8

Funding ALMA

"Success in research needs … luck, patience, skill, and money."

Attributed to Paul Ehrlich

What was true for the great German pharmacologist Paul Ehrlich in the late nineteenth century remains true today, not only for research itself, but for research facilities as well. The funds that made ALMA possible were the result of very different processes in Europe, East Asia, and North America. Each process required good fortune, patience, and skill in varying measures depending on the circumstances. Fortunately for astronomy, governments around the world were ultimately generous in their support, sharing a vision for transformational science.

Europe

That the European participation in ALMA was united under ESO made for a huge simplification of the funding and approval process. The alternative would have required negotiations with at least a half dozen science funding agencies who, in turn, would need to persuade their governments to supply the money. It was the approach first taken by NRAO when trying to find international partners – specifically in Europe – for the MMA. Luckily, that effort was not successful, doomed by the feeling in Europe that a large millimeter wavelength array should only be built as a pan-European project. ESO exists to do precisely that.

The procedure at ESO for approving and thereby funding a major project is superficially simple. It only requires the consent of the ESO Council. The Council is made up of two representatives from each member state, one of whom is from the member state's government, so that their vote of approval reflects

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their government's commitment to provide funds. ESO's budget is guaranteed, made up of contributions from the member states that are a percentage of each state's gross domestic product. ESO's budget can vary with economic conditions in Europe, but continuity from year to year is assured. The largest projects, which cannot be accommodated in that basic budget, require special contributions over and above the annual payments. If sufficient commitments can be obtained, and if the project has been shown to be scientifically meritorious and technically feasible by the Scientific Technical Committee (STC), the project proposal goes to the ESO Council for approval. It should also be mentioned that ESO can borrow money if necessary. Its assured annual funding makes it a very low risk borrower.

Even though ESO Council has the ultimate say, a process of study and review every bit as elaborate for ALMA as those in the United States, Canada, and Japan was undertaken and lasted for several years before the final consent was given, following the important endorsement of the STC. In some sense, the timing of ALMA as a potential ESO project was ideal. This did not escape the notice of Riccardo Giacconi, ESO Director General at the time, who was a savvy strategic thinker. The Very Large Telescope (VLT) on Paranal was nearing completion. ESO's budget to build the VLT was large, and if continued at that level could fund the next big project. Plans for an Overwhelmingly Large Telescope (OWL) were underway, but that project was not shovel-ready. ALMA was a scientifically exciting project that could fill the gap. The timing was also ideal in that the United Kingdom wished to join ESO. When a new state becomes a member of ESO it must pay an amount equal to its share, based on gross domestic product, of the existing ESO infrastructure. In the case of the UK, this initiation fee prevented the need for any increases in the special contributions from other member states as ESO pivoted from the VLT to ALMA. The proposal to build ALMA was submitted to the ESO Council in December 2000. An operations plan followed in March 2001. The ESO Council approved the proposal in July 2002.

Japan

Progress to funding Japan's participation in ALMA might have been hampered by the changes in bureaucratic contacts that accompanied the absorption of Monbusho into MEXT as the ministry responsible for science and technology and the later creation of NINS. However, Norio Kaifu, the NAOJ Director, had the political skills to manage these shifting sands. Progress was definitely set back by the economic crisis of 2001, following a tripling of prices for stocks and real estate in Japan in the years prior to 2001.

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When the Bank of Japan increased interest rates, the bubble in asset prices burst, and along with it the dream of the Japanese radio astronomers to be full and equal partners in ALMA. The decade 2001–2011 has been called the "lost decade," an era in which the Japanese economy stopped growing and the government found itself with tight budgets. Gradually, the mood changed and by 2004 MEXT was willing to commit to $180 million (FY2000) to be spent over eight years, completing Japanese deliverables on the same schedule as ESO and NRAO.

