Report on the Review of Costs for the Atacama Large Millimeter Array

Submitted to the ALMA Board, 21 November 2005

Report on the Review of Costs for the Atacama Large Millimeter Array

ALMA Cost Review Committee:

Bryan Anderson	University of Manchester
Nelson Baloian	University of Chile
Steven Beckwith (Chair)	Johns Hopkins University
James Crocker	Lockheed Martin Corporation
Thijs de Graauw (Deputy Chair)	Netherlands Institute for Space Research (SRON)
Peter Dewdney	Herzberg Institute of Astrophysics
Ron Ekers	Commonwealth Scientific & Industrial Research Organization (CSIRO)
Guido Garay	University of Chile
Rolf Guesten	Max-Planck-Institut für Radioastronomie
Paul Ho	Academia Sinica Institute for Astronomy and Astrophysics
Junji Inatani	Japan Aerospace Exploration Agency (JAXA)
Alain Omont	Institut d'Astrophysique de Paris (IAP)
Steve Padin	University of Chicago
Fabio Pasian	Osservatorio Astronomico Trieste
Thomas Phillips	California Institute of Technology
Yasuo Tanaka	Max-Planck-Institut für Extraterrestriche Physik
Jean Turner	University of California, Los Angeles
Robert Williams	Space Telescope Science Institute
Lisa Wolff	Space Telescope Science Institute

Executive summary

The ALMA Cost Review Committee (CRC) reviewed the financial estimates presented by the ALMA project to complete the re-baselined version of the Atacama Large Millimeter Array (ALMA) with 50 antennas covering wavelengths between 300μm and 3mm. The following points summarize the main conclusions of this review:

- The science capability of ALMA remains compelling. As designed, ALMA will be one of the most important next generation facilities for astronomical research and will remain so for several decades.
- ALMA's technical readiness level is high. There is little risk that the project will be delayed because of technical issues.
- The overall management structure is adequate to carry out the project provided that each part executes its functions expeditiously.
- Each Integrated Product Team (IPT) is being managed well. Each IPT has developed robust plans to deliver the individual elements of the observatory.
- The detailed project plan is realistic and contains adequate detail and contingency for cost and schedule in most areas. There is no obvious impediment, major item overlooked, lack of coordination, or lack of planning among the major work elements.
- The estimated operations costs appear to be adequate and not excessive. At an annual rate of approximately 7% of the capital investment cost, the cost is comparable to that of other astronomical observatories scaled to the size of ALMA.

The committee examined the reasons for cost growth over the previous three years and the changes in project management to address them. It found:

- The cost growth in individual IPT areas resulted primarily from early lack of detailed planning and incomplete understanding of the scope of each IPT area, not from growth in the project specifications – in fact, the scientific scope has decreased.
- Delays in securing the contracts for the procurement of all the antennas led to an increase in cost and a decrease in scope in the plan.
- The strengthened role of the Joint ALMA Office (JAO) in project management has been the single greatest improvement to mitigate further surprises in ALMA's cost. It appears that the JAO now has the project management tools and expertise to accurately forecast cost in response to changes in the project work and schedule.
- Similarly, there is renewed attention to the role of project management within the two Executives, ESO and NRAO, lending further confidence to the current cost basis.

There are, nevertheless, potential risks for further cost growth in the execution of the project. The committee identified four principle risk factors in its review of ALMA:

- The cost assumes that the project and each of its elements will be executed to schedule. Poor schedule discipline and delays in antenna integration could increase the overall project cost. The partnership has the main responsibility to make decisions early enough to enable work progress and to manage both Executives and the JAO to ensure effective functioning of the organization. The Board must act expeditiously and effectively to enable the project to stay within its current cost estimate.
- The schedule calls for rapid increases and decreases in the number of skilled workers in many IPT areas. The ability of the project to hire, train, retain, and transition staff at a rate commensurate with the plan is a cost risk. We are especially concerned about the

lack of a plan to hire staff in Chile, an area with potential risk for cost growth similar to what happened as a result of delays in the signing of the antenna contracts.
- Delays in early implementation of an operations plan together with delays in funding to begin work on some elements of operations could increase the long-term costs of the project.
- The committee did not attempt to estimate the impact of having two different antenna designs within the array but believes there is likely to be some increase in the cost of the project owing to this choice.

Although the project is at a high level of technical readiness, experience with other major projects shows that unforeseen problems inevitably arise with otherwise well-understood components. Most of the project money will be spent on infrastructure items whose costs depend more on the price of labor and commodities than on the development of technology. These problems may be solved within the scope of this project using the planned contingency only if the decisions and management reactions to the problems are made rapidly and efficiently.

In summary, *the committee believes ALMA can be built to the current cost estimate, assuming resources are available, and providing that the execution of the program is robust at all levels of the project.*

I. Overview

The ALMA Cost Review Committee (CRC) met in Garmisch, Germany from 13-16 October 2005 to review the cost basis for the re-planned ALMA project. The CRC consisted of 19 members with broad expertise in all areas of ALMA technology as well as project management. During the four-day meeting, it heard presentations from ALMA staff covering all 10 major work elements of ALMA, called Integrated Product Teams (IPT), including Management, Site construction, Antenna procurement, Front-end receivers, Back-end electronics, digital Correlator, Computers and Software, Systems Engineering, Science, and Operations.

The CRC reviewed cost estimates, schedules, management plans, management processes and coordination tools. It spoke with representatives of the project, mostly managers, and reviewed documents that created the ALMA partnership and its governance structure. It did not attempt a comprehensive independent estimate of all the IPT costs as would take place in a formal audit; nevertheless, it gained enough insight into the project to give individual members confidence in their ability to verify the current cost basis for ALMA based on their experience with similar projects.

One of the reasons for the CRC review was a sharp growth in the estimated project costs during the previous three years, ultimately leading both to an increased cost and a decreased scope for the project. Part of the committee's charge was to determine the reasons for the cost increase and estimate the risks that the current cost basis is not yet adequate to complete the project. The committee spent some time on this task.

The ALMA project, its managers and staff gave the CRC superb support throughout this review. They were open, responsive, helpful, and provided a wealth of detailed material allowing an in-depth review of the project. The presentations by the staff were uniformly excellent. The CRC expresses its gratitude to the ALMA staff for their professionalism in helping us understand the challenges faced by the project, the reasons for cost growth and the basis for the new cost estimate. We are confident that the ALMA staff shared our goal of enabling the most thorough review possible in the limited time available.

Part of the committee's charge was to make recommendations on areas that may have been overlooked and suggestions to the project for improvement. There are four issues highlighted in the Executive Summary and described in this section that warrant attention by the ALMA project, including its Board and the Executives, for cost control. Additionally, this report contains many suggestions in the sections on individual IPT areas. We stress, however, that these suggestions are made as an aid to the managers and should not be considered binding recommendations to ensure the project remains on schedule and within budget. The CRC expects that these recommendations are addressed by the ALMA IPT leaders, which may lead in individual cases to a plan or action item to be reported to the ALMA board. The ALMA board should track these action items. In a complex project, it is impossible for a review committee with limited time and scope to capture all the items that will factor into management's decision making as the project progresses.

Overall, the committee was impressed with ALMA. It is an ambitious project to advance the state-of-the-art in millimeter-wave astronomy by several orders of magnitude along different dimensions: angular resolution, sensitivity, spectral coverage, dynamic range, and image fidelity. It makes use of previously developed technology in almost all areas ensuring that the project is in a high state of technical readiness and is robust in its efforts to achieve the projected gains. Its observational capabilities will address forefront questions in astronomy including the formation of galaxies after the Big Bang and the creation of planetary systems around other stars, to name only two of the problems it will tackle. The enormous gain in observing capability ensures that it will be one of the premier astronomical observatories in the world for decades to come.

The committee believes the current cost basis for ALMA accurately reflects the cost to completion of the construction phase with adequate margins for contingency and schedule slips in most areas. ALMA can be built to the current cost on the current schedule, if the project is tightly managed and expeditiously executed. The principal risks for further cost growth are lack of management discipline and inability to react quickly when unforeseen problems arise by making the right adjustments quickly. Most of the responsibility for ensuring adequate discipline lies with the Board, although authority for the technical management should be delegated to the Joint ALMA Office (JAO) and the executive managers in the European (hereafter, EU) and North American (hereafter, NA) partners, as appropriate to their separate roles.

Ia. Cost Increases from Early Estimates

It was relatively easy to understand the reasons for cost growth over the last three years. The early cost basis relied on ad hoc and sometimes inconsistent methods of estimate coupled with assumptions about component costs prior to having tendered bids for the components. Often, the estimates were parametric, based on scaling analogous work from other projects. Many of the assumptions appeared reasonable at the time but were shown to be inadequate for the unique circumstances of ALMA following component testing and requests for quotations. For example, estimates of the site construction costs relied heavily on ESO's experience building the Very Large Telescope (VLT) array on Mt. Paranal in Chile combined with the experience building the APEX radio telescope. The change in altitude from the 2600m at Mt. Paranal to 5000m at the Chajnator site, early tests of the proposed antenna foundations, and a sharp increase in construction labor rates over the last three years owing to a boom in the Chilean copper mining industry doubled the price from the initial estimates.

Similarly, the price of many commodities rose sharply over the last year, contributing to a cost that made 64 antennas prohibitively expensive. Since the antennas are made primarily of steel and/or carbon fiber, their cost depends more on the price of these commodities than anything else. If the antennas had been procured according to the originally planned schedule, the project would have been able to purchase the full complement of 64 antennas for about what ALMA will pay for 50 antennas today. This example shows how the state of technological readiness is only one element in determining overall cost and cost risk. It is difficult to see how the project could have foreseen this combination of circumstances, but it also demonstrates how timely execution of the original plan would have obviated this cost increase and retained the original scope of ALMA.

Eventually, the project created the Joint ALMA Office and staffed it with experienced project managers employing consistent methods of estimate across all IPT elements. By creating a detailed Work Breakdown Structure (WBS), often going 5 levels deep in work elements, and using industry standards for cost estimates, the JAO refined the estimates by incorporating current labor and commodity prices. They were also able to test prototype antennas and some of the other components to ensure that the design of the major components was mature, lending further confidence to the cost basis.

As the project moves forward, it is likely to encounter additional surprises such as happened with the antenna procurement. Because of ALMA's high state of technical readiness, the ALMA staff should be able to overcome technical problems – for example, in assessing the phase coherence of the atmosphere – with modest adjustments to the schedule and little cost growth. Delays in major construction items – such as we saw with the antennas and the site – have much greater potential to drive up the costs. Rapid procurement and integration will better ensure that the actual cost meets the currently projected price. Overall, the committee believes that strict adherence to the current schedule is the most prudent way to proceed; the high state of technical readiness combined with the burden of high staff cost during the peak periods of construction drive this preference.

The efficacy of the newly created JAO in creating good estimates also underscores the committee's belief that the JAO is the best entity to manage most of the work. Its experienced project managers track progress closely and can react to unforeseen problems more quickly than either of the Executives or the Board. The committee believes that appropriate delegation by the Board to the JAO for many of the project decisions is likely to facilitate schedule discipline and lower the risk of cost growth.

Similarly, the Board will need to act expeditiously to guard against delays caused by procurement of major elements or creation of important policies properly retained under Board control. The project needs a policy in place to hire staff in Chile, for example; delays in implementation of that policy will exacerbate the challenge of rapid staff buildup as early as next year and cause a ripple effect on the work schedule that will be felt throughout the project with potentially large increases in the cost. The CRC believes there is potential for significant cost growth in the overall project, if the partners are unable to agree on a robust plan for hiring Chilean staff, similar in impact to the large growth caused by delays in signing the antenna contracts.

The management structure in ALMA resembles in many ways a matrixed organization, with the JAO in charge of managing the work and the EU and NA executives supplying staff and resources to carry it out. The Board in this case is the only body to resolve problems that might arise between the JAO and the executives, and it thus plays a special oversight role in the project requiring active management. The Board needs to make sure that it operates in such a manner to carry out this management effectively.

The staffing plan requires rapid increases and reductions of the number of people in several IPT areas during the course of construction. Experience shows that it is difficult to identify, hire and train highly skilled technical workers and deploy them to remote sites. The committee identified this issue as a cost risk. It is likely that the project will need some additional contingency money to cover this risk. They should additionally create a comprehensive staffing plan using experienced human resources personnel to minimize the contingency risk.

Finally, although ALMA will not begin operations for a few years, some operations tasks require preparatory work now. Many of these tasks will also require staff with deep technical knowledge of ALMA gained during the construction phase. It is important that the project begin work on the operations phase now, through planning, funding of preparatory work, and commitment to employ mission-critical staff before they leave the project.

