ALMA Project Plan

Version III

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Prepared by the Joint ALMA Office in consultation with the Executives and approved by the ALMA Board

The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership of Europe, North America and East Asia in cooperation with the Republic of Chile. ALMA is funded in Europe by the European Organization for Astronomical Research in the Southern Hemisphere (ESO), in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC) and the National Science Council of Taiwan (NSC) and in East Asia by the National Institutes of Natural Sciences (NINS) of Japan in cooperation with the Academia Sinica (AS) in Taiwan. ALMA construction and operations are led on behalf of Europe by ESO, on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI) and on behalf of East Asia by the National Astronomical Observatory of Japan (NAOJ). The Joint ALMA Observatory (JAO) provides the unified leadership and management of the construction, commissioning and operation of ALMA.

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1. PROJECT DESCRIPTION

1.1 Project Overview

The Atacama Large Millimeter/submillimeter Array (ALMA) is a revolutionary instrument in its scientific concept, in its engineering design, and in its organization as a global scientific endeavor. ALMA will provide scientists with precise images of galaxies in formation, seen as they were twelve billion years ago; it will reveal the chemical composition of heretofore unknown stars and planets still in their formative process; and it will provide an accurate census of the size and motion of the icy fragments left over from the formation of our own solar system that are now orbiting beyond the planet Neptune. These science objectives, and many more, are made possible owing to the design concept of ALMA that combines the clarity of detail in images provided by an interferometric array of at least 66 antennas together with the brightness sensitivity of a fully filled aperture.

The challenges of engineering the unique ALMA telescope begin with the need for the telescope to operate in the thin, dry air found only at elevations high in the Earth's atmosphere where the light at millimeter and submillimeter wavelengths from cosmic sources penetrates to the ground. ALMA will be sited in the altiplano of northern Chile at an elevation of 5000 meters (16,500 feet) above sea level. The ALMA site is the highest, permanent, astronomical observing site in the world. On this remote site superconducting receivers that are cryogenically cooled to less than 4 degrees above absolute zero will operate on each of the ALMA antennas, 54 or more of which are 12 meters in diameter and 12 of which are 7 meters in diameter. The signals from these receivers will be digitized and transmitted to a central processing facility where they will be combined and processed at a sustained rate greater than 10^{16} operations per second. As an engineering project, ALMA is a collection of at least 66 precisely-tuned mechanical structures each weighing more than 80 tons, cryogenically cooled superconducting electronics, and optical transmission of data at terabit rates - all operating together, continuously, on a site very high in the Andes mountains.

The challenges of communicating the mission and the excitement of ALMA to the citizens who ultimately sponsor the Project is a task as vital as the engineering challenges. To this end a comprehensive program of education and public outreach is an integral part of the ALMA Project.

1.2 Project Technical Deliverables

The ALMA construction project will deliver an antenna array capable of meeting the scientific requirements as summarized in Section 2. A tabular summary of the technical description of ALMA as derived from those science requirements is presented in Table 1-1 followed by brief description of the key table elements.

Table 1-1. ALMA Technical Summary

Array[1]	
Number of 12-m Antennas (N_{12})	at least 54
Number of 7-m Antennas (N_7)	12
Total Collecting Area $\pi/4\ (N_{12}D_{12}^2+N_7D_7^2)$	at least 6569 m^2
Total Collecting Length ($N_7D_{12}+N_7D_7$)	at least 732 m
Angular Resolution	0.2" lambda (mm)/baseline (km)
Array Configurations	*(Dimension of filled area)*
Compact: Filled	80 m
Continuous Zoom	80-18500 m
Highest Resolution	18.5 km
Total Number of Antenna Stations	192
Antennas[1]	
Diameter (D_{12})	12 m
Surface Accuracy	25 micrometers RMS
Diameter (D_7)	7 m
Surface Accuracy	20 (D_7) micrometers RMS
Pointing	0".6 RSS in 9 m/s wind
Path Length Error	< 15 microns during sidereal track
Fast Switch	1.5 degrees in 1.5 seconds
Total Power	Instrumented and gain stabilized
Transportable	by vehicle with rubber tires
Front Ends[2]	*(All frequency bands)*
84 - 116 GHz SIS	-*Dual polarization*
125 - 163GHz SIS	-*Noise performance limited*
211 - 275 GHz SIS	*by atmosphere*
275 - 370 GHz SIS	
385 - 500 GHz SIS	
602 - 720 GHz SIS	
787 - 950 GHz SIS	
Water Vapor Radiometer	183 GHz
Intermediate Frequency (IF)	
Bandwidth	8 GHz, each polarization
IF Transmission	Digital
Correlator	
Correlated Baselines	at least 1225 (=50x49/2) + 120 (=16x15/2)
Bandwidth	16 GHz per antenna
Spectral Channels	at least 4096 per IF
Data Rate	
Data Transmission from Antennas	120 Gb/s per antenna, continuous
Signal Processing at the Correlator	1.6 x 10^{16} multiply/add per second

[1] ALMA can be thought of as two arrays, one comprising at least fifty 12-m antennas, and the other four 12-m and twelve 7-m antennas. These two arrays can be cross-correlated or operated separately.
[2] Receivers in three additional atmospheric windows have been deferred to future development.

Array Site: ALMA will be built on the Chajnantor altiplano in the Atacama Desert of northern Chile. Its approximate coordinates are 67 degrees, 45 minutes West, 23 degrees South. The site is at an elevation of slightly over 5000 m. The site land is administered by the Chilean Ministry of National Assets and set aside by Presidential decree as a protected region for science. Measurements made *in situ* continuously since 1995 of the atmospheric transparency and stability confirm that the site has superior conditions for millimeter-wave and submillimeter-wave astronomy and it will meet the science requirements for the ALMA Project.

Antennas and Antenna Configurations: Fifty-four[3] or more ALMA antennas will each have a reflecting surface 12 meters in diameter, with a parabolic cross-section. The remaining twelve each have a reflecting surface 7 meters in diameter. The number and size of the antennas is determined from imaging requirements; the materials used in their construction are dictated by the fact that ALMA will operate 24 hours a day and hence the antennas must maintain their performance when fully exposed to the thermal variations and wind gusts imposed by the site environment. Each antenna is fully steerable; more than 85 percent of the celestial sphere is above the horizon at the Chajnantor site. Four of the 12-m antennas are equipped with a nutating subreflector that can move the telescope beam back and forth quickly on the sky and enable the acquisition of high quality total power images.

The antennas are all movable among 192 prepared antenna locations, or stations. Each station has a concrete foundation to support the antenna and provision for electrical power and data communications. The antennas are moved by a specially designed antenna transporter. The ability to move the antennas, and hence to rearrange them on the ground, provides ALMA with the capability to match its angular resolution to the science requirements of its users. The 12-m array will be delivered with a range of antenna configurations forming arrays as small as 150 meters in diameter (for the study of large or low surface brightness objects) and as large as 18.5 km in diameter (for the study of small, high surface brightness objects). The Atacama Compact Array (ACA), comprising four 12-m and twelve 7-m antennas, will be delivered with a range of antenna configurations forming arrays less than 80 meters in diameter.

Front End Electronics: Each of the sixty-six antennas will be equipped with a receiving system, or front end, capable of detecting astronomical signals in seven frequency bands. These are coherent detectors, meaning that they employ a common local oscillator signal to convert the received signal frequency to a much lower intermediate frequency that is subsequently digitized and transmitted to the central electronics building where it is combined with the signals from all other antennas. The local oscillator is a deliverable of the front end electronics task, but the intermediate frequency transmission and processing is a deliverable of the back end task. Further, each of the seven frequency band cartridges includes two receivers operating in orthogonal senses of linear polarization so that the full polarization state of the received radiation can be measured. The receivers are based on superconducting mixers that operate at temperatures at 4 K. All of the

[3] There is a possibility that partners may provide additional antennas.

cartridges are included in a single cryogenic dewar located at the Cassegrain focus of an individual antenna.

Also at the Cassegrain focus, but removed from the optical axis of the telescope, is a water vapor radiometer tuned to the 183 GHz line of terrestrial water emission. Each 12-m antenna has such a water vapor radiometer that is used to measure the column of atmospheric water vapor above the antenna; from these measurements the phase distortion of an astronomical signal resulting from its passage through the screen of atmospheric water is determined and its deleterious effects may be removed from the measured astronomical signal. This is a technique identical in its purpose and application to adaptive optics as used for ground-based telescopes operating at visual and infrared wavelengths. For ALMA the technique is applied digitally after signal detection; for optical/infrared telescopes the technique is applied prior to signal detection using analog techniques (i.e., physically distorting the shape of one or more mirrors in the signal path). To maximize the observing efficiency, an additional seven dewars, as well as seven cartridges of each frequency band, and seven water vapor radiometers will be available. Six will be provided for the 12-m array by the European and North American executives, the seventh, for the ACA, will be delivered by the East Asian executive.

Back End Electronics: The intermediate frequency that is output from the front end is amplified and digitized at the antenna by the back end electronics. In order to process the 8 GHz bandwidth of the intermediate frequency signal, the back end electronics subdivides that signal into four 2 GHz sub-bands for transmission to the correlator. Back end timing signals and reference oscillators synchronize the operation of the antennas and the data collection.

Correlator: The correlator is a special-purpose digital signal processor. It combines the digitized intermediate frequency signals from all the antennas pair wise; there are at least 1225 + 120 antenna pairs[4] in ALMA and the correlator produces a set of complex correlation coefficients (fringe amplitude and phase) as a function of baseline and frequency. Images or the angular distribution of the astronomical source on the sky are created by Fourier inversion of these complex (phase and amplitude) data.

Computing and Software: The computing system has the task of scheduling observations on the array, controlling all the array instruments, including pointing the antennas, monitoring instrument performance, monitoring environmental parameters, managing the data flow through the back end electronics and presentation of these data to the correlator. The output of the correlator is again the responsibility of the computing task where it is processed through an image pipeline, calibration is applied, and first-look images are produced. Finally the science data and all associated calibration data, monitor data, and derived data products are archived and made available for network transfer.

The deliverables from the computing task include the software system necessary to achieve the functionality noted above and the hardware necessary to run that software and manage the data flow.

[4] Antenna pairs of 50x49/2 and 16x15/2 are usually correlated separately.

Organization: The system engineering, scientific oversight, and management necessary to coordinate the task activities of the ALMA technical team responsible for production of the ALMA technical system noted above are integral deliverables of the ALMA Project as well. The project safety office is included in the management function and its head reports directly to the ALMA Director.

1.3 Project Programmatic Scope

1.3.1 Data Products

The fundamental data products from ALMA are calibrated, pipeline-processed images. These images may be either continuum images of astronomical sources or spectroscopic images which reveal the kinematics or distribution of different atomic or molecular species. These images, together with the uv-data files (i.e., the cross-correlation data prior to the Fourier transform), calibration files, and monitor information files, will be delivered in a timely manner following completion of the scheduled observing program to the astronomer who proposed the observation. All of these same data will be written to a permanent archive.

The burden this programmatic deliverable imposes on the ALMA construction project is threefold. First, the ALMA software system must be capable of defining a default calibration strategy based on scientific key values assigned in advance to each scheduled proposal. This is needed to assure that the pipeline-processed images that go into the ALMA archive are of a consistent and understood quality. Second, the ALMA software system has a firm requirement for a pipeline-processing capability; this was highlighted in Section 1.2 above as a technical deliverable. Further, that pipeline processor must accommodate multiple datasets for the creation of a single image (e.g., observations made of a single source using two or more array configurations all addressed to a specific scientific goal). Third, the ALMA software system requirement includes provision for a permanent archive that is network-accessible - this involves both an adequate software system and the hardware needed to support the archive.

1.3.2 Array Operations Facilities and Infrastructure

A primary safety guideline for the ALMA Project is to minimize the number of staff assigned to the 5000 m Array Operations Site (AOS). This guideline has many ramifications that can be summarized by the statement that ALMA will be operated remotely. That is, the array operator and all personnel involved with astronomical observations and maintenance of array instrumentation will be located at ALMA facilities at lower elevation. This leaves on the AOS only those personnel needed to assure the security of the site, people whose task it is to maintain the back end electronics and the correlator at the central electronics building on the array site, those responsible for module exchange - replacing failed instrument modules with functioning spares that are stored on the AOS - and those whose task it is to transport the antennas as needed for array reconfiguration. In order to achieve this goal the entire array must be designed and built to be modular in character, and wherever possible to be self-diagnosing. Each instrument must have provision for an adequate number of monitor points that are reported to the control computer in real time.