The proposal for Japan to join ALMA had to undergo rigorous review. The Council for Science Technology of MEXT was one such major hurdle. Final review was by the Council for Science, Technology, and Innovation, a cabinet-level body that included among its members no less than the prime minister, Jun-Ichirō Koizumi. In August–September 2004 an agreement was signed by Arden Bement (NSF), Catherine Cesarsky (ESO), and Yoshiro Shimura (NINS) that made Japan a partner in ALMA. Shimura was a constant supporter of Japanese radio astronomers through all the reorganizations of funding agencies. The agreement was amended in 2006 to recognize an agreement between Taiwan's ASIAA and NINS. Taiwan joined forces with Japan just as Canada had with the United States, making the ALMA parties Europe, North America, and the East Asia. The patience of the Japanese radio astronomers had paid off. The agreement was announced in the NRAO Newsletter[1] by Al Wootten.

> *Japan entered the ALMA Project with the signing of an Agreement Concerning the Construction of the Enhanced Atacama Large Millimeter/Submillimeter Array. The Agreement was signed by Arden L. Bement, Acting Director of NSF, Catherine Cesarsky, Director General of ESO, and Yoshiro Shimura, President of the National Institutes of Natural Science (NINS) of Japan. All parties had signed the document by September 14, 2004, making Japan an official partner in an Enhanced ALMA, to be known as the Atacama Large Millimeter/Submillimeter Array (same ALMA acronym). Final negotiations on an operations plan for Enhanced ALMA are expected to be concluded by the end of 2005. Japan will provide the Atacama Compact Array with its correlator, three receiver bands, and other components. The value assigned to the Japanese contribution to Enhanced ALMA is $180M (FY2000 US$). Assuming all three partners are able to meet their commitments, the final project will be cost-shared 37.5 percent, 37.5 percent, 25 percent, between North America, Europe and Japan, respectively. The observing time, after a ten percent share for Chile, will be distributed accordingly.*

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North America

A new Congress of the United States is convened every two years following elections, and passes legislation that, among many other things, authorizes the expenditure of government funds. What a given Congress cannot do is bind a future Congress to actually appropriate the necessary funds for projects that have been authorized. This stricture means the annual budgets of a multiyear project like ALMA are subject to review and appropriation every year. Although appropriations committees often follow the guidance in an agency's budget request, they are not obligated to do so and continuity is not guaranteed. This fact of the US science funding process makes it far more political than those of ESO or Japan. Consequently, good fortune, patience, and skill played large roles in achieving funding for the MMA and the US participation in ALMA.

The MMA had received the first funds of a three-year program of design and development in January 1998, while Neal Lane was the NSF director. It was expected that funds for construction of the MMA would follow in NSF's Major Research Equipment (MRE) line. In August 1998 Lane was succeeded as director by Rita Colwell, a prominent biologist. In the NSF budget request for FY2001, National Ecological Observatory Network (NEON) appeared in the MRE line and the MMA was notably absent. As FY2000 was to be the third and final year of MMA design and development, it was not clear what would happen to the project if it failed to gain funds for construction. Putting the construction of the MMA behind that of NEON posed an existential threat to the MMA and US participation in ALMA.

NSF, as part of the executive branch of the US government, is forbidden by law from lobbying Congress. The legislative side of its Office of Legislative and Public Affairs (OLPA) only works, in principle, to maintain good relations with the relevant congressional committees, answer their questions, and keep them informed. Other visitors to the "Hill" (the cluster of congressional offices surrounding and including the Capital), it was hoped by NSF, would only argue for support for science in general, as did the American Astronomical Society and other professional science organizations on a regular basis. Advocating for particular NSF programs was discouraged, with an important exception. If a project was approved at NSF and included in its budget request, then outside appeals to Congress for the project were not only sanctioned but quietly encouraged. Because the NSF had funded design and development, the engagement of professional help to secure Congressional support for ALMA construction was appropriate.

