Lessons Learned from ALMA

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Introduction and Background

ALMA arose from the amalgamation of separate projects in the U.S., Europe, and Japan to build large millimeter/submillimeter arrays. Extensive site surveys resulted in all three groups intending to site their projects at high altitude near the Atacama Desert in northern Chile. Initial discussions on combining efforts were focused on making the electronics sufficiently compatible that the arrays could occasionally be joined to increase collecting area and resolution. Initial funding in the U.S. was for the MMA, proposed to be an array of 40 8-m dishes, for which official development funds began in 1998. There was no serious funding beyond concept development and some hardware R&D for the European or Japanese projects at that time.

NRAO, at NSF's request, looking for partners with whom to share the cost of MMA, approached ESO, and Riccardo Giacconi, then Director General of ESO, recognizing the scientific importance of the projects, encouraged the European and U.S. groups to combine forces to build a single array as the ALMA (Bilateral) project, with shared time in proportion to contribution. Japan, which at that time wanted to build the short-baseline Atacama Compact Array with 12 7-m antennas, and 4 12-m total power antennas, later entered into an agreement to collaborate with the bilateral ALMA partners; the level of integration gradually increased, and all three regions now share in the building and operation of ALMA. In addition, Canada joined as a partner with NSF; Taiwan entered as a partner both with Japan, and separately, with North America; and the U.K. joined ESO, partly to share in ALMA. Thus all partners were eventually accommodated within one project. The scientific objectives and interests of the different national groups were similar but not identical, and some compromises in the various proposed designs were thus necessary. The original baseline involved 64 12-m diameter dishes working up to 950 GHz, plus a compact array contributed by Japan, although cost growth necessitated a rebaselining carried out in 2005-2006.

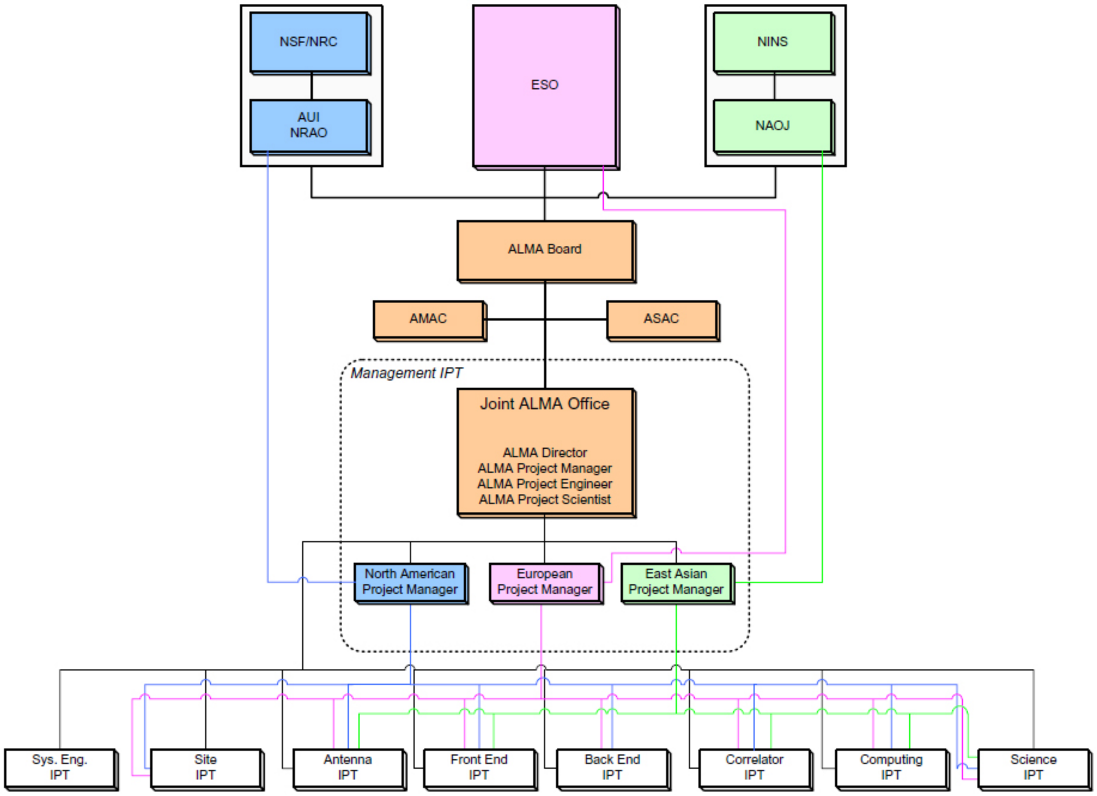
While the end result will indeed be transformational and scientifically far more productive than any of the partners could have afforded acting alone, regional interests and differing cultures have inevitably led to disagreements and conflicts, which produced delays and increased costs. All the participating regions wanted responsibility for development work with intellectual content and challenge, all partners also expect some visibility and economic return. Procurement processes, programmatic guidelines, and long-term funding stability are all areas that differ from party to party. ESO procurements follow rules which encourage spending in ESO member states and some return to ESO's participating nations; procurements must be approved by the ESO Finance Committee, a set of non-scientist national representatives. In contrast, NRAO/AUI procurements are only lightly restricted, the major exception being that construction of facilities within U.S. boundaries must use U.S.-produced concrete, steel, *etc*. The ESO system is designed to try and spend the money in the member states and is judged on the basis of long-term cost to the organization – over the lifetime of the project. In the US, the capital funding must be kept strictly separate from the operations costs. Japan has its own procurement policy, with strong industrial involvement. While the partners try to accommodate each other's systems, the contrasting rules of engagement lead to very different perspectives on any cost benefit analysis and some conflict is unavoidable.