The following sections of the report present the reviews of individual IPT areas and the major findings with respect to cost estimates. Unless otherwise noted, costs are in year 2000 dollars.

II. Review of Integrated Product Team costs

1. Management IPT

Beckwith, Ekers (lead), Omont, Tanaka, Wolff

- The maturity of the project, a strengthened project management organization, and the use of proven methods to forecast costs give the CRC confidence that ALMA can be managed to a specified cost and schedule.
- ALMA's management structure is adequate to carry out the project within its projected budget, provided it can execute its governance and management functions to carry out the current plan.
- The reasons for cost growth are straightforward to understand in almost all cases. The Project has taken steps to ensure that the problems will not be repeated in the future.
- Failure to execute to the current plan is the main risk of further cost growth. A considerable portion of the early cost growth was under the control of the Management[1] indicating an inability to execute the original plan.
- Four areas require additional work to estimate their impacts on the final project cost:
  - impact of requirements to staff the project at rates commensurate with their estimated needs
  - cost of hiring staff in Chile; there is presently no policy to deal with Chilean-based staff.
  - impact of a hybrid array (current cost assumes a homogeneous array)
  - impact of integrating Japan into ALMA

1.1 Reasons for cost growth: ALMA Project

The ALMA project grew markedly in cost since the start of the construction phase. Some of this growth was outside the control of the Management, an unavoidable consequence of working with initial estimates that did not capture the full scope of the work. Some of this growth was within the control of the Management itself and can thus be viewed as avoidable. Failure to control costs that are within the Management's control suggests a potential for further cost growth in the future, if Management cannot execute its plan well. This circumstance also suggests allocating more contingency to handle future management difficulties with ALMA.

The CRC examined the reasons for cost growth in each IPT area since the project began construction. Cost growth occurred in about the same proportion in two categories:

- Growth in many individual sub-elements of the different IPT areas, especially the cost of the site construction, excluding the antenna IPT.
- Growth in the cost of the antennas, the single largest component of the project.

[1] By Management, we include the ALMA Board and two Executives along with managers of individual IPT elements. We will capitalize Management in subsequent references to these elements of ALMA.

The reasons for cost growth in the individual sub-elements resulted from a combination of factors, only some of which were under the control of the Management. Some growth occurred because the early cost estimates were based on parametric extrapolations from similar projects that did not have special requirements of ALMA. This was the case for construction, where an extrapolation of the costs of the VLT site at 2600m – an entirely reasonable approach at the time in the opinion of the CRC – proved to be inadequate to capture the real cost of working at the 5000m elevation of ALMA. There are similar examples in other IPT areas. These costs could have been controlled earlier only if construction had been delayed until complete testing had been done on all elements to improve the cost basis from a parametric estimate to vendor bids or at least to vendor or engineering estimates, but they did not arise because the Management was unable to execute its plan.

A second reason was inadequate knowledge of the cost of integrating all the elements together – system engineering – and the management effort needed to do so. Some these costs could have been known more accurately only by delaying construction until more design and testing had been done. Some of the problems would have been alleviated by the early adoption of proven methods to estimate the management costs with allowance for system engineering.

A third reason was sharp increases in the cost of essential commodities and labour for the project. The booming Chilean economy, the rise in the price of copper, the rise in the exchange rate of Chilean currency, and the high demand for Chilean labor especially in the construction and mining industries increased the costs of two critical IPT elements: antennas and site. Although it was impossible to foresee the economic changes, it would have been possible in at least one case to retire the risk by reacting quickly to a vendor bid. In general, it represents lack of adequate contingency to mitigate the risks of fluctuations in the local economy.

The rise in the cost of the antennas is a special case. One year prior to this review, the Management had a firm bid from an antenna vendor to provide 64 antennas for a price of approximately $185M. The Management elected not to accept the bid at that time but instead delayed the decision to buy antennas by nine months in the case of one partner and more than one year in the case of the other. The original bid was extended twice and finally expired by the end of 2004. The vendor subsequently tendered a new offer at a higher price. Currently, the Project has ordered half the antennas from the original vendor for 25% more than the original bid and intends to order the other half from a separate vendor for approximately the same price. Thus, the Project will purchase 50 antennas for about $300M, at least half of which are from the vendor whose price was initially 25% lower. ALMA will now be an array that combines two different antenna types – a hybrid array. It is likely that additional costs will accrue to the ALMA Project owing to this choice. The committee made no attempt to assess how much these costs will be.

Failure to execute the original plan led to a substantial increase in cost and decrease in scope from a planned 64 antenna array to a 50 antenna array. The CRC did not determine exactly how much of this increase could have been prevented by better execution of the plan, but we believe it is significant enough to warrant comment and to create concern about Management's ability to execute its plan. The Management will have to react expeditiously in the future, for example to obtain firm bids for construction, or else there is a risk of further cost growth. The CRC views management execution as an important factor to ensure that the current cost estimate is reliable.

1.1.1 Cost Growth of Management IPT

The Management IPT costs grew by $35M from $47M to $82M between the original estimate and the replan, an increase of almost a factor of two. The labor budget doubled, the travel budget increased fivefold, and materials and subcontracts increased by a factor of 1.6. The contingency rate for this IPT decreased as a percentage of the total to 5% but still increased slightly in dollar value.

The main reasons for these increases were a $24M increase in project-wide scope to cover the JAO budget, a $6M increase to charges for Other Direct Costs (ODC) mostly on the NA side, and a $5M increase in the funding for the NA ($1.1M) and EU ($3.5M) project offices.

There are several elements to the large increase in JAO costs, all of which reflect real needs to ensure good project management. The single largest item is $9M for the purchase and use of a Project Management Cost System (PMCS). The CRC believes this is a good investment to allow the project managers to track costs using an Earned Value system that has proven worthwhile in other large construction projects. The labor budget increased by $2.3M with the addition of a Project Engineer, Project Scientist, and Operations Head budgeted through 2007, along with associated support staff. These positions are normally funded in scientific projects of the magnitude of ALMA, and their addition to the JAO is welcome. The 2002 cost estimate neglected to include IT support for the Chilean offices in Santiago or Chajnantor; correcting this oversight was necessary. Most of the other increases represent more realistic appraisal of the needs based on the experience of the last 3 years.

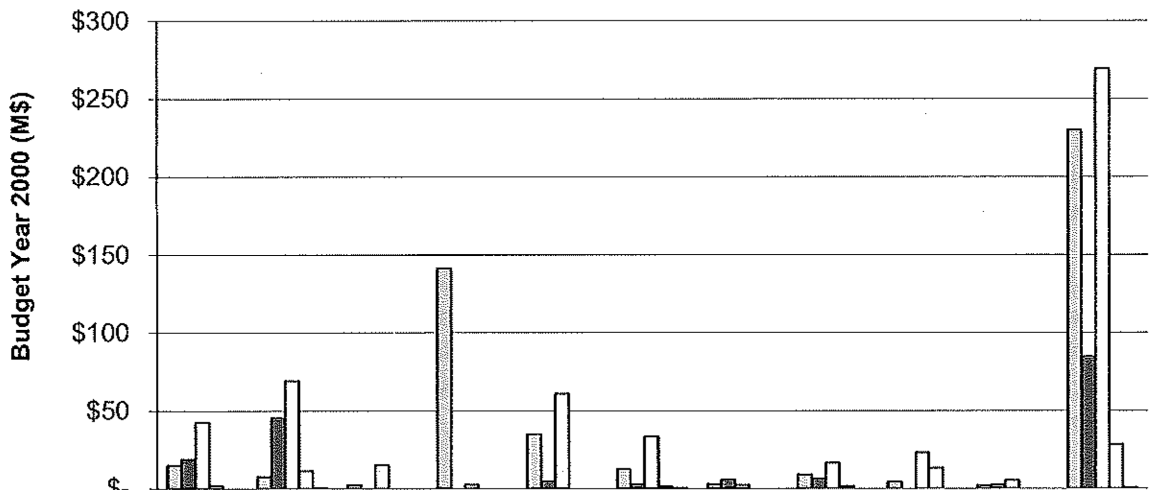
Other Direct Costs (ODC) were estimated in 2002 at a rate of 27%. This rate failed to capture the NA costs. As with the JAO costs, experience uncovered many areas overlooked in 2002. Adding these areas back into the budget brought the rate to 36%, increasing the NA share substantially, although the EU ODC costs went down upon reducing the labor pool to which the rates were applied. Rates for ODC in other NA institutions often vary widely up to several times this number; there is no uniform standard with which to compare. The CRC examined the list of items included in ODC and concluded that they were all reasonable, although we made no attempt to audit this budget for completeness.

Finally, the CRC believes a strengthened JAO combined with stronger management in the two Executives is a great benefit to the project and necessary to guard against further cost growth. We believe, therefore, that the cost growth in the Executives of $5M is a needed investment to ensure good project management during the construction phase.

1.2 New Cost Basis

The new cost estimate resulted from the use of proven methods to allocate contingency to areas with remaining risk. The Management is implementing an Earned Value System to assess and track ALMA's progress and developed a Work Breakdown Structure (WBS) in most cases to five levels. Some of the work elements are reasonably advanced, making it possible in principle to forecast accurately the cost to complete. The Management did not provide the committee with an estimate of completed work in each IPT area, although we understand that work has progressed markedly in many areas. The CRC, therefore, cannot ascribe a reliability factor to their estimate based experience with similar projects.

There are now two firm bids for the antennas, the single largest cost element. The contracts appear to have sufficient safeguards against further cost growth. Of the remaining elements, 41% of the cost is in firm vendor bids, 13% is in vendor estimates, and 42% results from engineering estimates. The majority of the engineering estimates are for elements that will be provided by non-profit organizations, principally the front-end electronics, where the engineering estimates are often the only cost basis that will be available until the work is completed. This distribution lends confidence that the new estimate is accurate, assuming the scope of the work is well known.



	MGMT.	Site	Antenna IPT	Antenna NA Procure.	Front End	Back End	Correlator	Computing	SE&I	Science	Total
1 Bid	$14.7	$7.5	$2.3	$141.1	$34.9	$12.0	$2.6	$8.8	$4.0	$2.0	$230.0
2 Quote	$18.6	$45.2	$0.1	$-	$4.5	$2.5	$5.3	$6.3	$0.1	$2.2	$84.7
3 Eng. Est.	$42.4	$68.9	$14.9	$2.4	$60.9	$33.2	$2.1	$16.1	$23.0	$5.1	$269.0
4 Param. Est.	$1.9	$11.1	$-	$-	$-	$1.0	$-	$1.3	$13.0	$0.1	$28.3
5 Guess	$0.0	$0.2	$0.0	$-	$-	$0.3	$-	$-	$-	$-	$0.6

Figure 1: This figure shows the distribution of project costs among categories of confidence from the highest confidence (Actual Bid) to the lowest (Wild Guess) including one of the two antenna contracts. The high proportion of actual bids lends confidence to the current cost basis. Of the Engineering estimates, many are in work provided by the partners where there will be no vendor quotations or bids.

The strengthened role of the JAO is an important factor to instill confidence in ALMA's management structure. The newly employed Project Management Cost System (PMCS) should give adequate insight into the progress of work to give managers the information needed to make timely decisions. Both EU and NA have hired new project managers to oversee the work of the executives, thus strengthening the ability of the executives to execute their work. The creation of the ALMA Management Advisory Committee (AMAC) with experienced project managers and executives is an important way to enhance expertise at the Board level. The committee sees greater use of the AMAC as a good way to reduce management risk.

Under the review of Operations, we recommend that the Project put an operations plan into place quickly and begin operations funding, initially at a low level, to ensure against growth in the lifetime costs of the project.

1.2.1 Project Scope

The committee checked project scope in each IPT area in most cases to a depth of five levels in Work Breakdown Structure (WBS.) The fourth WBS level normally captures about 85% of the project scope, and the fifth level is typically more than 90%. Spot checks in some cases where the committee had expertise to check the assumptions revealed no major oversights. The short review period of 3 days made it impossible to do complete audits of any area. With this caveat, the committee was satisfied with all areas it examined.

1.2.2 Schedule

The project schedule focuses at first on the delivery of the first 5 antennas. Antenna delivery appears to define the critical path for almost all other work elements. By the time the first antenna is delivered, site preparation, several front and back-end systems, the correlator, and a computer system for first-order analysis will be ready. There appears to be adequate margin in the schedule for each of these elements to minimize risk of delay. The antenna deliveries are under control of the manufacturers. The Management described stipulations in the signed contract that assure adequate safeguards against late delivery, although the CRC did not look at the contract language itself and make an independent judgment.

