scales. The analysis of meteorological and climatic variations in the atmosphere of Mars will be a valuable complement to future space missions. Searching for molecular trace species likely to be present in these planets, such as sulfur-bearing compounds in Venus and organic species in Mars, will become possible. Wide bandwidth capabilities will allow us to probe the deep atmosphere of Venus. Mapping HCN and CO, and searching for other nitriles on Neptune, will provide information on the whether the origin of such molecules is internal or external. It will be possible to detect and map tropospheric species such as PH_3 in the giant planets. During very dry conditions at the high-altitude site proposed for ALMA, the mapping of H_2O and HDO on the four Giant Planets will provide clues on the origin of water.

ALMA will also observe the atmospheres of Pluto and the satellites of the giant planets. ALMA will be able to detect SO_2 and SO in the plumes of the volcanoes on Jupiter's moon Io and may discover other trace constituents. Mapping the millimeter lines of CO, HCN, HC_3N, and CH_3CN in the stratosphere of Titan with high spectral resolution will provide the vertical and latitudinal distributions of these constituents, giving better constraints on the photochemistry that occurs in Titan's atmosphere and its response to seasonal effects. ALMA will have sufficient sensitivity to detect and map CO, and perhaps other species, such as HCN, in the tenuous atmospheres of Pluto and Triton. This will provide clues on the nature of the interaction between their icy surfaces and their atmospheres.

The scientific reach of ALMA thus extends from the most distant objects in the Universe to details of the nearest objects in our solar system. It will be one of the major astronomical facilities of the 21st century.

2.5 Scientific Requirements

High angular resolution is of great importance both for observations of the distant Universe and for detailed studies of the processes of star and planet formation nearby in our own Galaxy. It is clear from HST observations that an angular resolution of at least 0.1 arcsec is needed for high redshift studies, particularly at the longer wavelengths (eg. 3 mm) most relevant for the galaxies at the very highest redshifts. Similarly, an angular resolution of 10 milli-arcsec or better is required to resolve the gaps in protoplanetary disks created by forming planets, and such resolution should be achieved at least at the shorter (submillimeter) wavelengths accessible to ALMA. Both requirements imply baselines of 10 km or greater.

Such high angular resolution cannot be exploited without adequate sensitivity. The noise in brightness temperature increases as the square of the baseline. However, millimeter astronomy is the domain of *cold* matter, so the brightness temperatures to be observed are low. In the case of spectral lines, bandwidths are limited by the linewidths, so increasing bandwidth does not help. Furthermore, modern receiver performance is approaching quantum limits and/or the atmospheric noise limits. Therefore, the only way to increase the sensitivity is to increase the collecting area of the array. An angular resolution of <0.1 arcsec can only be achieved for thermal lines with a collecting area approaching 10,000 square meters. The other main driver for very high sensitivity is the detection of the most distant galaxies in the Universe. If galaxies formed by successive mergers of sub-galactic objects, the highest possible sensitivity will be needed to detect the first luminous objects.

The large size and collecting area can only be achieved with a large array of antennas. The collecting area of an array can be enhanced by increasing the number of antennas, their size, or both. There were thus several trade-offs to be considered. Small antennas have higher precision and give better wide-field imaging. The use of large antennas maximizes the collecting area, and reduces the number (and therefore cost) of receivers and the demands on the correlator. In view of the overriding importance of high sensitivity, the largest possible antenna size was chosen. The surface accuracy required for efficient operation at submillimeter wavelengths, 25 μm rms or better, is difficult to achieve for antenna diameters greater than about 12 meters, so this determined the antenna size. An array of 64 12-meter diameter antennas provides a total collecting area of over 7,000 square meters, satisfying the sensitivity requirements given above. This large number of antennas also provides excellent high-resolution imaging capability, which will be very important for the science objectives of ALMA. The 2016 independent baselines will give very good instantaneous coverage of the u-v plane, allowing high resolution "snapshot" images of high fidelity.

Thus, the angular resolution and sensitivity requirements are satisfied by ALMA, an array of 64 12-meter diameter high precision antennas with baselines extending up to 12 km. The receivers should provide complete wavelength coverage of the atmospheric bands over the range 0.3 to 10 mm, as elaborated in the Science Volume of this proposal. The front-ends will be built to accommodate all ten receivers needed, and will be populated initially with the four of highest priority. Other requirements include wide instantaneous bandwidth (16 GHz per antenna), a flexible correlator system allowing spectral resolution as high as 5 kHz (5 m/s at 1-mm wavelength), and water vapor radiometers to correct the atmospheric pathlength fluctuations. The site must obviously be large, flat, and very high (to minimize the atmospheric attenuation at these wavelengths). The 5000-meter altitude Llano de Chajnantor in the Atacama desert region of northern Chile is ideal.

3. Technical Summary

Arrays of antennas, operating on the principle of aperture synthesis were built in the sixties and seventies for centimeter wavelengths – the VLA of NRAO with 27 elements being the biggest. Since then, the technique has been extended into the millimeter wavelength regime by a number of instruments, ranging from 5 to 10 antennas of diameters 6 to 15 m and baselines up to several hundreds of meters – the IRAM at Plateau de Bure in Europe and the BIMA and OVRO arrays in the U.S. With ALMA we aim to provide millimeter and submillimeter astronomy (wavelength from 0.3 to 10 mm) with an instrument of unequaled capability, a jump with respect to current telescopes larger than that achieved by the VLA twenty years ago.

The astronomical and astrophysical arguments have been summarized in Section 2. In the following sections we summarize the technical aspects and characteristics of ALMA. A detailed description of the instrument is presented in Volume 3 of this proposal. The major technical parameters of ALMA are listed in Table 3-1.

Table 3-1. Major Technical Specifications of ALMA

Telescope principle	Aperture synthesis (interferometers)
Number of Antennas	64 Cassegrain antennas of 12-meter diameter
Number of baselines	2016
Number of configurations	Five, maximum baselines: 150, 500, 1500, 3000, 12000 meters
Number of antenna stations	250, antennas transportable between them
Site	Chajnantor, Northern Chile, 5000-meter altitude
Frequency coverage	30 - 950 GHz, except atmospheric absorption regions
Receiver complement	One cryogenically cooled unit accommodating 10 frequency band cartridges (4 installed initially) plus water vapor radiometer
Signal transport	In digital format over optical fibers
Correlator	Reconfigurable digital correlator with 12 configurations and 1024 spectral channels
Software	Control and data handling, data pipeline, image production, remote control and observation
Operation	Service observing with Operations Center near San Pedro de Atacama, 50 km from site at 2500-meter altitude

ALMA offers observers a true imaging telescope of unsurpassed flexibility, sensitivity, and angular resolution over the entire millimeter and submillimeter region of the electromagnetic spectrum accessible from the earth.

3.1 The Site

ALMA will be built on the Chajnantor altiplano in the Atacama Desert of Northern Chile (Figure 3-1). Its approximate coordinates are 90° W, 23° S. The site is at an altitude of slightly over 5000 m. It is about 50 km from the nearest town, San Pedro de Atacama. San Pedro, with about 1500 inhabitants, is the oldest, continuously inhabited village in Chile. It has recently become a favorite goal of tourists, which has caused an improvement in the infrastructure. Because work at 5000-meters altitude is extremely hard, the operation of ALMA will be done from the Operations Support Facility (OSF) to be located near San Pedro at an altitude between 2500 and 3000 meters. Access to the site is remarkably easy: a new paved highway, connecting Antofagasta with northern Argentine, runs a few km from the site. There are regular airline connections between Santiago de Chile and Calama, a mining town one-hour drive north of San Pedro. A natural gas pipeline, crossing the Andes from Argentine runs through the site. It is likely that ALMA will be powered by this gas. Chajnantor has superior atmospheric conditions for astronomy at millimeter and submillimeter wavelengths. This has been confirmed by *in situ* measurements of atmospheric transparency that have been carried out over several years. We know of no other site on earth that combines these excellent atmospheric conditions with easy accessibility in a country with a well-developed astronomical infrastructure.

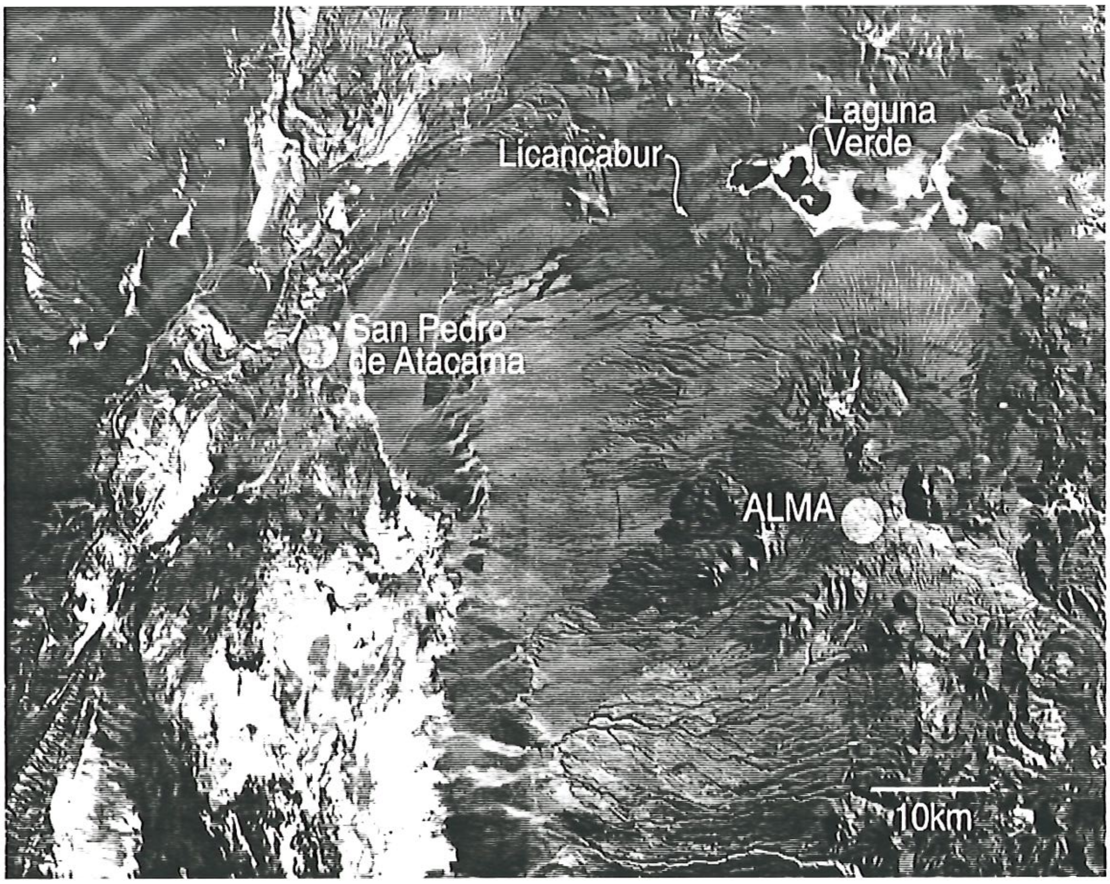


Figure 3-1. Satellite image of the vicinity of the ALMA site at Llano de Chajnantor and San Pedro de Atacama

3.2 Antennas

The 64 individual elements of the array are accurate reflector antennas of 12-meter diameter. The chosen size and number of elements provides a good combination of sensitivity, field of view, speed of observation, and completeness of imaging. The antennas are of a traditional design with a number of innovative features to reach the very stringent specifications in accuracy. The reflector is supported by an altitude-azimuth mounting, providing all-sky coverage. The received radiation is brought to the focal point behind the main reflector, where the receiver unit is located in a shielded room, fixed to the elevation section of the antenna. The main specifications and parameters of the antennas are listed in Table 3-2.