The guidelines to minimize the size of the operating staff, maximize the operating effectiveness of that staff, and to minimize the instrumental "downtime" all lead to the requirement to locate the operating staff close to the AOS but at lower altitude. Here the considerations are to provide a work environment that is at an elevation where the deleterious effects of a reduced oxygen environment are minimized but nevertheless a work environment that is sufficiently close to the AOS that instrumental problems can be investigated and solved quickly. We refer to this operations and maintenance facility as the Operations Support Facility (OSF). One of the deliverables of the ALMA Construction Project is to connect the OSF to the AOS by means of a road for the transportation of the antennas and operations/maintenance staff, and a communications highway involving buried optical fibers over which the astronomical data and the instrument monitor data are carried in real-time, and at high bandwidth. These links will give the ALMA operations staff a virtual presence on the AOS that will be adequate to investigate problems quickly and begin the process of effecting a cure.

During construction, the antennas will be erected by the antenna contractor at the OSF and, once accepted by the Project, they will be carried on the antenna transporter to the AOS. The location for the OSF is ~15 km east of San Pedro and south of the Paso de Jama road. From this location a restricted-use road will be built connecting the AOS to the OSF in a direct line that can be used not only to transport the assembled antennas to the AOS without using the public highway, but can also be used to return the antennas to the OSF for repair and maintenance. Operationally, only routine antenna maintenance, and no antenna maintenance crew, will be located at 5000 m altitude. All major antenna work will be done at the OSF. The proximity of the OSF to the AOS makes it possible at some time in the future to locate the array correlator at the OSF thereby moving still more operations staff off the 5000 m site; this is a decision to be made later in the operational phase of the array.

1.3.3 Construction Project Interface to ALMA Operations: Commissioning and Early Operations

ALMA is kept coherent in the sense that all antennas sample the incoming wavefront from an astronomical source at the same relative phase. This is done by transmitting to each antenna a common local oscillator signal and then delaying processing of the intermediate-frequency data from each antenna according to the instantaneous source-antenna array geometry. The data received by each antenna and transmitted to the central array electronics building for processing by the correlator also take into account the difference in transmission times from each antenna to the central building. Thus, ALMA has some components of its technical baseline that are multiples of 66 or more (e.g., the antennas; receiving system) and some components of the technical baseline that are individually unique (e.g. the local oscillator generator that serves as the reference for the whole array; the correlator). The array cannot function as a scientific instrument without all the unique devices, but it can function, albeit at reduced capability, with fewer than the full complement of all antennas or other equipment modules that are antenna-based.

Early Science Operations

It is the fundamental programmatic goal of the ALMA construction project to begin operating ALMA as an interferometric array for scientific research as soon as it is possible. Scientific observations during commissioning of the array can: (i) make use of experienced scientists to uncover hardware and software problems so that such problems are readily identified and it is possible to implement design changes to solve those problems early in the construction project; (ii) refine array instruments and techniques that depend on actual array site conditions that affect science research programs; and (iii) gain early operating experience that can be fed back to the construction project so that changes can be made to improve reliability or maintainability of the array. As soon as commissioned, the partial array will move to early science operations in which the general community will be invited to apply for some fraction of the observing time.

Requirements for Instrument Priorities and Instrument Commissioning

- The one-of-a-kind array instrumentation modules must be given highest priority among construction tasks so that they are completed as early in the Project as possible and the early science operations may commence with the first few antennas in Chile.
- Hardware delivered will be integrated, verified, and commissioned subsystem module-by-subsystem module. Once commissioned, each subsystem module will be placed into service in the operating array.

Requirements for ALMA operations derived from the fundamental programmatic goal

- The initial complement of the ALMA operations team must be in place at the OSF and on the array site at the time the first array subsystem modules are commissioned. It will be the responsibility of these operational staff to maintain and operate the commissioned modules.
- The details of the scientific operations plan need to be defined and implemented at the time the first few antennas arrive on site.

Future operational considerations – very long baseline interferometry

It is envisaged that, once operational as an array, ALMA will also be available to participate in the millimeter VLBI networks, worldwide, giving those networks unprecedented sensitivity and resolution, applicable in a wide variety of important astronomical studies.

1.4 Education and Public Outreach

The ALMA partnership will develop an active program of educational activities with ALMA as its focus. This program will be a cooperative endeavor of the NRAO Education and Public Outreach Office, the ESO Education and Public Relations Department, the ALMA Project Office of NAOJ, and the Joint ALMA Observatory in Chile. The goals are:

1) To communicate the scientific mission of ALMA accurately and appropriately to students of all ages;
2) To illustrate, through visual material accessible via the internet, the technical concepts of ALMA including those that form the basis for superconducting electronics, the transmission of electromagnetic waves as digital signals, and the formation of an image from multi-aperture data. The primary thrust will be to communicate the fact that these techniques, although developed for radio astronomy, are not unique to radio astronomy, but instead they touch many aspects of everyday life including medical diagnostics, transportation systems, and weather forecasting;
3) To "personalize" scientific research by emphasizing that "real people" are engaged in that research. Here the intent is to make available through print and the internet the photographs and background of those scientists using ALMA at a particular moment. An important goal is to highlight the diversity of those individuals illustrating that scientific research is a career option available to everyone.
4) To provide training for Chilean physics, engineering, and computer science college-level students through work at the observatory as part of cooperative and summer work programs, alongside students from East Asia, Europe, and North America.

The public information goals of the Education and Public Outreach (EPO) task include all of the above with the additional highlight of making available to the public contact information for the scientists who use ALMA. This provides a close and personal connection between the individuals who benefit directly from ALMA and the people who provide the opportunity for that benefit. It also serves to provide a very large number of contact points enabling the public to address questions to scientists with whom they may share common interests or common background.

In Chile, ALMA Operations will work cooperatively with Regional Chilean officials to:

1) Provide an additional tourist destination near the community of San Pedro de Atacama;
2) Enlarge the educational opportunities, particularly technical opportunities, in the locality;
3) Provide full employment opportunities in the breadth of ALMA operational activities for citizens of the region. Accomplishing these goals may involve establishing an appropriate visitor center illustrating ALMA, its scientific mission and its user community, and providing technical educational programs either in, or in conjunction with, local schools.

2. ALMA SCIENCE REQUIREMENTS

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

ALMA should provide astronomers a general purpose telescope which they can use to study at high angular resolution millimeter/submillimeter wavelength emission from all kinds of astronomical sources. ALMA will be an appropriate successor to the present generation of millimeter/submillimeter-wave interferometric arrays and will allow astronomers to:

- Image the redshifted dust continuum emission from evolving galaxies at epochs 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;
- Image gas-rich, heavily obscured regions that are spawning protostars, protoplanets and proto-planetary disks;
- 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;
- Image solar active regions and investigate the physics of particle acceleration on the surface of the sun.

No instrument, other than ALMA, existing or planned, has the combination of angular resolution, sensitivity and frequency coverage necessary to address adequately all of these science objectives.

ALMA is conceived and designed to be a long-lived user observatory. Its scientific impact at any time will be determined by the quality of its instruments and the creativity and industry of its scientist-users.

ALMA will have the capability to extend the high-resolution imaging techniques of radio astronomy to millimeter and submillimeter wavelengths to achieve an astronomical imaging capability equal in clarity of detail to the imaging capability of the Hubble Space Telescope (HST) and large ground-based telescopes. It will do so at wavelengths where the richness of the sky is provided by thermal emission from the cool gas and dust from which stars and all cosmic objects form. In this sense, ALMA is the appropriate scientific complement to the Very Large Telescope (VLT), Gemini, and the Subaru Telescope, as well as to the HST and its successor instrument, the James Webb Space Telescope, instruments which image light from stars and collections of stars such as galaxies.

The primary science requirement for ALMA is the flexibility to support the breadth of scientific investigation to be proposed by its creative scientist-users over the decades long lifetime of the instrument. However, three science requirements stand out in all the science planning for ALMA done in Europe, North America and East Asia. These three Level-1 Science Requirements are the following:

1) The ability to detect spectral line emission from CO or CII in a normal galaxy like the Milky Way at a redshift of $z = 3$, in less than 24 hours of observation.

2) The ability to image the gas kinematics in protostars and in protoplanetary disks around young Sun-like stars at a distance of 150 pc (roughly the distance of the star-forming clouds in Ophiuchus or Corona Australis), enabling one to study their physical, chemical and magnetic field structures and to detect the tidal gaps created by planets undergoing formation in the disks.

3) The ability to provide precise images at an angular resolution of 0.1". Here the term precise image means representing within the noise level the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees.

These requirements drive the concept of ALMA to its current technical specifications. A simplified flow-down of science requirements into technical specifications is:

1) For high redshift galaxies, the translation of the science requirement into a performance specification can be easily made by comparison with the results obtained by current millimeter arrays, which have collecting areas between 500 and 1000 square meters. These arrays can detect CO emission from the brightest galaxies, amplified by gravitational lensing in one to two days of observations. Signals from normal, unlensed objects will be typically 20-30 times fainter.

The sensitivity of an array is essentially controlled by three major factors: the atmospheric transparency, the noise performance of the detectors, and the total collecting area. Compared to current mm arrays, by locating ALMA on a better site, the contribution of the atmosphere will be minimized. The noise level of the detectors cannot be reduced by much more than a factor of 2, because these receivers are approaching fundamental quantum limits. An important factor of square root 2 will be gained by the requirement that ALMA support front end instrumentation capable of measuring both states of polarization. The remaining factor 7-10 can only be gained by increasing the collecting area by a similar amount. Hence, the ALMA goal is to achieve at least 6500 square meters in collecting area.

The spectral lines of scientific interest as diagnostics of the gas content and dynamics of a galaxy early in the history of the universe have frequencies that are fixed in the rest frame of the galaxy, but we observe these lines at a frequency that depends on the redshift of the particular galaxy. Since galaxies are found at every redshift (i.e., age), the goal of the ALMA Project is to provide the capability to observe in all atmospheric windows from

30-950 GHz so that galaxies of all ages may be studied. Initially, the Project will support observations in the seven highest-priority frequency bands. Additional capabilities can be added in the operational phase of ALMA. Since the redshift of the galaxies will initially be essentially unknown, the instantaneous bandwidths of the receivers should also be as large as possible.

2) A similar sensitivity argument can also be made for the studies of protoplanetary disks: going from the 0.5" angular resolution obtained in the best images with current millimeter arrays to the 0.1" resolution comparable with that of optical telescopes requires a factor 25 improvement in sensitivity, similar to that mentioned above. In addition, proper study of the kinematics requires spectroscopy with velocity resolutions finer than 0.05 km/s, or a few 10 kHz only.

Gaps created by proto Jupiter-mass planets in protoplanetary disks are expected to be of the order of 1 AU in size. Combined with the distance of the nearest star forming regions, 60-140 pc, this implies that ALMA needs to provide 10 milli-arcsecond resolution or better. This can be obtained by combining high frequency (650 GHz and above) observations with array configurations approximately 10 km in physical dimension.

The sensitivity of ALMA highlighted above will allow, for the first time, the opportunity to investigate the structure of the magnetic field both in the larger protostellar regions and in the small protoplanetary disks, by observing polarized emission from dust. The spatially-resolved kinematics of a rotating, infalling protostellar envelope provides insight into the hydrodynamics of star formation, whereas the morphology of the magnetic field probes the magnetodynamics. The combination of the two will allow astronomers to discover the physical process by which magnetic fields accelerate or impede the process of star and disk formation. The requirement to support these observations emphasizes again the firm requirement for the ALMA receiving system to have full polarization capability. The formation of stars and planets also causes changes in the density, temperature and chemistry in the envelopes and disks. Wide frequency coverage is essential to probe these different conditions.

3) High fidelity imaging requires a sufficient number of baselines, in order to cover adequately the uv plane (i.e., the time/frequency domain in which the data are sampled). Detailed studies of the imaging performance of aperture synthesis arrays have shown that imaging performance implies a minimum number of antennas, 40 or above, and accurate measurements of the shortest baselines, as well as of the large scale emission measured by total power from the antennas. Such accurate measurements can only be obtained with high quality antennas, with superior pointing precision. High fidelity imaging also requires the ability to perform calibrations to “freeze” the atmospheric turbulence which distorts the radiation coming from celestial sources.

