<u>Program Plan</u>

ALMA

ALMA Project Overview

The Atacama Large Millimeter/Submillimeter Array (ALMA) is a collaborative venture of the U.S. National Science Foundation, a coalition of European institutes represented by the European Southern Observatory (ESO), and the National Astronomical Observatory of Japan (NAOJ). The NSF, as the U.S. partner in ALMA, also represents minority participation by the National Research Council of Canada (NRC) so that the NSF is properly the *North American* partner in ALMA. The three ALMA partners are working toward a project that embraces equality of effort and contribution from, and benefit to, the partners. As we begin the NRAO FY2002 Program Year a signed ALMA partnership agreement exists between North America and Europe (only) for an initial Design and Development project phase. Events during the program year are expected to produce a signed ALMA partnership agreement between all three partners–North America, Europe and Japan--for the construction phase of the project to begin in FY2003.

The North American participation in ALMA is executed by AUI/NRAO and funded by the NSF through their Cooperative Agreement with AUI for management of the NRAO. The U.S. participation in ALMA grew out of the Millimeter Array (MMA) Project which was proposed to the NSF in 1990 by AUI and funded for a 3-year Design and Development phase that began in 1998. In 1999 the NSF agreed with the European coalition to merge the MMA with the European Large Southern Array (LSA) project to create the *bilateral* ALMA Project. Subsequently the NRAO ALMA project management, and the ESO ALMA project management have worked cooperatively on a common design and prototyping effort. This work has led to a jointly-agreed work breakdown structure (WBS) for the design phase, and a complete draft of the WBS for the construction phase of the bilateral project that includes a thorough cost estimate and project schedule. The construction phase project has not been approved by either partner. Indeed, with the request of NAOJ that Japan become a third ALMA partner, work has begun to establish the scope, cost, schedule and division of effort for a *tri-lateral* project. The results of this work will be presented to the potential partners for their approval early in the 2002 NRAO Program Year.

Thus a thumbnail overview of ALMA is this:

- ALMA is a joint project being planned by the NSF and ESO, each of these entities representing other participating parties;
- ALMA is engaged in a common design and development program managed cooperatively by the NSF, acting through AUI/NRAO, and ESO;
- A common ALMA construction program WBS, cost, schedule and division of effort has been developed jointly by AUI/NRAO and ESO for the bilateral project;
- NAOJ has requested to join ALMA as a third partner bringing additional resources, scientific capability and providing a cost savings to the other two partners;

- A common ALMA construction program WBS, cost, schedule and division of effort for the trilateral project will be completed and presented to the ALMA partners for their approval in the 2002 NRAO Program Year.

Science Objectives

The ALMA Project will provide scientists with an instrument uniquely capable of producing detailed images of the formation of galaxies, stars, planets and the chemical precursors necessary for life itself.

ALMA is a radio telescope. It is designed to operate at wavelengths of 0.4 to 9 millimeters where the Earth's atmosphere above a high, dry site is partially transparent and where clouds of cold gas as close as the nearest stars and as distant as the observable bounds of the universe all have their characteristic spectral signatures. It will image stars and planets being formed in gas clouds near the sun, and it will observe galaxies in their formative stages at the edge of the universe which we see as they were nearly ten billion years ago. ALMA provides a window on celestial origins that encompasses fully both space and time.

ALMA will provide an unprecedented combination of sensitivity, angular resolution and imaging fidelity at the shortest radio wavelengths for with the Earth's atmosphere is transparent provide a wealth of new scientific opportunities. In particular, the scientific specifications for ALMA were chosen to allow astronomers to:

- Image the redshifted dust continuum emission from evolving galaxies at espochs of formation as early as z=10;
- Trace through molecular and atomic spectroscopic observations the chemical composition of star-forming gas in galaxies throughout the history of the universe;
- Reveal the kinematics of obscured galactic nuclei and quasi-stellar objects on spatial scales smaller than 300 light-years;
- Assess the influence that chemical and isotopic gradients in galactic disks have on the formation of spiral structure;
- Image gas-rich heavily obscured regions that are spawning protostars, protoplanets and pre-planetary disks;
- Determine the temperature of the photosphere of thousands of nearby stars in very part of the Hertzsprung-Russell diagram;
- Reveal the crucial isotopic and chemical gradients within circumstellar shells that reflect the chronology of invisible stellar nuclear processing;
- Obtain unobscured, sub-arcsecond images of cometary nuclei, hundreds of asteroids, *Centaurs,* and Kuiper-belt objects in the solar system along with images of the planets and their satellites–observations that chan be done for astrometric or astronomical purposes during daylight or nighttime hours;
- Image solar active regions and investigate the physics of particle acceleration on the surface of the sun.

This list of specific science capabilities leads to a definition of common science requirements that can in turn be used to establish requirements on the technical performance of ALMA. Foremost among those science requirements are precision imaging and sensitivity. Precision imaging and sensitivity enable the entire spectrum of science to be done with ALMA, irrespective of whether the scientist wishes to study solar system objects or galaxies twelve billion light-years away. Quantitatively, the *level 1 Science Requirements* for ALMA are the following:

ALMA Level-1 Science Requirements

- The Ability to provide precise images at an angular resolution comparable with that expected from the Next Generation Space Telescope (NGST), viz. Resolution better than 0".1. The term *precise imaging* means images not limited by imaging artifacts at a dynamic range less than 1000:1 over the entire sky visible from the ALMA site;
- The ability to detect CO emission in a *normal* galaxy like the Milky Way at a redshift z=3 in less than 24 hours of observation. The scientifically related requirement is this: the ability to image the kinematics of such a galaxy using the NII or CII emission line in a single source transit;
- The ability to image the gas kinematics in a solar mass protostar with a protoplanetary disk at the distance of the star-forming clouds in Ophiuchius or Carina Australis.

Technical Objectives

The technical challenge to the ALMA designers is to build a telescope that extends the high-resolution imaging techniques of radio astronomy to millimeter and submillimeter wavelengths.

High Resolution Imaging

High resolution imaging is achieved by making use of the technique of aperture synthesis, that is, using many individual antennas to *synthesize* the imaging performance of a single antenna very much larger than the individual antennas. Aperture synthesis is the technique used, for instance, by the Very Large Array to image at centimeter and meter wavelengths. ALMA will use 64 individual precision antennas all operating in concert to extend the aperture synthesis technique to observations at millimeter and submillimeter wavelengths. The signals received by the superconducting receivers on each antenna are digitized and processed in a special purpose computer or signal correlator. Images of astronomical objects and cosmic phenomena are made using computer algorithms designed to correct for atmospheric propagation effects and for the fact that the *synthesized* telescope is in fact made up of individual, separated antenna elements. The image forming optics of ALMA is a computer.

The objects that a scientist wishes to study often are embedded in larger structures that are physically or causally related to the objects of interest. Examples would include a protoplanetary disk found within the molecular envelope of a protostar, or the active nucleus of a spiral galaxy. In many cases, perhaps most, the physical context in which an object is found illuminates its origin or evolution. For this reason, the scientist will need to image both very small structures (the protoplanetary disk or galactic nucleus) and the much larger embedding structure (the molecular cloud or spiral galaxy). ALMA realizes this capability by means of rearranging the physical layout of the antennas on the site. Such *reconfigurability* provides ALMA with a zoom-lens capability.

In figure ??1on the following page ALMA is shown in its most compact configuration. Here the 64 ALMA antennas are shown arranged close together for observations of large regions of the sky at low resolution (level of image detail). The antennas may also be arranged in progressively larger oval configurations for higher resolution observations of smaller regions of the sky. In the lower right of this image one of the antennas can be seen being moved from one location to another. Also illustrated in this image are the ALMA control building, maintenance shops and the tall antenna assembly building.