From its beginning, AUI had considered hiring a legislative liaison firm as being unnecessary. But when Riccardo Giacconi became AUI President on 1 July 1999 that changed. Perhaps from his experience as Director of the

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Space Telescope Science Institute, he felt that advancing ALMA in the United States Congress required professional expertise and experience. At the urging of Anneila Sargent, he decided to engage Lewis-Burke Associates, a firm specializing in science advocacy. Sargent knew the head of the firm, April Burke, who handled legislative affairs for Caltech. The AUI Board of Trustees was of mixed opinion. Those who had worked in university administrations tended to be supportive while the more idealistic faculty members were opposed. But Giacconi, fresh on the job, was given approval to go ahead. He accompanied Burke on only one visit to a congressman's office, that of Representative James Sensenbrenner of Wisconsin, the chairman of the House Science Committee. The visit was a bad experience for Giacconi, indeed, it was so uncomfortable for him that he said he would never do it again. In future, he said, Vanden Bout would make the visits. Lewis-Burke would turn out to be an invaluable aid to funding ALMA. Hiring them was one of Giacconi's best decisions at AUI.

NSF budget requests are sent to the Office of Management and Budget early in the government's fiscal year, which starts on 1 October, for inclusion in the President's budget request for the following fiscal year. The request is embargoed until the President's budget request is sent to Congress. The situation for the MMA – that there was no request for MMA construction, or even for more design and development, for FY2001 – was known to all interested parties by the time of the VLA 20th anniversary celebration on 23 August 2000. The event was significant in that both Senator Domenici of New Mexico, ranking minority leader on the Senate Budget Committee, and NSF Director Colwell had accepted invitations to attend and make remarks. The acceptance was with some trepidation on Colwell's part. NRAO had submitted a proposal to upgrade the VLA on 1 July 2000. She had been warned by OLPA[2] that the senator would be sure to urge her to support the project. She was willing to do this, but only if the funding was additional to NSF's budget request. While NRAO would have welcomed Domenici's support of the Expanded Very Large Array (EVLA) project, staving off the impending death of the MMA had higher priority.

Ultimately, that rescue had to wait a year. Domenici was proud of the presence of the VLA in his state and it came ahead of the MMA in his priorities. In earlier visits to his office,[3] the conversation would always turn from the MMA to the VLA. While no one but the two participants know what was said between Domenici and Colwell in the private meeting they had during the anniversary celebration, the Senate report language[4] accompanying the NSF appropriation for FY2001 made the sense of their meeting clear:

> *In last year's Senate report, the Committee expressed its support for enhanced operations and maintenance and development of new instrumentation at the Very Large Array and the Very Long Baseline Array in New Mexico …*

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> *these astronomy facilities need to be supported in their operations, and new instrumentation and upgrades must be provided toe keep them as world class facilities. Accordingly, the Committee provides an additional $13,000,000 above the fiscal year 2001 request levels for the astronomical sciences subactivity for these facilities. … The Committee recommends an appropriation of $109,100,000 for major research equipment. … The Committee has provided … $6,000,000 for the Millimeter Array.*

The EVLA Project would be started with a portion of the extra funds added to AST budget and the MMA would receive the funds needed to continue for another year of design and development. Dickman recalls being notified of the design and development funding as a "*correction to a misunderstanding in the Director's office that had zeroed out additional funding*." NRAO made an estimate of what a one-year delay in the start of construction would cost. But what would happen in FY2002? Would ALMA construction begin then?