The combination of these three major requirements calls for a reconfigurable zoom-lens array covering baselines from a few meters up to several kilometers, observing over the full millimeter and submillimeter atmospheric windows. The maximum size of the individual antennas is driven by the required pointing and surface precision: a choice of

12-m antennas offers an excellent technological compromise. To provide no less than 6500 m^2 of total collecting area, at least 54 12-meter antennas and 12 7-meter antennas are needed, which is a large enough number to guarantee excellent imaging performance.

Further, to allow cancellation of atmospheric disturbances, the antennas must be equipped with water vapor radiometers to measure atmospheric path length variations and correct the image distortions such phase variations create. This is a technique identical in its purpose and application to adaptive optics as used for ground-based telescopes operating at visual and infrared wavelengths. In addition, ALMA is designed to be able to detect calibration sources such as quasars in a time short enough to minimize the atmospheric phase fluctuations so that the needed correction may be as small as possible. Detecting weak sources requires wide instantaneous bandwidth for all the front end receivers to maximize the continuum sensitivity.

The final major scientific requirement affects the diverse community that will use and benefit from the scientific capabilities that ALMA brings to extend their research endeavors: ALMA should be “easy to use” by novices and experts alike. Astronomers certainly should not need to be experts in aperture synthesis to use ALMA. Automated image processing will be developed and applied to most ALMA data, with only the more intricate experiments requiring expert intervention.

3. ALMA ORGANIZATION AND MANAGEMENT PLAN FOR CONSTRUCTION

The entities that create the ALMA Project are the *Parties*, who are the funding sources for the Project. The Parties have two initial responsibilities: (1) to each appoint an *Executive Agency*, or *Executive*, to carry out and manage the Project tasks and responsibilities that are agreed to belong to each Party; and (2) to establish jointly, and by agreement, an oversight body for the Project, the *ALMA Board*, composed of representatives of the Parties, the Executives and the user communities. While the ALMA Board is not a legal entity, the Executives are legal entities and they can enter into contracts, employ staff, etc., to construct and operate ALMA. In order to carry out their ALMA functions each of the Executives will create an *ALMA Project Office* and secure for that office the staff and resources necessary for the performance of the ALMA tasks assigned to that Executive. The ALMA Board has the responsibility to establish a *Joint ALMA Observatory* whose staff members will be employees of the Executives. As a first step toward the Joint ALMA Observatory, the Board has organized the Joint ALMA Office (JAO) that is authorized to direct and manage the overall ALMA Project. The JAO will carry out its management function by specifying, in concert with the ALMA Board, the scope, schedule, and tasks of the Project and managing the efforts of the Executives to provide the necessary deliverables. The ALMA Board also appoints the ALMA Science Advisory Committee (ASAC) and the ALMA Management Advisory Committee (AMAC).

3.1 Management Structure

The ALMA Project management structure, shown in Figure 3-1, is based on the concept of *Integrated Product Teams* (IPTs) of the three Executives. The ALMA Board serves the function of a board of directors, the JAO functions as the project management, and the IPTs function as task managers.

3.1.1 Joint ALMA Office (JAO)

The Joint ALMA Office is the focal point for implementation of the ALMA Project. In accordance with Articles 14 and 15 of the ESO/NSF/NINS ALMA Agreement, the JAO is composed of the following personnel who report to the ALMA Board:

- ALMA Director
- ALMA Project Manager
- ALMA Project Scientist
- ALMA Project Engineer

The responsibilities and authorities of these positions are defined by the ALMA Board.

In addition, the JAO will have the necessary staff to provide project control, scheduling, and supporting administrative functions. The staff of the JAO will be co-located. With approval of the ALMA Board, each key member of the JAO will be employed by one of the Executives.

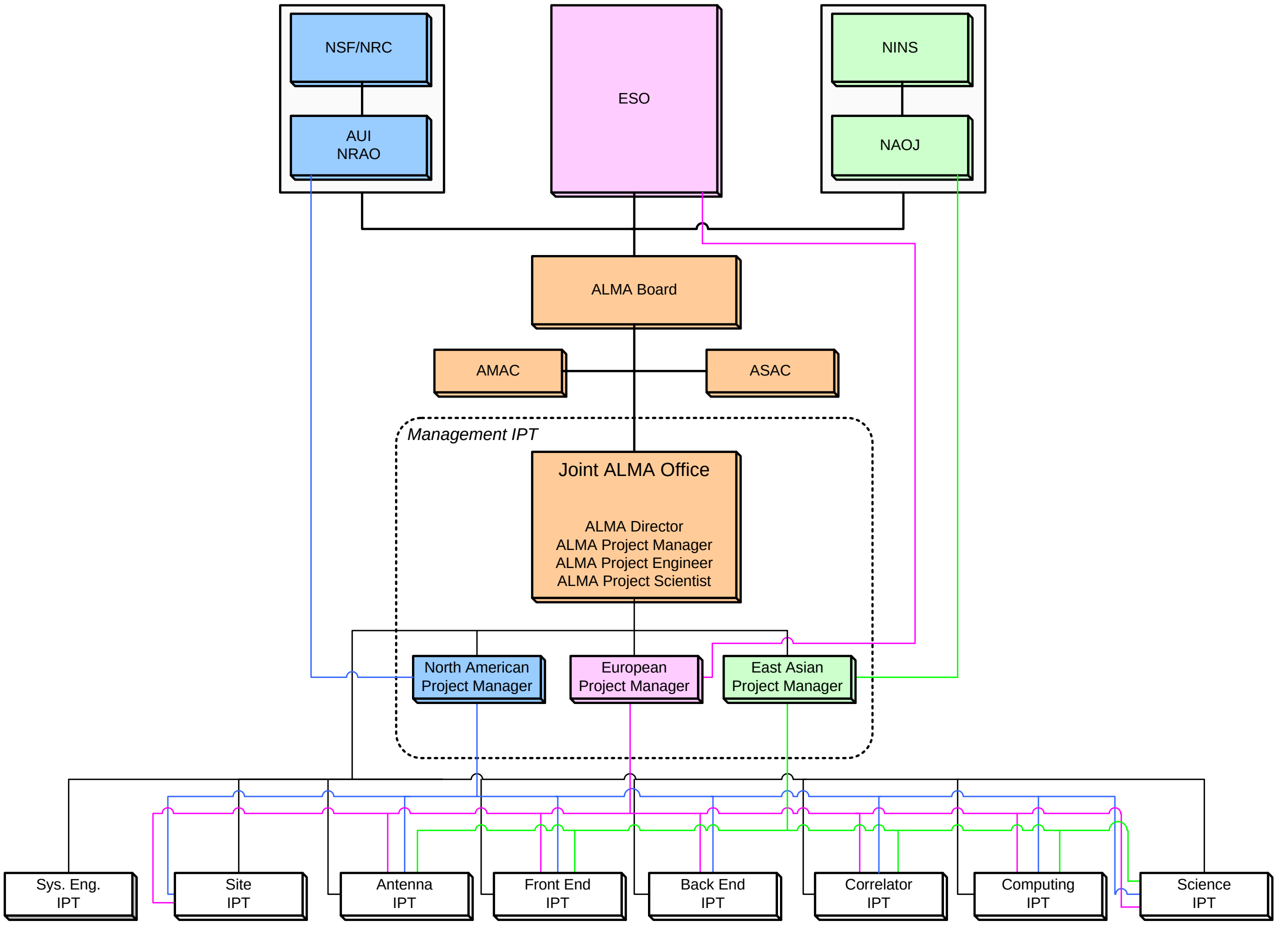

Figure 3-1. Project Organization for Construction

Project Scope and Schedule. The JAO will:

- Maintain the top-level scientific requirements and scope of the Project. The requirements and scope are defined by the ALMA Board in consultation with the JAO, taking into account input from the user communities (as represented by ASAC).
- Establish the technical requirements for the ALMA system. Working in conjunction with the IPT Leaders, their Deputies, and the European, North American, and East Asian ALMA Project Managers ("Regional ALMA Project Managers"), the JAO establishes the technical specifications corresponding to the top-level scientific requirements.
- Establish and maintain the Project Work Breakdown Structure (WBS) and Schedule, and maintain the Schedule of Values and Assignment of Deliverables.
- Establish and control the configuration. When the specifications or WBS must be changed, the JAO controls the change process and manages the consequences of a change.
- Define, maintain, and enforce Interface Control.
- Confirm key appointments.

Earned Value. The JAO will:

- Provide an impartial and consistent accounting of the earned value. This applies both to the baseline project and any additions or proposed alternatives.

Accountability. The JAO will:

- Establish and enforce acceptance criteria for delivered hardware and software.
- Be accountable to the ALMA Board for achieving the ALMA scientific requirements.
- Be accountable to the ALMA Board for management of the Project.

3.1.2 North American ALMA Project Office

ALMA work packages assigned to North America will be the responsibility of the North American ALMA Project Office, which will be part of the North American Executive (AUI/NRAO). The North American ALMA Project Manager will report to the ALMA Project Manager for all technical purposes; further details are given in Section 3.2.1. The North American Project Office will be responsible for ensuring that the resources are made available to carry out the NA work packages to specifications and schedule. Each work package will be covered by a formal agreement between the institution concerned and AUI/NRAO. Working through the Project IPT structure, the North American Project Manager will be assisted by IPT Managers within North America, each of whom has the responsibility for tasks within a given level-1 WBS. The IPT Managers will act either as the IPT Leader or Deputy in the corresponding IPTs.

3.1.3 European ALMA Project Office

The ALMA work packages assigned to Europe will be the responsibility of the European ALMA Project Office, which will be part of the European Executive (ESO). These work packages will be carried out in existing institutions across Europe, including ESO. The European ALMA Project Manager will report to the ALMA Project Manager. The European Project Office will be responsible for ensuring that the resources are made available to carry out the European work packages to performance and schedule. Each work package will be covered by a formal agreement between the institution concerned and ESO. Working through the Project IPT structure, the European ALMA Project Manager will be assisted by European IPT Managers drawn from the participating institutions. The IPT Managers will have the responsibility for tasks within a given level-1 WBS and will act either as the IPT Leader or Deputy in the corresponding IPTs.

3.1.4 East Asian ALMA Project Office

The ALMA work packages assigned to East Asia will be the responsibility of the East Asian ALMA Project Office, which will be part of the East Asian Executive (NAOJ). The East Asian ALMA Project Manager will report to the ALMA Project Manager. The East Asian Project Office will be responsible for ensuring that the resources are made available to carry out the East Asian work packages to performance and schedule. Each work package will be covered by a formal agreement between the institution concerned and NINS/NAOJ. Working through the Project IPT structure, the East Asian ALMA Project Manager will be assisted by East Asian IPT Managers drawn from the participating institutions. The IPT Managers will have the responsibility for tasks within a given level-1 WBS and will act either as the IPT Leader or Deputy in the corresponding IPTs.

3.1.5 Integrated Product Teams

The essence of the IPT concept is the recognition that the level-1 WBS tasks are shared between the three Executives. For this reason the leadership for those level-1 tasks is also shared. The IPT is that shared leadership. Each IPT consists of all those individuals who are assigned by one or another of the Executives with significant responsibility for work elements within a given level-1 WBS task. The Executives' respective task leaders provide the leadership of each IPT. One of these persons will be identified as the IPT Leader and the others will serve as the IPT Deputy Leader. The intent is that these three individuals will normally resolve any technical issues that arise within the IPT.

The IPT Leader and the Deputies are vested with the responsibility to assign, coordinate, and monitor subtasks as specified by the ALMA WBS. In practice, this means that each of these individuals is responsible for completing the assigned subtasks using the resources provided by their respective Executives.

The IPT management structure is a powerful method of organizing work carried out across geographic, institutional, and professional boundaries. It allows work packages assigned to different organizations utilizing different skill sets to be effectively coordinated. The IPT model is adopted for the ALMA Project to achieve the following goals:

- Provide a single point of integrative responsibility for each major work package. A single individual, the IPT Leader, is identified for each IPT. This Leader is responsible for assuring that the various work packages, when completed, will meet the Project schedule and the performance specifications.
- Provide common, coordinated, management of the IPT and the work groups within the Executives. The IPT Leader and the Deputies are themselves the work managers for the Executives. Common management provides the link between the Project coordination function and the means to accomplish the work within the Executives.
- Make decisions at the lowest level in the organization where sufficient knowledge is available. The organizational and technical complexity of the ALMA Project makes it impossible for all significant decisions to be deliberated Project-wide. Instead, responsibility will be delegated to the IPTs and will carry with it authority to make decisions within that particular IPT provided that the result is compatible with the overall scope and schedule of the Project.