Another major cultural difference is that NRAO had traditionally done most electronics work as in-house development with several stages of prototypes and on-the-sky testing, while contracting antenna and facilities construction, still often with significant staff involvement. On the other hand, ESO does very little construction in-house, and relies on a process in which the most important phase is writing down all requirements and specifications in advance, followed by a commercial procurement—all of this requiring a large amount of formal documentation. Japan is somewhere between these two extremes, with the NAOJ readily undertaking major technology development in-house if there is no commercial source. These cultural differences, combined with the understandable increased documentation and interface requirements necessitated by a billion dollar class program, and increased NSF review requirements, resulted in major mutual frustration, with NRAO engineers balking at the unaccustomed level of documentation and bureaucratic procedures, and ESO balking at both the number of reviews, and a perceived lack of documentation.

The final cost of bilateral ALMA is not only substantially larger than what was originally promised to the funding agencies, but in addition descoping led to a bilateral 12-m array that contains only 50 dishes instead of 64, with not all frequency bands included in the rebaselined construction project. The summary provides an overview of the reasons for the increases, and some detail is provided by major WBS element in the sections below. All costs are given in Year 2000 U.S. dollars.

1. Management

One area that was significantly underestimated is management. There was a traditional NRAO-style Project Book for the NRAO MMA project, which summarized in successive editions the requirements and status of development. As the bilateral project evolved, groups were formed of those working in the same area, to satisfy everyone's regional requirements. A management-by-consensus structure was invented, with formal Integrated Product Teams (IPTs) involving both partners, with a leader from one Executive and a deputy leader from the other. It now looks like this:



A key feature of this organization is that the money flows *around* the central Joint ALMA Office (JAO), not through it (blue, green, and pink lines). Expenditures are controlled by the "Executives", namely the North American, European, and Japanese Project Managers, who report to the directors of the NRAO, ESO, and the NAOJ respectively. The JAO is delegated programmatic direction by the Executives by the ALMA Board, whose membership includes representation of the Executives and funding agencies. The only IPT which reports directly to the JAO is Systems Engineering, whose approval is usually needed on decisions made by the other IPTs. However, all change requests have to be approved by the JAO, and contracts and contract changes above specified thresholds have to be approved by the Board. Within each IPT, there is an IPT Leader, a Deputy IPT Leader, and a Japanese IPT leader. The Site IPT also has a strong reporting line to the JAO. Decision-making at the IPT level is by consensus unless there is an irreconcilable conflict, in which case the decision goes to the IPT Leader but can be appealed to upper-level management.