Production of front and back end electronics for subsequent antennas is planned to stockpile items for future antenna deliveries. The schedule shows a good margin between the rate of increase of this stockpile and the rate of antenna delivery. Assuming the site infrastructure has been completed by the time the fifth antenna is in place, the majority of work shifts to installation and commissioning of antennas on a regular schedule as they are delivered. By that time, the initial problems of installation, commissioning, and integration into the array should have been worked out, greatly reducing the likelihood of schedule slip. Computer support for data reduction can be developed in parallel with little effect on schedule or cost – even slips in this area should not affect the project cost.

There was some discussion within the CRC about the uncertainty in ALMA's phase compensation method, the technique of correcting phase fluctuations in the received signals at the different antennas caused by the atmosphere. This uncertainty arises from the lack of experience at the ALMA site and cannot be reduced until a few antennas are in place and the Management can assess the robustness of their compensation techniques. The CRC debated the impact of this uncertainty, and concluded that the Management has a prudent plan for construction considering the running costs of integrating 50 antennae into an array. We deemed the risk acceptable.

1.2.3 Contingency

The systematic development of risks and the calculation of contingency funds lends confidence that there is adequate contingency to buy down risk in most IPT areas, excepting those called out specially in this report, for example the costs of a hybrid array and the contingency for antenna procurement. The processes developed to consistently catalogue and process risks will assist the

ALMA team with risk mitigation. The contingency funds are currently calculated for each IPT and held by the Executives, although JAO approval is required for spending above certain limits. The CRC understood that the JAO planned to collect the contingency funds for central management. The committee believes this approach to funds management is prudent. The committee suggests that the JAO:

- hold a contingency allocation that is available to offset costs and schedule slips related to executive and partner processes integration,
- increase the contingency for some work elements as outline in the individual sections below,
- continue to refine the contingency calculation and association of the funds with a critical path work items, and
- use contingency funds to strategically lower the risk level of high and medium risks catalogued in the RiskRegister, to medium and low respectively.

1.3 Management of ALMA

The management structure of a project affects the ability of decision makers to obtain the information they need to make a decision in a timely manner, to decide, and to implement those decisions as planned. The ALMA structure can in principle be efficient for decision making, provided that the partners understand the need to execute their governance processes expeditiously. As presented to the committee, the ALMA Project resembles a matrix organization, in which the two executives, EU and NA, provide resources to a central project management organization, the JAO, and the ALMA Board governs all three organizational elements. To function effectively, the Board will have to ensure that its decisions support the ability of all three elements to carry out their work, use its authority to resolve disputes that may arise between any of the elements, especially between the JAO and either executive, and hold the different elements accountable for delivering on their promises. Failure to do so means risk of further cost growth. The CRC made no attempt to quantify this risk.

The presence of two separate and equal executives has the potential for instability in decision making when disagreements arise over the execution of the project elements. The Management described itself to the CRC as "an unstable equilibrium governed by goodwill." Such an arrangement certainly can work, as successful marriages demonstrate, but it needs special attention to governance if the risk of dissolution or the cost of the relationship is to be minimized, as the divorce rate shows. There are various governance mechanisms to guarantee success, one of which is to use a third party to resolve disputes, a role most naturally be played by the ALMA Board in the current structure. It is outside the charge of the committee to recommend specific approaches to management, but it is appropriate to voice our concern that poor coordination of the executives along with the relatively late strengthening of the project management through the JAO most certainly gave rise to considerable cost growth during the early phase of ALMA. These problems must not recur in the future, if ALMA is to be built to the current cost estimates.

The creation of the AMAC has been an excellent way to bring more experienced project management to the high-level decisions needed by the Board. Strengthening the AMAC/Board ties and use of AMAC expertise should alert the Board to the timing of decisions that affect the ability of the project managers to execute the plan.

1.3.1 Joint ALMA Office

The JAO is an important organizational element to execute the project. The JAO has had a positive impact on the project by enforcing proven management principles, discipline, and using good tools for estimating cost and tracking progress. Delegation of authority for the project execution to the JAO is a good way to reduce cost risk and was a factor in our assessment of the cost basis, although the Board must subsequently hold the JAO accountable for its responsibilities.

1.3.2 ALMA-J

Incorporating the Japanese contribution into ALMA for completion of Enhanced ALMA is an opportunity to significantly upgrade the power of ALMA for little cost to NA and EU. Although the management of ALMA-J (involving NAOJ as a third executive) is separate, closer cooperation gives significant advantages to the ALMA Project by increasing the pool of expertise. Maintaining tight schedules to keep deliverables between JAO and ALMA-J is crucial in order to minimise the cost impact. The CRC believes that there are further advantages to accrue from closer collaboration with the Japanese, who have considerable expertise in millimeter-wave techniques and substantial resources that can mitigate some of the risks of cost growth in common areas such as infrastructure.

1.3.4 Staffing requirements

The Management IPT provided detailed descriptions of the methods used by the ALMA IPT Leads to develop labour estimates. The CRC found the approach to be thorough, producing credible FTE estimates for a very complex program of work. It is not evident to the CRC that the cost of recruitment was included in the labor costs. There is evidently a provision that includes the costs to the Executives in ODC; it is unclear how the costs of recruiting in Chile will be covered.

There could be cost growth in the form of schedule delays if new staff cannot be hired and trained at a rate commensurate with the project schedule. The ALMA Project would benefit from a Human Resource plan that might logically be managed by the JAO. Of particular concern is the delay of the Chilean workforce agreements. We identified this area as another "tall pole" problem, similar to the antenna procurement. It is apparent that the ALMA Board is having difficulty formulating a robust plan for hiring Chilean labor, and it is exactly this kind of difficulty that will make it impossible for the Project to execute its plan to schedule. The ripple effect caused by delays in hiring adequate staff might lead to the kind of significant cost growth that was caused by delays in signing the antenna contracts.

The CRC believes that a focused look at human resource issues now will significantly reduce the potential for cost growth in labor and minimize the schedule delays that can arise from understaffing.

1.3.5 Deferral of purchases

It is possible that deferring the purchase of some items could save money or defer spending until the operations phase, if further cost cutting is needed:

- The Project could defer the full compliment of WVR's as proposed in BCP5 ($4.6M). The full compliment is not needed for early operations, and the initial tests might indicate ways to redesign this item after gaining some experience with the ALMA site. We note later in this report (section 9) that the WVRs are, nevertheless, important as a way to complement the fast-switching mode and thus reduce wear on the antennas over the lifetime of the project.
- The Project could slow down the commissioning of baselines beyond 4 km (BCP2 for 12.6$M), if necessary. Long baseline interferometry is the most difficult aspect of ALMA. Its implementation might benefit from the experience gained from commissioning a compact array. We caution, however, that long baseline interferometry is one of the most scientifically compelling reasons for building ALMA, and there should be no delay in bringing it about if there is a risk of losing the capability altogether.
- The decision to construct a permanent power station moves part of the operating costs into the construction budget. If this item were financed under the NA budget, it might be offset by EU operating funds for the deferred items.

1.3.6 Other Management Areas

The CRC looked at several areas of management that are working well and lend further confidence to the new cost basis:

- Status reporting methodology
- Future liens on contingency list
- Schedule and critical path
- Management of logistics

Overall, the Management appears to have good processes in place to handle the construction phase of ALMA.

2. Site IPT

Crocker (lead), Garay, Ho, Turner, Williams

- Cost for the Site IPT grew from an initial estimate of $67M plus an additional 20% assumed to be contributed by the Japanese to a re-baselined estimate of $118M plus an assumed Japanese contribution of $37M for a total of $156M. The site costs thus increased by almost factor of two, or $50M for the ALMA Project (NA + EU).
- Cost growth in the Site IPT resulted primarily from three factors:
  - Approximately half of the $50M increase, $23M, resulted from refined understanding of the costs of building at the 5000m ALMA site combined with a sharp increase in Chilean labor rates and cost of currency since the original estimates.
  - About one third of the $50M increase, $16M, accrued from the decision to build a power station at the site. The original cost estimates assumed purchasing power from the Chilean grid, costs that would largely be borne during the operations phase.
  - About one fifth, $11M, came from an increased contingency allocated to the Site IPT to bring the risk assessment into line with DOE standards.
- The review committee believes the current cost estimates accurately reflect the needs to develop the site, are reliable, and contain adequate contingency to mitigate risk of further cost growth.
- There are some areas, such as the Residence, where savings might still be made in site construction without impacting the scientific requirements, depending on how the partners view the importance of the long-term operating environment.

2.1 Cost Growth and new Cost Basis

The Site IPT is the second most expensive project element. Increasing site costs have the potential to increase the total project costs substantially, which could result in diminished scientific capabilities for ALMA. The review committee paid special attention to the reasons for the cost increases in this IPT and the potential for further increases in the future.

The rebaselined site costs increased by almost a factor of two in the new cost table. The cost increases fall into three categories that separately account for comparable fractions of the increase:

- Refined understanding of the real costs of building at the ALMA site – including sharp increases in Chilean labor rates and the value of the currency.
- The decision to build a stand-alone power station to operate ALMA, effectively moving a long-term operational cost into the capital construction budget: $20M total cost.
- Allocation of $11M additional contingency to the Site IPT.

The decision to build a stand-alone power station is a sound way to ensure that ALMA's full scientific potential is realized, owing to the inherent unreliability of Chile's current power grid. It is also likely that the true costs of buying power from the grid are high enough that the lifetime costs of ALMA will be lower with a stand-alone power station. The decision has the effect of shifting costs from the operations to the construction phase, an apparent increase in cost that is expected to reduce the lifetime costs.

The current plan is to obtain power via generators fed by the natural gas line from Argentina into Chile that passes very near the AOS. There is some risk that the supply of this natural gas might not be dependable in the future, owing to worldwide demand and uneasy relations between the two countries. This risk led the project to explore a fall-back plan of utilizing the grid but with a back-up diesel generator. In any event, ALMA needs reliable and uninterruptable power for construction and operation, meaning the need for an on-site (back-up) generator even if it gets power from the grid most of the time. The Management realized that it would be more cost effective in the long term to generate its own power via generators. The primary risk of this approach is the possibility that natural gas may become unavailable in that region of Chicle in the future, forcing reliance on diesel fuel, which could make this (fall-back) option more expensive.

The JAO commissioned a study by Fichtner, Inc. to estimate the costs and risks of all reasonable options for power to the OSF and AOS. Their study concluded that hooking onto the national grid would require purchasing a land line of 120 km length at a cost of order $20M. The cost of generating power on site was estimated to be $16M in 2003, a number that has since risen. The cost of obtaining power from the national grid *and* providing for a generator backup when the grid goes down is $26M.

The Management concluded that an 'island power plant' with local generation for ALMA is the best option for power. But the rapidly changing cost environment for power led the JAO to request another study of options for ALMA to make sure they understand the most cost-effective solution. It is clear to the review committee that even the cheapest source of power will cost significantly more than the initial estimates from 2002; we all notice the increased price of gasoline. The substantial increase in the re-baselined estimate for power was thus inevitable and must be accepted as the cost of doing business at an inaccessible site in Chile. A final decision on how power will be obtained will be based on the new study.

The remaining increase has several components, all of which the review committee believes are necessary. Chile's booming economy coupled with a rise in the demand for copper and consequently construction labor in the Chilean mining industry has driven up the cost of labor and currency since the original cost estimates. The risk of price inflation was not taken into account with the early contingency budget (5.7%) for site construction, and the project included a more generous 17.7% contingency rate in the most recent cost basis to guard against further growth. The additional contingency alone accounts for about $11M of the cost growth.

The review committee believes this new approach to contingency is prudent and lends confidence that the project understands the true risks of construction at the ALMA site.
Using the DOE scheme resulted in significant increase in reserves from the original estimates. The original budget carried only a 5.7% contingency while the current line budget carries 17.7% for the site items, a much more realistic estimate.

The review committee looked at individual WBS elements of the Site IPT re-baselined cost estimates and believes they are sound. Members of the review team have experience with construction costs in Chile and the difficulties managing remote sites. The site IPT team provided us with a professional, detailed and thorough analysis of the cost estimates documented in the WBS sub-elements. The development of the cost basis has been carried out with industry-proven methods. Civil Engineering firms in Chile and other countries have been engaged to develop the engineering estimates, some major activates now have actual bids to support budget projection and in the case of the antenna foundations actual prototypes have been constructed and estimates obtained from two contractors. The associated uncertainties are clearly identified.