3.1.6 Management IPT

The JAO together with the European, North American, and East Asian Project Managers constitute the Management IPT.

3.1.7 ALMA Scientific Advisory Committee

The ALMA Science Advisory Committee (ASAC) will provide regular scientific advice to the Project through reporting to the ALMA Board. The ALMA Board, in consultation with the JAO, will define the terms of reference of the ASAC and appoint its members. Written reports of the ASAC's discussions will be made to the ALMA Board by the chair of the ASAC following each committee meeting, and relayed to the ALMA Director by the Board Chair.

3.1.8 ALMA Management Advisory Committee

The ALMA Management Advisory Committee (AMAC) will provide regular management, cost, schedule, and technical advice to the Project through reporting to the ALMA Board .The ALMA Board, in consultation with the JAO, will define the terms of reference of the AMAC and appoint its members. Written reports of the AMAC's discussions will be made to the ALMA Board by the chair of the AMAC following each committee meeting, and relayed to the ALMA Director by the Board Chair.

3.2 Management Controls – Relationship of JAO to Executives

The organization of the JAO provides the centralized decision-making and Project direction required to maintain the Project schedule and successfully manage ALMA construction activities that are carried out by the Executives. On the other hand, the risks in ALMA are borne by the Executives and it is recognized that there may be instances when the Executives cannot accept the legal, financial, or political risk associated with a proposed JAO decision. In these cases, of necessity, the JAO will need to seek an acceptable alternative. The Executives agree not to impose their prerogatives unnecessarily, exercising their right to alter JAO decisions only in cases where the risks are judged to be large.

While career development decisions for Executive project personnel reside with the Executives, it is important for the JAO to participate in the processes which lead to these decisions for key ALMA personnel: IPT leaders/deputies and above.

3.2.1 Role of the Regional ALMA Project Managers

The Regional ALMA Project Managers perform a critical role in maintaining the linkage between the Joint ALMA Office and their respective Executives. In addition to reporting for technical purposes to the ALMA Project Manager as provided in Sections 3.1.2 to 3.1.4, the Regional ALMA Project Managers, who shall be physically located with their Executives, are responsible for managing the execution of the work packages under their control and for reporting cost, scope and schedule information to their respective Executives in sufficient detail to permit the Executive to exercise their managerial and legal responsibilities consistent with the subsections below.

3.2.2 Budget Process[5]

The value of each work package in the WBS is the estimated cost plus a contingency that reflects the risks and uncertainty of the estimated cost. The budgeted value of each work package will be established as the estimated cost at the outset of construction, exclusive of any contingency. A time-phased budget based on this value, broken down into the major categories of expenditure (labor, materials, travel, contracts, etc.), will be established and documented for each work package. The Work Package Manager must request approval of any changes to this budget. Documented requests for budget changes will be directed to the Project Manager of the responsible Executive. The responsible Executive Project Manager can approve the budget change request, subject to the provisions of Section 3.2.4, and if it can be absorbed within the overall budget, including contingency, of the responsible Executive. The JAO must be informed of any budget change that is so approved. Any budget change that cannot be absorbed within the overall budget of the responsible Executive must be brought to the attention of the JAO. If the responsible Executive wants to request a corresponding change in the value of its contribution, the change must be submitted to the ALMA Board for approval.

3.2.3 Cost Control[6]

Primary responsibility for cost control rests with each Executive. Each Executive will use their established financial reporting and information system to track expenditures and provide this information to the JAO. At the lowest level the Work Package Managers regularly monitor expenditures versus the budget (expenditure plan). Financial information comes either from the responsible Executive or the financial reporting and information system of the institution responsible for the work package, as appropriate. In addition, the Work Package Manager produces an estimated cost to complete the work at least twice per year. The Project Manager of the responsible Executive monitors regularly the cost performance of the aggregate of work packages for which she/he is responsible and reports the status to the JAO. The JAO in turn monitors the total Project performance and reports it to the ALMA Board in semi-annual reports and meetings. However, responsibility for taking corrective action and/or requesting a budget change rests with the responsible Executive.

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[5] The reporting and the JAO control concerning the budget, cost and contingency described here apply to the European and North American Executives. For the East Asian Executive, detailed monitor and control of the financial aspects by JAO are not practical due to technical reasons, and the Executive takes financial responsibility in ensuring the realization of tasks and deliverables assigned.

[6] Same as 5.

3.2.4 Contingency[7]

On each side the aggregate contingency of all of the work packages for which each Executive is responsible will be pooled at the level of the Executive. IPT Managers will be allocated those funds indicated by the "Task Subtotal" column shown in the tables in Appendix A. The pooled contingency will be held and controlled by the Project Managers of each Executive. When a Work Package Manager is convinced that the tasks in the work package cannot be completed for the budgeted cost, the Work Package Manager will request a budget change as described in Section 3.2.2. The approval of the JAO, and Board approval if the Value concerned exceeds $l million or €1 million, shall be required for the use of contingency in excess of $500,000 or €500,000 by the Executives.

3.2.5 Business Procedures

Each Executive will use their established business and administrative procedures. These include personnel policies and procedures, contracting and contract management procedures, accounting and financial reporting procedures, travel policies and procedures, and shipping/import/export procedures.

3.2.6 Schedule Control

Schedule definitions are currently under revision. The baseline schedule is controlled at the level of the funding agencies.

Level-1 Milestones are specified by the ALMA Board, which must approve all changes to Level-1 Milestones. The JAO will establish and maintain a project master schedule based on Level-1 Milestones. Each IPT will build up a set of Level-2 Milestones for which it is responsible, consistent with the Level-1 Milestones. Each Work Package Manager will develop and maintain a set of Level-3 Milestones for their work packages, consistent with Level-2 Milestones. Schedule status will be reported up through the project organization –from work package managers to IPTs, to the JAO, and finally to the ALMA Board. Level-2 Milestones are given in Appendix B.

3.2.7 Management Reporting[8]

The Work Package Managers will receive monthly reports of the financial status of their work packages from the responsible Executive and provide a monthly report of technical, schedule, and financial status to the relevant IPT. The IPTs will conduct periodic reviews of the status of the work packages for which they are responsible and provide a report to the JAO. The JAO, through the Project Managers of the Executives, will provide status

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[7] Same as 5.
[8] Same as 5.

reports to the Executives. The ALMA Director will provide a monthly report of the Project status to the ALMA Board.

3.2.8 Project Management Control System

The JAO will be responsible for the implementation and operation of a Project Management Control System (PMCS) that will be used as a project management tool by the JAO and the Executives to track actual progress vs. milestones, to identify critical path linkages, and other project management functions. The European and North American Executives will provide the JAO with the data necessary to operate such a system, as will the East Asian Executive.

3.2.9 Programmatic Reviews

The IPT reviews referred to in Section 3.2.7 will be informal programmatic reviews at the working level. In addition, the ALMA Director will conduct formal programmatic reviews of the entire Project. Each IPT, including the JAO, will present the technical, schedule, and financial issues that will affect their ability to achieve their goals of the work packages for which they are responsible. The reports from the ALMA Director to the ALMA Board will follow from the Director's programmatic reviews.

3.2.10 The ALMA Configuration

The term "ALMA configuration" refers to all those documents that define the Project. For the purpose of configuration control, the ALMA documents are divided into four groups:

- Board-level documents
- Project-level documents
- IPT-level documents
- Non-controlled documents

Configuration control acts on the documents that define the Project. The process that is used depends on the type of document to be controlled.

Configuration control is made up of four main elements:

- A means of formally requesting a change
- A process for analyzing the technical, performance and schedule impacts of the proposed change
- A process for making a decision concerning the change
- A process for communicating that decision

The application of these elements to each of the four types of ALMA documents is as follows:

- Board-level documents include this Project Plan, official cost and task division documents, the top-level Science Requirements Document, and international agreements passed by the ALMA Board. Baselining of, and changes to, Board-level documents can be requested by Board members and require direct action by the ALMA Board; it is the responsibility of the ALMA Director to implement changes approved by the Board.

The ALMA Project Manager defines which documents are project-level documents and then determines when a version of each document is to be submitted to the Configuration Control Board (CCB) for baselining. Once baselined, all change requests must be presented to the CCB.

- Project-level documents include the Project Book, top-level engineering requirements for each major subsystem, and ICDs between subsystems that cross IPT or WBS boundaries. Change Requests (CRs) to project-level documents can be initiated by any of the work package or work element managers and require action by the CCB.

- IPT-level documents include detailed drawings and documents intended to implement the contents of project-level documents. Control of these documents is the purview of the IPT management. It is the responsibility of the IPT management to ensure that these documents are consistent with all applicable project-level documents.

- Non-controlled documents include the ALMA Memo Series and other documents that do not officially define the Project. Baseline and change authorization for these documents depends on the document type, but all such processes are outside CCB control.

Configuration Control Board (CCB). The Configuration Control Board is responsible for managing changes to all project-level documents. The CCB is chaired by the ALMA Project Manager. A senior member of the System Engineering IPT will serve as the CCB Secretary.

In addition to the ALMA Project Manager, the CCB shall consist of the following permanent members:

- Regional ALMA Project Managers
- ALMA Project Scientist
- ALMA Project Engineer

Additional temporary CCB members may be added at the discretion of the CCB Chair when she/he feels that a particular issue needs special consultation. In any case, as noted below, the CCB solicits input from all IPTs prior to considering a requested change. It is anticipated that most actions will be carried out by consensus of the CCB membership. If efforts to reach consensus fail, a vote of the members will be necessary. The ALMA

Director has the authority to rescind actions of the CCB by informing the ALMA Project Manager and the ALMA Board.

Configuration Control

A well-defined and organized process for controlling and communicating changes throughout the complex and geographically dispersed ALMA Project is essential. Configuration control processes ensure that changes proposed are accepted only after their impacts are well understood and that all parts of the Project are aware of changes in a timely manner. A process involving the Configuration Control Board will be used to control changes affecting scope, schedule and performance.

3.3 Safety and Health

Many ALMA construction activities will take place at existing organizations (e.g., ESO, NAOJ, NRAO, including Chilean operations, and other East Asian, European, and North American institutions) with established safety and health policies and regulations that comply with applicable national or international requirements. The ALMA Project will abide by these established policies and will only create new rules and regulations if no applicable rules and regulations exist. The persons responsible for safety and health management at the participating organizations will report the results of any relevant safety and health audits or reviews to the ALMA Director, in addition to fulfilling their normal reporting procedures to the Executives. Members of the ALMA Project staff will serve on safety and health committees at their respective locations.

An ALMA Safety Committee reporting to the ALMA Director will be established to:

- Define project-wide safety policy;
- Establish safety standards applicable to ALMA;
- Oversee implementation of the safety program;
- Establish emergency procedures and a reporting process.

The ALMA site at 5000 meter altitude in Chile presents unique safety and health challenges. The ALMA Project will abide by all applicable safety and health rules and regulations imposed by Chile. The applicable Chilean rules and regulations will be defined in the course of the negotiations to obtain the necessary permissions for construction and operation of ALMA.

4. WORK BREAKDOWN STRUCTURE, SCHEDULE OF VALUES AND ASSIGNMENT OF DELIVERABLES FOR ALMA CONSTRUCTION

4.1 Work Breakdown Structure

The ALMA Work Breakdown Structure (WBS) is a detailed description of all the tasks necessary to construct the instruments and software required for ALMA; to construct the buildings, roads, antenna foundations, utilities and infrastructure needed for the support of those instruments and software; to integrate the whole into a properly functioning synthesis array telescope on the Chajnantor site in northern Chile; and to manage the construction project on behalf of the sponsoring ALMA partners.

The ALMA construction project has adopted a management structure based on the Integrated Product Team (IPT) concept. The IPT concept provides a method of managing tasks carried out across multiple organizations and locations. Each Level One WBS element is managed by an IPT responsible for delivering the required products on time, within the specified cost and meeting the Project requirements.