In the initial phase of ALMA, cost estimation was done on an *ad hoc* basis and depended on the experiences of scientific and technical staff in doing similar work in the past. The funding agencies were understandably unhappy with this approach, and the project in 2001 adopted a Basis of Estimate methodology, using the LIGO formalism as the template (see Appendix).

In 2004, the project added a separately calculated Risk Register with significant risk enumerated and explained, and an assessment of probabilities and impacts independent of the Basis of Estimate calculations.

Initially, scheduling was done by one person using *Microsoft Project*; but it rapidly became apparent that this was an insufficient tool for ALMA, and a formal Project Management Control System was needed. The project chose *Open Plan* for scheduling, combined with *Cobra* for cost tracking. Several professional schedulers were hired to work with the ALMA staff at many levels to enter tasks and schedules and cross-link them. Since items are designed, built, and tested at many institutions and companies, for most items there is not only a set of tasks to be done, but also an event of *delivery* and a linked event of *acceptance*. The relationships are complex and the schedule at present contains 23,482 lines and perhaps 100,000 links and dependencies.

The initial cost estimate for project-wide management for ALMA-B in October 2002 was $26M including contingency. The final number is expected to be $93M (258% overrun). While some amount of this increase involved the moving of indirect costs to the Management line, much of it came from an increased allowance for contingency. The contingency allowance in October 2002 was only 8.4% overall, which was much too low for such a large and complex project with so many unknowns. (During the rebaselining, a cost contingency of 30-40% was required, and a schedule contingency of one year was also added.)

The initial ALMA budget estimate for Management was much too low primarily because we did not include an adequate contingency, and did not adequately estimate costs for the overhead associated with managing and coordinating a large multinational project, namely

- Time spent preparing for and attending internal and external review meetings, a severe burden with a substantial impact on schedule
- Resolving fundamentally different approaches in development and procurement, particularly in antenna procurement, which was held up for more than a year after initial evaluation of test antennas
- Detailed scheduling and recosting
- Setting up and operating a business entity in Chile
- Accommodating fluctuating currency exchange rates
- Travel for management and review meetings

3. Site

The Site work is all the infrastructure at the Operations Support Facility (OSF) and Array Operations Site (AOS)—buildings, roads, utilities, antenna foundations, power, cable trenching, etc.—as well as the Santiago Central Offices (SCO). It's not exciting, but it's essential.

The October 2002 estimate for site costs of a 64-antenna ALMA array was $68M. The present end-of-project cost estimate is $123M (67% overrun after correcting for NAOJ's entry and related contribution).

The initial ALMA budget estimate for Site was much too low because we did not adequately estimate costs for:

- The implications of operating in Chile, including fluctuating currency exchange rates
- The impact of a construction boom in Chile, with major mining projects competing with our relatively tiny needs for construction
- Having to build and operate our own power independently from the Chilean power grid on a permanent basis (further exacerbated by international politics affecting the natural gas supply)
- The staff cost for a *turno* system (8 10-hour days at the site, then 6 days off) and the number of staff who would choose to live in Santiago (lots of air travel)
- Increase in the cost of materials (concrete, rock, steel, etc.) because of worldwide demand

- Increase in the cost of diesel fuel for generators
- Difficulty in recruiting staff within Chile and relocating international staff to Chile

4. Antennas

The NRAO performed extensive FEM analysis of an 8-m antenna design with steel pedestal, carbon fiber backup structure, machined aluminum panels, and various metrology options in order to show that, conceptually, one could be built which meets specifications for an affordable price. When the design was changed to a 12-m dish, most of the calculations were repeated. This straw man design was then supplied to potential bidders along with the analysis. The NRAO intention was to procure one prototype antenna and to own the design.

ESO and NAOJ also built prototype antennas; by agreement, all 3 12-m prototype antennas were installed at the ALMA Test Facility at the NRAO/VLA site and evaluated by the same team. This caused some headaches because of the requirement to preserve proprietary information about the performance of each design.