The CRC believes that there is little risk of scope growth in site construction. We have confidence in the validity of the cost estimates in the re-baselined project plan.

2.2 Schedule

Several site activities have the potential to impact the project's critical path and need to be managed carefully to minimize impacts. In the near term, antenna pads must be installed to support the antenna assemblies as they arrive. This installation may require expedited action by the executives to obtain the required approvals to place contracts.

Next the antenna transporter must be available at the site before the antennas are installed. There remains some uncertainty about the schedule for the transporter.

Finally the OSF and AOS buildings must be kept on schedule to insure that the project wide schedule is not impacted.

2.3 Potential Cost Savings

The Site IPT is a significant fraction of the total budget. Therefore, savings and deferred actions in the construction budget provide a way to help other project areas should problems arise during construction. The Management has identified areas within the Site IPT in which significant cost savings can be achieved without impact to the science. Because items in the Site IPT are costly, potential savings here can have large impact to the ALMA Project as a whole.

Potential areas for reduction include:

- Re-optimization of the antenna layout following a reduction of antenna pads from 200 to 175 to save $5.5M.
- Optimization of the layout to minimize the length of the roads connecting the antenna pads. Savings in road and the associated utilities should be explored as part of a complete re-optimization with potential for saving without science impact.
- A reduction of the size and quality of the buildings could result in 5-8 M$ in saving without immediate impact to the science.
- The number of people needing on-site residence needs refinement. The present estimate derives partly from experience with the VLT and partly from the estimated need for

technical staff during operations. Since the operations plan is not yet final, construction of the residence should be delayed until firm requirements are available. Saving of as much as $4M may be achieved. The CRC recognizes that the partners may place different values on the need for quality on-site quarters but assumes they could find a mutually acceptable way to share the cost burden based on those values.

The first area for potential cost reduction is in the number of antenna pads. Due to the re-optimization of the antenna configuration for a 50-element array, the number of required pads has decreased to 175 from 200, with savings to the Site costs of $5.5M. This option is listed as a BCP, although the CRC believes this proposed reduction could be accepted immediately. It appears a further optimization could reduce the length of the roads connecting the antenna pads. Savings in road and the associated utilities should be explored as part of a complete re-optimization with potential for further saving without science impact.

A second area is in the permanent technical buildings at the 2900m OSF. Here, design-to-cost modifications could generate substantial savings without affecting the scientific capabilities of ALMA. The initial cost estimate of the OSF technical building was $13M in 2002. The re-baselined cost of this building, based on current vendor bids, is $26.8M, a factor of two higher than the initial estimate. The Site IPT leads and Project Manager stated that negotiations are underway following design modifications that could substantially reduce the cost of the OSF technical building. The estimated savings are similar in magnitude to the savings in antenna pads, potentially $5-8M.

A third area is the Residence at the OSF. Cost of the Residence is one of the two biggest areas of risk in the Site IPT, since there is no design or cost estimate yet for this facility. The current cost is estimated to be $9.2M based on Mt. Paranal residence for the VLT. The VLT model is not necessarily the best for the ALMA facility. In addition, the cost per square meter of the OSF technical building bids is significantly higher than assumed for the Residence estimate ($1800/sq m); the OSF is presumably a more accurate reflection of current construction costs in the area.

The requirements for the Residence will not be known until the Operations Plan has been finalized. The review committee suggests that the ALMA Camp be maintained until such time as the Operations Plan is in place and the needs in terms of the Residence are well understood. The Residence will house the scientific and technical staff working on site, in addition to visitors. Because of the remoteness of the site, and the desire of the Project to minimize its impact on the nearby historical town of San Pedro de Atacama, the Residence must be an attractive and comfortable place in which to live and work. The Project believes that cost savings are possible while achieving these goals by considering pre-fab construction. The Panel notes that there are three BCPs associated with the Residence, including $5.2M for prefab construction and $1.2M for deleting the sports facility. It is apparent that the Residence is an area in which potentially substantial savings are possible with careful planning and design.

Finally, the results of the study by Fichtner, Inc. should be used to determine the best trade between capital investment and long-term operation costs and reliability.

3. Antenna IPT

Dewdney, Guesten (lead), Phillips

Timely delivery of antennas that meet ALMA's specifications is the critical driver of the ALMA Project. Over the last three years, the cost per unit increased markedly owing both to increases in the contractor prices and to refined assessments of the risks for construction at the ALMA site. The CRC believes further cost increases can be prevented if the project avoids modifications of the specifications in the statement-of-work contained in the signed antenna contracts. Principle facts contributing to these conclusions are:

- Antenna construction will start soon: the NA contract for 25 units has been signed and the EU contract is in the final approval process.
- The statement-of-work, defining the contractors' work packages, is comprehensive.
- The Antenna IPT work packages are well-developed. The risks are clearly identified, and mitigation actions are well understood.

There are, nevertheless, factors that suggest further risk in cost growth:

- Operation of two separate types of antennas in the array will impact the cost and schedule of the project; no estimates of these impacts were available for the review.
- A contingency of 5% of the contracts' value appears too low to the CRC.
- There is little margin in the delivery schedule.
- The cost estimate of the nutating secondary is lower than our experience suggests.
- The forward maintenance planning for spare components is budgeted only for the first two years, and there is no budget line for antenna spare components beyond this time in the Operations Plan.

There are several areas where changes in the currently planned approach may lower risk of underperformance for modest investment:

- Construction and testing engineering prototypes of the antenna pads and interfaces before proceeding to mass production may substantially lower the risk of cost overruns in this critical area.
- Optical pointing telescopes for all the antennas would cost about $1.5M and provide a redundant method to ensure good pointing.
- Care should be taken not to eliminate the possibility of achieving sub-25 μm accuracy within the present contractual boundaries. The AIV group should make an effort to adjust the surfaces to higher accuracy than 25 μm after delivery.

3.1 Background

The antennas are the highest cost IPT item in ALMA, and they will also be difficult to modify once delivered. The CRC reviewed the Antenna IPT (AIPT) work packages including specifics of both antenna contracts. In a confidential meeting, we heard about key aspects of the still-to-be-placed European contract to assess its cost risk compared to the NA contract.

Our assessment is based on a 50-antenna project baseline. We did not analyze the programmatic impacts of the ESO/FC recommendation to proceed with separate (NA/EU) antenna contracts.

The project will need to calculate the cost-impact of a hybrid array to provide an accurate cost for ALMA to the partners.

3.2 Contracts

3.2.1 Antenna contracts WP 1.03.050.0500 (NA) and .0505 (EU)

The statement-of-work (SOW), ALMA-34.00.00.00-007-A-SOW, is thorough and covers the interfaces and activities well. It establishes contractual boundaries applicable to both contractors in a well thought out manner. To guard against risk of further cost growth, the Executives must exercise strict configuration control of this SOW.

An important component of the contract is the manufacturing and quality assurance plan, which is – in response to the SOW - to be provided to the Project for approval. This plan includes a quality assurance plan and acceptance sign-offs at the component level as well as for the final assembled antenna. Although the plan is an early deliverable, the data package was not available for review. These documents are important to a thorough review of the risks to antenna production and implementation – the CRC recommends that they receive a critical evaluation before sign-off, perhaps even with the assistance of an external review panel.

3.3 Reason for Cost Increase

The cost of antennas has risen from an estimated price of $104M for 32 antennas in 2002 to a newly quoted price of ~$150M for 25 antennas from the ALMA 2002 baseline to the 2005 baseline plan. The major increase was between the initial estimate and the first fixed-price bid that was about twice as expensive as first assumed. There were some changes in the assumptions about antenna procurement that led to these increases, and to a large extent the increased costs reflect a better understanding of the true needs of ALMA by the contractors.

Subsequent to receipt of the initial fixed-price bid, delays in accepting the offer ultimately led to a further 25% increase in the price of the antennas. Currently, the Project will spend about as much money to purchase a 50-antenna array as it would have for a 64-antenna array approximately one year ago. The Management attributed the change to increases in the costs of raw materials, increased complexity, a better-defined strategy of acceptance, and re-evaluation of impact of work at the OSF. The CRC accepts this assessment, as there was no obvious way for the committee to obtain a deeper understanding of the reasons for the cost increases from the contractors.

The cost of the antennas was the single biggest factor that forced the rebaselined ALMA project to decrease scope from 64 to 50 antennas at the same time that the overall project cost increased by approximately a factor of 1.4, assuming the cost of the ESO contract is similar to that of AUI's. We made some effort to determine if some or all of this cost increase might have been avoided by adopting a different strategy for managing the prototype contracts, acceptance tests, and subsequent acceptance of firm bids from the antenna vendors.

The information received by the CRC suggests that at least some and perhaps most of the cost increase between 2004 and 2005 could have been avoided by a more aggressive management of the prototype vendors, the approach to testing, and the timing of the decision to purchase antennas. Many of the factors that led to delays in procurement and testing of the prototypes were under the control of the Management, as was the timing of the decision to sign a contract. Several of the problems with prototype acceptance might have been prevented by different management decisions at early stages in the planning. This general conclusion is important, because it creates concern that *future antenna procurement and integration* risks further cost growth unless there is some change in management foresight. One consequence of the prototype history is that it shows the 5% contingency allocated to the Antenna IPT is low compared to the historical needs, and leads the CRC to conclude that it is optimistic for the production of 50 antennas as well.

3.4 Current Basis of Budget and Schedule

The Executives have built-in safety measures to ensure delivery of the antennas on schedule.

- The NA partner has contracted with Vertex/RSI to provide 25 antennas. It calls for delivery of the first six antennas for a fixed price. For the following units, the price may vary between a floor and ceiling price ($169-183M) based upon an equally weighted average of published indices of steel/fuel/consumer price index (CPI) in the USA. The contract is staged, and payments follow the successful meeting of milestones. There is no explicit delivery-based penalty or bonus.
- The EU partner negotiated a fixed price contract with a second vendor. The details are confidential, but the terms of the contract are broadly similar to the Vertex/RSI contract. The EU contract contains penalties for late delivery, and the vendor must obtain bank guarantees as protection against insolvency or non-delivery. The contract can be cancelled for non-performance. Official acceptance of this contract is expected within a few months.

We believe the schedule margins with the contractors are tight. The risks of late delivery are not transparent to us.

The SoW refers to specifications and Interface Control Documents (ICDs) that define all of the mechanical, electrical and control interfaces to the antennas. The CRC notes that discipline will be needed on the part of the entire ALMA project to avoid any modifications to the contract or the ICD's if the contract price is to be maintained. Changes will spark costly contract change orders. Any open design issues with the antennas and their interfaces have to be closed quickly to maintain schedule.

The CRC is concerned about timely delivery of the infrastructure required for the contractors to begin construction at the OSF and AOS sites. Preparation of the contractors' camps and work area and the first antenna pads must be in place soon. The demands on infrastructure preparation could become even more acute with the re-planning needed to accommodate two antenna contractors. The Management must carefully monitor the relevant Site IPT work packages.

The CRC has no detailed insight into the cost breakdown of the successful bidders, but we notice a surprisingly low cost item for on-site assembly in one of the quotations. To gain more confidence in the contractor's work assessments, the Antenna IPT should ask for clarification.

The contingency allocated to the AIPT budget is 5%. Although the contract has a ceiling price built in to guard against price fluctuations in the components, it is common for science projects to request change orders that can increase the contract price during the project development. The CRC recommends reviewing the amount of contingency allocated to the Antenna IPT to make sure there is adequate margin to cover unexpected problems integrating the (anticipated) hybrid array.

3.5 Spare Parts and Maintenance

The design lifetime of the antennas is 30 years with maintenance. The Board believes that special attention to detail in the design will be needed to ensure that the contractor follows 30-year design practices. In addition, a maintenance program is required to achieve the 30-year life. The cost and scope of the maintenance program could be high. Careful trade-offs between construction costs and maintenance costs will be needed. There is probably very little experience with long design lifetimes in harsh environments resembling those at the AOS site. The CRC recommends that AIPT staff pay special attention to this area.

Of particular concern is the apparent lack of forward maintenance planning: spare components are budgeted only for the first two years ($70k per antenna), but there is no budget line for antenna spare components beyond this time. We presume that this budget will be included in the final Operations Plan; it does not appear in the current Operations estimates (section 10.) It is cost effective to obtain adequate spares when they can be purchased as cheaply as possible. Most likely the opportune time will occur during construction, when large orders for components are being placed by the contractor. Certain critical components, such as specialized motors, frequently have short market availability, and spares may become unobtainable a few years after the antennas are purchased. The Management needs to note this potential problem.