The ALMA WBS was derived in three steps. First, the scientific requirements for ALMA were specified by the ALMA Science Advisory Committee (ASAC). Second, a technical description of an array capable of meeting those requirements was outlined by the technical leaders of the ALMA Project in Europe, North America, and East Asia. Close and frequent interaction was required between the ASAC and the technical project leadership to assure that the planned technical capabilities met the science requirement priorities. Third, a plan for design and fabrication, or procurement, of all the hardware modules and subsystems was established. Costs were estimated for all tasks and subtasks. The process was informed and constrained by the estimated resources the sponsors were intending to commit to ALMA. The resulting project description was organized into the WBS which specifies in sufficient detail the tasks and the resources, both personnel and financial, required to realize those tasks for the completed Project.

The WBS for the ALMA construction project is included below. The WBS is organized into nine level-1 tasks:

1. Management (*)
2. Site Development
3. Antenna Subsystem
4. Front End Subsystem
5. Back End Subsystem
6. Correlator
7. Computing Subsystem
8. System Engineering and Integration
9. Science

* Note: Education and Public Outreach and Safety are functional tasks of the Management IPT.

4.2 Schedule of Values[9]

Costs and contingencies were developed for each subtask of the WBS and rolled up as the summed costs of tasks; the task costs were subsequently rolled up as the summed project cost. The basis for the cost estimates was a bottom-up sum of the costs associated with each subtask of the project-wide WBS. The European, and North American technical leaders, working together, developed estimates for the entire task product tree using a standard project-supplied *ALMA Cost Data Sheet* that asked the technical leaders to provide for each task:

- Task description
- Task duration (or start and stop dates and predecessor tasks)
- Currency used for materials, supplies and contract expense
- Basis of the estimate
- Contingency
- Staff effort
- List of materials and estimated cost of each
- List of contracts and estimated cost of each
- Cost parameterization.

Personnel costs are fully burdened costs. That is, the personnel costs include personnel benefits and a percentage of institutional indirect costs. The institutional indirect cost is a uniform percentage derived from the major partner institutions; this is done to make the personnel cost independent of where the work is performed.

Contingency was separately calculated for each subtask. The contingency methodology used was a *bottom-up* computation of the sum of three separately calculated contingencies. These three contingencies correspond to three different risk factors: the technical risk (how difficult is the task?), the cost risk (what is the uncertainty on the cost?), and the schedule risk (how does this task affect the overall schedule?). Estimators evaluated the technical, cost and schedule risk factors for a particular WBS task and then entered those factors in the ALMA Cost Data Sheets.

The resulting costs and contingencies are shown on the WBS at level-3. Where the costing estimates were made at a lower level, these have been rolled up and displayed at level-3. Three cost columns are shown: the level-3 task cost, computed as described above, the computed task contingency, and the task *Values* which is the sum of cost and contingency for each task.

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[9] For historical reasons, this process was followed by the European and North American Executives only. The assignment of Deliverables and their Values for the East Asian Executive was made as described in 4.4.

4.3 Assignment of Deliverables

As stated in Article 2 of the bi-lateral ALMA Agreement and in Article 4 of the ESO/NSF/NINS ALMA Agreement, two ALMA Parties, North America and ESO, will make equal value contributions to ALMA with the work equally and equitably shared between North America and ESO, and the East Asian Party will make a value contributions to ALMA as defined in the latter Agreement and its Amendments.

For the assignment of deliverables between North America and ESO, using the *Values* assigned to level-3 tasks, the tasks were divided between the two Parties in a manner that (a) led to an equal assignment of value to both sides; (b) led to a division of equal risk, as measured by contingency, to both sides; and (c) respected particular institutional experience on both sides. The division of *Values* was also informed by the funding schedules planned by both parties over the ten-year duration of the construction project.

The resulting division of *Values* is presented in the WBS for each level-3 task as a percentage division between Europe and North America. A Cost Summary sheet, included with the WBS, presents explicitly this same information rolled up to level-1.

<u>Value:</u> An ALMA Partner executing a particular level-3 task will receive for the successful completion of that task credit for the *Values* assigned in the WBS. The Partner has the discretion to carry out the task in the manner the Partner chooses to be in its best interest, but the *Values* is not affected by that choice.

<u>Responsibility:</u> Task responsibility is assigned at WBS level-2. This is noted for each task in the final (right-most) column in the WBS. The level-2 tasks are referred to as *work packages* that the responsible partner may wish to assign to one of its participating institutions. Each work package is sub-divided into *work elements*. These are the level-3 tasks to which *Values* are assigned. Usually the work elements are assigned wholly to one partner or the other. In the case of shared level-3 tasks the division of effort as 100 percent to one side or another is made at a still lower level.

4.4 Deliverables and Values for East Asian Executive

The assignment of Deliverables and their Values for the East Asian Partner and Executive was made in the same spirit, but through a somewhat different process, as described in the ESO/NSF/NINS ALMA Agreement. To realize the task and deliverables assigned to the East Asian Partner, the East Asian Executive built up the lower level WBS for execution within it. For the successful completion of that task, the East Asian Partner is credited 25% of the total *Value* of ALMA.

5. ALMA CONSTRUCTION PROJECT TIME SCHEDULE

CURRENTLY UNDER REVISION

Level 1 Milestones	Date
Start Antenna Evaluation at ALMA Test Facility	Q4 2002
Begin Initial Phase of Civil Works in Chile	Q4 2003
Central Back End System Ready to Install at Array Site	Q1 2005
Initial Phase of Civil Works in Chile Complete	Q2 2005
First Antenna-Based Back End Subsystem Ready for Installation at OSF	Q2 2005
First Production Antenna Available in Chile at OSF	Q4 2005
Initial Front End Subsystem Available at OSF	Q4 2005
Start Early Science Operations	Q3 2007
Completion of Construction Project	Q4 2011
Start Full Science Operations	Q1 2012

6. OPERATIONS PLAN FOR THE ATACAMA LARGE MILLIMETER ARRAY

6.1 ALMA Operations Organization and Management Structure

ALMA is a joint scientific venture among Europe, North America, and East Asia, with participation by the Republic of Chile. ALMA operations will serve these communities in a way that distributes the burdens and benefits in a mutually agreeable way. The organizational structure for ALMA operations is derived from the organization of the Project for the construction phase and is shown in Figure 6-1.

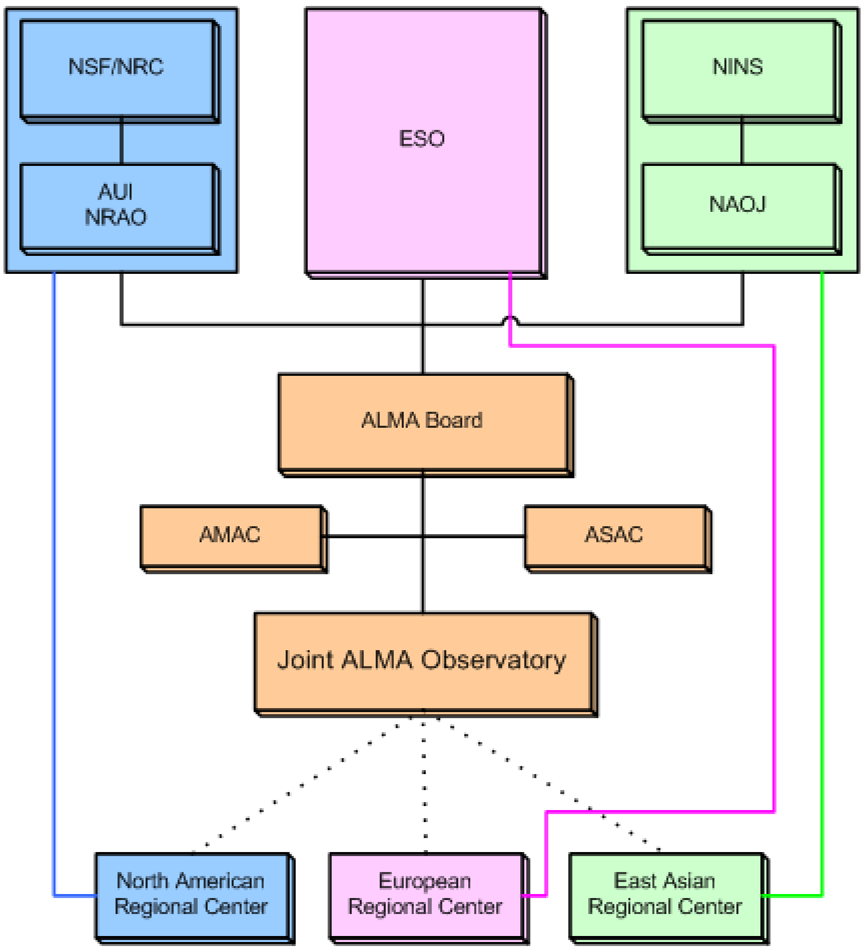

Figure 6-1. ALMA Organization for Operations

The Joint ALMA Observatory is staffed and funded by the Executives, and overseen by the ALMA Board, composed of representatives of the Parties, the Executives and the user communities. The function of the Joint ALMA Observatory is the operations and maintenance of the array at the Array Operations Site (AOS) and the Operations Support Facility (OSF) in Chile. Its top-level organization view is shown in Figure 6-2. Figures 6-3 through 6-4 below show the organizations of the three major sub-elements.

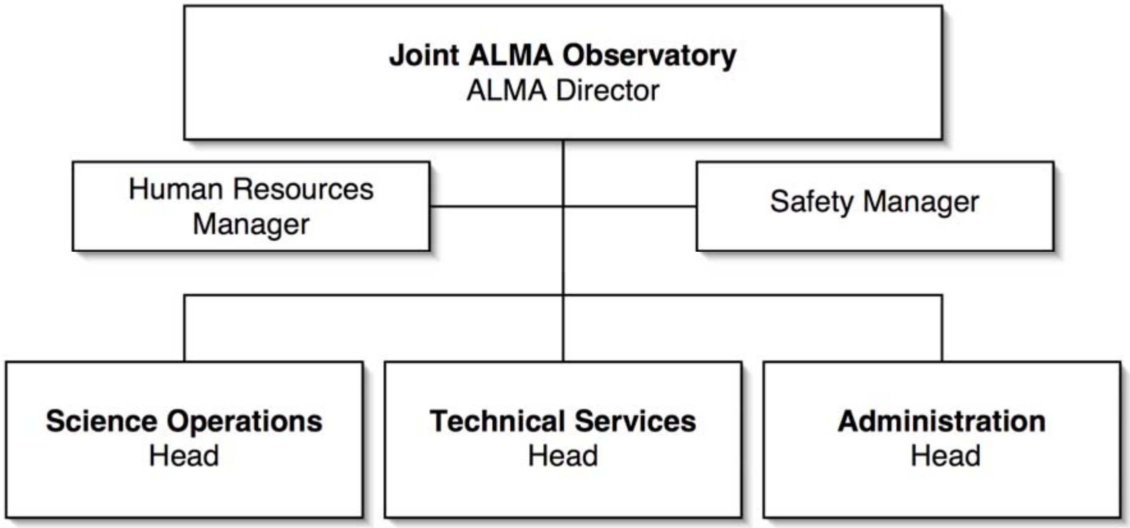

Figure 6-2. ALMA Chilean Operational Structure

The ALMA Director's Office (ADO) is the focal point for operations management of the Joint ALMA Observatory. The ADO will be composed of the following personnel:

- ALMA Director
- Head of Administration
- Head of Science Operations
- Head of Technical Services.

The ALMA Director leads the Joint ALMA Observatory and reports to the ALMA Board. The ALMA Director shall have the responsibilities and authorities as stated in the bi-lateral ALMA Agreement and the subsequent ESO/NSF/NINS Agreement. The ALMA Board appoints the ALMA Director and the remaining key personnel in concurrence with the ALMA Director.

In response to the ALMA Director's requirements, the Executives hire the necessary staff for ADO activities. All ADO staff will be co-located in Santiago de Chile at the Central Office, except for tasks better executed at the Operations Support Facility near San Pedro de Atacama, as deemed necessary by the ADO. Each member of the ADO will be employed by one of the Executives.

All Joint ALMA Observatory staff members are employees of the Executives assigned to ALMA subject to the approval of the ALMA Director. All Joint ALMA Observatory staff members in Chile are managed by, and report to, the ALMA Director.