Table 3-2. Major Parameters of the ALMA Antennas

Diameter primary reflector	12 meters
Reflector surface accuracy	25 μm
Pointing accuracy - absolute, anywhere	2.0 arcsec
Pointing accuracy - relative, within 2 deg	0.6 arcsec
Delay error	20 μm
Operational temperature range	-20 to 20° C
Operational wind velocity	up to 10 m/s

The main challenge for the antenna design is the requirement of pointing accuracy, which is to be realized at the windy Chajnantor site. In daytime operation, which is routine for radio astronomy, the effects of heating by sunlight on the structure must also be controlled in order to avoid excessive deformations, which could lead to pointing errors and changes in the reflector shape. A further challenge for the designer and fabricator lies in the large number of antennas to be built. Special attention must be given to aspects of series fabrication in order to minimize the cost.

Using identical specifications and requirements, both the U.S. and European side of the project have contracted for a prototype antenna. The designs have passed the Critical Design Review in November 2000 and the antennas will be delivered to the site of the VLA in New Mexico by the end of 2001. There they will be thoroughly tested by a joint test team of North American and European participants with a view of selecting the better of the two. Afterwards, the two prototype antennas will be used as a "Test Interferometer" to test prototype electronic equipment and software for ALMA. Figure 3-1 shows the overall configuration of the European prototype antenna.

Both contractors for the prototype antennas have selected carbon-fiber reinforced plastic (CFRP) as material for the support structure of the reflector. This material has a better stiffness to weight ratio than steel or aluminum and, most importantly for our purpose, exhibits a very small coefficient of thermal expansion. This makes it possible to reach the high surface accuracy. CFRP has successfully been used already in a few (sub)mm-telescopes. The reflector surface of the antennas will consist of accurately machined aluminum panels. This is also a well-proven technology and achieving the required accuracy has been demonstrated.

The altitude-azimuth mounting of the antenna will be of steel. The tipping receiver cabin houses the receiver front-end, a large cryostat in which the different receiver modules are inserted. An advanced control and servo system will move the antennas to the desired positions at the required velocity. The control of the array will be executed from the central control facility at San Pedro.

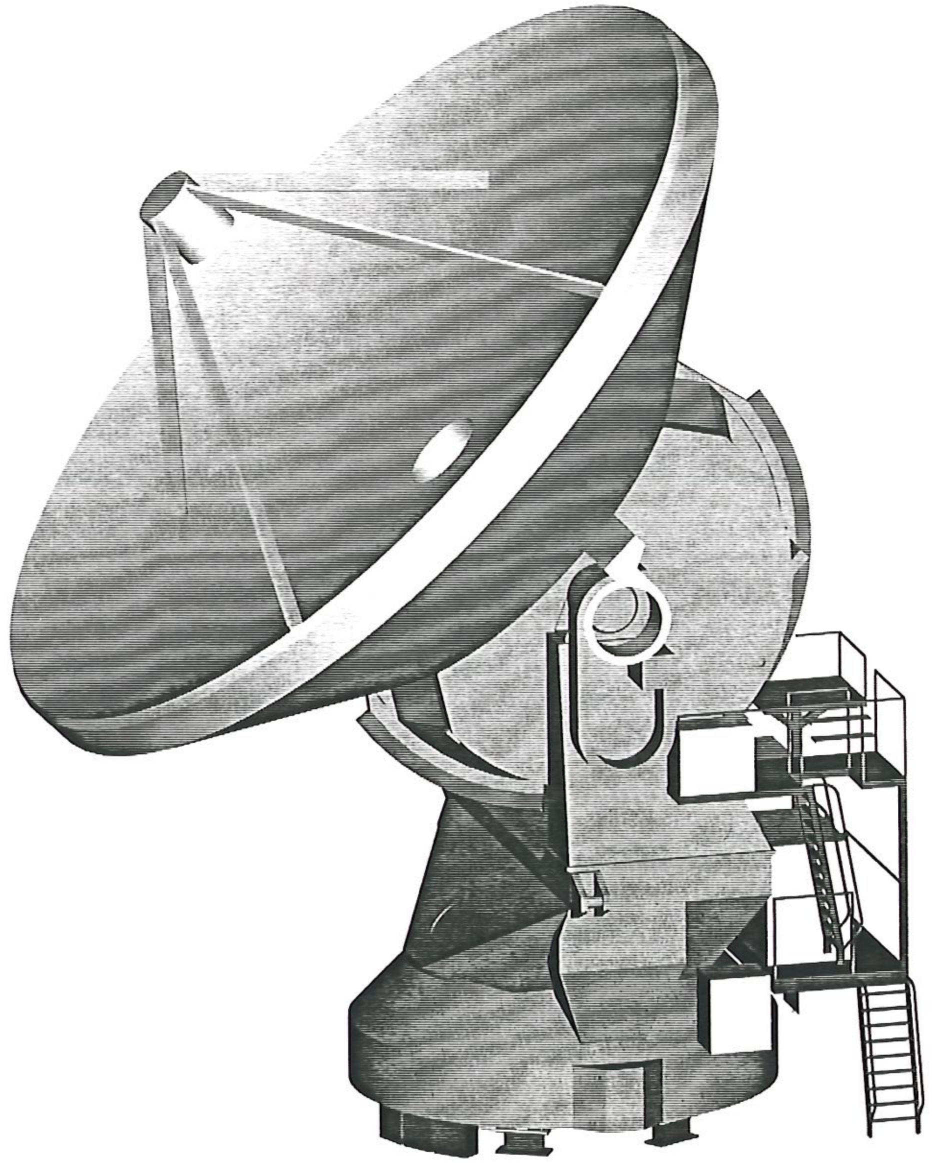


Figure 3-2. The European prototype antenna (3-D view courtesy of the European Industrial Engineering/Costamasnaga Consortium)

The antennas will be moved to different "stations" depending on the chosen configuration of the array. To this end, they will be disconnected from their concrete base, picked up by a transporter and moved to the new location. The transporter will travel over unpaved terrain. The baseline configurations of ALMA are summarized in Table 3-3.

Table 3-3. Specifications for ALMA Configurations.

Min. Baseline	Max. Baseline	Array type	Resolution at 1 mm
15 m	150 m	Filled	1.0 arcsec
18 m	500 m	Ring or Log Spiral	0.3 arcsec
25 m	1500 m	Ring or Log Spiral	0.1 arcsec
30 m	3000 m	Ring or Log Spiral	0.05 arcsec
100 m	12000 m	Ring	0.01 arcsec

3.3 Front-end Electronics

The front-end electronics are located in the receiver cabin at the antenna. ALMA will observe over the frequency region from 30 to 950 GHz. For technical reasons it has been split into 10 bands that are shown in Table 3-4. There will be two receivers for each band, observing the full polarization state of the received radiation. ALMA will observe in only one band at any given time. In the baseline construction project, only the four bands of highest scientific priority (3, 6, 7, and 9) will be implemented.

Table 3-4. Frequency Coverage of ALMA

Band No.	Frequency range (GHz)	Receiver type
1	31 – 45	HEMT amplifier
2	67 - 90	HEMT amplifier
3	89 – 116	SIS mixer
4	125 – 163	SIS mixer
5	163 – 211	SIS mixer
6	211 – 275	SIS mixer
7	275 – 370	SIS mixer
8	385 – 500	SIS mixer
9	602 – 720	SIS mixer
10	787 - 950	SIS mixer

At the extremely high frequencies of ALMA, current technology provides direct amplification of the received radiation only in the lowest two bands, where a few radio astronomy groups have developed state of the art HEMT amplifiers. The remainder of the front-ends will use SIS (superconductor-insulator-superconductor) diodes to mix the received signal to an intermediate frequency (IF) in the range 4-12 GHz, where it can be readily amplified. The state-of-art in SIS mixers is mainly the work of a few specialized laboratories and radio observatories. Sensitive receivers have been built over the entire ALMA frequency range. However, it should be noted that this is cutting-edge development, mastered only by few laboratories. Fortunately, most of these are directly involved in ALMA. A great challenge for ALMA is to obtain a control of the processes needed to reach good performance that will also be reliable and suitable for series fabrication.

The individual frequency bands will be made in the form of cartridges that will be inserted in a large common cryostat. The complete front-end unit will have a diameter of 1 m, be about 1-m high and have a mass of about 500 kg. The cryostat will be cooled to 4 K by a closed-cycle cryocooler with compressor. The cartridge concept allows for a great flexibility in operation of the array. It will be possible to exchange cartridges during full operation of the array. Another advantage of the cartridge layout with well-defined interfaces is the fact that different cartridges can be developed and built by different groups among the ALMA participants without the risk of incompatibility between them. A preliminary consensus on the division of cartridge development between the groups has been reached.

Because observations at (sub)millimeter wavelengths are extremely sensitive to the amount of water vapor in the earth's atmosphere, every antenna will be equipped with a water vapor radiometer (WVR), which is essentially a separate receiver tuned to the frequency of the water vapor absorption line at 183 GHz. The WVR will be an uncooled receiver and will take atmospheric data continuously, while the astronomical observations at other frequencies are underway. The WVR will enable these observations to be corrected for the influence of water vapor in the lines of sight between each antenna and the observed source.

3.4 Back-end Electronics

The SIS-mixers must be provided with a local oscillator (LO) signal to convert the received frequencies to the IF-band. Because the principle of interferometry is critically dependent on measuring the phase between the received signals, this LO signal must be derived from a central master oscillator and be kept phase stable up to the injection point in the mixer. The LO subsystem is one of the most critical elements of the electronic system. The signals will be transported, as are all other digital and analog signals, by optical fibers.

After amplification in the IF-section, the signals are digitized and send on optical fiber, together with control and monitor data to the central correlator. Current digital technology does not allow the direct digitization of the ALMA IF-bandwidth of 8 GHz. Therefore, the received bandwidth is subdivided in 4 "base bands" of 2 GHz each before digitization. Allowing for the two polarizations in each receiver, 8 digitized signals will be sent from each antenna to the correlator. The correlator forms the heart of the array. Here all signals from the 64 antennas come together and are multiplied ("correlated"), each antenna with all others for a total of 2016 baselines representing the correlated signal between all two-element interferometers of the array. These 2016 signals contain the so-called complex fringe visibility for all baselines (uv-plane coordinates) of the observed object. The brightness distribution of the observed object can be derived by Fourier transformation of this set of numbers.