NSF's intention became known in the spring of 2001 when yet again the budget request for the MRE line did not include the MMA. Once again, the project faced a crisis. There was no request for construction funds or even a continuation of design and development. Would Senator Domenici help this time? Now that the EVLA project was underway, he turned out to be more amenable to discussing ALMA.[5] The EVLA and ALMA were both large radio interferometers, making it possible, in principle, to construct electronic components that would serve both projects. It was stated in visits to Domenici's office that although ALMA was to be located in Chile, much of the electronics would be made by NRAO in Socorro.[6] At the same time, at the urging of Lewis-Burke Associates, a letter campaign was organized. A list of 86 radio astronomers was asked to write letters[7] to their Congress members urging support for ALMA. While there is no direct evidence of the campaign's impact, Domenici did save the day. The Senate language for the FY2002 NSF budget[8] provided the first construction funds for ALMA in the amount of $12.5 million.[9]

> *The Committee recommends an appropriation of $108,832,000 for major research equipment. … The Committee has provided … $12,500,000 for initial construction of the Atacama Large Millimeter Array (ALMA) radio telescope. … The Committee supports initiation of construction of the ALMA radio telescope and has provided the necessary resources to start construction.*

In November 2001, the National Science Board approved the start of ALMA construction at the request of NSF Director Colwell. This was a huge step, essentially guaranteeing US partnership in ALMA. The following year went according to plan: the NSF requested $30 million for ALMA construction, a request that

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was funded by Congress. The US participation in ALMA would not have happened were it not for the fact that a powerful Senator chose to give it his support simply because his state was home to an NRAO facility in which he took pride. In two years, ALMA would face another near-death crisis, this time one of global dimensions involving all the partners.

Project Reset

In 2004, it became clear that the cost estimate for the project was significantly less than what was needed. During the two years since construction began, funds budgeted for contingency were used to make up for increased costs. After Massimo Tarenghi became Project Director, the search for his replacement as Project Manager led to hiring Tony Beasley, who had just completed the construction of CARMA. Beasley accepted the position, moved to Chile, and discovered that he had signed on to a project in trouble. Unless drastic action was taken, funds available from contingency would soon be exhausted and ALMA would run out of money well short of project completion. The project needed to be "rebaselined," that is, it needed a new credible cost to complete, hopefully on the same schedule.

The process for establishing a new budget was similar to that of the first cost estimate, but this time with the benefit of experience. Every element of the WBS was reexamined and an estimate of the cost of the labor and materials to complete it was made, down to the individual part. A risk (the odds of failure) associated with completing the task was assigned and used to calculate the contingency that should be added to the estimate. For example, a task with only a 10 percent chance of failure would have a contingency of 10 percent of the estimated cost. Then the estimates and contingency for all the elements were added together. A cost estimate for the entire project was completed by 8 September 2005. Table 8.1 shows a comparison between that estimate and the original budget. The new project estimate, with contingency, implied that $242 million (FY2000) in additional funding was needed to complete ALMA. This was a 40 percent increase over the original estimated budget of $552 million (FY2000) adopted in the Bilateral ALMA Agreement! What accounted for the increase? What were the options for recovery: reduced scope, more funding, or some combination of both? Unless a path to completion could be found, the project was dead.

The largest increases were in Management, Site Development, Antennas, and System Engineering. Two of these increases were largely the result of a failure to recognize the complexity of the tasks. Managing a large, international project turned out to be much more difficult and expensive than originally

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Table 8.1

Level One WBS Task Integrated project team (IPT)	Original 2002 Estimate Cost (1,000s) $FY(2000)	11/2005 Estimate Cost (1,000s) $FY(2000)	Cost Increase (1,000s) $FY(2000)	Percent Increase (%)
Management	17,313	46,900	29,587	171
(Overhead on labor)[1]		35,670	35,670	n/a
Site development	70,049	117,682	47,633	68
Antennas[2]	227,739	319,966	92,227	40
Receivers	108,982	116,684	7,702	7
Back end	49,765	55,886	6,121	12
Correlator	14,856	10,288	−4,568	−31
Computing	34,468	37,504	3,036	9
System engineering	20,125	43,916	23,791	118
Science	9,173	9,785	612	7
Total	552,470	794,281	241,811	44

[1] Overhead on labor was distributed across the IPT categories in 2002; listed separately here.