The necessary scientific interactions and support of the respective communities with ALMA will occur through ALMA Regional Centers (ARCs) operated and managed by the Executives. The ARCs will have “core functions” determined by the ALMA Board, as well as “additional functions” which may differ among the ARCs and are managed by the Executives. The internal organization of the ARC is the responsibility of the Executive. The tasks of the ARCs are discussed further below.

Each ARC will have a Manager. Like all ARC employees, the ARC Manager is hired by and reports to the regional Executive. The ARC Manager is responsible for providing Board-approved operational deliverables to the Joint ALMA Observatory and the regional ALMA user community, per the detailed requirements and schedule established by the ADO.

Analogous to the ALMA Management IPT for Construction, the Joint ALMA Observatory shall have a Management Team that consists of the Head of Administration, the Head of Science Operations, the Head of Technical Services, and the ARC Managers. The Management Team is led by and reports to the ALMA Director.

In conjunction with the Joint ALMA Observatory Management Team, the ALMA Director is responsible for:

- Establishing end-to-end operational priorities and schedules, subject to the review and approval of the ALMA Board
- Ensuring that sufficient operational interfaces are implemented and maintained between the Chilean operations group(s) and the ALMA Regional Centers (see below).

The ALMA Director is responsible for resolving operational conflicts between the Chilean operations group(s) and the ARCs. As necessary, the ALMA Director shall take such conflicts to the Executive and/or Board level for discussion and resolution.

The organization of the ADO and its relationship to the ARC Managers provides the necessary centralized decision-making and direction required to manage a distributed operations structure. On the other hand, the risks in ALMA operations are borne by the Executives. It is recognized that there may be instances when the Executives cannot accept the legal, financial, or political risk associated with a proposed ADO decision. In these cases, of necessity, the ADO will need to seek an acceptable alternative. But the Executives agree not to impose their prerogatives unnecessarily, exercising their right to alter ADO decisions only in cases where the risks are judged to be large. The career development decisions for ALMA Regional Center personnel reside with the Executives while it is important that the ADO participate in the processes that lead to these decisions for ARC Managers.

The European, North American, and East Asian ALMA Regional Center Managers (the “ARC Managers”) perform a critical role in maintaining the linkage between the ALMA Director’s Office and their respective Executives. In addition to reporting for operational purposes to the ALMA Director as provided above, the ARC Managers are responsible for managing the execution of the operational tasks under their control and for reporting cost, scope and schedule information to their respective Executives in sufficient detail to permit the Executive to exercise their managerial and legal responsibilities consistent with the subsections below.

The roles of the ASAC and AMAC as defined in Section 3 shall continue during ALMA operations.

6.2 ALMA Operations and Maintenance Model

6.2.1 Guiding Principles of ALMA Operations

An ALMA operations plan that enables scientists to realize the enormous potential of ALMA is a fundamental deliverable of the Project. This goal can be achieved with the following principles underlying its operations plan:

(a) The operations plan, just as in construction, embodies the guiding principles of the bi-lateral ALMA Agreement (Article 2) and the ESO/NSF/NINS ALMA Agreement (Article 4), namely parity, merit, utilization of existing facilities, and free movement of materials.
(b) The Operations Plan is in accordance with the agreements signed by the ALMA Executives with the host country, Chile.
(c) The operations plan incorporates structures that maximize the scientific productivity of ALMA by facilitating and encouraging the fullest possible engagement of ALMA user communities, beyond their use of observing time, in the further development of ALMA. This includes opportunities for technical upgrades and development of new instrumentation and software over the lifetime of the array.
(d) The operations plan should ensure safe, efficient and cost-effective operations of the array and at the same time ensure delivery of data products of high and consistent quality, which can be used by both experts and non-specialists for scientific analysis.

These principles have consequences for the joint ALMA operations that are summarized in the following guidelines:

(i) The Joint ALMA Observatory is a service observing facility, for which the scientific demand will be very high. The astronomer is not normally required to be present when her/his observations are executed.
(ii) Following guidelines to be agreed by the ALMA Board, scientific observations with ALMA will be continually monitored to maintain parity of access by the Executives to relevant conditions (e.g., weather, stringency, source availability). The goal is to avoid creation of significant imbalances on time scales of a year.
(iii) ALMA operational activities in Chile are limited to what is required to acquire, certify and archive the scientific data of the scientific teams proposing observations; this includes certain business functions and other

activities requiring proximity to the array. For safety reasons, the number of ALMA staff working at the array site at 5000 meters elevation must be kept to an absolute minimum.

(iv) The main interface between the user communities and ALMA is through the ARCs including proposal handling and support for data reduction and archival research. The fundamental user interface provided by the ARCs involves observing preparation including preparing the scheduling blocks, and delivery of the standard pipeline data products to the user from the archive as soon as possible after observation.

(v) Development work on hardware and software is carried out by the Executives.

6.2.2 ALMA Operational Tasks and Deliverables

The operational tasks of ALMA start with the receipt of proposals for observations from the astronomical community. In accordance with the guidelines enumerated above, it is assumed that the potential users will propose a program of observations to their respective ARC. Once reviewed and accepted for observation in a manner to be decided by the ALMA Board, the astronomer will provide to the Observatory an observing script that specifies the observational goals in astronomical terms. That is, the astronomer specifies the target object, frequency, spectral resolution, array configuration (if applicable) and the desired on-source integration time, signal-to-noise desired, or the *uv*-coverage needed. It is the task of the Joint ALMA Observatory and the ARCs to deliver to the astronomer the following:

- A proposal preparation package, including a time estimator and a data simulator, which is capable of complete end-to-end simulation of the observations.
- Raw data and real-time calibrated, pipeline-processed, images of the target object.
- Calibrated *uv* data set including tables of the calibrations that have been applied, and tables of the monitor data, including prevailing metrological conditions, atmospheric transparency measurements and instrumental performance measures.
- Data path to a copy of this same information that has been submitted to the ALMA archive and notification of the proprietary period to that data.
- User support, including an off-line software analysis package for data manipulation, analysis, imaging and presentation aimed at both non-specialists and experienced users.

In order to supply these deliverables to the astronomer, the following functions should be carried out:

- Review the source script and scheduling blocks with the astronomer. The observations may be split into several scheduling blocks that can be carried out at different times. Each script will have a scientific rating and a threshold criterion for "*stringency*" that needs to be met before the program is run.
- Ensure that the array hardware and software at the OSF and AOS are functioning and maintained to specifications.

- Select a sequence of calibration observations that will enable the astronomer to meet her/his goals and that are consistent with the archive policy.
- Conduct pre-observations, if necessary, to select a nearby source for fast-switched phase calibration. Determine the position of that phase calibration source to the precision needed.
- Execute the program observations, including standard pipeline processing of the data.
- Perform a data quality assessment to confirm that the pipeline-generated images are free of corruption resulting from defective instrumentation.
- Transmit all astronomical and monitor data to the astronomer.
- Transmit the raw data, pipeline-processed images and the monitor data to the ALMA archive including with that data a date at which the proprietary period for the astronomer ends.
- Transmit copies of the archive to the ARCs.
- Provide support to the astronomers on issues related to proposal preparation, data reduction and archival research.
- Provide user feedback to the array operations.
- Ensure that array instrumentation and software is regularly upgraded and expanded over the lifetime of the array.

The following section outlines the different locations at which the above functions are carried out. A summary is included in Table 6-1.

6.2.3 Implementation Plan

Array Operations Site (AOS) - Chajnantor:
ALMA will be operated remotely from the mid-level Operations Support Facility (OSF) to minimize the number of ALMA staff at 5000m. This leaves on the AOS only those personnel needed to assure the security of the site, those responsible for module exchange – replacing failed instrument modules with functioning spares – and those whose task it is to transport the antennas as needed for array reconfiguration. The array will be designed and built to be modular in character and wherever possible self-diagnosing: each instrument will have provision for an adequate number of monitor points that are reported to the control computer in real time. The AOS will be connected to the OSF by means of a private road for the transportation of the antennas, and a communications highway involving buried optical fibers over which the astronomical data and the instrument monitor data are carried in real time and at high bandwidth. The AOS is further discussed in Section 6.5.

Operations Support Facility (OSF):

The main function of the OSF is the operation of the array and the acquisition of the astronomical data based on the proposal scheduling blocks. This includes responsibility for the calibration sequence, dynamic scheduling and execution of the observations, and a quick-look processing and inspection of the data for quality assurance.

Table 6-1. Summary of the Main Functions at the Different Locations

Location		**Main Functions**
AOS		
- Chajnantor:		Antenna re-configuration Instrument module exchange Security of site
OSF		
- San Pedro de Atacama:		Array scheduling + operations Quick-look reduction Maintenance + repair antennas Maintenance + repair instrumentation Administration, Safety
Central Office		
- Santiago :		Standard pipeline reduction Quality assessment Archive production Business functions Science offices
ARCs		
- EU, NA, EA:	Core:	Proposal handling User support for proposals, data reduction Host of archive copy, archival research support Provide feedback to Santiago/OSF on quality evaluations Provide user feedback to array operations
	Additional:	Advanced software/techniques* Training, summer schools* Financial support users*
Development		
- EU, NA, EA:		New/upgrades instrumentation New/upgrades software Additional functions for ARCs*

* Implemented separately by the Executives.

Another important function is the maintenance and repair of instrumentation and antennas. The location of the OSF is discussed in Section 1.3.2, and includes residential facilities for staff at the OSF and AOS, and offices for administration, safety and health. The personnel at the OSF and AOS will work turno shifts.

Central Office, Santiago:

The Santiago office is the location for all those business and administrative functions not directly related to the operation and maintenance of the array, and is the functional node for nearly all governmental relations, contracting and import/export administration. Santiago provides a living environment (schools, medical care, shopping, partner employment) that will aid retention of those members of the ALMA professional staff who are hired from abroad or may be on assignment from the Executives, and who will be working turno shifts at the OSF/AOS. The Santiago facility will contain offices for the staff astronomers to pursue their personal research.
The Chilean Regional Center will be provided with the basic software tools necessary for the preparation and submission of observing proposals, data analysis, and archival research.

The Central Office is further discussed in Section 6.5.

The Joint ALMA Observatory in Chile is responsible for data quality assessment and science product production. It is also responsible for operating the joint ALMA Archive. All astronomical and monitor data and pipeline data products (i.e. science images), once checked, are ingested into the joint ALMA Archive. These data and pipeline products are also transmitted to the ARCs, to be distributed to the users. The exact location and operational process for these tasks is still under discussion by the Executives and shall depend on staffing and computing infrastructure costs.

ALMA Regional Centers –Europe, North America, East Asia

Each Executive shall establish an ALMA Regional Center. Each ARC shall have a Manager. The internal structure of these ARCs is the responsibility of the Executives. These ARCs will be responsible for providing a "core package" of operationally critical services to ALMA operations in Chile and their respective regional user communities including:

- Phase 1 operations (e.g., proposal handling, proposal scientific ranking, and proposal preparation user support);
- Phase 2 (e.g., observation preparation user support, observation submission review, up to and including preparation of the scheduling blocks to be communicated to the Joint ALMA Observatory);
- Data product support (e.g., delivery of pipeline data products, user support for standard ALMA data products and data processing tools, basic data reduction support);
- ALMA archive operations (e.g. holding and serving a copy of the ALMA Archive, basic archive user support users). ALMA data will be made available to the Virtual Observatory (VO), but until the VO is firmly established, data archiving and dissemination must be carried out in a way that is not dependent on VO planning.

The final definition of this core package is to be determined and subject to Board approval. As part of the Board approval process, this core package will be assigned a cash value. This cash value will be considered part of the Executives' contribution to the Joint ALMA Observatory operations budget.

Each Executive may provide additional ARC services above and beyond Board approved operational critical activities. Such additional activities have no formal cash value in the context of the Bi-lateral and ESO/NSF/NINS ALMA Agreements and do not form part of the Executives' contribution to the Joint ALMA Observatory operations budget. They include, but are not limited to:

- Extended archive and data reduction support (e.g. one-on-one data processing support in a dedicated physical location, modified pipeline versions, re-processing of large and/or complex datasets, advanced simulation development);
- Analysis of data products that are not yet adequately covered by the standard pipeline analysis & long term trends analyses of data to assist Chilean operations. The analyses will include user feedback, and will be communicated both electronically, and through regular staff visits to Chile.
- Providing eventual enhancements to the standard pipeline analysis system;
- Support for special projects (e.g. public surveys and large programmes);
- Science community development (e.g. financial support for ALMA research, post-doctoral fellowships, training schools and workshops, ALMA-related specific science workshops, and advanced public outreach activities).