[**Figure ??1]

The antennas can be moved into larger configurations using a special fork-lift type vehicle that runs on rubber tires. The antennas cannot be placed just anywhere. They must be attached to prepared concrete foundations. ALMA has 250 antenna foundations or "stations" for the 5 array configurations. Each station is connected to the site electrical power and communication network. An antenna moved from one station to another can be simply "plugged in" and it will be ready to resume observations.

The largest array configuration is an oval configuration nearly 14 kilometers in diameter. This large configuration will give images with the highest angular resolution, a resolution as high as 7 milli-arcseconds (7 one-thousandths of an arc second). As an aid to visualizing the range of array configurations figures ??2 and ??3 illustrate how the smallest and largest ALMA array configurations would appear on some familiar Washington DC landmarks.

[**Figure ??2 and figure ??3]

Operation at Millimeter and Submillimeter Wavelengths

The challenge of engineering the unique ALMA telescope to operate at millimeter and submillimeter wavelengths begins with the telescope site. Water vapor in the Earth's atmosphere strongly absorbs *light* from cosmic sources at millimeter and submillimeter wavelengths ~~that reaches the Earth;~~ little of that light may reach the surface of the Earth. The solution is to locate ALMA in the thin, dry air found only at elevations high in the atmosphere. For this reason, ALMA will be sited in the Altiplano of northern Chile at an elevation of 5000 meters (16, 500 feet) above sea level; this area known as the Llano de Chajnantor is directly east (downwind) from the Atacama desert, the driest desert in the world. A photo of the site is shown as figure ??4]. The ALMA site is the highest, permanent, astronomical observing site in the world. As an engineering project, ALMA is 64 precisely-tuned mechanical structures each weighing more than 100 tons, superconducting electronics cryogenically cooled to less than 4 degrees above absolute zero, and optical transmission of terabit data rates–all operating together, continuously, on a site more than three miles high in the Andes mountains.

[**Figure ??4 Site]

In order to make efficient use of the exceptional atmospheric transparency above the Chajnantor site it is necessary to design the receiving system such that the noise contributed by the receiver is as low as possible, that is the noise is close to the quantum limit. The ALMA receiver noise specification is set with this requirement in mind. In addition, the ALMA *synthetic aperture* must remain coherent; this sets a specification on the permissible instrumental phase distortion which in turn sets a specification for many things including the accuracy of the antenna primary mirror surface, the stiffness of the antenna backing structure and quadripod support, and the phase noise resulting from transmission of the local oscillator reference signal in fiber optic cables. All of these requirements serve to define the ALMA technical system, or project *scope and specification,* as outlined for the bilateral ALMA project in table ???1.

[**Insert Table VIII.2 from the 2001 Program Plan–Change the Table title to "Baseline Bilateral ALMA Scope and Specification"]

Project Status

In both the U.S. and Europe, ALMA is in a design and development phase. The objectives of this phase of the work are (1) to complete the project description including scientific and technical requirements, the proposed technical and management approaches, a work breakdown structure and the cost estimate and schedule for the construction phase of the project as derived from the WBS; and (2) to develop the complete ALMA technical specification by means of prototypes and demonstrate through performance measurements on the prototype components that the specifications are being met. Presently the project description, (1) above, is complete for the bilateral ALMA project and prototype components of the critical technologies are in fabrication and/or test. A summary of that work organized by the level-1 WBS tasks is presented below.

<u>Administration</u>
The principle administrative task involves establishing a thorough management structure for the joint U.S.-European project and implementing that structure within the technical teams. The approach adopted is based on Integrated Product Teams (IPTs) in which the responsibility for each major task is assigned to one partner or the other but the work is executed jointly by the technical teams of both partners. That is, responsibility is assigned but the effort is shared. The goal is to have the IPT structure in place and functioning by the time the ALMA project moves into construction.