As mentioned above, the actual hardware deals with 8 times 2016 signals, but this is not all. A great part of the astronomical programs in the mm-range concerns the observation of spectral lines from molecules. Thus it is required to analyze each of the correlated outputs in frequency space to obtain the spectral distribution of the received radiation. A typical number of frequency points over the spectrum is of the order of 1000. Because different astronomical objects require different spectral bandwidth and resolution, it will be possible to configure the correlator optimally for the observation. About a dozen configurations will be available, providing spectral resolutions from 5 m/s up to 40 km/s. The basic design of the correlator is essentially completed. Because of the rapid development in high-speed digital electronics, it has been decided to work in parallel on a possible design of a "future correlator". The decision whether such an advanced correlator will be realized will be taken before the actual hardware assembly of the second quarter of the baseline correlator will commence, probably in 2004.

3.5 Computing and Software

As with any large and complicated scientific instrument, ALMA will require a vast amount of computing power and software. This includes real-time software to monitor and control hardware devices, software to schedule the array, to format the data for post-processing, and to archive and store the data. The main characteristics of the system are summarized in Table 3-5.

Table 3-5. Major Characteristics of the Computing Subsystem

Sustained data rate, science data	6 MB/s (Average), 60 MB/s (Peak sustained)
Dynamic scheduling	Nearly automatic scheduling of the array, accounting for weather and other conditions, to optimize the scientific throughput of the array.
Image pipeline	First-look images produced automatically for standard observing.
Archiving	Networked archive of all ALMA science data and associated calibration data and derived data products.

The data flow software will encompass the total processing of an ALMA observation, from the preparation of a proposal by an observer, through to production and archiving of cleaned images/data cubes from the array. Support will thus be provided to the proposer/observer, the proposal reviewers and those responsible for granting ALMA observing time, the array operations staff, and the archival researcher. The real-time software to control and monitor all hardware is linked to the data flow software to enable a fully automated, remote control of the array and its observational processes.

3.6 Construction and System Integration

Site development and antenna fabrication will be done primarily under industrial contracts. On the other hand, the numerous subsystems of the electronics will be designed and constructed by a number of institutions participating in the ALMA project. These will be assembled to front-ends, the correlator, etc. in a few integration centers. The complete, tested subsystems, along with the antennas, will be delivered to the OSF in San Pedro for final assembly and installation into the array on Chajnantor. These activities will be under the responsibility of the systems integration team and will commence in 2004. Once a completely outfitted antenna or a significant part of central electronics or software has passed the functional tests performed by the system integration team, they will be transferred to the array operations for commissioning observations before being added to the astronomical operations of ALMA.

The principle of ALMA allows observations to commence with a limited number of elements of the array. There are several good reasons for an interim operation of a partial array. Through accurate astronomical measurements any fault or deficiency in the antennas, electronics, or software will be discovered early, enabling corrective measures to those parts not yet fabricated. It will also provide experience for determining the best mode of array operations and training for the ALMA operations staff. Finally, original and unique astronomical observations will be possible as soon as the order of 10 antennas are operational.

3.7 Array operation

The operating centers for the ALMA will be the instrument itself at the 5,000-m site on the Llano de Chajnantor, the Operations Support Facility (OSF) near San Pedro de Atacama at an altitude of 2,500 m and 50 km from the telescope, an administrative support facility in Santiago de Chile, and various technical laboratories of ALMA members in the United States and Europe. While a few management personnel should live in San Pedro de Atacama, we expect most of the Chilean support staff will commute from other Chilean communities on a rotating work period basis. To operate ALMA in Chile, a rotating shift system will be employed for staffing the operations center and the maintenance of ALMA itself. Despite the plans described in Volume 3, we consider it likely that the actual mode of operations will evolve over time as the ALMA staff gains experience operating in Chile.

ALMA will be operated as a remote, service observatory without the astronomers who proposed the observation needing to be present at the operations center, although they may choose to do so. In addition, service observing will give the local staff the freedom to execute observing programs to match the current array status and atmospheric conditions. The data flow software will provide the tools for this. It enables preparation of observing proposals and translation of the observing requirements into array-level configurations and observing scripts. A dynamic scheduler will be used to maximize the observing efficiency of ALMA in service mode. Observations will be scheduled based on assigned scientific priority, as well as appropriate match to the existing observing conditions. Observing parameters may be adjusted to take account of changes in these conditions. A near-real-time pipeline, capable of feeding back results to the observing process, and of producing images, which should be of final quality in the majority of cases, provides the real-time link to the observer. An archive to store raw data, images and data cubes, calibration data, observing programs (including proposals and observation parameters) will enable later analysis by the observer or other astronomers.

4. Management Summary

ALMA is a global endeavor of nations and scientific institutes worldwide. The challenge and cost of building and operating ALMA will be shared among the participants. This cooperation brings to the project a broad base of experienced people and resources. Properly used, this breadth of experience has the potential to reduce risk in many areas. The challenge is to manage these combined resources in a way that empowers the participants and effectively coordinates their efforts. The management plan for the ALMA construction project, described in the Management Volume and summarized here, is designed to meet this challenge.

4.1 The ALMA Agreement

The construction, commissioning, and operation of ALMA will be governed by an international Agreement between two Parties, the U.S. National Science Foundation (NSF) acting for the North American organizations involved, and the European Southern Observatory (ESO) acting for the European organizations involved. Drafts of this Agreement have been exchanged and negotiation of the final agreement is underway. The principal features of draft Agreement are:

- Guiding principles:
  - *Parity* – the Parties will make equal value contributions. To the maximum extent possible work will be equally and equitably shared between the Parties;
  - *Equity* – the Parties and the participating organizations and institutions will obtain intellectual and economic benefit from ALMA in proportion to the value of their contributions, and consistent with the timely and cost-effective execution of assigned tasks;
  - *Merit* – key personnel will be selected through international search, solely on the basis of merit and qualification;
  - *Utilization of Existing Institutions* – the Parties will only establish new institutions for ALMA if absolutely necessary. Personnel will be provided through secondment arrangements.
- An ALMA Board will be established as the supervisory and regulatory body. The Board is not a legal entity. It will have five members from each Party plus one member from Chile.
- The Board will establish standing Management and Scientific Advisory Committees.
- The Parties will each appoint an Executive empowered to act on behalf of the Party to arrange for carrying out the tasks required to construct and operate ALMA. Funding of the project will be provided through the Executives.
- The Executives will propose for Board approval a joint project organization for construction and commissioning, as well as a project organization for operations.
- The Executives will define key personnel and jointly select them by an open, worldwide search. The Board will approve appointments of key personnel.
- The Parties will contribute equally according to agreed valuations and payment schedules. The Executives will each administer, report on, and account for funds contributed by their respective Party.

- Subawards will be made by competitive tender to the maximum extent practicable. Board approval will be required for subawards over $1,000,000 (or Euro) and all subawards over $250,000 will be reported to the Board.
- Observing time will be allocated equally between the parties after an agreed allocation to Chile as host country. The Board will determine data rights.
- Provisions for Intellectual property rights, withdrawals, defaults, and disputes.
- The initial duration of the agreement will be to 2021, renewable at subsequent 5-year assessment points.

4.2 The ALMA Management Plan

Organization and Management Structure. The management structure proposed for ALMA is shown in Figure 4-1. In addition to providing control of performance, cost, and schedule; the appropriate management structure must satisfy the guiding principles of parity, equity, and utilization of existing institutions, as defined in the draft ALMA Agreement. Primary governance of the project comes through the ALMA Board with the assistance of its Scientific and Management Advisory Committees. The ALMA project will be implemented by the two Executives using their existing infrastructure and participating institutions - ESO on behalf of itself and participating European organizations, and Associated Universities Inc./National Radio Astronomy Observatory (AUI/NRAO) on behalf of the NSF and participating North American organizations.

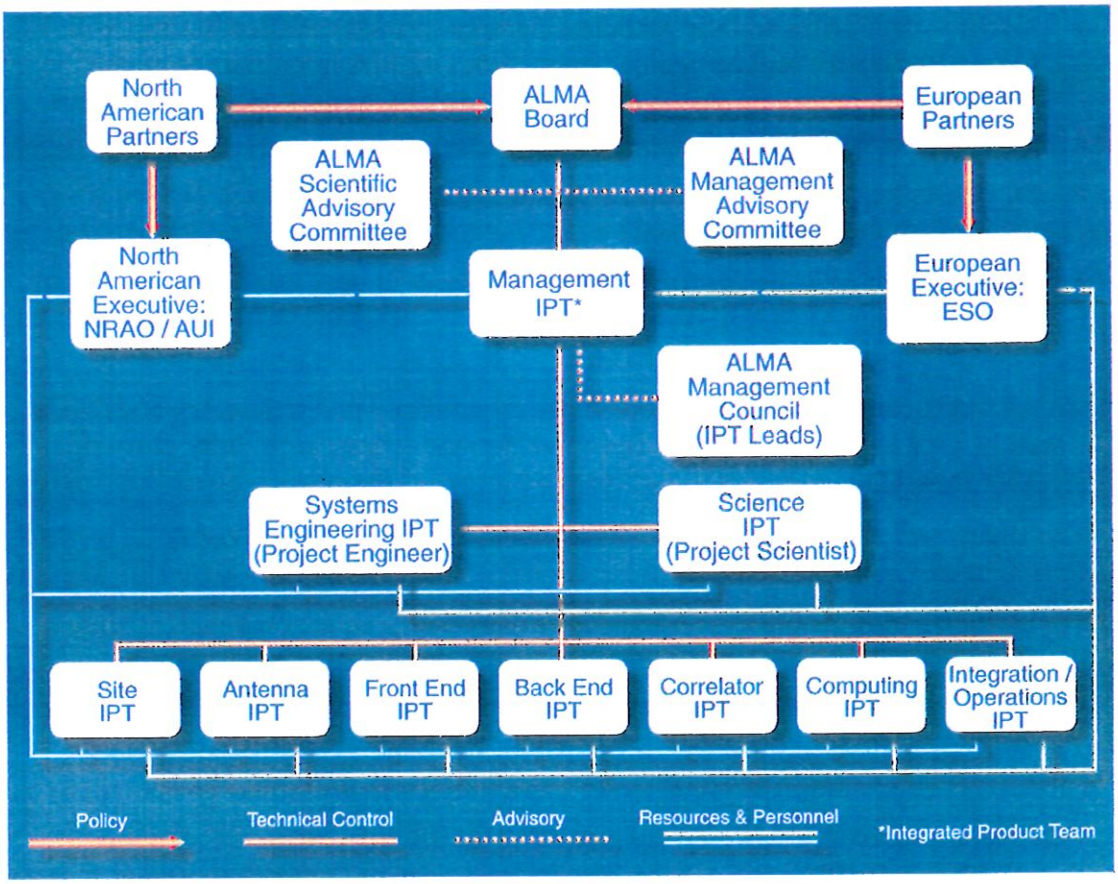


Figure 4-1. The ALMA construction project management structure based on Integrated Product Teams.

Given the guiding principles and given that the Executives will maintain responsibility for their respective task resources and budgets, it is not possible to organize ALMA in a single hierarchical management structure. The Integrated Product Team (IPT) concept, tailored to the requirements of a bilateral partnership of equals, will effectively meet the needs of the global ALMA project.