3.6 Antenna Work Packages

3.6.1 WPs 1.03.030.0321/21, 1.03.045.0450/51, 1.03.050.0500

The Antenna IPT leads believe that planned staff supported by consulting contracts for specialized quality assurance are adequate to track manufacturing and the assembly at the OSF – providing there are no unforeseen increases in work loads. The CRC believes that the work load will be high on the Antenna IPT, in particular during the period when the first antennas are being fabricated (see "staffing"). With the addition of a contract for another type of antenna to a different company, the current staffing plan may be inadequate.

It will be important to monitor the contractors for quality control very soon. It will also be important to maintain contract management staffing as long as necessary. Close monitoring of the contractors and their subcontractors is crucial, particularly now that new suppliers will be involved.

There appears to be a strong tendency for the NA and EU-based parts of the AIPT to work independently. The Management should make every effort to encourage a single team effort. As result of separate antenna contracts, this goal will be even more challenging.

The CRC notes that the antenna AIV process in Chile is the responsibility of the System & Engineering IPT. The AIPT subcommittee did not review this aspect of antenna procurement and installation. This separation of work packages between the two IPTs requires good upfront planning. Since the workload will be enormous during the antenna commissioning, staffing and coordination of both the Antenna IPT and the System & Engineering IPT during this phase must be carefully thought out. The project should make every effort to ensure "continuity of expertise" (e.g. in holography), particularly for antenna commissioning, a critical work package. It is very important that expertise developed during prototype testing be fully transferred to the SysEng IPT.

The CRC believes that the antennas should not be finally accepted until they have been transported to the AOS and placed on several pads, and then finally shown to have retained their surface accuracy.

3.6.2 Transporter WP 1.03.070.0600

The design of the transporter is finished, and the ICDs are closed with full compatibility to ALMA-J antennas. Bids have been received, and signature is imminent. The cost has increased significantly to $5M for two units. The CRC advises re-assessing the impact of two antenna contracts and the reduction in the number of antennas from 64 to 50 on the transporter needs. If there is a need to change array configurations more frequently than originally anticipated or if there are difficulties encountered with two antenna types, there may be a need for another transporter (additional costs of order $2M).

3.6.3 Nutator WP 1.03.065.0580

The Project plan calls for four antennas to be equipped with nutating subreflectors, with an additional unit purchased as a spare. These units including the electronics package have to be delivered by NA for installation on the ALMA-J 12m antennas at a cost of $1.3M. The timing of procurement may soon become critical – an RFP for fabrication should be released before the beginning of 2nd quarter of 2006. There is as yet no final design, however, implying some risk to this part of the Project plan. The CRC also believes that the budgeted cost ($2M) is lower than it should be. It may be difficult to procure the nutators for this price. This is a technically challenging Work Package, and the CRC believes that special management attention is needed.

3.6.4 Optical telescope WP 1.03.062.0590

The design of the optical pointing telescopes (OPTs) is not yet final, but the CRC does not believe that this is a critical problem. Costs are a minor compared to most other costs ($0.2M for 6 units).

3.6.5 Antenna Foundation WP 1.03.050.0510

The costs of this WP are minor ($0.6M). The ICDs between the foundations and all three types of antennas are now frozen. The CRC suggests that a prototype foundation should be built and verified to minimize programmatic risk before start of construction of 100+ units without such verification.

4. Front & Back End Electronics

Anderson, Baloian, de Graauw (lead), Inatani, Padin, Pasian

- Both the Front-End (FE) and Back-End (BE) IPTs are in excellent shape to meet schedule and budget. The development program results indicate that prototypes of most of the systems meet the challenging requirements, in some case by large margins.
- The IPT teams are now adequately staffed. Interactions within the teams and with higher management seem to be working well.
- Project schedule information input and tracking are now in place and appear to function effectively.
- Because of the large quantity of components operating under harsh conditions quality is a paramount issue and, when insufficient, a potential time bomb for the operations and operating costs. Although Performance Assurance and Quality Assurance (PA/QA) plans have been implemented down to the level of the subcontractors, the CRC strongly recommends that the ALMA project manager together with the IPT management constantly verify that these plans are indeed implemented, in particular concerning the Parts, Materials and Processes requirements.
- Comprehensive tracking of failures and failure modes is also vital for the integration and operations phases of ALMA. The CRC strongly recommends that the Management IPT, supported by the IPT managers maintain a comprehensive central log of all failures and fixes.
- Most Interface Control Documents (ICD), including those about electromagnetic crosstalk are in place and accepted. Outstanding ICDs are mainly related to computing.
- Some specifications remain uncertain and will not be fixed until February 2006. Any specification changes could be a risk of cost growth (SRR follow-up items.)
- Cost estimates are based on demonstrated prototypes and experienced engineering estimates in most cases; the CRC believes they are reliable.
- The contingencies are smaller than the CRC would have used, but with the close-out of the remaining open development issues in 2006 the risk of cost growth will be substantially reduced.
- Electromagnetic interference (EMI) and compatibility (EMC) must be tested soon. Problems with interference could result in expensive rework and delays.
- Communication and interaction within the IPTs and with other IPTs have been growing in the past 6 months to a reasonable level and the upward trend in open communication should be continued,

The FE and BE are among the technically most challenging subsystems of ALMA. ALMA's unique scientific performance probably depends more on these subsystems meeting their specifications than any other IPT area. The deliverables are also critical to the master acceptance, integration and verification schedules; the BE is on the critical path. Both subsystems have complicated procurement lines. Tight project management and tracking are important to ensure that these IPTs stay on schedule.

Nevertheless, the CRC believes that the FE & BE work is well in hand with adequate contingency to handle changes in scheduled deliverables. In particular, ALMA can be tested and used for science with a fraction of the bands available. Thus, if there are problems meeting specifications for some frequencies, the other frequencies will still be useful for array integration and science verification. This redundancy of capabilities is a major factor to mitigate risk of short term cost growth in the FE and BE systems.

4.1 Front End IPT

Each antenna will be equipped with a receiver, or FE, capable of detecting cosmic radiation in six frequency bands. NA and EU will each provide two bands. An additional two bands will be provided by NAOJ. The design and infrastructure of ALMA allows the installation of up to ten receiver bands covering the atmospheric windows in the range 30 GHz to 950 GHz.

The ALMA receivers are coherent detectors, meaning they measure both the amplitude and phase of the electromagnetic waves, and they accurately measure the relative phase across different elements of the array. They use a common local oscillator signal to convert the received signal frequency at each antenna to a much lower intermediate frequency (IF) that is transmitted via the BE electronics to a single electronics building, where signals from all antennas are combined. Each separate frequency band receiver cartridge includes two receivers operating in orthogonal linear polarizations, allowing measurement of the complete polarization state of the cosmic radiation. All receivers will utilize superconducting mixers operating at temperatures below 4 K. The receiver cartridges for all bands are housed in a common cryostat located at the Cassegrain focus of each antenna.

Each antenna will also have a radiometer mounted at the Cassegrain focus but not on the optical axis of the telescope to measure the 183 GHz emission line of terrestrial water vapor. The radiometers measure radiation from atmospheric water vapor so that the phase variations caused by the vapor can be estimated. Those phase variations will be removed from the data as they pass through the correlator, enormously boosting the array performance. Because the project has no experience yet applying this technique at the ALMA site, there is some risk that the approach will need to be modified following initial testing. The CRC believes this risk is manageable within the current contingency for budget, although we note that it requires careful attention to the schedule for installation of antennas in the latter phases of construction.

4.2 Front-end IPT deliverables

Each FE Sub-system is an assembly that includes the following hardware units:

- Receiver cartridges for ALMA Bands 3 (84-116 GHz), 6 (211-275 GHz), 7 (275-373 GHz) and 9 (602-720 GHz)
- First local oscillator (LO) system
- An intermediate frequency system with an interface to the ALMA BE
- Water Vapour Radiometer operating at 183 GHz

- Amplitude calibration device based on dual loads (ambient and higher temperature)
- Solar attenuator
- Band 7 quarter wave plate
- All mechanical infra-structure to provide the necessary mechanical, thermal and optical environment required by the cartridges, including helium compressor, control unit, buffer tank and lines
- All support electronics and associated software to power, manage, tune, control and monitor this subsystem
- Mechanical mounting (FESS) to the antenna for 1) FE assembly, 2) Water Vapour Radiometer and 3) Amplitude Calibration device.

FE IPT deliverables to the project:

- 50 FE assemblies to contain cartridges for the 10 frequency bands. Each FE assembly initially contains 6 receiver bands, 1 Water Vapor Radiometer, and 1 amplitude calibration device
- Two FE service vehicles
- Holography receivers
- Spare parts, notably 3 spare FE assemblies.
- Services:
  - Training of operations/maintenance staff;
  - AIV support to the ALMA Observatory

4.3 Cost Growth and the new Cost Basis

The Fe IPT costs grew from $99.6M to $116.7M between the 2002 plan and the replan, an increase of about 17% in absolute terms; with the 20% decrease in number of antennas the actual cost increase is then about 37%.

For the FE IPT the increase in the cost estimates arose mainly from:

- better knowledge of the true cost to build to the original specifications based on more detailed estimates than could be done in 2002,
- changes in the organization or addition of tasks to the FE work elements.

Most of the cost increase is in the cold multipliers (+%6.5M), FE integration work (+$6.9M), support for integration and testing (+$1.6M) and the FE Support Structure (+$1.8M). The photonic LO development moved to the BE IPT (-$1.4M).

For the cartridges, the increased unit costs are offset by the reduction to 50 units plus spares; the total cost is, therefore, about the same as the 2002 estimate, which is remarkable considering the high technology level that is involved. In the rebase-line and the new cost estimates, performance requirements remained unchanged. The costs were recalculated from bottom-up in great detail. The significant change of scope by reduction in total number of units to match antennas offset the cost overrun considerably.

In the Basis of Estimate, the numbers for the NA and EU tasks are difficult to compare because NRAO tasks are performed largely internally and ESO tasks are contracts with other organizations. In all cases, costs have been estimated by detailed calculations at deep WBS levels. About one third comes from actual bids, two thirds are "experienced" engineering estimates.

The level of contingency for the FE IPT is relatively small (13 %). With most of the development work completed, the CRC believes that the contingency could be adequate. Furthermore, most of the critical issues will be dealt with fairly soon, within 6 months.

4.4 Concerns with Front-End development:

- The interface of the cryostat to the FESS is a concern owing to the lack of a validated design. The design of the FESS itself is uncertain. It is important that this interface issue be resolved soon, as it could impact the cost of the antennas.
- An accurate 3-D model (CAD and physical) of the receiver cabins combined with all its contents is needed to ensure interface compliance. No 3-D design of the cryostat mount is available, although it is expected to be soon.
- The reliability of the supply for sole-source custom devices (e.g., SIS junctions, amplifiers) is a concern and has the attention of the IPT. As precaution many critical devices are ordered or already in hand for the complete project lifetime. The cost risk is small, but there is potential for a schedule slip if a supplier would fail.
- The open issues with band-9 cartridge (LO power doesn't yet meet spec; 4-12 GHz isolator not yet demonstrated) are a concern, but there is a plan to address these issues. Low LO power may impact the cost, but the contingency seems adequate; Resolving the isolator issue might require a small change in the specification.
- Open issues about Monitor and Control and EMC of the cartridges during observations should be resolved as soon as possible.
- The European FE integration centre is behind in development. This delay does not pose an immediate risk to the project, but it should, nevertheless, be resolved soon to ensure that it does not impact other areas on the critical path.
- The greatest risk for the FE IPT is at the integration phase. The schedule calls for the FE to deliver parts early so as not to get on the critical path. It is important that SE IPT identifies potential risks and mitigation strategies, e.g., integrate complete systems as soon as possible. Rework after initial integration is a risk that needs a specific plan and contingency.
- The FE IPT should investigate whether costs could be reduced by accelerating the production schedule of certain elements such as cartridges. A secondary positive effect is that it may help to retain senior staff through the (shorter) production phase.