[2] The 2002 cost was for 64 antennas; the 2005 cost is for 50. The costs in 2005 for other IPTs assume 50 antennas and are net the consequent savings.

anticipated, requiring more staff, face-to-face-meetings, and communications than a one-nation project. In addition, the decision to build the ALMA headquarters in Santiago shifted the cost of housing the JAO from operations (rent) to construction. System engineering was woefully underbudgeted for a project as complex as ALMA. Making sure all the components worked together, were delivered to specifications, and passed commissioning tests required many more people than was thought at the start. The challenges posed by the high-altitude site were simply not appreciated in the beginning. Early exploration of the site was an exhilarating lark compared to the difficulties of moving earth for roads, pouring concrete for antenna pads, laying cables, and erecting the building to house the ALMA backend and correlator. Labor at 5,000 m elevation is slow and hard, and thus expensive. These difficulties were compounded by an economic boom in Chile that drove up building costs. The cost for the antennas increased significantly due to rapidly escalating costs for steel and for oil, the raw material for carbon reinforced epoxy. The increased cost for 64 antennas over the amount budgeted in 2002 was so large as to seem unaffordable to the project management under any reasonable scenario. Accordingly, in the budget of 8 September 2005, as presented to the ALMA Board

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in their 15 September 2005 telecon, the number of antennas was reduced to 50 and the budgets for receivers and the backend system were adjusted accordingly. Beasley has written an account,[10] dated 26 September 2005, of the evolution of project budgets leading up to the new estimate.

Along with the new proposed budget estimate, the ALMA Board was given a menu of options for further cost savings, beyond the reduction in the number of antennas. The Board also received the report[11] of the Science IPT and ASAC containing its advice on the proposed reduction in scope. The ASAC recognized the necessity of reducing the number of antennas to 50. In choosing which other options to select, the Board followed the advice of the ASAC.[12] Savings of an additional $17 million (FY2000) were realized by reducing the number of antenna pads from 216 to 175, reducing the scope of the residence quarters at the OSF, and eliminating the antenna hanger on the high site. Budgets for furniture and travel were cut by twenty percent. Road maintenance was outsourced, moving the expense for equipment to operations. These savings were relatively small compared to what was required, but they demonstrated good faith in that everything, not just the number of antennas, was on the table for cost cutting consideration.

The next step was acquiring the additional funding implied by the new cost estimate. That required establishing the credibility of the estimate. A cost review was scheduled by the ALMA Board for October 2005 in Garmisch Partenkirchen, Germany, to be chaired by Steve Beckwith (MPIfA), who was well acquainted with the ALMA project from previous service to ESO as chair of its Science Technical Committee. It was a major event, with thirty-six participants from the three ALMA Executives twenty participants for the review panel itself, and more from NSF and the ESO Board. The review came to be known as the ALMA Cost Review (ACR). On the first day, the panel heard presentations about the project in general and then from each of the IPTs. The second day was devoted to executive sessions in which the panels drilled deeper into the costs derived by each IPT and held discussions that would lead to a report. The report[13] dated 21 November 2005 was submitted to the ALMA Board for acceptance. The report's executive summary concluded with this statement: "*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*."

The report contained numerous recommendations, with specific recommendations for each IPT, but the bottom line was that the panel believed the cost estimate to be credible. That estimate had been prepared with the assumption that all 50 antennas would be of the same design. By late 2005, contracts had

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been let for the purchase of two designs, 25 each. A potential consequence of multiple designs was increased costs, both for construction and for operations. Accordingly, as was mentioned in the previous chapter, a review called the ALMA Delta Cost Review (ADCR) was held to review the project's estimate of those costs. The review was held in Balston, Virginia, near NSF headquarters, on 26 January 2006. The panel[14] was a subset of the ACR panel. They confirmed the additional funds required, completing a package that could be presented to the NSF.