At the top level, a common Management IPT, consisting of the single, central project management plus the European and North American Project Managers from their respective Executives, coordinates the work of the project. Each of the IPTs reporting to the Management IPT consists of those individuals who have significant responsibilities for subtasks within a given level-1 WBS task (see below). Because the level-1 WBS tasks will generally be shared between the two Executives, the IPT members will come from both Executives. The IPT staff will generally not be co-located; each individual works within the infrastructure of his or her Executive. Each IPT is led by an IPT Leader and an IPT Deputy Leader, who have been assigned overall responsibility within their respective Executives for a given WBS level-1 task. The IPT Leader and Deputy Leader, along with the other IPT members will manage, coordinate, and monitor subtasks within their WBS element. In practice, this means that each of these individuals is responsible for completing the assigned subtasks within the existing infrastructure of, and using the resources provided by, their respective Executives. Accountability throughout the project is ultimately assured by the necessity for the common Management IPT and both Executives to report to the ALMA Board.

Work Breakdown Structure. The Work Breakdown Structure (WBS) for the ALMA project identifies the project tasks as well as the hierarchies and dependencies of the tasks. During Phase 1 the joint project management team has developed the WBS. The ALMA Phase 2 WBS is presented in abbreviated form at the end of this Executive Summary. The complete WBS and WBS dictionary defining each task can be found in the Management Volume of this proposal. The WBS for Phase 2 construction includes the following ten level-1 tasks:

1. Management
2. Site Development
3. Antenna Subsystem
4. Front-end Subsystem
5. Local Oscillator Subsystem
6. Back-end Subsystem
7. Correlator
8. Computing Subsystem
9. System Engineering and Integration
10. Science

Schedule. The detailed ALMA project schedule is given in the ALMA WBS. Because the schedule depends on the funding schedules of the two partners, it awaits a final iteration that includes commitments to funding schedules by the two partners. In the absence of those commitments, the ALMA baseline schedule drawn from the WBS, at the highest level, is the following.

2002	January	ALMA Construction Project Start
2002	August	Test Interferometer Operations Start
2003	January	Site Civil Works Begin in Chile
2003	April	Prototype Antenna Decision

2003	April	Release Electronics Systems for Production
2003	August	Contract for Production Antennas
2004	October	First Production Antenna Arrives in Chile
2006	January	Interim Operations Start
2010	July	Construction Complete
2010	September	Commissioning; Full Science Operations

Division of Phase 2 Tasks between Europe and North America. A division of responsibilities for Phase 2 tasks between Europe and North America has been worked out and proposed to the ACC by the joint Phase 1 project management. The ACC has endorsed this division of responsibilities as a basis for the corresponding Annex of the ALMA Agreement. The detailed task-by-task division of responsibilities is presented in the summary Phase 2 WBS at the end of this Executive Summary. From an European perspective, the division can be summarized at level-1 of the WBS as:

- Management – overall value $24 million with Europe responsible for tasks totaling 50% of the overall value: 50% of the Joint Project Office as well as 100% of the European Project Office.
- Site Development – overall value $85 million with Europe responsible for tasks totaling 62% of the overall value: 100% of site development engineering and management as well as funding 60% of the site development contracts.
- Antennas – overall value $211 million with Europe responsible for tasks totaling 51% of the overall value: 50% of antenna subsystem engineering and management and funding of 50% the antenna production contract(s). Europe has 100% responsibility for antenna transporters.
- Front-end Electronics – overall value $89 million with Europe responsible for tasks totaling 70% of the overall value: 50% of front-end subsystem engineering and management and 100% responsibility for the front-end cryostats, the warm optics, the water vapor radiometers, plus the two of the four frequency bands.
- Back-end Electronics (combining the Local Oscillator, Backend, and Correlator WBS elements) – overall value $84 million with Europe responsible for tasks totaling 14% of the overall value: 100% of the high-speed sampler/digitizers and 50% of the fiber optics transmitters and receivers.
- Software and Computing – overall value $32 million with Europe responsible for tasks totaling 50% of the overall value: 50% of the computing subsystem engineering and management and 50% of the software development tasks.
- System Engineering and Integration – overall value $20 million with Europe responsible for 50% of system engineering and management plus 50% of system integration.
- Science – overall value $7 million with Europe responsible for 50% of the scientific effort supporting construction.

Plan for the Division of Phase 2 Tasks within Europe. During 2000 the European project held three meetings of the heads of European institutions participating in Phase 1 of ALMA. The first two meetings were devoted to determining the degree of interest and capability of the institutions in performing tasks during Phase 2. This formed the basis for the European position in the negotiation of the division of responsibilities between Europe and North America. The following European institutions (in alphabetical order) are participating in Phase 1 of ALMA and have expressed an intent to participate in Phase 2.

- Astronomical Institute of the Ruhr-University, Bochum (Germany)
- Centre d'Etude Spatiale des Rayonnement (France)
- Delft Institute of Microelectronics and Sub-micron Technology (Netherlands)
- European Southern Observatory
- Institut d'Astronomie de l'ETH Zurich (Switzerland)
- Institut de Radioastronomie Millimetrique (France, Germany, Spain)
- IRA and CAISMI – CNR (Italy)
- IXL Universite de Bordeaux (France)
- Jodrell Bank Observatory (UK)
- Lund Observatory (Sweden)
- Max Planck Institute for Radio Astronomy (Germany)
- Microwave Engineering Center for Space Applications (Italy)
- Mullard Radio Astronomy Observatory (UK)
- Netherlands Foundation for Research in Astronomy (Netherlands)
- Netherlands Research School for Astronomy (Netherlands)
- Observatoire de Bordeaux (France)
- Observatoire de Paris, DEMIRM (France)
- Observatorio Astronomico Nacional (Spain)
- Onsala Space Observatory (Sweden)
- Osservatorio Astrofisico de Arcetri (Italy)
- Rutherford Appleton Laboratory (UK)
- Space Research Organization Netherlands (Netherlands)
- UK Astronomy Technology Centre (UK)

The third meeting of the heads of institutions started the process of determining responsibilities for the European Phase 2 tasks within Europe, i.e., determining for which specific tasks the institutions listed above will be responsible. The agreed steps to determine the distribution of tasks within Europe are:

- Institutions to submit written statements reconfirming the tasks of interest by the end of November 2000.
- In early January 2001 the project to formally solicit letters of intent/proposals from interested institutions to be submitted in early February 2001.
- Project to propose distribution of responsibilities within Europe to the European Co-ordination Committee for approval at their April 2001 meeting.

4.3 Relations with Chile

The necessary permissions to construct and operate ALMA in Chile have not yet been obtained. The prospective ALMA site is located in the Cerro Chascon Sector in the County of San Pedro de Atacama, Region II of Antofagasta. This area was declared 'a place of scientific interest' by a Chilean Executive Decree in June 1998, in specific recognition of radio astronomy projects. Subsequently, in July 1998 the Chilean Ministry of National Assets granted a five-year concession of this scientific reserve to the Chilean National Commission of Scientific Investigations and Technology (CONICYT) in order to implement scientific projects in astronomy. In July 1999 and January 2000, respectively, AUI/NRAO and ESO each signed agreements with CONICYT granting access to perform development planning and characterization studies at the site. These agreements govern until the date when a framework is agreed by the parties to regulate their relations permanently.

The ACC has established a team (three members each from Europe and North America) to enter into negotiations with Chile. The team is charged to develop a strategy for communicating with Chile and to negotiate with the appropriate sectors of the Chilean government and astronomical community in order to secure the appropriate and necessary permissions for construction and operation of ALMA over the projected lifetime of the instrument. In carrying out this task the team will place primary emphasis on the option whereby ESO will legally represent the interests of the ALMA project in Chile on behalf of the ALMA partnership. In this case the ALMA project in Chile is envisaged to be established on the basis of the existing Convention between ESO and Chile.

On the Chilean side, the government has formed a local coordinating committee made up of all interested governmental agencies plus representatives of the astronomical community. The first formal meeting between the ALMA negotiating team and the Chilean local coordinating committee is to take place in early 2001.

5. Cost Summary

A clear understanding of the cost basis for the Joint ALMA construction project is needed before firm commitment to proceed with Phase 2 of ALMA can be made. By early 2000, the joint Phase 1 design and development effort was sufficiently advanced that it could be used to estimate the baseline cost for the construction phase of the project. The compilation of a detailed construction cost estimate was completed and presented to the ALMA Co-ordination Committee (ACC) in April 2000.

As described in the Cost Volume of this proposal, the cost estimating process proceeded in three steps. First, the scientific requirements agreed by the joint ALMA Scientific Advisory Committee were used to define technical requirements for the array. Second, those technical requirements were made specific through a thorough system design and specification of the entire scope of hardware and software modules and subsystems. Third, a plan for design, fabrication, and integration of all of the hardware and software modules and subsystems was established.

This plan is embodied in the project work breakdown structure (WBS) described in the Management Volume of this proposal and presented in summary form at the end of this volume. A cost data sheet generated for each element of the WBS specifies the resources, both personnel and financial, needed to complete the WBS task, including a contingency based on an assessment of the technical maturity and risk. All labor and indirect (benefits, overhead, etc.) costs are included in the estimates. The total construction cost is then the task-by-task sum of the WBS costs.

The estimated construction cost of the 64-antenna ALMA built at the Chajnantor site in the Chile was 466.5 million (in year 2000 US$) plus $86.0 million of contingency, for a total estimated construction cost of $552.5 million. The exchange rate assumed in the cost estimate was 1 US$ = 2 DM = 1.0225 €. The construction was assumed to begin in 2002 and have a duration of nine years.

Between April and October 2000 the joint project management reviewed and refined the ALMA construction costs as presented to the ACC in April. The revised cost estimates for some tasks reflect design decisions or greater design maturity. For other tasks, mistakes have been corrected. On balance, the increased costs for areas requiring additional funds were offset by cost savings realized in other areas. The revised estimated construction cost is $467.7 million plus $84.7 million of contingency. The total estimated construction cost is unchanged at $552.5 million.

As described in Section 4.4, in parallel with reviewing the estimated cost, the joint project management has negotiated a division of responsibilities for the Phase 2 WBS tasks between the European and North American sides of the project. The basic concept for ALMA is that each task will be assigned a value and the party responsible for a given set of tasks will receive benefits (e.g., observing time) proportional to the value of the tasks completed. The value of each task was agreed to be the estimated cost including contingency. The amount of contingency indicates the level of risk associated with the task. The goal of the negotiation was to arrive at a division of tasks that balanced the value and risk between the two sides while respecting the interests and capability of each side to perform particular tasks. This goal was achieved and the resultant division of responsibilities for the complete WBS is described in the Management Volume. Table 5-1 summarizes the estimated cost (value) for each of the ten level-1 WBS elements of ALMA construction and the division of value and contingency between Europe and North America. The value and risk is divided equally between the two sides.