5. Back End electronics

Anderson, Baloian, de Graauw (lead), Inatani, Padin, Pasian

5.1 Back End IPT

The IF signals from the FEs are amplified, digitized at the antenna and transmitted to the control building via fiber optics connections. To process the 16 GHz bandwidth of the IF signal, the

Back End electronics system subdivides that signal into eight sub-bands of 2 GHz for transmission to the correlator. Other very important elements of the BE are the timing signals and the LO reference subsystem to synchronize the operation of the array and the data collection.
The BE IPT also support tests of prototype and pre-production hardware at the ATF, and AIV in Chile

5.2 Back End IPT deliverables

BE IF Processor (downconverter and total power) *[2 per antenna]*

- Data transmission system (xmtr, rcvr) [4 ea per antenna]
- Digitizer & demux/clock [1 ea per antenna]
- Fiber optics (fiber, patch panel, optical mux/demux [1 ea per ant], optical amplifier & controller [1 per antenna])
- LO reference and timing (125 MHz, 25 MHz, TE) [6 modules per antenna plus 3 modules at AOS Technical Building]
- Photonics LO reference (142 GHz) [2 assemblies per antenna plus 67 modules at AOS TB]
- Power supplies, hardware [2 PS per antenna; 11 at AOS TB]
  Total: 1,281 production modules and assemblies for 50 antennas

5.3 Cost Growth and the new Cost Basis

For the BE IPT the cost grew from $46M to $55.9M between the 2002 plan and the replan, an increase of about 20% in absolute terms; with the 20% decrease in number of antennas the actual cost increase is then about 40%.
For the FE IPT the increase came from:

- a substantial reorganization of the work elements
- changes in the technical approach in many areas

Because the work elements were re-organized, it is difficult to compare the 2002 and 2005 estimates directly.

The engineering support for the ATF and in Chile has substantially increased ($4.4M). The majority of the increase comes from the LO Reference System (+$9.1M) which includes now a.o. the Low Frequency reference, the photonic LO. On the other hand, the Digital Transmission System has decreased (-$3.6M) due to decrease to 50 antennas together with some cost savings from new technologies. Management cost increased by 50 % (+$1M)

During re-baselining, all deliverables were investigated and given a Basis of Estimate to provide better cost to complete estimates. Also the costs are now captured in the COBRA system, allowing for tracking of costs and Earned Value Management metrics. The present cost estimates are based on actual bids one third of the time and based upon experienced engineering estimates the other two thirds. A small fraction is based upon guesses.

Most of the IPT contingency is set aside for the major critical issues which will be dealt with fairly soon, within 6 months. The levels of contingency for these items range from 24 to 64%. The level of contingency for the BE IPT is relatively small but probably adequate.

5.4 Concerns with Back-End development:

The LO photonic subsystem is crucial for performance, and it is a single point failure for the ALMA system. Many parts have been tested, but a full end-to-end test has not yet been demonstrated. The biggest uncertainty in the integrated system is from mechanical noise due to the cable wraps. The fiber laser synthesizer redesign is also a concern. Contingency in this area is, indeed, higher than the average for the BE IPT, reflecting the IPT's awareness of the problem. We believe the photonic LO is the biggest risk in the FE & BE IPTs. We suggest that a technical review be carried out in the near future. A back-up plan with decision dates should also be made and brought to an implementation level to ensure no delays will occur in case the baseline system has serious problems.

The BE IPT is responsible for the overall EMI/EMC performance of ALMA. It has most of the necessary ICDs in place and a preliminary test at the ATF is planned end 2005 with a full test in the pre-production antenna at the end of 2006. The CRC is concerned about the late reality tests for the BE deliverables. More thorough testing in a production at the ATF early in 2006 could help avoid costly rework.

6. Correlator IPT

Anderson (lead), Dewdney, Garay

- The correlator and tunable filter bank meet all of the requirements, have come in under budget, and pose little threat to costs or schedules. Some of the hardware is already in hand.
- The long-term reliability of the field-programmable gate arrays in the tunable filter bank requires a reduction in the working temperatures. Plans to do so are well developed but not yet implemented.
- Cosmic rays at the ALMA site will cause temporary mis-operation of an individual FPGA in the correlator and tunable filter bank every few days. This risk may be mitigated by good operational procedures and by training of the operational staff. It poses no other threat to the project.
- The long-term risk of maintaining the correlator could be reduced by making long-term employment guarantees to a few key staff, particularly to the Chilean engineer currently assisting correlator construction in Charlottesville.

The Correlator IPT currently represents the smallest risk to the ALMA project; indeed, it is already ahead of schedule and under budget, and the CRC believes it is on track to meet or exceed all its milestones. The documentation and the verbal presentations from Management impressed the review committee and lent confidence to this assessment.

The Correlator IPT has an excellent, multinational team. It is well managed and productive. The first quadrant of the correlator is finished and tested with only one exception noted below. An associated Tunable Filter Bank (TFB) prototype to enhance the spectral resolution of the correlator has also been developed. The correlator-TFB combination meets all of the requirements, has come in under budget, and poses little threat to cost or schedule.

The IPT has procured and tested all the critical components for the correlator. It has completed manufacture of a significant fraction of the printed circuit boards. Many of the circuit boards have been tested and await assembly of the next correlator quadrants.

A prototype TFB has been developed, manufactured and tested with the correlator. The field programmable gate array (FPGA) devices in the prototype dissipate substantial power and, therefore, run at high temperatures. A change to use a later-generation, cooler-running FPGA is under development. A small amount of redesign is required but this does not require a large amount of effort or carry a significant risk to either costs or schedules.

The correlator group of the CRC dispensed with presentations on the second day of the review and concentrated on the tests remaining on the correlator, long-term reliability and operations.

The IPT has conducted tests with a DTS prototype and with a simulator designed independently to replicate the functionality of the interface specified in the ICD. Full tests of the interface with the optical receiver of the Data Transmission System (DTS) have not been possible because the latter is being reworked. The tests carried out so far meet all expectations, and the committee believes the delay in full testing does not pose a risk to either cost or schedule.

The chips on the correlator board run at temperatures and voltages well within their ratings. The operational lives of the correlator boards are not expected to be affected significantly by wear-out mechanisms over the lifetime of ALMA. Even with the changes to the FPGAs in the TFB, the FPGAs may run at case temperatures of about 70 C and junction temperatures perhaps 10 C higher. These elevated temperatures will shorten the expected lifetimes. The CRC recommends an investigation of measures to lower the temperatures by, for example, using heat sinks on the chips.

High-energy radiation such as cosmic rays can cause changes in the states of configuration switches within FPGAs. These transitory effects are expected to occur every few days at the 5000 m site of ALMA. The events will cause temporary mis-operation of the correlator and TFB until the FPGAs configurations are reloaded into the devices. Plans exist to update the configurations at every available opportunity, at least several times per day. An operational staff needs to be trained to handle these events.

Current estimates are that a correlator board will fail every few weeks. A faulty board can be identified by the diagnostic software and be replaced after electrically isolating its section. Board replacement requires only a few minutes by an on-site operator. Diagnostic software in a test fixture can pin-point faults to one or two chips, and boards can typically be reworked for repair about three times. The spare chips and boards are sufficient to last for the expected life of the correlator.

A Chilean engineer is currently assisting in correlator construction in Charlottesville. The intention in the long term is for him to provide support for the correlator on site in Chile during operations. The Management might want to formalize this arrangement in his contract to ensure that he remains on staff through the operations phase of ALMA.

7. Computing IPT

Baloian, Ho, Pasian (lead), Wolff

- The scope of work for the Computing IPT appears to be complete. The IPT estimates of cost and time needed to compete this work are sound. There is adequate contingency to cover the remaining risks in most areas.
- The Computing IPT has developed efficient methods for managing distributed development teams. The CRC is confident that the Computing IPT can deliver on time and within budget with the caveats about contingency allocations below. ALMA-J staff will provide in-kind contribution that should reduce the overall cost to ALMA of the computing deliverables.
- There is some risk in development delay resulting from the plan to include the support team only late in the project as part of operations. There is no plan for overlap and training. It would be useful to include some operations and science staff within the Computing IPT to aid this coordination.
- There are many interfaces between the computing IPTs and other elements of the project. Late addition of requirements or change in ICDs common in computer development may have a costly impact. Until the main ICDs are finalized (many are not), the currently planned contingency is likely to be too low.
- Development and testing currently rely on simulators not actual hardware. Simulators can miss critical aspects of the computing environment that will be discovered only during testing with actual elements of the array. It would be appropriate to raise the contingency for the software that has only limited access to the actual hardware it will ultimately control.
- The CRC believes that investment in software that makes it easy to use ALMA has a value much higher than its cost (5.5% of the total) and should remain unchanged in the baseline plan.
- The Computing IPT has tools in place to track development history and provide an estimate of costs for work to be completed. Although valuable, the review committee was concerned that these methods will not accurately capture the true costs of working with a distributed development team and may conflict with the development culture of the different groups. There is presently no plan to retain the expert knowledge of the developers for an extended period to maintain the systems. This absence implies long-term risk not included in the baseline plan.

The CRC was impressed by the progress of the Computing IPT. The managers provided a thorough explanation of the cost estimates, progress, and work to be done, giving us confidence that we could assess their plans. Although there are some difficulties in agreeing on commonly understand methods for the evaluation of the work performed up to now, the development effort and costs of ALMA computing appear to be well managed.

The approximately 1 million lines of code written to date represent about 1/3 of the total for the construction phase of ALMA. There has been no need for contingency to date, although we note that level-of-effort work is common in the early stages of software development and the need for contingency may not become apparent until much later.

The two principal concerns of the review committee concern use of simulators for testing and potential for scope growth in absence of complete agreement on interface requirements with all other ICDs. The former risk is likely to be small. ALMA is a straightforward extension of aperture synthesis techniques that have been used in radio astronomy for 50 years. Having two different antennae designs has minimal impact on software development. The latter risk will be retired as soon as final ICDs are agreed upon with all other IPTs.

7.1 Cost Growth and new Cost Basis

The cost for the computing IPT grew by $8M to $37M in the re-baseline exercise. The initial estimates left out the effort needed for maintenance and upgrades following the transition to operations. Additionally, the actual cost of staff hired to carry out the work were not known at the time of the initial estimates and proved to be larger than assumed. Using a more conservative approach to allocation of contingency as in other IPTs lead to further cost growth.

The CRC believes the current estimate of staffing needed to complete the outstanding work is accurate. It has confidence that the Computing IPT has been thorough. We note, however, that complete computing requirements are notoriously difficult to estimate at the outset of a project. Despite the best efforts of the team, the current contingency of 17% is optimistic about the state-of-knowledge that exists today. There are still outstanding ICDs or draft ICDs not agreed to by all parties. There remains the possibility that as the different IPT areas better understand their exact requirements the scope of computing will grow.

7.2 Suggestions for risk reduction or savings

- The Support Team will come on board late as part of operations; this setup will need to relocate to Chile some of the development staff for extended periods of time. Ideally, a proper overlap (6-9 months) between Computing IPT development staff and operations should be planned to allow handover of the software system; if there are any delays in the handover, there will be delays in the development activities. In any case, the Operations Plan needs to include an appropriate means to transfer software maintenance to operations staff.
- The IPT managers identified the main risks as uncertainties about interfaces between the Computing IPT and groups, some internal to ALMA. Reliable software requires robust interface standards to function effectively as part of a larger system. It is especially notable that the link between the Science IPT and the Computing IPT appears to be weak. Embedding Operations and Science expertise within the Computing IPT would be a good way to alleviate the risk of missed elements that will later require rework.
- Finalizing the pertinent ICDs and defining the software requirements are important steps to retire the risk of cost growth in computing. Until the main ICDs are signed and software requirements are further elaborated, a contingency as high as 25% should be considered for those areas of software and computing affected by this issue.
- The software developers and testers are using simulators in the absence of instrument hardware. It is not cost effective to build robust simulators, meaning there is some risk that problems with the software will not be discovered until the first antennas are

delivered, a time when computing could drive the critical path. In this area, too, contingency is low.

- Software is one of the key elements allowing a unique observing facility to be available to the scientific community at large. The added value of easy to use software allowing researchers to exploit the capabilities of ALMA is much higher than its incremental cost (5.5% of the total). As a consequence, the CRC suggests retaining this work element in any considerations of de-scope (BCP10). In addition to aiding scientists using ALMA during the operations phase, experience with other facilities shows a number of other benefits that reduce the risk of cost growth in the operations phase, including: ease of commissioning, scheduling, service observing and support for the Virtual Observatory (VO); once stable, ALMA will produce much more than 100 terabytes per year requiring VO capabilities to function effectively, hence an easy to use software system that works well with the VO.
- The mechanism of "maintaining efficient management in a goodwill-driven system" has worked adequately to date in allowing the Computing IPT to maintain its schedule. It may require additional management attention in the next few years as the scope of the management challenge increases.
- The IPT should make an effort to verify their methods of determining task progress by tracking computing milestones against the current plan and understanding the discrepancies.
- As with other IPTs, it will be useful to have a plan for retaining staff expertise in computing over the course of the project.