It was a high priority of the Science IPT to have the project agree on a single 12-m antenna design in order to make the science goals easier to achieve, since many systematic effects would be expected to cancel to some degree if the antennas had the same sidelobe response and responded in the same way to thermal and wind effects. It was also a management priority because of the expected cost savings from a large, single production run. It was also an engineering priority because it would mean only one set of antenna interface and maintenance requirements. The performance of all 3 prototypes was roughly comparable and acceptable, although they differed somewhat in surface and pointing accuracy. The quoted prices were also comparable. Alas, the desired single design was not achieved.

The differences in the procurement processes under the different home organizations and cultures resulted in endless argument over minor details of measured performance, and a new round of testing was undertaken. NRAO had to follow its approved procurement process, under US law; ESO followed a European procurement process with a separate Call for Tender (CfT) with the same specifications, of course. Bidders could respond to NRAO, to ESO, or to both; two bidders responded to both.

In addition, the procurements were placed as build-to-specification, so that the vendors would be responsible for design defects, adding to the cost but reducing the contingency requirement. NRAO and ESO, operating according to their separate procurement rules, placed contracts with different vendors. The NAOJ later procured its own 12-m antennas from a third vendor. Agreement *was* reached on a common specification for the antenna transporter interface, and for attachment to a foundation, so that any 12-m antenna may be placed on any 12-m pad (but not the 7-m pads).

The overhead associated with this (how to mount cables and electronics, dealing with three different antenna control units, having three sets of spares, etc.) has been considerable. The added cost associated with two antenna designs was formally estimated to be about $8M to NA.

The cost per 12-m antenna was estimated in October 2002 as $3.4M; the final cost at completion of the project is now estimated to be $5.7M, including in each case all Antenna IPT tasks and contingency (68% overrun).

The initial ALMA budget estimate for Antennas was much too low because we did not adequately estimate costs for:

- The unprogrammed costs associated with evaluating 3 antenna designs, and the delays associated with negotiations between the Executives
- The overhead of NRE costs for 3 antenna designs
- Substantial redesign after prototype evaluation
- Increase in the cost of materials (steel, carbon fiber, aluminum) because of worldwide demand, exacerbated by the procurement delays
- The real cost per unit from the manufacturers compared to the budgetary estimates obtained before prototypes were built and tested

5. Front End

The Front End IPT is responsible for the FE Assembly (cryostat with cold and ambient temperature receiver components), FE Power Supply, Amplitude Calibration Device (arm and wheel with ambient and heated RF loads), and Water Vapor Radiometer (183 GHz).

Several possible FE configurations were studied, and at the inception of the ALMA-B project a Joint Receiver Design Group was formed to decide on the design. Because several institutions with experience in mm and sub-mm receivers wanted a role with intellectual content, a modular concept was adopted with one large cryostat, 10 holes for inserting cold receiver cartridges, and a chassis supporting the FE part of the Local Oscillator, power distribution, monitor & control, photonic LO reference distribution, and IF signal switching. Different institutions acquired their roles through horse trading of intellectual content carried out at the highest management level on a project-wide basis with other intellectual content, to the dismay of some of the FE engineering groups and the delight of others. The FE Assembly has many interlocked inter-dependencies among the various groups, which has promoted close cooperation.

The initial plan was to build, as quickly as possible, 8 pre-production units of all the electronics, in order to move into an early science mode with enough baselines and antennas to produce useful results (the original early science target schedule was October 2007!). The costs would then be re-estimated based on experience for the remainder of the production run. Once the estimates for NRE and pre-production units came in from the participating institutions, it became apparent that the original plan to equip ALMA with all 10 receiver bands could not be accomplished within the expected budget. The science was then prioritized by band, with the result that Bands 3, 6, 7, and 9 would be built, but supporting electronics would be built to support eventually all 10 bands. When the NAOJ joined, they added Bands 4 and 8, and even later obtained funding for Band 10. A separate funding line in Europe has added a handful of Band 5 receivers.

The Front Ends have turned out to be considerably more expensive than originally estimated, and the desire to meet or exceed all the requirements and not make reasonable tradeoffs, despite cost growth was not challenged early on. In October 2002, the cost with Bands 3, 6, 7, and 9 was estimated to be $1.62M each. The present end-of-project cost is now estimated to be $2.34M each (about 35% overrun after adjusting for an increase in scope of the FE LO to accommodate bands 4, 8, and 10).