Development - Executives in Europe, North America, and **East Asia,**

The Executives are responsible, in consultation with the ALMA Director, for providing upgrades to existing instrumentation and development of new instrumentation for ALMA. The ALMA Board shall be responsible for approving the prioritization of such upgrades. Following appropriate consultations with its advisory committees (e.g., ASAC, AMAC), the Executives will carry out these responsibilities in the same manner as the Construction Project, and with the affiliated institutes they deem most appropriate for the task. Such developments may range from hardware aspects (receiver upgrades, new receiver bands, second generation correlator, etc.) to software improvements (operations, data simulator, off-line analysis package, etc.). Development is discussed further in Section 6.6.

6.3 Science Operations

6.3.1 The Overall Science Operations Concept

Flexible (dynamic) scheduling is essential for ALMA, and this defines the overall science operations concept. The necessity for flexible scheduling arises because millimeter and especially submillimeter observations are critically dependent on atmospheric conditions. The capability of ALMA to make instantaneous images in continuum and spectral lines opens new possibilities in this respect: a given observation can be split into several shorter ones to optimize the use of the best atmospheric conditions.

Flexible scheduling implies service observing, and this brings several other advantages. Short projects, which may be commonplace with ALMA, can be handled easily in this framework, as well as “target of opportunity” observations of unpredictable phenomena. Service observing also facilitates the long-term monitoring and consistent calibration of the array. Service observing has been used for years at radio arrays and is the default mode of operation for the current millimeter/submillimeter interferometers. Another major objective for ALMA science operations is to make the millimeter and submillimeter Universe accessible to a wide range of astronomers, particularly those who are not specialists in this area. Therefore the input from the astronomer should be focused on scientific objectives rather than technical aspects, and the default output to the astronomer should be reliable images that can be readily used for scientific analysis. This objective also implies service observing. The Joint ALMA Observatory will be responsible for the quality of the data products and delivery to the ALMA Archive.

To assure that the major objectives are met and that the archived data and pipeline-produced images are of a high and consistent quality, a complete and comprehensive end-to-end data management plan will be implemented for ALMA. Such complete data management systems are currently also in use or being developed at other facilities, including the ESO-VLT, NRAO-VLA, and NAOJ-Subaru. The different steps in the entire observing process are outlined below.

6.3.2 ALMA Science Operations Organization

ALMA science operations tasks shall be split between the Joint ALMA Observatory in Chile and the ALMA Regional Centers.

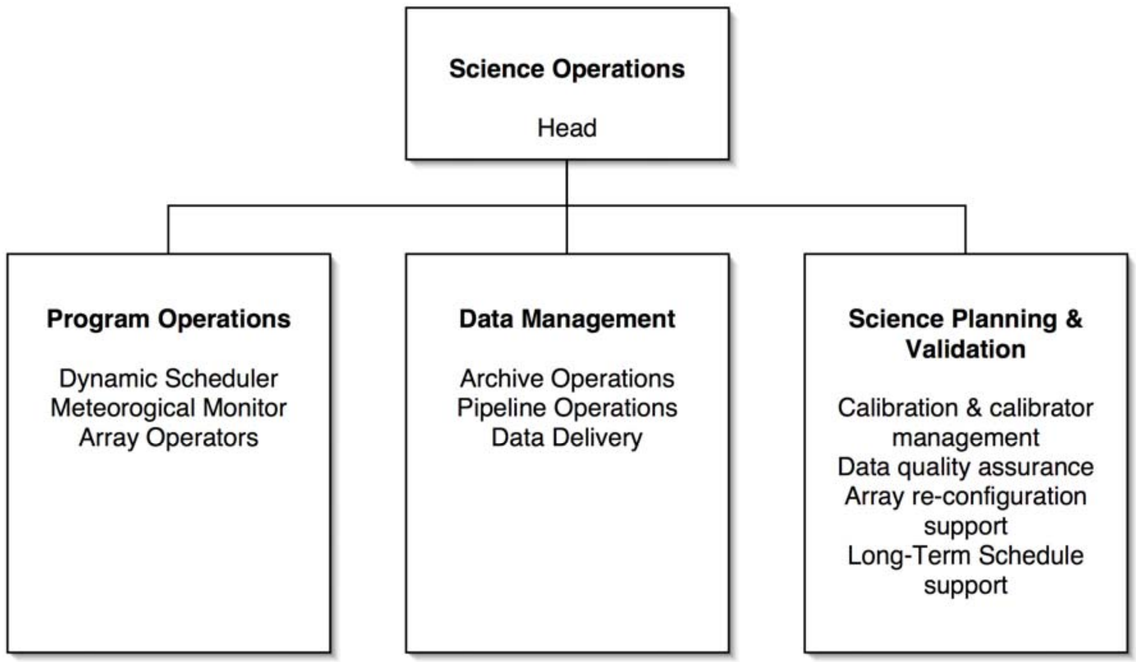

Figure 6-3. Organization of the Joint ALMA Observatory Science Operation

Science operations activities in Chile are the responsibility of the Science Operations department, under the leadership of the Head of Science Operations (see Figure 6-3). The Science Operations department will be split into the following groups:

- **Program Operations**: responsible for array operations as well as science and calibration program execution management, operation of dynamic scheduler, meteorological site monitoring, Scheduling Block (SB) execution and tracking, SB execution problem detection and resolution (in conjunction with ARCs), on-site, quick-look data quality assurance, and observing program status tracking.

- **Data Management:** responsible for archive ingestion of raw and processed data, data delivery to the ARCs and end-users; and science pipeline operations. It is important to minimize the delay in delivering calibrated data to the user. Data Management is also responsible for archive system operation and administration.

- **Science Planning and Validation:** responsible for calibration plan and calibrator selection, data quality assurance, array performance, and validation data products. A related task is array re-configuration support (baseline calibration, pointing re-calibration, beam shape monitoring).

The Science Operations department is also responsible for providing the following services:

- Core package ARC services to the Chilean ALMA user community
- Phase 1 technical review
- Phase 1 Long-Term Schedule construction and maintenance
- Phase 2 preparation and support to ARCs
- User documentation for various ALMA systems. ARC staff will provide inputs as needed to ensure that the user documentation meets user needs.

Although all Chilean operational tasks could occur at the OSF, this is not necessarily required, desired, or cost effective. Exact locations and distribution of these tasks within Chile, as well as the development of the necessary interfaces to the ARCs, is the responsibility of the ADO.

6.3.3 Proposal and Observation Preparation

The proposal submission (Phase I) and observation preparation (Phase II) will be done electronically. The Phase I proposal form will contain the scientific case and will be used largely for scientific evaluation, but it will also have enough information for an initial assessment of technical feasibility, done largely automatically by the data simulator.

The scientific Phase I proposals will be peer-reviewed in the manner to be decided by the ALMA Board. A prioritization of approved proposals will be used by the dynamic scheduler at the OSF to select proposals to be run in a particular period of time.

The astronomers of successful proposals interact in Phase II with the ARCs to produce Scheduling Blocks (SBs) which contain the detailed technical specifications of the observing program and which will be provided to ALMA Science Operations in Chile. The SBs will contain all the necessary information to define an observation, including the information required to prioritize observations based on the science ratings and the stringency conditions.

6.3.4 Observation Execution

The database of Scheduling Blocks (SBs) will provide the basis for the actual sequence of observations performed by ALMA. The first step is to determine and review the sequence of calibration observations and assure that it is adequate for the astronomer to meet her/his goals and that it is consistent with the archive policy. During the actual observations, the SBs will be prioritized in real time by an automatic dynamic scheduler at the OSF, in accordance with a variety of factors, including science rating, configuration requirements, source position, "stringency" (e.g., atmospheric conditions and phase stability) and hardware status.

Observations are carried out 24 hr per day, except during planned maintenance and instrumental downtime or when weather conditions prevent acquisition of scientifically useful data. The observations are carried out by a team of array operators and support scientists who work in shifts.

In addition to the standard flexible scheduling service observing mode, other possibilities may exist for various special cases, e.g. targets of opportunity. Furthermore, the ASAC has recommended the implementation of eavesdropping, in which the astronomer monitors the observations in real time, and preset "breakpoints" in observing programs.

Pipeline data processing will be an essential element of ALMA operation. The pipelines will support calibration and quick look data reduction, and provide calibrated images for science analysis. For calibration, the pipeline will apply all phase and amplitude calibration data, including the results from the water vapor radiometers; it will apply passband calibrations to spectral line observations and any other meteorological information as may be provided. Phase and amplitude calibration results will be fed back to the scheduler and operator as the observing progresses. Whenever the calibration data identify hardware problems, a status report will be logged at system level for maintenance purposes, and made available to both the operator and dynamic scheduler, with the relevant information also submitted for incorporation into the ALMA Archive.

The quick-look pipeline will keep up-to-date calibration data as new data are taken, including antenna- and baseline-based amplitude and phase. It will apply calibration data to the science data on-the-fly to monitor the incoming data for an initial assessment of the quality (e.g., does the calibrator have the expected flux?, is a strong line detected where expected?), and to produce early science results (current spectrum, quick-look images) when requested (e.g., after breakpoints).

The ALMA Director, or designate, will monitor the distribution of ALMA observing time, and provide annual statistics to the Board showing the distribution of time used among the ALMA partners, the Republic of Chile, and other countries. The ALMA Director shall ensure that the Observatory is meeting its fractional time allocation obligations to the Executives, averaged over some interval. In order to achieve parity with the agreed upon distribution of observing time, the ALMA Director may direct the assignment of observing time to be altered in subsequent periods with the approval of the Executive Directors.

6.3.5 Post-Processing, Quality Assessment and Archiving

For standard observing modes, the science data pipeline will operate in fully automated mode. The products will be calibrated images. Output of the science data pipeline will be assessed for quality by the Science Operations staff in Chile. It is essential that a single team is responsible for this task to ensure homogenous, consistent reduction and calibration of the data and uniform data quality. This team should consult scientists from the ARCs, which will ensure feedback from users and facilitate detection of any subtle data problems.

All the data previously obtained since the Project started will be available for processing. This means raw data and calibration data obtained in different array configurations, including total power data for measurements of zero and short *uv* spacings. The information on the data quality and array performance will be fed back to the array observations at the OSF as well as to the regional support staff at the ARCs.

The raw and calibration data, all monitor data, and the standard pipeline-produced calibrated images will be delivered to the archive. A copy of the entire archive will be hosted at each ARC for further processing and analysis. Each Executive will receive a copy of all the data taken by ALMA. The data should be made available promptly to the users.

6.3.6 Data Analysis Support and Archival Research

Once the data have been shipped to the user in East Asia, Europe, North America, Chile or elsewhere, the loop has been closed and the observation process is complete. However, there are three further important elements in the system: data analysis support, archival research and user feedback. In many cases where the observation was a straightforward image and the default or requested pipeline processing was adequate, no further interaction will be required. There will also be cases, however, where the astronomer has questions on the standard pipeline products and may want to try a different reduction scheme, or special programs where a variety of algorithms will be required to extract the science from the data. The ARCs will provide this support with core services ranging from simple advice, to provision of appropriate data analysis documents and products (which could be standard pipeline or off-line data processing software packages), to in-depth assistance for users who require it. The software packages are developed by the Executives and the affiliated institutes the Executives may choose to involve. It is also the core function of the ARCs to provide user feedback to the OSF in Chile, both electronically and through regular visits to Chile.

The proprietary period for science data will be as decided by the ALMA Board, after which they will be made publicly available in the archive. For complex projects, such as surveys or projects requiring many configurations, it may be appropriate for the proprietary period to start once all the data have been collected. Phase and flux calibrator data, on the other hand, will be made public immediately.

A copy of the complete archive will be maintained by the ARCs in East Asia, Europe, and North America. The archive will include raw data, calibration data and the images produced by the standard pipeline. They will also include meta data such as all user input, abstract from the proposal, observing scripts as used, the observation descriptors, relevant environmental data, the monitor data, relevant fault logs, and the pipeline reduction scripts. Except for the most complex programs, the images could also be re-generated on-the-fly with the latest version of the standard pipeline using the reduction script and the visibilities extracted from the archive. The archives will be accessed through the Archive Search Tool. Assistance in the use of the archive will be provided by the respective ARCs. The ARCs plan to interact with the Virtual Observatory to make the ALMA Archive available to the world-wide community after the proprietary periods for the data have expired.