8. System Engineering & Integration IPT

Crocker, de Graauw, Inatai, Padin, Phillips (lead), Tanaka

- The JAO has brought effective Systems Engineering approaches to manage IPT interfaces and changes in work; this approach gives the CRC confidence in the new cost basis for ALMA and is a substantial improvement over the past several years.
- Recognizing the need for more systems engineering work than earlier assumed has raised the cost estimate; the CRC believes this increase is prudent and fully supports the approach.
- Estimates of the Systems Engineering work needed for construction and integration of ALMA appear to be complete and support the new cost basis.
- The review committee identified several areas of concern in its examination of Systems Engineering issues:
  - There is a need to recruit technical staff quickly, and there is no hiring & transition plan in place. Among the more challenging tasks is the need to hire 60 systems engineers with experience in radio interferometers over the next two years.
  - Implementation of the highest frequency bands will be challenging. The project needs to demonstrate band 9 interferometry soon (in Chile).
  - The use of two different antenna designs may substantially increase the workload for the SE&I IPT above that currently planned. The surface alignment and the need to manage two sets of interface documents will be especially challenging.

The current SE&I IPT is well-organized and appears to be functioning effectively. The IPT requirements are the result of considerable thought. The SE&I IPT is using modern systems engineering practice with effective processes for managing changes and interfaces between IPTs. We encourage the IPT to follow through with effective project tracking and control to minimize schedule and cost risk.

The CRC believes the attention to systems engineering and integration is important and a significant improvement over the situation several years ago. It increases our confidence that the project has all the tools in hand to control its costs by reducing the likelihood of interface problems that will show up during system integration.

8.1 Reasons for Cost Growth and new Cost Basis

The cost increase for the SE&I ITP is about $28 M. The estimated value for the 2002 budget is $16 M, whereas the current cost is $44 M. This is a large increase, but it includes many tasks that have been transferred from other ITPs. Of the $44 M by far the largest cost is labor, so much effort has to be expended in both training and supervising.

The major categories of SE&I are:

- Management. This was $1.9 M in the March, 2002 budget and stands at $2.3 M in the September, 2005 budget. A moderate increase reflecting increased staffing to cope with the greater load.
- Phase 2 Systems Engineering. This is essentially unchanged, going from $6.4 M to $6.9 M.
- Prototype Antenna Evaluation – completed.
- Prototype system Integration. This provides support for ATF site testing over a much longer period than originally anticipated. The cost increased by $2.8 M.
- Test equipment. The whole budget now resides with the SE&I ITP rather than the Site ITP. The increase for SE&I is $6.1 M.
- ALMA System Integration. A huge increase in the load on the SE&I ITP is due to the surface measurement and adjustment program for all antennas arriving at the site. This work was originally part of the antenna IPT. In addition, the time to check and integrate the receivers and back-end equipment was underestimated in the 2002 budget. The cost of system integration increased from $6.1M to $21.9 M.
- Commissioning. Now under the SE&I ITP rather than Operations. An increase in the SE&I ITP budget of $1.4 M.

The total SE&I budget is now $43.9 M with a contingency of about $3.9 M, or 8.8%. So if there is a one-year delay caused, say, by late antenna delivery, essentially all SE&I contingency will be needed to pay salaries. The current SE&I contingency is probably too small, and should be reviewed. Apart from this item and the aforementioned difficulties of hiring large numbers of suitable personnel in Chile, the SE&I budget looks reasonable.

8.2 Suggestions for cost containment/risk reduction

There are a few areas that the committee believes need attention now to preclude problems with systems integration:

- Attention to staffing challenges and human resources. AIV requires 44 staff members working in Chile in 2007, 60 in 2008 reducing to 10 at the end of the project in 2012. It will be challenging to hire and train qualified people as quickly as they need them, and it will also be challenging to retain the needed talent throughout the project when the staff understands the planned reduction in force. Failure to find appropriate SE&I staff will delay the project at a cost of ~15M/yr. Furthermore, the staffing profile assumes no vacancies. This assumptions belies experience with almost all large projects and represents a cost risk that requires a specific, currently unplanned contingency. Continuity is important during ALMA construction. SE&I must maintain a core of expertise throughout the construction phase. The Chilean staff will include many technical experts. Hiring this staff might be facilitated by a collaboration with a Chilean institution.
- The interface between AIV in Chile and staff in the IPTs in North America and Europe requires careful management to avoid divisions within the project (them vs us). This is a risk to cost and schedule. Close involvement on the site of the IPT members in AIV will help.

- Allocation of contingency does not appear to be well correlated with the assessed risk. This lack of correlation should be addressed. In addition, the SE&I contingency appears to be low for such a critical task, where any delay will have serious cost implications.
- It is important to finish the outstanding ICDs as soon as possible to avoid potentially expensive changes.
- We suggest that the final surface alignment with holography be done at the high site with a celestial source. The AIV plan should include an astronomical beam measurement at high frequency to measure the efficiency (to check the holography results and focus). The alignment plan should include measurements of the beam on the secondary.
- An accurate 3D model (CAD and a physical prototype) of the receiver cabin and contents is needed to ensure interface compliance. A design mistake in this area has serious cost implications.
- The high frequency bands are technically very challenging, so a demonstration of band 9 operation, on a long baseline in Chile, is needed as soon as feasible.
- The current ALMA performance model may not be adequate for resolving trade-offs between IPTs. SE&I should consider a full end-to-end simulator.
- The scope of SE&I is significantly increased by having two different antenna designs in ALMA-B, and by adding ALMA-J. The cost and schedule consequences of this must be quantified.

9. Science IPT

Beckwith, Ekers (lead), Omont, Tanaka, Wolff

- The Science IPT is working effectively to ensure rapid commissioning and full science operations of the array. It has made sound estimates of the scope and cost of the work.
- Because the Science IPT will become the basis for the operations group, the management needs to address human resources issue of retention or transfer of expertise soon to ensure a smooth transition to full operations. The difficulty of recruiting a project scientist is already of concern to the CRC and raises the possibility of project delays owing to understaffing.
- Complete phase correction using water vapor radiometer (WVR) measurements is an important goal. It would be prudent to test its feasibility at the ALMA site with the actual equipment to be used for ALMA quickly to assess any site-specific problems before full implementation of phase corrections.
- Implementation of the longest baselines (more than a few km) could be delayed if necessary to save money as construction proceeds, but it is important to avoid making any decisions that would prevent their future implementation which is required to meet one of the key science objectives.

The Science IPT is responsible for commissioning the array and certifying its performance for full science operations. Planning for this work is advanced, and the IPT understands their work well. This IPT has a key role in the evaluation and communication of the science impact of the re-baselining. The work is mostly level-of-effort from staff already employed by the Executives, and the cost of the Science IPT is modest (~$10M or 3% of the total project costs) compared to the importance of developing good procedures for acceptance and calibration of the facility. Nevertheless, the Science IPT costs grew by almost 30% from a planned $7.5M to $9.7M.

9.1 Reasons for Cost Increase and new Cost Basis

Cost increases in this IPT were mainly in the result of scope growth in its work. The Science IPT had to develop new requirements for the commissioning phase as they better understood the challenges of ALMA over the last three years. They also recognised that more effort and testing hardware would be needed for the high risk but critical WVR phase correction system. The reduction in number of antennas actually increased the work-load in this IPT, as simulations and configuration studies had to be redone and the array layout re-optimised.

The current estimate of scope – hence, cost – for this IPT appears to be complete. There are areas where slightly more work could benefit other IPTs with savings. In a section 2 of this report, we identify potential savings on road construction if the array configuration could be further modified. Such savings would only be realized if Science IPT could carry out a new optimization of the array with an eye toward road length. We were also concerned about coordination between the Science IPT and the Computing IPT that could lead to growth in the latter area: there is some risk that the software will not deliver the scientific functionality expected by the user community. Close coordination between the two IPTs is one way to reduce this risk.

9.2 SCIENCE IPT

The Science IPT is working effectively to ensure rapid commissioning and full science operations of the array. This IPT will become the basis for the operations group. The project needs to pay attention to human resources issues soon to ensure it can retain the talent needed for a smooth transition to full operations.

The Science IPT provides the high-level science specifications and requirements documents. Their work covers a range of activities:

- Calibration strategies, including the analysis of the WVR and fast switching techniques which are critical for the success of ALMA. These studies require site characterisation and will intensify when the first hardware is available for on site testing.
- Configuration studies with detailed site and antenna movement constraints
- Proposal analysis based on ~120 proposals from 80 scientists simulating 3 years of work.
- Simulations including packages for use by the user community.
- Studies of image quality.
- Communications with the numerous ALMA science advisory bodies in NA and in EU. The number of separate groups involved increases the workload in this area. Public outreach is also handled by the Science IPT.
- Operations verification.

9.3 ALMA Science

ALMA will have an extraordinary impact for the study at a range of angular resolution millimeter and submillimeter emission from all kinds of astronomical sources, mostly from molecular gas and dust. ALMA has two major goals, understanding the early evolution of galaxies and understanding the formation of stars and planets. These drive the level-1 science requirements and the technical specifications

ALMA will observe the physical and chemical conditions in the interstellar medium of galaxies and its structure and dynamics, from local interstellar clouds of the Milky Way to the limits of the Universe. One of the main outcomes will be the understanding of the complex processes of star formation in various conditions, and the assembly of galaxies. ALMA will be able to detect major bursts of star formation since their first apparition in the Universe. It will have the ability to detect spectral line emission from CO and C+ in normal galaxies, similar to the Milky Way at a redshift of less than z=3 (more than 10 billion years ago, when the Universe was only 15% of its present age) provided the total collecting area (number of antennas) is not too compromised.

The second major goal is to use the ability to provide *precise* images at the resolution of 0.1" to observe the last stages of stellar formation and especially the formation of planetary systems similar to ours. ALMA will have the ability to image the gas dynamics in a solar-mass protostellar/protoplanetary disk to within a few AU of the star in the closest star forming interstellar clouds. This ability will enable the study of the physical, chemical and magnetic structure of circumstellar disks and the search for tidal gaps created by planets undergoing formation.

ALMA has also many other important goals on a rich variety of other astrophysical objects: extragalactic research includes active galactic nuclei, gamma ray bursts, intergalactic clouds, galaxy clusters (Sunyaev-Zel'dovich effect), gravitational lenses, etc.; Galactic research includes all kinds of interstellar clouds, proto-stellar and young objects, and their chemistry, the Galactic center, etc.; circumstellar shells and their chemical composition reflecting stellar nuclear processing; Solar System research includes cometary nuclei and comas, asteroids, Kuiper Belt Objects, images of the planets and their satellites, etc.; solar active regions and the physics of particle acceleration. No other instrument existing or planned will approach the combination of angular resolution, sensitivity and frequency coverage (with polarization capability) to address adequately these scientific objectives.

We draw attention to the case for using ALMA as a very high sensitivity node in future mm and submm VLBI experiments. The proposal to look for the distortions in images of SgrA* due to the black hole in the Galactic center is particularly exciting and is of fundamental importance. It will only be possible with Earth-scale baselines at submm wavelengths with ALMA sensitivity. This is not a level-1 science requirement and consequentially VLBI capability is not currently included; however at this stage it is most important to make sure that such capability is not designed out as a future option. We note that other science experiments, such as mm solar imaging are still under consideration.

9.4 Rebaselining

The re-baselining activity identified a set of options (BCP's) which can reduce cost. In most cases, the main impact of adopting the option is on the science capability of ALMA. The CRC could not make an independent assessment of individual BCP's but we have looked at the process to see if the proposed BCP's are effective and credible.

The ASAC is established as an advisory committee to the board on ALMA science issues. It receives input from a variety of science working groups in NA and EU. The ALMA Board asked ASAC to assess the science impact of the BCP's; the findings are summarized in their reports of October 2004, March 2005, and October 2005. We examined the ASAC reports and the comments from the Science IPT from the standpoint of process and potential to reduce risk by adopting BCPs, noting that the Science IPT has a key role as the interface between the ALMA project and the science community. In this role, they have been particularly careful not to make judgements or set priorities on these issues themselves.

There are two BCP's with major cost impact we comment on here:
i) Reducing the number of antennas. The main impact is on speed of observation, which increases as the square of the collecting area, although it does hamper some other goals such as image quality. In March 2005, the ASAC concluded that "a submillimeter array with 50 or more operating antennas would be a superb instrument that would surpass all existing arrays by a wide margin." The CRC agrees that this BCP is a reasonable way to address cost growth at this stage of the project.

ii) Deferring implementation of the longest baselines. The ASAC notes that implementation of the longest baselines (more than a few km) could be delayed, but that it is important to avoid making decisions that may prevent the future implementation. The longest baselines are a key component of Primary Scientific Requirement 2, imaging of gas and dust in protoplanetary disks.