One of the authors (Dickman) had played a major role as an ALMA Board member in organizing the two reviews just discussed above. Now as the person responsible for ALMA at AST/NSF, he wanted to build a bullet-proof package that asked for increased funding. That required two more elements, both independent of the ALMA Project itself. First, Wayne Van Citters, Director of AST, asked the Committee on Astronomy and Astrophysics of the National Academy of Sciences to assess the impact on ALMA of a reduction in the number of antennas.[15] Van Citters specifically asked the CAA to address four questions:

- *What would be the impact on the attainability of the level-1 science requirements?*
- *What would be the loss of speed, image quality, mosaicing ability, and point-source sensitivity? (A parametric representation of these performance changes would be welcome.)*
- *Would ALMA still be sufficiently transformational to warrant continued support by the United States?*
- *Is there a particular threshold in the number of antennas, below which ALMA would suffer a significant degradation in its performance in the above or other relevant scientific areas sufficiently serious to warrant attention?*

The CAA committee, chaired by Meg Urry of Yale University, included these conclusions in their report[16]:

- *The committee concludes that two of the three level-1 requirements, involving sensitivity and high-contrast imaging of protostellar disks, will not be met with either a 40- or a 50-antenna array. It is not clear if the third requirement, on dynamic range, can be met with a 40-antenna array even if extremely long integrations are allowed for.*
- *The committee concludes that speed, image fidelity, mosaicing ability, and point source sensitivity will all be affected if the ALMA array is descoped. The severest degradation is in image fidelity, which will be reduced by factors of 2 and 3 with descopes to 50 and 40 antennas, respectively.*
- *The committee concludes that despite not achieving the level-1 requirements, a descoped array with 50 or 40 antennas would still be capable of producing*

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> *transformational results, particularly in advancing understanding of the youngest galaxies in the universe, how the majority of galaxies evolved, and the structure of protoplanetary disks, and would warrant continued support by the United States.*

The report was in rough agreement with that of the ASAC – 50 antennas were sufficient for transformational science – but it had the *imprimatur* of the National Academy of Sciences and would carry much more weight at NSF in an argument for approval of the rebaselined budget with its requirement for a forty per cent increase in funding.

Next, NSF commissioned yet another cost review, this one reporting to NSF rather than to the ALMA Board. The review was called the NSF Cost/Management Review (NCMR). It was chaired by Donald Hartill of Cornell University and was held at NRAO headquarters in Charlottesville on 30 January–1 February 2006. The NCMR panel was provided with the reports of the ACR and ADCR as background material. It also heard presentations from project management, each IPT, and of the operations plan. At the close of the review, the panel made twenty observations,[17] the first 10 of which they judged already to be under control and 10 more that required close attention: increasing the contingency, safety on the high elevation work sites in Chile, and management recommendations in a number of areas. But most importantly, the panel validated the cost estimates of the ACR and ACDR. The panel opined that no more than $14.2 million of the increase was due to project failure, namely, the failure to complete prototype antenna testing in a timely manner, which caused a delay in the antenna procurement.

Additional budget relief arrived in December 2005. An MOU[18] was signed, whereby, ASIAA of Taiwan would join the United States and Canada in the North American partner to ALMA, while they also continued to collaborate with Japan. Taiwan would contribute the cost of two to three fully equipped antennas ($30 million current year dollars over 10 years) and make an appropriate contribution to operations. A goal was to deliver a minimum of $15M in the form of equipment made in Taiwan. In return, Taiwanese astronomers could compete for the North American share of the observing time and participate in ALMA committees. This initiative was driven by Mike Turner, following his strong belief in ALMA as a facility capable of transformational science. Although the amount of money was not large compared to the total project cost, acquiring a new ALMA partner for North America sold well in the NSF Director's office.

Dickman had informed the ALMA Board at its 27 January 2006 meeting of the necessity of the Hartill Review if NSF was to approve the cost increase.