<u>Site Development</u>
In the design and development phase of the ALMA project the site development task is limited to development planning. The main issues for which planning is in progress include the following:

- Identifying a location for the Operations Support Facility (OSF) that is near enough to the village of San Pedro de Atacama that general infrastructure support can be made available, but also near enough to the array site that the OSF can function effectively as the center for array operations and instrument maintenance and repair. The elevation of the OSF should not be higher than approximately 3000 meters above sea level so that the OSF staff can carry out their tasks without the need for supplemental oxygen;

- Identifying a route for a road to connect the OSF to the array site. The road would be used to transport equipment and personnel as necessary. That road may be the existing international highway to Argentina known as the Paso de Jama. An alternative route is also being studied that would make it possible to move the antennas from the array site to the OSF for major outfitting or repair (such as routine painting).
- Carrying out an environmental impact survey for the array site, the OSF location and the road connecting the two;
- Planning for utilities. In particular, a comparative study is underway to determine whether the cost/benefit ratio is higher for ALMA to use commercial electrical power or whether ALMA should plan to generate its own power from locally-supplied natural gas;
- Constructing a first draft of a site layout plan for both the array site and the OSF that can be used to guide the efforts of the contract architectural and engineering firm to be hired in the construction phase of the project.

Prior to the approval for ALMA construction by the partners, and permission is obtained from the government of Chile, no funds or effort will be expended on site development in Chile.

Antennas

Two contracts have been let for prototype antennas, one by the U.S. and the other by ESO. The bid packages for the two prototype antennas were written to identical technical specifications; the successful bidders on each side responded with significantly different designs that each meet not only those specifications, but they also satisfy an identical set of detailed Interface Control Documents (ICDs). The ICDs were carefully coordinated to insure that each antenna will have compatible mechanical, electrical and control interfaces. Both prototype antennas will be erected at the VLA site in 2002. A competitive evaluation will follow.

Front End Subsystem

The front end task has three components. The first is to fabricate two identical dual-channel (3mm and 1mm wavelength) front ends specifically to be used for the testing program of the two prototype antennas. These *evaluation front ends* will be thoroughly tested in the laboratory to characterize their performance and to assure that the data acquired from them will provide the basis for a valid comparison of the prototype antennas. These are not ALMA prototype front ends. The second task is to design and fabricate a receiver to be used for holographic measurements of the surface of the two prototype antennas. This is a prime focus receiver operating at 3mm that will receive a monochromatic broadcast tone in two channels simultaneously; one signal from one channel includes reflection from the antenna primary mirror and the other is detected directly from the transmitter. The phase difference between the two channels measured while the antenna is scanned over a raster of positions can be fourier inverted to produce a map of the local spatial distortions of the primary reflector. The one holography receiver will be used for both antenna prototypes. The third task is to design the ALMA front end.

The ALMA front end is a single cryogenic dewar, or vessel, that is designed to accommodate ten frequency band receivers or *cartridges*. Initially only four cartridges will be built, for the bands at 3mm, 1mm, 0.85mm and 0.45mm respectively. In 2001 a successful preliminary design review (PDR) for the front end subsystem was held. As a result of that PDR the WBS and cost model for the front end task was reassessed, and the delivery schedule was modified. The plan is to develop the ALMA front end in two stages of prototype–an engineering model to be followed by a fully functional prototype–both to be complete before series production begins. Prototypes of the critical technologies are in fabrication for delivery by the end of calendar 2001.

Local Oscillator Subsystem

The task for the local oscillator subsystem is in fact two tasks, namely, development of the baseline LO system and design experimentation with an alternative photonic system.

The baseline LO system uses a YIG generated microwave source that is multiplied and amplified to 100-122 GHz where it is phase-locked to a reference tone. To reach the higher millimeter and submillimeter wavelengths the 100-122 GHz LO "driver" is multipled in diode semiconductors. Multipliers needed for the LO for all four of the initial ALMA frequency band cartridges are being designed, fabricated and tested.