Table 5-1. ALMA Task Values and Partner Allocations (Year 2000 US k$)

WBS Level 1	Task Cost	Contin-gency	% Cont.	Subtotal	NAmer. Cost	NAmer. Cont.	Euro. Cost	Euro. Cont.
1. Management	22,734	1,137	5%	23,871	11,592	580	11,142	557
2. Site Development	72,203	12,834	18%	85,037	27,322	4,902	44,969	7,932
3. Antenna	183,088	27,915	15%	211,003	90,089	13,507	93,000	14,408
4. Front-end	70,540	17,916	25%	88,456	21,032	5,516	49,508	12,399
5. Local Oscillator	26,866	6,436	24%	33,303	26,866	6,436	0	0
6. Backend	27,179	7,218	27%	34,397	17,717	4,130	9,461	3,088
7. Correlator	13,424	3,442	26%	16,866	13,424	3,442	0	0
8. Computing	27,394	4,920	18%	32,314	13,697	2,460	13,697	2,460
9. System Engr. & Integration	17,679	2,585	15%	20,263	8,839	1,292	8,839	1,292
10. Science	6,629	331	5%	6,960	3,314	166	3,314	166
Totals	**467,735**	**84,734**	**18%**	**552,469**	**233,804**	**42,431**	**233,932**	**42,303**

Converting to €, the estimated cost of the European share is 239.195 k€, plus 43.254 k€ of contingency, for a total value of € 282,5 million. Within Europe, ninety percent of the funding is assumed to come from ESO with the United Kingdom as a member state. The remaining ten- percent is assumed to come from Spain or other non-ESO member states. As described in the Management Volume, it is proposed that ESO be the executive organization for the European side of the project and as such administer and manage all of the European funds. The total European contingency would be held and managed by the ALMA European Project Office at ESO.

The schedule of expenditures has been projected for each element of the WBS. A schedule for expenditure of contingency has also been assumed. Together these add to a schedule of required annual contributions as shown in Table 5-2. The 90% ESO share and remaining 10% share of the total European contribution are also shown.

Table 5-2. European Contribution Schedule (Year 2000 k €)

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Expenditure	7.764	13.961	19.671	30.662	31.179	34.485	32.099	31.795	26.395	11.184
Contingency	0	0.181	0.491	2.671	3.140	7.354	7.354	7.354	7.354	7.354
Contribution	7.764	14.143	20.163	33.333	34.319	41.839	39.453	39.149	33.750	18.537
90% Share	6.987	12.728	18.146	30.000	30.887	37.655	35.508	35.235	30.375	16.684
10% Share	0.776	1.414	2.016	3.333	3.432	4.184	3.945	3.915	3.375	1.854

Work Breakdown Structure. The following pages contain the WBS for ALMA Phase 2 construction. In addition to the task titles, this summary version of the WBS shows for each task: the value (estimated cost plus contingency), the division of responsibility between Europe and North America, and the start and finish dates.

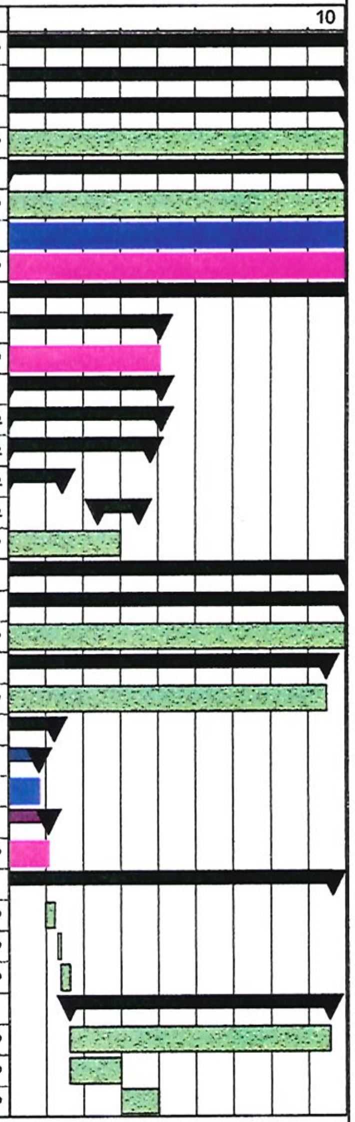
Atacama
Large
Millimeter
Array

ALMA Cost Summary

Phase 2 Tasks with Cost Data Sheets selected

(Costs in Thousands of Year 2000 US Dollars)

ACDS#	WBS (f)	Task	Start	Finish	Task Total	Cont.	Cost	US %	Eur %
		ALMA Joint Work Plan	1998-06-01	2011-07-29	$467,735	$84,734	$552,469	50%	50%
	1	**Management/Administration**	1998-06-01	2010-12-31			$23,871		
	1.20	Agreements in Chile	1998-06-01	2010-12-31			$2,310		
3	1.20.25	Chilean Institutional Relations	2002-01-02	2010-12-31	$2,200	$110	$2,310	50%	50%
	1.30	Phase 2 Management	2002-01-01	2010-12-30			$21,561		
4	1.30.05	International Project Office	2002-01-01	2010-12-30	$7,257	$363	$7,620	50%	50%
5	1.30.10	U.S. Project Office	2002-01-01	2010-12-30	$6,863	$343	$7,206	100%	
6	1.30.15	European Project Office	2002-01-01	2010-12-30	$6,414	$321	$6,734		100%
	2	**Site Development**	1998-06-01	2011-07-29			$85,037		
	2.05	Site Development Management	1998-06-01	2006-01-19			$2,236		
7A	2.05.05	Site Development Management Phase 2	2002-01-01	2006-01-19	$2,033	$203	$2,236		100%
	2.18	Construct Chilean Facilities	2002-01-01	2006-02-01			$82,801		
7D	2.18.05	Array Site	2002-01-01	2006-02-01	$46,525	$8,375	$54,900	39%	61%
7E	2.18.10	Operations Support Facility (OSF)	2002-01-01	2005-10-21	$16,700	$3,006	$19,706	39%	61%
7F	2.18.15	Array/OSF Access Roads	2002-01-01	2003-06-16	$3,795	$683	$4,478	39%	61%
7G	2.18.18	Array/OSF Communication Links	2004-05-28	2005-06-30	$2,225	$401	$2,626	39%	61%
7H	2.18.20	Chilean Phase 2 Facilities	2002-01-01	2004-12-31	$925	$167	$1,092	39%	61%
	3	**Antenna Subsystem**	1998-06-01	2010-12-31			$211,003		
	3.05	Antenna Management/Subsystem Engineering	1998-06-01	2010-12-31			$5,136		
8	3.05.05	Antenna Management Phase 2	2002-01-02	2010-12-31	$3,475	$174	$3,648	50%	50%
	3.05.10	Antenna Subsystem Engineering	1998-06-01	2010-07-01			$1,488		
9	3.05.10.10	Production Antenna Engineering Support	2002-01-01	2010-07-01	$1,353	$135	$1,488	50%	50%
	3.10	Prototype Antennas	1998-09-22	2003-04-01			$2,159		
	3.10.05	U.S. Prototype Antenna	1998-09-22	2002-10-30			$1,079		
10	3.10.05.45	US Post Acceptance Evaluation	2001-11-01	2002-10-30	$850	$230	$1,079	100%	
	3.10.10	European Antenna Prototype Procurement	1999-03-31	2003-01-30			$1,079		
11	3.10.10.40	Euro Post Acceptance Evaluation	2002-02-01	2003-01-30	$850	$230	$1,079		100%
	3.15	Production Antennas	2001-06-01	2010-08-31			$199,070		
12	3.15.05	Final Design Modification and Documentation	2003-01-01	2003-04-01	$119	$16	$135	50%	50%
13	3.15.15	Prepare Antenna Bid Package	2003-05-01	2003-05-28	$83	$11	$93	50%	50%
14	3.15.20	Production Antenna Tendering	2003-05-29	2003-08-20	$73	$8	$81	50%	50%
	3.15.30	Production Antenna Contract	2003-08-21	2010-08-01			$195,741		
15A	3.15.30.05	Prod. Ant. Contract Supervision	2003-08-21	2010-08-01	$3,010	$452	$3,461	50%	50%
15B	3.15.30.10	Prod. Ant. Contract Year 1	2003-08-21	2004-12-29	$11,650	$1,748	$13,398	50%	50%
15C	3.15.30.15	Prod. Ant. Contract Year 2	2005-01-01	2005-12-29	$15,300	$2,295	$17,595	50%	50%



Summary Tasks: **underline**

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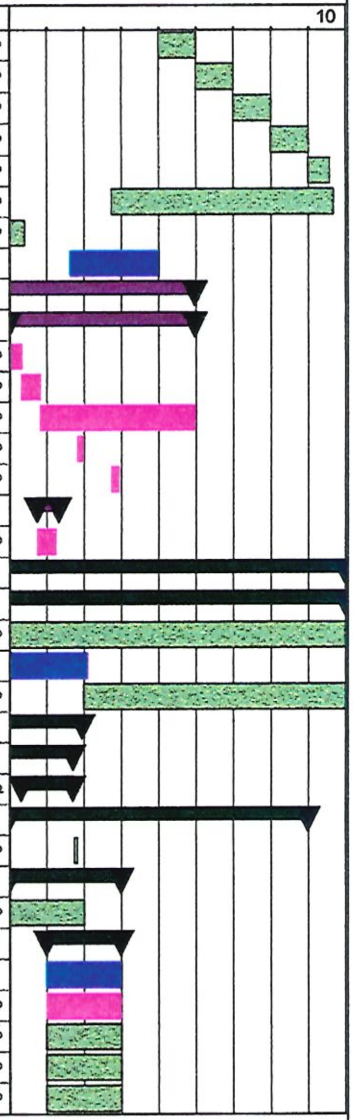
ALMA Cost Summary

Phase 2 Tasks with Cost Data Sheets selected
(Costs in Thousands of Year 2000 US Dollars)