The initial ALMA budget estimate for Front Ends was too low because we did not adequately estimate costs for:

- Extensive review and coordination meetings, and substantial documentation requirements (reworked specifications, ICDs, design documents, test documents, review documents; for example, for Warm Cartridge Assemblies—the LO drivers—the labor for generating documentation required for acceptance is 40% of the total)

- The real cost per unit compared to the budgetary estimates made before prototypes were built and tested—everything took longer and cost more than the original estimates

6. Back End

The Back End consists of central photonic Local Oscillator and distribution, photonic LO receiver unit within the FE Assembly, analog IF filtering and downconversion, and digitization + transmission + reception of digitized signals within the correlator.

The phase-locking of two lasers to produce a beat note constituting the LO reference at the antenna was a challenging and lengthy development because of the requisite phase stability, the most demanding specifications being for interferometry at 950 GHz on baselines of 18 km and beam-forming for VLBI at 300 GHz. At the inception of ALMA, there was a single LO Group responsible for the entire LO system, including the parts in the Front End; but at ESO insistence the LO was split into a Back End and a Front End component; this led to some lack of coordination and probably caused both delays and cost increases. In addition, the system requires photomixers to convert the beat note back to an electronic signal, work done at RAL.

Also challenging was development of custom SiGe chips for an in-house 3-bit A/D converter and demultiplexer producing 4 Gsamp/sec for a net 96 Gbps of data per antenna, and the conversions to multi-color optical and back to electronic format. The development and part of the production were ESO work carried out at U. Bordeaux and RAL. Final modules were produced by NRAO using subassemblies supplied by ESO.

The remaining major work—analog IF downconversion and filtering—was done by the NRAO and the major challenge was decreasing cost by making integrated, surface mount circuit boards instead of submodules interconnected by cables.

The Back End work has turned out to be slightly *less* expensive than originally estimated. In October 2002, the total Back End cost was estimated to be $53M. The present end-of-project cost is now estimated to be $49M (8% underrun).

Although the challenging development items were expensive, the majority of the expense was in replication of modules by commercial suppliers, and this process was well managed.

7. Correlator

The ALMA Baseline Correlator was designed for up to 64 antennas and many designs were complete before the rebaselining to 50 12-m antennas, so the design was left intact, providing some spare inputs and the ability to cross-correlate data from all but 2 ALMA-B + ACA antennas.

Work toward a "second generation correlator" at U. Bordeaux resulted in a design for a 32-output Tunable Filter Board (TFB) which we were able to make plug-compatible with the original design single output digital filter designed in 2000. This now gives 32X the frequency resolution of the original promised performance at no increase in cost (Moore's Law at work).

A complete prototype 2-antenna correlator was built and tested before production quantities of the custom chips and circuit boards were ordered.

Success in the field was also ensured by hiring a young Chilean digital engineer at an early stage and moving him to Charlottesville for 3 years of training, and as a result he has written substantial amounts of the firmware and software for the correlator. He will assume full responsibility for the correlator in Chile when the last piece is delivered in 2011.

In October 2002, the total correlator cost was estimated to be $13.9M. The present end-of-project cost is now estimated to be $11.3M (23% underrun).

The correlator was pushed along on a fast track, and prototype boards were in use before the documentation requirements increased—this undoubtedly saved both time and money. Also, all the circuit boards, cables, etc. were produced commercially in large batches, and not in-house as originally planned; the resulting savings over the original estimate was substantial. It also helped that the work was mostly done by one group at one location. Swapping the original filter board by the TFB produced elsewhere was relatively painless.

8. Computing

Computing includes all the software needed to operate the equipment, acquire data, and archive it. The development cost for the CASA image processing software was shared with the EVLA. This is a well-integrated, worldwide development team.

In October 2002, the total Computing cost was estimated to be $34.5M. The present end-of-project cost is now estimated to be $37.5M (9% overrun). Given the history of software development projects, this is a remarkable achievement!

9. **Systems Engineering and Integration**

This category mixes two things: traditional systems engineering, with processes to review and control requirements, specifications, and interfaces; and final assembly, integration, and test in the field.