The alternative "direct photonic LO" is generated in a fast photodiode detector as the difference frequency between two infrared lasers. The photonic LO is a new technology. The issues to be addressed include design of the photodiodes that are capable of providing sufficient power at high frequencies and an evaluation of whether the phase and amplitude noise on the photonically generated LO will meet the ALMA specifications.

Backend and Correlator Subsystems

The 16 GHz analog IF output of each ALMA frontend is digitally sampled at the antennas and the digital signal is sent by fiber optic cables to the correlator. Prototype designs of the hardware needed for the sampler and the IF transmission based on a parallelization of commercial components are being fabricated and tested.

Two correlators are planned for ALMA. The first is a single-baseline "test correlator" specifically built for the test interferometer. It will be used for the evaluation tests of the two prototype antennas. This correlator, and its software, is complete and is ready to be used with the prototype antennas at the VLA site. The second correlator is the ALMA baseline correlator. Its task is to cross-correlate the digital IF signals from all 2016 pairs of ALMA antennas. Prototype correlator boards have been successfully tested for the long term accumulator and the digital filter; these boards are shown in figures ??5 and ??6. The correlator computation is done in a specially designed ASIC chip; the chip design is finished and prototyping is underway.

Computing Subsystem

The software system for ALMA also is done in two task steps. First, the software to support testing of the prototype antennas is being adapted from existing software used in other astronomical applications. This includes not only the software needed to drive the antennas, but it also includes the software system by which instruments and controlled and monitored, the software to be used in holographic measurements of the antenna surface, the software for the test correlator, and the software system by which the pointing and astronomical data is analyzed. The second step is to provide for the software needed by ALMA itself. Here the software system design is being developed in concert with the ALMA software group in Europe, design decisions are made (such as the decision to use an AMBSI standard monitor and control bus), and a division of effort for the software task in the construction phase of ALMA is negotiated.

System Engineering and Integration

The test interferometer will also serve not only to test the prototype antennas but also to test the system concepts to be employed for ALMA; hence a substantial effort is directed toward the test interferometer. Site preparations are underway at the VLA site. The antenna foundations are being constructed and the utility and communications cables are being laid. Planning for the antenna testing program is complete in draft form, including the schedule for the tests, and criteria have been established for the competitive antenna evaluation.

Configuration control for the ALMA project is a primary responsibility of the system engineering group. A process to maintain and control the configuration has been established and agreed by the U.S. and European partners, and a configuration control board is in place to facilitate the process. This is necessary for proper management of the project.

Science and Imaging

Scientific advice is provided to the project through the ALMA Science Advisory Committee (ASAC). The Project Scientists from the U.S. and Europe jointly chair the ASAC and solicit from the ASAC advice on technical questions that have a potential impact on the science performance of ALMA. Current questions under study involve the science priorities to be established for those deferred science capabilities that may become part of the scope of the three-way project (i.e. with Japan).

The science and imaging team has the responsibility to establish the array configuration layout that will maximize the imaging capability of the instrument, and to establish the calibration system necessary. A configuration PDR held in February 2001 led to preliminary agreement for the layout of all 250 antenna stations; this information has been supplied to the site development group. A calibration PDR was held in June 2001 which provided a course of action to be implemented over the next two years.

Program Plan for 2002

It is anticipated that FY2002 will be the last year of design and prototyping: The FY2002 Program Plan is based on the expectation that ALMA construction will begin on the first of October 2002.

The "pacing item" for the ALMA Project is procurement of the production antennas. Since the production antenna contract is meant to follow a competitive evaluation of the two prototype antennas at the test interferometer, the focus of the ALMA effort in 2002 will be the test interferometer. The plan for the test interferometer in FY2002 includes:

- Completion of the test interferometer site, including provision for temporary office, laboratory and residential space;

- Installation of a tower (50 m high) for the holography transmitter and outfitting of the tower with the transmitter itself together with needed utilities and communication system;
- Delivery of the prototype antennas;
- Delivery of the holography receiver and software system;
- Delivery of the evaluation front ends (2 units);
- Delivery of the LO system;
- Delivery of the IF system;
- Complete end-to-end laboratory test of the test interferometer instrumentation system, including software system and validation that it meets specifications;
- Delivery of nutating secondary mirrors for the two prototype antennas;
- Initiation of the prototype antenna testing program by means of a joint U.S.-European science and technical team.