ACDS#	WBS (f)	Task	Start	Finish	Task Total	Cont.	Cost	US %	Eur %
15D	3.15.30.20	Prod. Ant. Contract Year 3	2006-01-01	2006-12-28	$30,600	$4,590	$35,190	50%	50%
15E	3.15.30.25	Prod. Ant. Contract Year 4	2007-01-01	2007-12-28	$30,600	$4,590	$35,190	50%	50%
15F	3.15.30.30	Prod. Ant. Contract Year 5	2008-01-01	2008-12-29	$30,600	$4,590	$35,190	50%	50%
15G	3.15.30.35	Prod. Ant. Contract Year 6	2009-01-01	2009-12-30	$30,600	$4,590	$35,190	50%	50%
15H	3.15.30.40	Prod. Ant. Contract Year 7	2010-01-01	2010-07-29	$17,850	$2,678	$20,528	50%	50%
16	3.15.35	Production Antenna Acceptance at OSF	2004-10-01	2010-08-31	$1,317	$184	$1,501	50%	50%
17	3.15.40	Antenna Test Equipment/Facilities	2001-06-01	2002-05-30	$559	$134	$693	50%	50%
18	3.15.45	Production Antenna Nutator	2003-08-21	2005-12-27	$645	$181	$826	100%	
	3.20	Antenna Transporters	1999-10-01	2006-12-21			$4,519		
	3.20.20	Antenna Transporters	2002-01-01	2006-12-21			$4,519		
19	3.20.20.05	Prepare Transporters Bid Package	2002-01-01	2002-04-29	$94	$19	$113		100%
20	3.20.20.10	Transporters Tendering	2002-04-30	2002-10-28	$29	$7	$36		100%
21	3.20.20.20	Supervise Transporters Contract	2002-10-29	2006-12-21	$3,173	$1,015	$4,188		100%
22	3.20.20.22	Transporter 1 Evaluation at VLA Site	2003-10-28	2003-12-15	$80	$16	$96		100%
23	3.20.20.25	Transporters Acceptance at OSF	2004-09-28	2004-11-29	$72	$14	$86		100%
	3.25	Antenna Foundations	2002-10-02	2003-05-01			$120		
24	3.25.05	Final foundation design	2002-10-02	2003-04-01	$109	$11	$120		100%
	4	**Front End Subsystem**	1998-06-01	2010-12-31			$88,456		
	4.05	Front End Management/Subsystem Engineering	1998-06-01	2010-12-31			$3,828		
25	4.05.05	Front End Subsystem Management Phase 2	2002-01-01	2010-12-31	$2,823	$141	$2,964	50%	50%
26	4.05.15	Evaluation Front End Engineering Support Phase 2	2002-01-01	2004-02-02	$145	$15	$160	100%	
27	4.05.20	Production Front End Engineering Support	2004-01-01	2010-12-31	$640	$64	$704	50%	50%
29	4.10	SIS Mixer Development	1998-06-01	2003-12-17	$75	$39	$113	100%	
	4.25	Prototype Front Ends	2001-02-16	2003-09-17			$4,801		
33A	4.25.40	Front End Qualification Model	2002-05-01	2003-09-17	$3,201	$1,600	$4,801	40%	60%
	4.30	Production Front Ends	2002-01-01	2009-12-29			$79,714		
69	4.30.20	Documentation	2003-10-01	2003-10-28	$115	$18	$133	50%	50%
	4.30.27	Production Front End Mixer fab & test equipment	2002-01-01	2004-12-28			$6,462		
70	4.30.27.05	Build SIS mixer fabrication equipment	2002-01-01	2003-12-29	$1,397	$196	$1,592	50%	50%
	4.30.27.10	SIS test dewars	2003-01-01	2004-12-28			$1,031		
71	4.30.27.10.05	Build SIS Mixer Test Dewar & Rack #1	2003-01-01	2004-12-28	$452	$63	$515	100%	
72	4.30.27.10.10	Build SIS Mixer Test Dewar & Rack #2	2003-01-01	2004-12-28	$452	$63	$515		100%
75	4.30.27.15	Build Wafer Evaluation Test Sets	2003-01-01	2004-12-28	$268	$48	$317	50%	50%
76A	4.30.27.20	General SIS mixer test equipment	2003-01-01	2004-12-28	$126	$6	$132	50%	50%
77A	4.30.27.25	SIS Fab Test and Measurement Equipment	2003-01-01	2004-12-28	$1,205	$181	$1,386	50%	50%



Summary Tasks: **underline**

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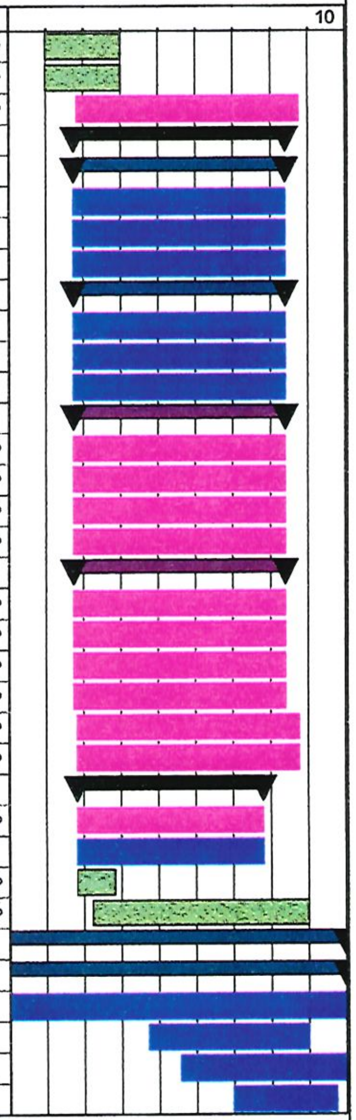
ALMA Cost Summary

Phase 2 Tasks with Cost Data Sheets selected

(Costs in Thousands of Year 2000 US Dollars)

ACDS#	WBS (f)	Task	Start	Finish	Task Total	Cont.	Cost	US %	Eur %
78A	4.30.27.30	Near-field feed measurement equipment	2003-01-01	2004-12-28	$455	$68	$524	50%	50%
79	4.30.27.35	Signal and LO sources	2003-01-01	2004-12-28	$1,299	$182	$1,481	50%	50%
80	4.30.35	Production Front End Cryostat & Front End Chassis	2003-11-03	2009-10-07	$14,872	$2,974	$17,846		100%
	4.30.40	Production Front End Cartridges	2003-10-01	2009-05-29			$33,947		
	4.30.40.05	Band 3 (89-116 GHz) Production Front End Cartri	2003-10-01	2009-05-29			$7,426		
81	4.30.40.05.05	Band 3 Internal optics, feed, & polarizer	2003-10-01	2009-05-29	$1,105	$221	$1,326	100%	
82	4.30.40.05.10	Band 3 SIS mixer & internal IF amplifier	2003-10-01	2009-05-29	$1,905	$991	$2,896	100%	
84	4.30.40.05.20	Band 3 Other components	2003-10-01	2009-05-29	$2,670	$534	$3,204	100%	
	4.30.40.10	Band 6 (211-275 GHz) Production Front End Cart	2003-10-01	2009-05-29			$7,426		
85	4.30.40.10.05	Band 6 Internal optics, feed, & polarizer	2003-10-01	2009-05-29	$1,105	$221	$1,326	100%	
86	4.30.40.10.10	Band 6 SIS mixer & internal IF amplifier	2003-10-01	2009-05-29	$1,905	$991	$2,896	100%	
88	4.30.40.10.20	Band 6 Other components	2003-10-01	2009-05-29	$2,670	$534	$3,204	100%	
	4.30.40.15	Band 9 (602-720 GHz) Production Front End Cart	2003-10-01	2009-05-29			$10,057		
89	4.30.40.15.05	Band 9 Internal optics, feed, & polarizer	2003-10-01	2009-05-29	$1,852	$519	$2,371		100%
90	4.30.40.15.10	Band 9 SIS mixer & internal IF amplifier	2003-10-01	2009-05-29	$1,905	$991	$2,896		100%
91	4.30.40.15.15	Band 9 LO injection	2003-10-01	2009-05-29	$440	$123	$564		100%
92	4.30.40.15.20	Band 9 Other components	2003-10-01	2009-05-29	$3,302	$925	$4,226		100%
	4.30.40.20	Band 7 (275-370 GHz) Production Front End Cart	2003-10-01	2009-05-29			$9,038		
93	4.30.40.20.05	Band 7 Internal optics, feed, & polarizer	2003-10-01	2009-05-29	$1,433	$401	$1,835		100%
94	4.30.40.20.10	Band 7 SIS mixer & internal IF amplifier	2003-10-01	2009-05-29	$1,905	$991	$2,896		100%
95	4.30.40.20.15	Band 7 LO injection	2003-10-01	2009-05-29	$440	$88	$529		100%
96	4.30.40.20.20	Band 7 Other components	2003-10-01	2009-05-29	$2,952	$827	$3,779		100%
121	4.30.45	Production Front End Warm Optics	2003-11-03	2009-10-07	$2,379	$666	$3,045		100%
122	4.30.50	Production Front End Electronics	2003-11-03	2009-10-07	$3,997	$1,119	$5,116		100%
	4.30.55	Production Calibration Equipment	2003-11-03	2008-10-22			$7,099		
123	4.30.55.05	183 GHz water vapor monitor system	2003-11-03	2008-10-22	$5,053	$707	$5,761		100%
124	4.30.55.15	Front End Test & Calibration System	2003-11-03	2008-10-22	$1,116	$223	$1,339	100%	
125	4.30.60	Front End Test Equipment/Facilities	2003-11-03	2004-10-29	$1,508	$241	$1,749	50%	50%
126	4.30.65	Production Front End Ass'y, Integration & Test	2004-04-01	2009-12-29	$3,373	$944	$4,317	50%	50%
	5	**Local Oscillator Subsystem**	1998-06-01	2010-12-31			$33,303		
	5.05	LO Management/Subsystem Engineering	1998-06-01	2010-12-31			$4,484		
127	5.05.05	LO Management/Subsystem Engineering Phase 2	2002-01-01	2010-12-31	$1,542	$77	$1,619	100%	
128	5.05.20	LO Ref Engineering Support	2005-09-22	2009-12-31	$366	$37	$403	100%	
129	5.05.25	Photonic Dist Engineering Support	2006-08-01	2010-12-27	$366	$37	$403	100%	
130	5.05.30	Millimeter LO Drivers Engineering Support	2007-12-28	2010-09-29	$542	$54	$596	100%	



Summary Tasks: **underline**

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ALMA Cost Summary

Phase 2 Tasks with Cost Data Sheets selected

(Costs in Thousands of Year 2000 US Dollars)