In this area, there was a lack of adequate system engineering culture in the project from an early stage, and also a significant culture clash later on. Traditional NRAO systems engineering often consisted of conversations in a hallway, resulting in sketches implemented as designs by the consenting parties; this was not adequate for ALMA. ESO systems engineering, on the other hand, is extensive and considered central to success, but was not fully applied to ALMA. Developing a common approach was an issue, and inadequate system engineering persisted. One issue involved implementation of a commercial documentation management package in order to hold all documents centrally, but the server was located in Chile, and response latency has been poor at best. The documents are in a tree with inadequate cross-references and a nearly useless search function. Systems engineering failed to deal with these issues adequately, and few people can find what they are looking for in a reasonable length of time. As a result, there is a lot of e-mailing of documents instead of use of the database.

A second issue involves traceability of requirements and specifications from Science Requirements through System Requirements to Subsystem Specifications, dear to the heart of Systems Engineering. Despite a lot of effort, some of the specifications and requirements at the Science level never made it in the correct form down to the level of the design engineers. For example, an early specification on beam squint mysteriously disappeared from the Front End specification some time in 2002, and as a result pre-production cartridges for bands 7 and 10 (which use a wire grid beamsplitter and separate feeds for each polarization) fail to meet the requirement and need rework. The astronomers' and engineers' definitions of polarization isolation have never been reconciled, and the real requirement is still in dispute.

In Chile, integration and test has been much slower than anticipated, even though excellent staff were hired and have worked in an exemplary and dedicated manner.

In October 2002, the total Systems Engineering and Integration cost was estimated to be $24.3M. The present end-of-project cost is now estimated to be $48.7M (83% overrun after correcting for NAOJ's contribution).

The initial ALMA budget estimate for Systems Engineering and Integration was much too low because we did not adequately estimate costs for:

- Lack of system engineering early on, and failure of the partnership to realize the need for adequate system engineering in such a large project, nor to assess the real impact of the differing perspectives
- An extended period of testing more prototype antennas than originally planned
- Much slower than expected progress on integration and test

10. **Science**

The Science team has ultimate responsibility for the performance of ALMA. This includes generation and review of requirements and specifications and how they affect the ultimate success of observations. It also includes participation in testing and evaluation of the results at every level.

In October 2002, the total Science cost was estimated to be $9.8M. The present end-of-project cost is now estimated to be $11.9M (21% overrun).

The initial ALMA budget estimate for Science was slightly too low because the tasks of the Science group, although not difficult to define, were difficult to estimate. It was not possible to do more than make an educated guess at the level of effort which would be required.

Summary

The total estimated cost for a 64-antenna array with 4 receiver bands in October 2002 was $562M. The cost at completion for a 50-antenna bilateral array (not including the ACA or operations budget) is now estimated to be (again, in FY2000 dollars, not then-year dollars) $785M. This is an overrun of 40% for a system with 28% fewer antennas. If funding had been available for all 64 antennas the overrun would have been about 70% (not all costs are proportional to the number of antennas).

ALMA was specified, designed, and built by experts in the field of radio astronomy, including participants or consultants from almost every major radio observatory. They represented the collective wisdom of the planet in this field. Their estimates were founded on decades of study and planning, preliminary design, and site survey. We also note that the original cost estimate was done after technical feasibility had been established with prototype antennas and prototype receivers that essentially met specifications. Nevertheless, the costs were seriously underestimated. A number of factors went into this overrun but basically the greatly increased size and complexity of the system, as compared to previous experience, and the complexity of a major international project, were major contributors. The notes below attempt to generalize from the ALMA experience.