Phase correction is critical for the full science capability of ALMA, especially at the highest frequencies, and the use of WVRs remains a major goal that must be included in the re-baseline. They will complement fast-switching and could reduce the need to use this mode which will put mechanical stress on the antennas over the course of time. The decision about the immediate production of WVRs or deferring it after commissioning tests with the first antennae on the site should be taken after tests at SMA.

In general, the CRC agreed with the responses of ASAC about the impact of the re-baseline options on the science. In particular, deferring either one IF, or one polarization or one front end band would be equivalent to losing 40% of the observing time or one third of the science projects for saving 1-2% of the total cost of ALMA. This approach does not appear to be cost effective.

10. Operations

Beckwith, Ekers, Guesten, Omont, Turner, Williams (lead)

- The cost of Operations is estimated to be $46M per year, about 7% of ALMA's capital investment cost
- The operations plan is credible and complete. A detailed audit of each staff position revealed no obvious missing elements nor any elements that are not required to carry out the expected work.
- There are few options to save money over the plan. $46M per year may even be low
- There is no plan for transition from construction to operations; such a plan would help guard against difficulties with the onset of operations and lifetime cost growth
- It would be helpful to clarify the decision-making authority for operations within Management

In contrast to the other areas, operations is not yet a formal IPT, and Management has only recently estimated the cost of operations provisionally approved by the ALMA Board. Because operations follows construction, it is often neglected in the early phases of a project, since the operations work is not needed to complete construction. Tasks that fall under Operations are a more heterogeneous set than the tasks within each of the other IPT groups, covering such diverse activities as telescope maintenance, the data archive, telescope scheduling, instrument calibration, proposal submission and the peer review process, communications, the business office and personnel management, facilities upkeep, interfacing with the users via the ARCs, and a modest development effort.

The two Executives recently produced an ALMA Operations Plan and Budget Overview in two documents that set forth the tasks, responsibilities, and costs associated with the ALMA Observatory as it approaches the end of the construction phase and ramps up science operations. The Cost Review Committee found the 'ALMA Operations Plan' and the 'ALMA Operations Budget Overview' documents to be thorough and well done.

The basic features of the operations plan are as follows:

- The annual operating cost of ALMA is $46M in 2003 dollars
- 2/3 of costs are associated with Chile operations, which include the ALMA Director's Office (ADO)
- $10M of the $46M is devoted to on-going development costs and upgrades
- The ALMA Regional Centers (ARCs) are funded at a level of $3.5M for their core program, primarily devoted to the data archive and user interface
- No funds are provided for the purchase of spares
- 8% of the $46M, i.e., 10% of Chile operations costs, is for contingency

These figures were derived by comparing other projects similar to ALMA, i.e., large radio installations such as the VLA and observatories such as ESO/Paranal that operate in Chile, and determining those functions required to assure uninterrupted data collection and dissemination.

The other facilities have experience over many years with the various tasks associated with operation of a remote scientific facility; these tasks are, therefore, well known.

Although there are different options for operating an observatory in Chile, most of the large observatories have evolved to a common mode of operation that involves a 'turno', or approximately one week on duty, one week off duty shift, system in which certain functions are performed by a local staff while others are outsourced. The nominal plan pays proper attention to the question of safety at all of the sites.

Equally, the manner by which proposals are received and peer reviewed, observations are taken, the data calibrated, archived, and provided to the scientists, has evolved to a system that has many common features among observatories. Thus, the tasks required to operate ALMA are fairly well known, and it is straightforward to estimate the associated costs. The very detailed study by Silva and colleagues following a model in which observations are taken remotely in service mode, and the data path includes a core group of astronomers in San Pedro and Santiago, with some functions channeled through the ARCs, results in the operating budget of ~$50M per year in current dollars.

The plan assumes that ALMA will operate with 95% of the systems functioning properly for 95% of the time. This goal is ambitious and represents a risk factor for the observatory. Relaxing this requirement might be a source of some cost savings at the expense of observing efficiency. The nominal plan also has not taken into account the likelihood that there will be two types of antennae, a feature that will certainly lead to increased operating costs.

The CRC studied the proposed operations plan in detail with an eye to determining which tasks and responsibilities are truly essential to the operation of a forefront observatory, and what the associated costs are. Several of our members have extensive experience in the operation of large observatories in Chile, and they found the proposed operations plan to be well done. We examined work to the second level of WBSs, and found no major areas of effort that have been overlooked in the proposed plan, nor did we consider any of the proposed tasks to be unnecessary or inadvisable.

As a basis of comparison, we note that $46M is roughly 7% of the ALMA construction cost of ~$700M. This figure is similar to that of most observatories, which historically have incurred annual operating costs of between 5-10% of the total construction costs. Those observatories that have adopted budgets at the lower end of this range for periods exceeding a few years have normally experienced problems maintaining their infrastructure and scientific output.

The CRC could not identify alternatives to the proposed plan that would be significantly cheaper and yet deliver the same level of science. We conclude that the nominal operations budget of $50M is likely within 15% of the cost we would estimate independently and necessary for ALMA to achieve its goals. Since the nominal plan has not budgeted for spares and has allowed for a modest allotment of $10M per year for development, the CRC suggests that the $50M figure is probably conservative. Without sufficient development funds, it will be difficult to attract the technical people needed to carry out new projects. One way of solving this problem is to distribute development funds to the universities, who will subsidize some part of project development and help provide the high level talent required.

One of the primary problems we identified is the lack of a plan for transition from the construction phase to operations, including the transitioning of key personnel. There is an urgent need for the agencies to commit to an adequate operating budget to ramp up during construction. An operations schedule has not been set, and therefore hiring projected for 2005-06 cannot proceed. A flexible and efficient hiring process, especially in Chile, is urgently needed that provides for the authority required at all levels for hiring. We especially note that the continued absence of a Project Scientist in Chile is having an adverse effect on planning for operations including such cost-sensitive items such as requirements for operations at the site."

There is at present no plan for the integration of ALMA-J into operations, and this matter needs immediate attention.

Appendix 1: Summary of Recommendations in IPT Areas

1. Management IPT

a. Strengthen the AMAC/Board ties and use AMAC expertise to alert the Board to the timing of decisions that affect the ability of the project managers to execute the plan.
b. Someone or entity, perhaps the ALMA Board, should have the authority to resolve disputes between the Executives and the JAO and between the two Executives.
c. Create a human resources plan to ensure adequate staffing throughout the development and operations phases.
d. Decide quickly on a plan for hiring labor in Chile and put the plan in place.
e. Revisit contingencies allocated to IPT areas as suggested in this report, and ensure that the JAO hold sufficient contingency to to offset costs and schedule slips related to executive and partner processes integration.

2. Site IPT

a. Re-optimization of the antenna layout following a reduction of antenna pads from 200 to 175 to save $5.5M.
b. Optimization of the layout to minimize the length of the roads connecting the antenna pads. Savings in road and the associated utilities should be explored as part of a complete re-optimization with potential for saving without science impact.
c. A reduction of the size and quality of the buildings could result in 5-8 M$ in saving without immediate impact to the science.
d. The number of people needing on-site residence needs refinement. Saving of as much as $4M may be achieved.

3. Antenna IPT

a. Ensure that there is adequate contingency to cover change requests in the contracts to fully integrate the hybrid array – the CRC is concerned that 5% is optimistic.
b. Reconsider the transporter requirements for a hybrid 50-antenna array.
c. Build and verify a prototype antenna foundation to minimize programmatic risk before constructing 100+ units.

4. Front End Electronics IPT

a. Create a validated design for the FESS and interface to the cryostat; poor control of this interface issue be resolved soon, as it could impact the cost of the antennas.
b. Create an accurate 3-D model (CAD and physical) of the receiver cabins combined with all its contents to ensure interface compliance. No 3-D design of the cryostat mount is available, although it is expected to be soon.
c. Resolve the open issues with band-9 cartridge; the LO power doesn't yet meet spec; 4-12 GHz isolator not yet demonstrated. Resolving the isolator issue might require a small change in the specification.

d. Resolve the open issues about Monitor and Control and EMC of the cartridges as soon as possible.
e. Bring the European FE integration center on schedule to ensure that it does not impact other areas on the critical path.
f. The greatest risk for the FE IPT is at the integration phase. The schedule calls for the FE to deliver parts early so as not to get on the critical path. It is important that SE IPT identifies potential risks and mitigation strategies, e.g., integrate complete systems as soon as possible. Rework after initial integration is a risk that needs a specific plan and contingency.
g. The FE IPT should investigate whether costs could be reduced by accelerating the production schedule of certain elements such as cartridges. A secondary positive effect is that it may help to retain senior staff through the (shorter) production phase.

5. Back End Electronics IPT

a. Carry out a technical review of the LO photonic subsystem to ensure that it will meet spec in the integrated system.
b. Create a back-up plan with decision dates to ensure no delays will occur in case the baseline system has serious problems.

6. Correlator IPT

a. Investigate measures to lower the temperatures of the FPGAs by, for example, using heat sinks on the chips.
b. Create a training plan to assist operational staff in handling changes in the states of configuration switches with the FPGAs.
c. Consider the long-term support for engineering talent to maintain the correlator during operations.

7. Computing IPT

a. The Operations Plan needs to include an appropriate means to transfer software maintenance to operations staff.
b. Embedding Operations and Science expertise within the Computing IPT would be a good way to alleviate the risk of missed elements that will later require rework.
c. Until the main ICDs are signed and software requirements are further elaborated, assign a 25% contingency to those areas of software and computing without final ICDs.
d. Increase contingency in those areas requiring simulators in the absence of instrument hardware for testing.
e. Retain work on user-friendly software rather than eliminating this element to save money. Ensure that this software can support the Virtual Observatory (VO).
f. The IPT should verify their methods of determining task progress by tracking computing milestones against the current plan and understanding the discrepancies.
g. As with other IPTs, create a plan for retaining staff expertise in computing over the course of the project.

8. System Engineering IPT

a. Create a human resources plan to ensure adequate staffing in systems engineering. AIV requires 44 staff members working in Chile in 2007, 60 in 2008 reducing to 10 at the end of the project in 2012. The staffing profile unrealistically assumes no vacancies. Hiring this staff might be facilitated by a collaboration with a Chilean institution.
b. The interface between AIV in Chile and staff in the IPTs in North America and Europe requires careful management to avoid divisions within the project (them vs us). This is a risk to cost and schedule. Close involvement on the site of the IPT members in AIV will help.
c. Allocation of contingency does not appear to be well correlated with the assessed risk. This lack of correlation should be addressed. In addition, the SE&I contingency appears to be low for such a critical task, where any delay is likely to increase the project cost.
d. Finish the outstanding ICDs as soon as possible to avoid expensive changes.
e. The final surface alignment with holography should be done at the high site with a celestial source. The AIV plan should include an astronomical beam measurement at high frequency to measure the efficiency (to check the holography results and focus). The alignment plan should include measurements of the beam on the secondary.
f. Create an accurate 3D model (CAD and a physical prototype) of the receiver cabin and contents to ensure interface compliance (this suggestion is duplicated in the FE IPT.)
g. Demonstrate Band 9 operation on a long baseline in Chile as soon as feasible.
h. Consider a full end-to-end simulator for ALMA performance to resolve trade-offs between IPTs.
i. Quantify the cost and schedule consequences of having two different antenna designs in ALMA-B and by adding ALMA-J.

9. Science IPT

a. We concur with the ASAC that implementation of the longest baselines (more than a few km) could be delayed, but not if it jeopardizes the future implementation of the long baselines; they are a key component of Primary Scientific Requirement 2, imaging of gas and dust in protoplanetary disks.
b. Include WVRs in the re-baseline (i.e. do not de-scope this item.) The decision about the immediate production of WVRs or deferring it after commissioning tests with the first antennae on the site should be taken after tests at SMA.
c. We concur with the ASAC about the impact of the re-baseline options on the science. In particular, the Management should not defer either one IF, or one polarization or one front end band, equivalent to losing 40% of the observing time or one third of the science projects for saving 1-2% of the total cost of ALMA.

10. Operations

a. Finalize the operations plan soon. The draft plan has been very well done.
b. Create a funding ramp allowing immediate, albeit low funding for operations now as part of a steady transition from development to operations over the next five years.
c. Incorporate the integration of ALMA-J into the operations plan.