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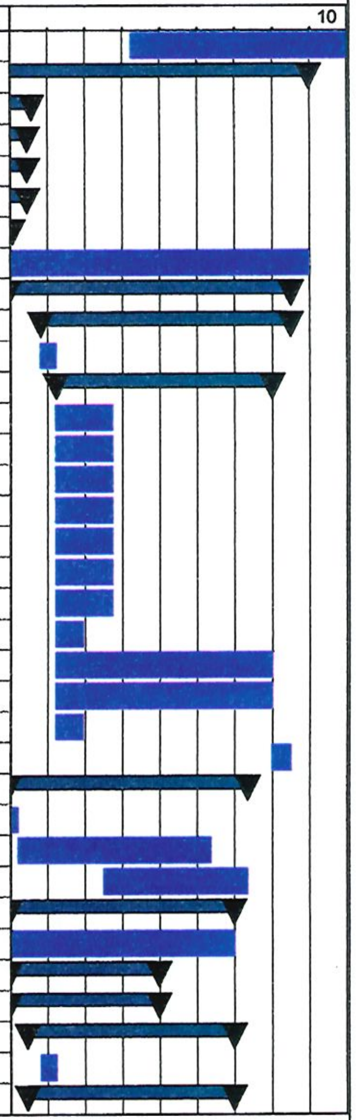
ACDS#	WBS (f)	Task	Start	Finish	Task Total	Cont.	Cost	US %	Eur %
131	5.05.35	LO Multiplier Chains Engineering Support	2005-04-05	2010-12-31	$1,330	$133	$1,463	100%	
	5.10	Prototype LO	1998-06-01	2009-12-24			$3,956		
132	5.10.05	LO Reference Prototype	1999-03-01	2002-08-01	$713	$143	$856	100%	
	5.10.10	Multiplier Chain LO Prototype	1998-06-01	2002-06-21			$425		
	5.10.10.25	Multiplier Chain Production for Prototype Front En	2000-02-01	2002-06-21			$425		
133	5.10.10.25.15	Band 9 (602-720 GHz) Front End LO	2001-08-06	2002-06-21	$156	$56	$213	100%	
134	5.10.10.25.20	Band 7 (275-370 GHz) Front End LO	2001-04-02	2002-02-01	$156	$56	$213	100%	
136	5.10.20	Photonic Phase Cal System	2002-01-01	2009-12-24	$1,938	$737	$2,675	100%	
	5.15	Production LO	2001-12-17	2009-06-30			$24,863		
	5.15.05	LO Reference: Production System	2002-11-01	2009-06-30			$12,037		
137	5.15.05.05	LO Ref: Final Design & Documentation	2002-11-01	2003-03-27	$65	$13	$77	100%	
	5.15.05.15	LO Reference Production Modules	2003-03-28	2008-12-30			$11,533		
138	5.15.05.15.05	FO Transmitter, LO Ref - Low Freq	2003-03-28	2004-09-30	$63	$18	$80	100%	
139	5.15.05.15.10	FO Receiver, LO Reference	2003-03-28	2004-09-30	$1,690	$473	$2,163	100%	
140	5.15.05.15.15	Two-Laser generator, RF synthesizer	2003-03-28	2004-09-30	$352	$42	$395	100%	
141	5.15.05.15.20	Second LO synthesizer	2003-03-28	2004-09-30	$4,248	$1,019	$5,267	100%	
142	5.15.05.15.25	Fringe Generator	2003-03-28	2004-09-30	$348	$70	$417	100%	
143	5.15.05.15.30	Central LO Reference Generator	2003-03-28	2004-09-30	$101	$12	$113	100%	
144	5.15.05.15.35	Sampler Clock	2003-03-28	2004-09-30	$853	$171	$1,024	100%	
145	5.15.05.15.40	H-maser Frequency Standard	2003-03-28	2003-12-11	$386	$77	$464	100%	
146	5.15.05.15.45	Power Supply Modules	2003-03-28	2008-12-30	$519	$26	$545	100%	
147	5.15.05.15.50	LO Ref Production supervision & int.	2003-03-28	2008-12-30	$674	$94	$769	100%	
148	5.15.05.15.55	LO Ref Production test & lab equipment	2003-03-28	2003-12-11	$270	$27	$297	100%	
149	5.15.05.20	LO Reference On Site Integration and Test	2008-12-31	2009-06-30	$334	$93	$427	100%	
	5.15.10	Photonic LO Distribution Production System	2001-12-17	2008-05-07			$3,239		
150	5.15.10.05	Photonic Dist: Final Design & Documentation	2001-12-17	2002-03-15	$65	$18	$83	100%	
151	5.15.10.15	Fabricate Photonic Dist Production System	2002-03-18	2007-05-09	$1,856	$798	$2,654	100%	
152	5.15.10.20	Photonic Dist On Site Integration and Test	2004-07-05	2008-05-07	$392	$110	$502	100%	
	5.15.15	Millimeter LO Drivers	2002-01-01	2007-12-27			$4,559		
153	5.15.15.05	LO Source Design and System Integration	2002-01-01	2007-12-27	$75	$21	$95	100%	
154	5.15.15.15	72-95 GHz LO Source	2002-01-01	2005-12-23	$1,775	$426	$2,201	100%	
155	5.15.15.20	100-120 GHz LO Source	2002-01-01	2005-12-23	$1,825	$438	$2,263	100%	
	5.15.20	LO Multiplier Chains	2002-06-24	2007-12-27			$4,348		
158	5.15.20.05	LO Multiplier Chains: Final Design & Doc	2002-11-01	2003-03-27	$116	$44	$161	100%	
	5.15.20.15	Millimeter LO Multiplier Chains	2002-06-24	2007-12-27			$4,187		



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ALMA Cost Summary

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ACDS#	WBS (f)	Task	Start	Finish	Task Total	Cont.	Cost	US %	Eur %
159	5.15.20.15.05	Band 3 (89-116 GHz) Receiver LO	2002-06-24	2007-09-05	$183	$44	$227	100%	
160	5.15.20.15.10	Band 6 (211-275 GHz) Receiver LO	2002-10-15	2007-12-27	$698	$237	$936	100%	
161	5.15.20.15.15	Band 9 (602-720 GHz) Receiver LO	2002-10-15	2007-12-27	$1,156	$393	$1,549	100%	
162	5.15.20.15.20	Band 7 (275-370 GHz) Receiver LO	2002-10-15	2007-12-27	$1,102	$375	$1,476	100%	
169	5.15.25	LO Test Equipment/Facilities	2002-01-01	2006-12-28	$612	$67	$679	100%	
	6	**Backend Subsystem**	1998-06-01	2010-12-31			$34,397		
	6.05	Backend Management/Subsystem Engineering	1998-06-01	2010-12-31			$1,967		
170	6.05.05	Backend Mgmt/Subsystem Engineering Phase 2	2002-01-01	2010-12-31	$1,687	$84	$1,772	100%	
171	6.05.20	Backend Engineering Support	2006-01-01	2010-12-30	$186	$9	$196	100%	
	6.10	Prototype Backend Subsystem	1999-02-22	2002-12-27			$2,792		
172	6.10.25	Prototype System IF Down-converter	2001-12-26	2002-04-23	$468	$94	$561	100%	
173	6.10.27	Prototype System Digital IF Tx & Rx	2002-04-24	2002-04-24	$741	$148	$890	50%	50%
	6.10.45	Prototype Digitizer/Sampler	2000-07-17	2002-12-27			$1,342		
174	6.10.45.50	Backend Digitizer/Sampler Prototype	2001-12-31	2002-12-27	$1,048	$294	$1,342		100%
	6.15	Production Backend	2002-11-01	2008-12-31			$29,638		
175	6.15.05	Backend: Final Design & Documentation	2002-11-01	2003-03-27	$129	$36	$165	100%	
	6.15.15	Backend Production Modules	2003-03-28	2008-12-31			$29,046		
176	6.15.15.05	IF Down-Converter	2003-03-28	2008-12-31	$7,777	$1,555	$9,332	100%	
177	6.15.15.06	Power Supply Modules	2003-03-28	2008-12-31	$490	$25	$515	100%	
178	6.15.15.07	Production Test & Lab Equipment	2003-03-28	2008-12-31	$416	$50	$466	100%	
179	6.15.15.10	Digitizer/Sampler	2003-03-28	2004-06-29	$2,183	$611	$2,794		100%
180	6.15.15.15	Digital IF Transmitters and Receivers	2003-03-28	2004-09-30	$11,720	$4,219	$15,939	50%	50%
181	6.15.20	Backend On Site Integration and Test	2004-10-01	2008-12-31	$334	$93	$427	100%	
	7	**Correlator**	1998-06-01	2010-12-31			$16,866		
	7.05	Correlator Management/Subsystem Engineering	1998-06-01	2010-12-31			$1,724		
182	7.05.05	Correlator Mgmt/Subsystem Engineering Phase 2	2002-01-01	2010-12-31	$497	$25	$522	100%	
183	7.05.15	Baseline Correlator Continued Support	2007-11-30	2010-12-30	$1,093	$109	$1,202	100%	
	7.15	Baseline Correlator	1998-07-03	2007-11-29			$15,112		
184	7.15.40	Prototype Correlator Production	2000-01-21	2002-11-29	$735	$206	$941	100%	
	7.15.45	Site Correlator Production	2002-07-09	2007-11-29			$14,172		
185	7.15.45.05	First 1/4 correlator	2002-07-09	2004-02-16	$2,745	$769	$3,514	100%	
186	7.15.45.10	Second 1/4 correlator	2003-11-11	2005-05-20	$2,740	$767	$3,507	100%	
187	7.15.45.15	Third 1/4 correlator	2005-02-14	2006-08-24	$2,740	$767	$3,507	100%	
188	7.15.45.20	Fourth 1/4 correlator	2006-05-19	2007-11-29	$2,846	$797	$3,643	100%	
189	7.20	Correlator Test Equipment/Facilities	2002-01-01	2007-12-28	$27	$2	$30	100%	

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ALMA Cost Summary

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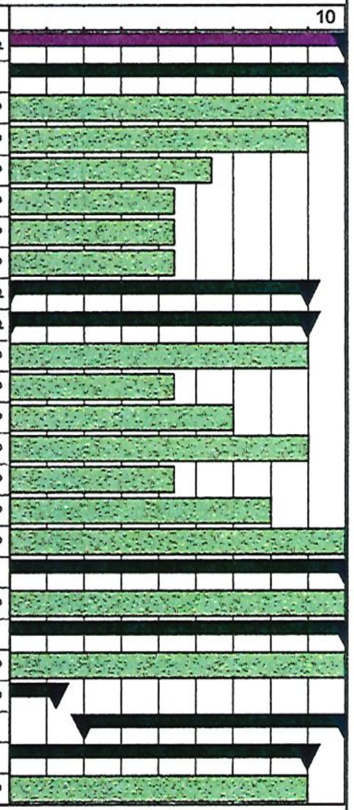
190	7.25	Future Correlator	1999-09-01	2010-12-30	$0	$0	$0		100%
	8	**Computing Subsystem**	1998-06-01	2010-12-31			$32,314		
191	8.05	Management	2002-01-01	2010-12-31	$2,449	$123	$2,572	50%	50%
191A	8.07	Computing Hardware	2002-01-01	2009-12-31	$3,197	$448	$3,644	50%	50%
192	8.10	Science Software Requirements	2002-01-01	2007-05-31	$1,171	$234	$1,405	50%	50%
193	8.15	High Level Analysis & Design	2002-01-01	2006-05-31	$659	$132	$790	50%	50%
194	8.20	Software Engineering	2002-01-01	2006-05-31	$1,847	$369	$2,216	50%	50%
195	8.25	Common Software	2002-01-01	2006-05-31	$2,346	$469	$2,815	50%	50%
196	8.30	Control Software	2002-01-01	2009-12-29	$3,925	$785	$4,710	50%	50%
197	8.35	Correlator Software	2002-01-01	2009-12-29	$1,947	$389	$2,337	50%	50%
198	8.40	Pipeline Software	2002-01-01	2009-12-29	$1,649	$330	$1,979	50%	50%
199	8.45	Archiving	2002-01-01	2006-05-29	$2,098	$420	$2,518	50%	50%
200	8.50	Scheduling	2002-01-01	2007-12-27	$669	$134	$803	50%	50%
201	8.55	Observing Preparation & Support	2002-01-01	2009-12-29	$699	$140	$838	50%	50%
202	8.60	Off-line Data Processing/Analysis	2002-01-01	2006-05-29	$1,048	$210	$1,258	50%	50%
203	8.65	Telescope Calibration	2002-01-01	2009-01-01	$599	$120	$719	50%	50%
204	8.70	Integration and Support	2002-01-01	2010-12-30	$3,094	$619	$3,713	50%	50%
	9	**System Engineering & Integration**	1998-06-01	2010-12-31			$20,264		
205A	9.05	SE&I Management	2002-01-01	2010-12-31	$2,216	$111	$2,326	50%	50%
	9.10	System Engineering	1998-06-01	2010-12-31			$9,340		
205B	9.10.37	Phase 2 System Engineering	2002-01-01	2010-12-31	$8,052	$1,288	$9,340	50%	50%
205C	9.15	ALMA Prototype Interferometer Evaluation	1998-06-01	2003-04-09	$1,789	$286	$2,075	50%	50%
205E	9.30	ALMA System Integration	2004-01-06	2010-12-31	$5,622	$900	$6,522		
	10	**Science**	1998-06-01	2009-12-31			$6,960		
206	10.30	Phase 2 Science Support	2002-01-01	2009-12-31	$6,629	$331	$6,960	50%	50%



Summary Tasks: **underline**

Joint Task — Summary (Joint) — Summary (Eur) — Summary (US) — Eur Task — US Task

Proposal Guide

The tables of contents of each of the proposal volumes as well as a glossary of terms and acronyms used in the proposal are reproduced here for the convenience of the reader.