Governance and cultural factors

- The merging of different traditions in development and procurement often led to delays and resulting cost increases. Different levels of required documentation and review led to extended periods of discussion, and sometimes conflicting or redundant processes. Different accounting processes, including different ways of accounting for "overhead" costs led to imprecise value balancing. Different ways of approaching testing and verification also led to delays in procurement. A general lack of adequate awareness of these issues on the part of both Executives of the bilateral project before cost estimates were done led to inadequate budgeting.
- The different long-term budgeting and funding approaches of the parties provide different perspectives about life cycle costs and sensitivity to schedule adherence, and also affect day-to-day issues like budget approval cycles. These differences must be accommodated by the joint project.
- In a complicated governance scenario for a major international project, one that lasts for a decade or more, as is the case for ALMA, some of the agreements and nuances are very subtle. Further, they evolve with time. The ALMA Board invented and oversaw new management processes as necessitated by changing conditions. While ALMA documented formal agreements and many working-level processes, these were not always maintained and revised as necessary; even if they had been, staff changes at the agency, board, executive and project level make it challenging to maintain the original spirit and intent of the founding fathers and mothers. The more complex and nuanced the arrangements, the bigger the risk that new people "will not get it." This leads to long deliberations, conflicts, and delays.
- The ALMA governance model is premised on an equal partnership that respects the understandably differing research cultures and needs of the partners. ALMA governance has been described as "an unstable equilibrium that is made to work by hard work and good will." It is essential that all parties subscribe to the basic principles of the ALMA agreement; the Joint ALMA Observatory reporting to the ALMA Board and working with all the Executives must actively maintain the equilibrium by being sensitive to the needs of all the Executives. Lack of full appreciation of the differences among the Executives continues to affect the project; such a lack of sensitivity decreases the level of "good will" necessary to maintain the equilibrium. This will be the case in any governance model that must serve different clients with different needs.

Large, long-term project factors

- The need to coordinate a major international construction project with project meetings, complex interface controls, multiple reviews to meet the needs of multiple funding agencies, and the cultural issues affecting procurements as discussed earlier, imposes a large burden on management; this has to be estimated and adequately funded.
- Worldwide changes in the price of commodities, including fuel, affect all projects; project components taking place in multiple countries are further subject to the effects of currency fluctuations.

- Specific conditions in individual countries, like the construction boom in Chile, can unduly affect project costs.
- Large projects, especially international, need added attention to the logistics of mass production and supply chain management.
- Construction and operations in remote locales entail added expense in attracting and retaining staff, especially those working on *turno* (*i.e.,* living remotely from the work site).
- Contingency, especially for big-ticket items, must be honestly assessed at the start of the project, and carefully managed as construction proceeds. When ALMA was re-baselined, substantial contingency had to be added.
- The difficulty of estimating costs for technically complex and sophisticated new instruments requires careful assessment of the level of technological readiness. Traditional cost estimating by scientists and engineers based on their previous experience, especially if based on smaller-scale projects, should be supplemented by professionals with cost estimating experience in comparable domains.
- Even with adequate technological readiness, the cost and schedule for integration and testing for a very large project must also be honestly assessed.
- Commercial outsourcing for large quantities of components should be pursued wherever possible.

Some successes

For ALMA, the areas which were fairly successfully estimated were:

- Digital systems—correlator, digitization, data transmission, monitor & control
- Analog systems for which commercial quantity production was viable, mostly at frequencies below 12 GHz where engineering is generally straightforward and commercial expertise is available
- Software (!)
- Science

Appendix: Basis of Estimate Costing

Risk factor	Technical	Cost	Schedule
1	Existing design and off the shelf hardware.	Off the shelf or catalog item.	not used
2	Minor modifications to an existing design.	Vendor quote from established drawings.	No schedule impact on any other item.
3	Extensive modifications to an existing design.	Vendor quote with some design sketches.	Not used
4	New design within established product line.	In-house estimate for item within current product line.	Delays completion of non-critical path subsystem item.
6	New design different from established product line. Existing technology.	In-house estimate for item with minimal company experience but related to existing capabilities.	Not used
8	New design. Requires some R&D development but does not advance the state-of-the-art.	In-house estimate for item with minimal company experience and minimal in-house capability.	Delays completion of critical path subsystem item.
10	New design. Development of new technology which advances the state-of-the-art.	Top down estimate from analogous programs.	Not used
15	New design way beyond the current state-of-the-art.	Engineering judgment.	Not used

- **Multipliers for Contingency:** use the following multipliers. The estimator can change the calculated contingency if necessary.
  Technical multiplier = 2 if design *or* mfg concerns only
  = 4 if design *and* mfg concerns
  Cost multiplier = 1 if material cost *or* labor rate concerns
  = 2 if material cost *and* labor rate concerns