Although the test interferometer will be the focus of the effort in FY2002, important prototyping tasks will continue directed toward the actual ALMA hardware itself. Most importantly in this regard is work on the front end system. The project deliberately chose to build front end hardware for the prototype antenna testing that was special purpose, it was not an ALMA prototype front end. This allows the ALMA front end designers to avoid having to concentrate their attention on two tasks simultaneously (the test interferometer and ALMA itself). Instead, they can work progressively toward delivery of the first production front end subsystem to Chile at the time it is needed when the first production antenna is planned to arrive in Chile. The same can be said of the correlator effort. The correlator needed for the test interferometer was delivered early in 2001 thereby freeing the correlator team to focus their efforts on design and prototyping of hardware needed for the ALMA baseline correlator.

Other ALMA task groups will work with to install the actual ALMA prototype hardware on the test interferometer so that it can be tested, incrementally, with the prototype antennas. The IF digital transmission system, including use of the digital filter cards, will be particularly important in this regard. The techniques to be used for system engineering will also get a thorough evaluation at the test interferometer.

The major tasks and milestones for the ALMA Project in the FY2002 year are summarized in Table ???.

Table ??? ALMA FY2002 Major Tasks and Milestones

WBS Level 1	WBS Task	Milestone or Deliverable
1.0	Administration	Establish International Project Office

2.0	Site Development	PDR Site Development Establish GPS coordinates of all antenna stations Identify OSF location and site layout Deliver preliminary layout of array site Deliver assessment of electric power options
3.0	Antennas	Deliver prototype antennas to VLA test site Deliver nutating secondary (2) Install metrology equipment on antennas Install holography tower Initiate antenna engineering evaluation
4.0	Front End Subsystem	Deliver holography receiver Deliver evaluation front end (2 units) Deliver holography transmitter & install Deliver ALMA engineering model FE
5.0	Local Oscillator	Deliver 80-240 GHz multiplier LO Deliver prototype 650 GHz multiplier LO Deliver prototype 345 GHz multiplier LO Deliver photonic system noise & power tests ALMA LO decision: multiplier or photonic
6.0	Backend Subsystem	Deliver digitizer for test interferometer Deliver IF transmission system for test Interf.
7.0	Correlator	Contract for prototype correlator chip Deliver prototype correlator boards
8.0	Computing Subsystem	Deliver software engineering standards Deliver common software design Deliver pipeline software plan Deliver high level system design Deliver monitor and control system design Deliver holography software
9.0	System Engineering	Deliver antenna evaluation plan Deliver optical pointing telescope Establish antenna evaluation team Initiate scientific antenna evaluation program
10.0	Science and Imaging	Deliver ALMA calibration plan Deliver prioritization of science enhancements CDR antenna configuration