The Executives may choose to add other functionalities to the ARCs (e.g., development of new interferometric data techniques, support for special surveys, interferometer schools and training, user funding, etc.) from their own resources outside the ALMA operations budget. The ARCs should be operated with an international and collaborative spirit, and some of the additional functionalities (e.g., advanced software) should be coordinated between the various ARCs.

6.3.7 Phase-in of Science Operations during Construction

When sufficient science capability is available, science operations will start – some years before completion of the full array. Experienced millimeter/submillimeter astronomers and technical staff will be asked by the JAO to join in the commissioning activities, with the expectation that they would provide important technical feedback on the facility and operations. This will be followed as soon as possible by a period of early science operations in which the general community will be invited to apply for some fraction of the observing time with the partial array. This will also be a period when observations relevant to the long-term operation of ALMA will be made (e.g., surveys for calibration sources) and first-look surveys which illustrate the capabilities of the array.

Thus, many elements of the operational setup must be in place from the outset and early operations staff is needed when the hardware arrives on Chajnantor. Initially, individual observations will be longer (fewer baselines), with a lower data rate and fewer users than after completion.

6.4 Technical Services

6.4.1 Operating ALMA at the AOS - Chajnantor

Overall concept. The environmental factors will impose severe constraints on the working conditions at Chajnantor. This leads to the decision of establishing the Operations Support Facility (OSF) at a lower elevation where the observatory control center and a large fraction of the technical services are to be located. The OSF is also the place where all the activities at the AOS are programmed and monitored on a real-time basis.

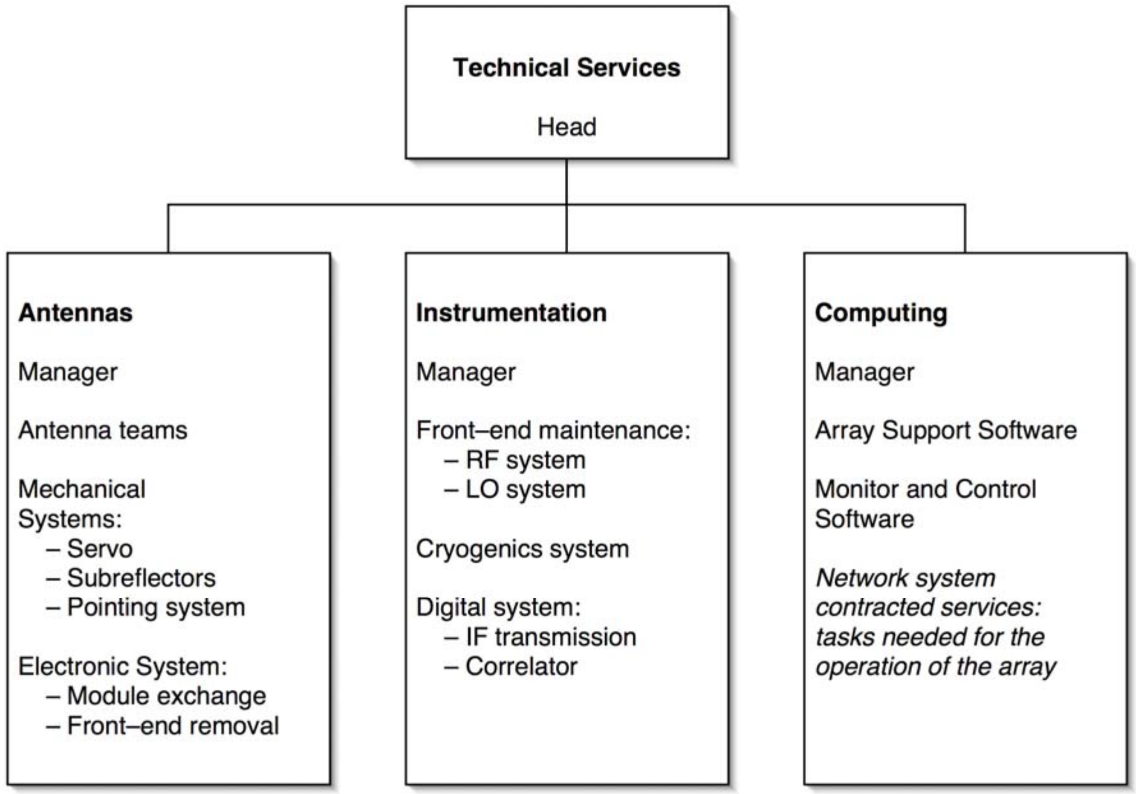

Figure 6-4. Organization of ALMA Array Operations

The aim is not only to minimize the number of staff at the AOS, but also to limit the number of the different crews operating at the high site. Essentially, only the antenna transport teams should be present on a daily basis at the AOS. When we speak of antennas here, we mean the antennas including all of the equipment and instrumentation installed on the antenna - most particularly the front end equipment. Therefore, all the support functions at Chajnantor for the antennas, including the exchange of the instrumentation modules, would be integrated under a single group belonging to the antenna group.

Safety integration at the AOS. Safety is an essential component of the ALMA operations. It is of crucial importance at Chajnantor. The safety procedures have to be fully integrated into the activities of the antenna teams. Their work checklists have to include all the safety requirements.

Other activities at the AOS. The antenna teams will not handle any infrastructure maintenance or domestic functions (cleaning, provision of supplies, etc.) at the array site. The infrastructure maintenance will be provided by the Facility Group stationed at the OSF. This group will go to the AOS for emergency cases and for scheduled maintenance (roads, buildings, power supply, etc.). They will not be on site on a daily basis.

6.4.2 Operating ALMA at the OSF

Overall concept. The OSF will be the focus for ALMA operations in Chile. The plan is to locate this facility at an elevation where the staff can work efficiently in a comfortable environment. The array will be remote-controlled from the OSF, and the main facilities for the technical support will be established there. Consequently, the OSF will include operations, maintenance and residential facilities. It will also provide the infrastructure for assembling antennas and outfitting them with receivers during the construction phase of ALMA.

Planning and monitoring of the tasks to be performed at the high site will also be provided from the OSF. The goal is not only to minimize the presence of the people at the high site, but also to supervise and control the activities at the array site to ensure efficiency and safety.

The OSF will be directly connected to the array site by a high-speed communications link and by road. It should be stressed that the OSF and the array site represent a fully integrated unit, from the functional, managerial and social point of view.

Location of the OSF. The ALMA Project Plan is to locate the OSF near, but not in, the village of San Pedro de Atacama. San Pedro is a historic village that is a popular tourist attraction owing to its historic and cultural significance. The OSF is not congruous with this particular appeal. Being not too distant from San Pedro, however, has the advantages of being near public transport, restaurants, hotels, some limited shopping, emergency medical care and police security. ALMA will not depend on San Pedro for utilities (potable water, electrical power, sewage); all these services will have to be provided privately for ALMA's own needs at the OSF.

The location selected for the OSF is about 15 km east of San Pedro and south of the road to the Paso de Jama. From this location a restricted-use road will be built connecting the AOS to the OSF in a straight line that can be used not only to transport the assembled antennas to the AOS without using the public highway, but also to return the antennas to the OSF for repair and maintenance. The direct link provides increased staff efficiency and safety at the expense of moving the OSF further from the amenities provided by San Pedro.

Scope of activities for the technical services. The technical services include the Antenna Group, the Instrumentation Group and the Computer Group. Only the latter will rely extensively on contracted services, while the first two groups will be staffed by ALMA employees as their activities are highly specialized and represent a vital component of the project core operation.

Antenna Group

a) Antenna teams
The scope of the activities of the antenna teams working at the array site is described in Section 6.4.1. These teams are complemented by continuous, on-line, support from the OSF where the planning, scheduling and monitoring of their tasks is established.

b) Antenna engineering services
The antenna arriving from the array site will be earmarked either for repair or overhaul. The repair work request will originate from the antenna teams. Prior to any antenna removal decision, a joint assessment of the failure will be established between the teams and engineering services. The regular overhaul scheme will be scheduled by the antenna engineering services, based on major servicing and realignment of each antenna every five years.

6.4.3 Instrumentation Group

This group will be required to maintain a broad spectrum of equipment, both at the front-end and back end side of the instrumentation chain. RF, LO, digital electronics, and cryogenic specialists will have to be included in the group.

a) Front end and LO support
In ALMA, antenna front ends are designed in a modular manner. The receiver band cartridges are built as separate units, which can be tested, and serviced, individually. Modularity and reliability should ease the maintenance efforts for the OSF engineers and technicians. Servicing will, therefore, basically consist of receiver cartridge tests and repair, and their insertion into the dewar. The RF support will also include the servicing of the water vapor monitors. The team specializing in the IF area will maintain the digitizing units and the fiber transmission equipment.

b) Back end support
The second segment of technical support will deal with all the electronic equipment at the back end, including the IF transmission system, first LO and correlator. Most of the equipment consists of solid state electronic components with very high reliability.

6.4.4 Computing and Software Group

Most of the efforts of the Computing Group at the OSF and the Central Office will focus on the integration of new software packages and updated versions of existing packages. Little software development is planned to take place in Chile. The software packages originate from the Executives at the ARCs, and those affiliated institutes the Executives may choose to involve. The team will have to provide feedback information to those sources and manage the integration of the updates on site. This implies a close collaboration with the ARCs where the software is developed. The Joint ALMA Observatory will have the overall responsibility for assuring that the software packages are developed according to common specifications.

The software team will also manage the networking and computer hardware maintenance for which contracted services will be used (computer peripheral exchanges, cabling, etc.).

6.5 Business Services and Facilities

6.5.1 Business Services

During ALMA's construction and operations phases, the business services required to support Chilean-based activities will be managed and executed by the European, North American, and **East Asian** Executives' staffs which, with the exception of legal and accounting/finance issues, will be in response to the programmatic direction from the ALMA Director. These business services include the following activities:

- Logistics
- Human Resources
- Contracts/Procurement
- Legal Issues
- Finance and Accounting Issues.

In performing these functions, the European, North American and East Asian Executives will follow their respective, ESO, NRAO, and NAOJ policies and procedures appropriately tailored for ALMA activities.

In order to maximize efficient use of staffing, and to foster ALMA's image in Chile as a single unified entity, the East Asian, European, and North American Executives will, whenever possible co-locate persons performing logistic, human resources and procurement/contracts. Additionally, whenever possible, the Executives will share positions and will cross-train their staffs to be knowledgeable about the unique requirements of each Executive. Whenever possible such functions will be "outsourced" with the appropriate contractual oversight exercised by the Executives.

The Executives' staff management shall ensure that persons performing these functions do so in a manner that (1) is consistent with the JAO/ADO direction while (2) adhering to the Executives' respective policies, procedures, contractual requirements and legal regimes.

6.5.2 Logistics - General Services

Logistics and General Services provide the following support

- Staff commuting (OSF/Array Site, OSF/home station)
- Board & Lodging – Travel agency
- Housekeeping
- Security.

All of these services will be subcontracted.

6.5.3 Facilities

The Facilities Group will provide the support for the ALMA infrastructure, both at the OSF and the array site. Its scope of activities includes:

- Supply and distribution of the power network
- Maintenance of the roads
- Maintenance of the buildings
- Maintenance of the outdoor safety implements.

The group will focus on the supervision and coordination of the contracted support in the area of civil engineering and electrical installations (not including the power installation at the antenna and ancillary instrumentation). It is the group's responsibility to develop the working programs, maintenance schedules and, thereafter, to monitor and commission the execution phase. Last, but not least, the contractor compliance with the safety regulations is under their responsibility. While functionally detached from the antenna teams, their activities are to be coordinated closely with the team leaders.

As already mentioned in the case of the antenna teams, the decision processes and the task scheduling are to be managed and administrated from the OSF.

6.6 Continuing Technical Upgrades and Development

Continuing technical upgrades and development of new capabilities will be required to maintain ALMA as the state-of-the-art facility for millimeter/submillimeter astronomy over the course of its projected life of up to 50 years. In particular, the rapid progress of electronic technology should make new hardware components and subsystems offering improved performance and higher reliability available for insertion into ALMA on much shorter time scales. Equally important, advances in software and computing should also offer improved performance and reliability that translate into more capability and reduced costs of operation.
Development activities will be carried out as described in section 6.2.3.