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ALMA Proposal Glossary

0".1	Angular Measure, one-tenth of a second of arc
ACC - Alma Coordinating Committee	Governing body of the ALMA Phase 1 Project
AIV	
Algorithms	Computer programs
ALMA Board	Successor body to the ACC for ALMA Phase 2
ALMA Test Interferometer Site	Common test location for two prototype antennas
ALMA - Atacama Large Millimeter Array	Refers to the entire international project
Ambient air	Air in close proximity to something
Amplifier	Electronic device to increase signal strength
Amplitude calibration	Process establishing a scale to source intensity
Angular resolution	Measure of the ability to discriminate detail on the sky
Aperture efficiency	Measure of fractional antenna power in the main beam
Aperture blockage	Geometric fraction of the antenna obscured by anything between the primary mirror and the sky
Apparition time	Time during which an astronomical object is visible
Arcsecond	Angular measure, 1/3600 of a degree
Array	Assembly, or grouping, of antennas
Array site	Location of the array
Asteroid	Solid body in the solar system, orbiting the sun but much smaller than a planet
Astrometric	Refers to astrometry, the position of objects on the sky
Atmospheric windows	Refers to the frequency spectrum over which the Earth's atmosphere is partially transparent
Atmospheric propagation effects	Any causal effect of the Earth's atmosphere on the free transmission of a cosmic signal to the ground
AUI - Associated Universities, Inc.	Management organization of the NRAO
Back-End	Equipment to process the signal after reception by the receiving equipment
Bandwidth	Refers to the extent of the frequency spectrum
Bilateral partnerships	Partnership limited to two entities

Call for Tenders	The process of seeking bids for a contract
Carona Australis	Southern hemisphere star forming region
Centaurus	Icy asteroids in the solar system orbiting between Neptune and Jupiter
CI	Neutral atomic carbon
CII	Once ionized atomic carbon
Circumstellar shells	Gaseous material surrounding a star
CNRS - Centre National de la Recherche Scientifique	French national science research agency
CO	Carbon monoxide gas
Collecting length	Product of the number of antennas in an array, N, multiplied by the antenna diameter D, i.e. (ND)
Collecting area	For an antenna it is the geometric area of the primary mirror; for an array it is the mirror array multiplied by the number of antennas in the array
Cometary nuclei	The solid ice/gas core of a comet
Continuum	Refers to a measurement made with no spectral (wavelength or frequency) discrimination
Correlator	Special purpose digital hardware to process the signals, in pairs, from all antennas in the array
Cosmic phenomena	Any naturally occurring process in the universe
Cryostat	Dewar assembly containing refrigerated instruments
Dewar	Insulated vessel
ECC - European Coordinating Committee	European ALMA partnership
EIE	Antenna fabricator, European Industrial Engineering
Emission (dust continuum, thermal, etc.)	Luminous process of astronomical object
Epochs of formation (z=?)	Time or duration in the history of the universe at which objects of a particular sort form
ESO - European Southern Observatory	International observatory
Fast switching	Rapid motion of the antennas pointing alternately at an astronomical source and a calibration source
Filling factor	Fractional area on the ground covered by array antennas.
First light	Initial detection of an astronomical signal by an antenna or array or antennas

Flux density	Measure of the signal strength of a source
FO transmitter	Fiber optics transmitter–device for sending an encoded signal along an optical fiber
Fringe generator	Electronic device producing a shaped signal
Fringe	Difference in time or frequency between two signals (usually from two antennas)–*beat note*
Front-End	Subsystem containing all heterodyne receiving equipment
GHz - Gigahertz	Measure of frequency, 10^9 Hertz
Hertzburg-Russell diagram	A chart plotting the color (or temperature) of a star against its magnitude (apparent intensity)
Holography	Interferometric technique to measure the surface shape of an antenna's reflecting surface(s)
Hour angle track	Angular extent on the sky, measured in hours, over which an astronomical source is observed
HP85106 Vector Network Analyzer	Electronic test equipment
HPBW	Half power beam width. Measure of the angle over which a device may receive a signal
HST - Hubble Space Telescope	NASA/ESA orbiting optical telescope
IF transmission	Transmission of the intermediate frequency resulting from a heterodyne mixing
IF	Intermediate frequency, result of hetrodyne mixing
IGN - Spanish Instituto Geografico Nacional	National science agency in Spain
InP	Indium Phosphate. Semiconductor material
Interferometric array	Grouping of antennas used as interferometers
Invisible stellar nuclear processing	Nucleosynthesis occurring at the center of stars
IPT - Integrated Product Teams	Management organization concept involving a teamed approach
IRAM - Institute de Radio Astronomie Millimetrique	Observatory operated as a collaboration between France, Germany and Spain
Isolators	Electronic designed to accept one signal and reject another
Kelvin (and MilliKelvin)	Measure of temperature. Zero degrees Celsius, or 32 degrees Fahrenheit, is 273 degrees Kelvin
Kinematics	Motion, usually of gas in response to a stimulus causing velocity

Kuiper-belt objects	Solar system asteroids or small planets orbiting beyond the orbit of Neptune
Light year	Measure of distance (not time). It is the distance light travels in one year.
Linear gains	Increase (usually of signal strength) of a device in response to a changed control parameter
LO source	Generation of a local oscillator signal
Local Oscillator	Heterodyne signal produced to mix with the desired signal from an astronomical source
LSA - Large Southern Array	Antecedent project of the ALMA project in Europe
MHz - Megahertz	Measure of frequency, 10^6 Hertz
MilliJansky	Measure of signal strength, one one-thousandth of a Jansky
MMA - Millimeter Array	Antecedent project of the ALMA project in the US
Monitor and Control System	Instrumentation and computer system to report status of array instrumentation
Mosaicing	Process by which images of the sky are made with multiple antenna pointings
MPG - Max-Planck-Gesellschaft	National science agency in Germany
NFR - Swedish Natural Sciences Research Council	National science agency in Sweden
NFRA - Netherlands Foundation for Research in Astronomy	National science agency in The Netherlands
NGST - Next Generation Space Telescope	NASA/ESA Project for an orbiting optical telescope of 8m diameter
NII	Once ionized atomic nitrogen
NOVA - Nederlandse Onderzoekschool Voor Astronomie	National astronomical sciences agency in The Netherlands
NRAO - National Radio Astronomy Observatory	NSF facility for radio astronomy research in the U.S. Operated by Associated Universities, Inc.
NSF - National Science Foundation	National science agency in the U.S.
Nutator	Device for controlled motion of the secondary telescope mirror
OCYT - Oficina de Ciencia y Tecnologia	National science and technology agency in Spain
Ophiuchus	Star forming region in the constellation Ophiuchus
Oscilloscopes	Electronic test equipment

OSF site	Location of the ALMA Operations Support Facility
OSO - Onsala Space Observatory	National radio observatory of Sweden
Particle acceleration	Physical process by which elementary particles are set in motion
Paso de Jama	International highway between the Chilean village of San Pedro de Atacama and the Jama region of Argentina
Phase calibration	Process to remove distortions due to the atmosphere on the instrumentation from astronomical signals
Photonic distribution	Sharing of an optical signal among many devices
Photosphere	Outermost layers of a star
PPARC - United Kingdom Particle Physics and Astronomy Research Council	National science agency of the U.K.
Preplanetary disks	Gaseous material orbiting a forming stars from which planets are, or may be, forming
Protogalaxies	First assemblies of gas clouds and stars condensing under gravity to become galaxies
Protoplanets	Assemblies of gas cloudlets orbiting a forming star that are condensing under gravity to become planets
Protostars	Assemblies of gas clouds condensing under gravity to become stars
QSO - Quasi-stellar objects	An energetic phase of galaxy formation characterized by emission processes occurring near a massive black hole
Quantum limit	Ability of a device to process a signal is limited by the requirement that the signal arrives in individual units, photons; the minimum signal is one photon
Radiometer	Heterodyne receiver
Radiometry	Any study employing use of a radiometer
Receiver noise	Random signal fluctuations characteristic of the receiver hardware itself, in the absence of a signal
Receiver	Device used to separate and/or amplify a desired signal from unwanted ones
Reconfigurability	Capability to arrange the distribution of antennas on the ground
Redshift	A measure of the motion of one cosmic source relative to another

RF	Radio frequency
RMS	Root mean squared: used to measure a changing quantity
San Pedro de Atacama	Historic village in the Atacama desert region of northern Chile
Santiago	Capital city of the Republic of Chile
Sidereal track	Duration of an observation of a celestial source. Angular measure in time.
Single axis reactionless nutator	Device to control motion of the secondary mirror whose motion does not cause a reactive motion elsewhere in the telescope structure
Single dish antenna	One antenna operating as a stand alone unit
SIS	Semiconductor device, a *sandwich,* made of 3 layers superconductor-insulator-superconductor
Solar active regions	Areas of the sun over which energetic activity is occurring
Spectral signatures	Any variation in the frequency spectrum of a cosmic source that are indicative of the emission or absorption of radiation
Spectroscopic	Observational technique to search for spectral signatures
Spillover	Emission received by an antenna that comes from a source other than the sky
Stokes Parameters	Physical characterizations of electromagnetic radiation
Subarcsecond	Angular measure. Less than an arcsecond
Superconducting receivers	Receivers based on use of superconducting devices as fundamental mixers or amplifiers
Synthesis telescope	Single telescope made up of individually-operating elements
UV-plane	Mathematical representation used to process signals received by a synthesis telescope.
UV-space	Mathematical space used to manipulate signals received by a synthesis telescope and make images
Vertex	Antenna fabricator, Vertex Antenna Systems, LLC.
VLBI - Very Long Baseline Interferometry	Technique for high resolution imaging using independent antennas

Wavelengths (millimeter and submillimeter)	Measure of a signal *crest-to-crest*
Weinzel Corporation	Manufacturer of electronic equipment
Zeeman-effect	Frequency splitting of a spectral signature in response to an imposed magnetic field. Used to measure magnetic fields in astronomical sources
Zenith optical depth	Fractional transparency of the Earth's atmosphere measured directly overhead (at the zenith)