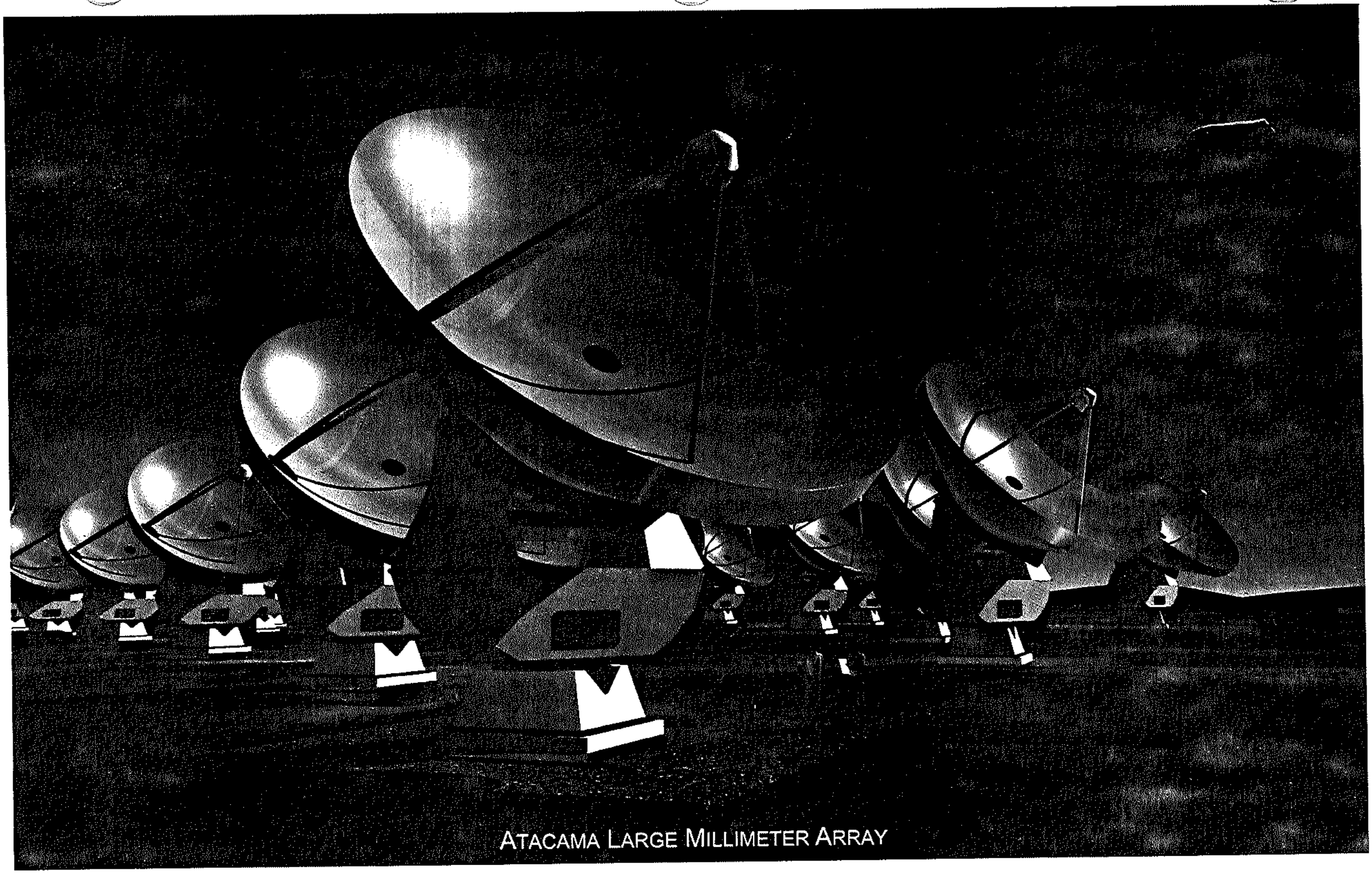
The entire scope of activities planned by both the U.S. and European partners in ALMA are set forth in the ALMA WBS. The milestones table above, Table ??? was abstracted from that WBS.

The ALMA resource plan for FY2002 is presented in table ????. This plan is written to the President's request of $9M for ALMA in FY2002.

Table ???? ALMA FY2002 Budget by WBS Element ($k)

WBS Element	Labor*	Travel	Contracts	Materials and Services
Administration	846	120	0	450
Site Development				
Antenna	153	75	50	150
Front End	1705	60	400	200
Local Oscillator	738	45	100	50
Backend System	767	45	30	160
Correlator	408	25	225	75
Computing	776	100	40	110
System Engineering	505	60	25	150
Science & Imaging	222	60		75
TOTALS	$6120	$590	$870	$1420

* 63 FTE employees



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