Catherine Cesarsky expressed concern that the process would delay ALMA construction. The Board was assured that the results of the review would be presented to the NSF Director in March 2006, and, pending his approval, to the National Science Board the following April, in time for inclusion in the NSF budget request for FY2008. A plan would be made for keeping the project on schedule. Dickman briefed[19] NSF Director Arden Bement on 2 March 2006 and the meeting was a success. On 7 April 2006, Bement sent a memorandum[20] to the NSB recommending approval of the new ALMA budget. It met with NSB approval, to the gratification of Dickman who had orchestrated much of the process. The NSF budget request to Congress for FY2008 asked for the necessary funds. They were appropriated by the US Congress as a routine matter. Furthermore, the request had outlined the requirements for the outlying years, so subsequent requests would also be routine, following the funding plan.

The resolution of the rebaselining crisis revealed a stark cultural difference between the ALMA parties. ESO's guaranteed annual income allowed it to cover the cost overrun by extending the schedule of payments by two years. This required Council approval, which was granted after consideration of the report of the ACR and confirmation that ALMA was affordable. By comparison, the US process was fraught with uncertainty. Its eventual success was due to a carefully prepared and validated justification presented to top NSF management. Both ESO's and NSF's steadfast commitments to advancing the frontiers of science through large, multiuser facilities carried the day. Japan's commitment was never in doubt. A major crisis had passed. With the funding for ALMA as secure as it could ever be, the project could continue construction uninterrupted. All that remained was to continue putting ALMA together and then make it work.

Notes

1 Wootten, H.A. 2005, ALMA Gains Capabilities with Japan's Entry, NRAO Newsletter #102 http://library.nrao.edu/public/pubs/news/NRAO_NEWS_102.pdf.

2 Clancy to Vanden Bout, private communication.

3 Michael Ledford of Lewis-Burke Associates to Paul Vanden Bout, private communication.

4 From the report of the Senate Appropriations Committee, Departments of Veterans Affairs and Housing and Urban Development, and Independent Agencies Appropriations Bill for FY2001, B. Mikulski, 20 July 2000. www.nsf.gov/about/budget/fy2001/pdf/tools.pdf.

5 McGuire to Vanden Bout, private communication. Carol McGuire was one of Senator Domenici's aides on the Senate Budget Committee staff.

6 NRAO did do work for ALMA at its Socorro, New Mexico, site, building the ALMA "backend," the system that digitizes the signals from the antennas and sends them to the correlator, and hosting the group that wrote the software for the ALMA real-time operating system that controls the array during observations.
7 The list and copies of many of the letters can be found at NAA-NRAO, ALMA, ALMA Planning, Box 2.
8 From the report of the Senate Appropriations Committee, Departments of Veterans Affairs and Housing and Urban Development, and Independent Agencies Appropriations Bill for FY2002, B. Mikulski, 20 July 2001. www.nsf.gov/about/budget/fy2002/pdf/tools.pdf.
9 The FY(2002) funds for ALMA construction were added to NSF's MRE account. The Major Research Equipment (MRE) account became the Major Research Equipment and Facilities Construction (MREFC) account in the FY(2003) NSF budget, the source of all succeeding US funds for ALMA construction.
10 The account by Beasley of the ALMA cost increase evolution can be found at NAA-PVB, ALMA, ALMA: The Story of a Science Mega-Project. https://science.nrao.edu/about/publications/alma.
11 The report can be found at NAA-PVB, ALMA, ALMA: The Story of a Science Mega-Project. https://science.nrao.edu/about/publications/alma.
12 A spreadsheet with all the cost savings options that shows those the ALMA Board approved can be found at NAA-PVB, ALMA, ALMA: The Story of a Science Mega-Project. https://science.nrao.edu/about/publications/alma.
13 The report *Review of Costs for the ALMA* (Beckwith Report) can be found at NAA-NRAO, ALMA, ALMA Rebaselining. https://science.nrao.edu/about/publications/alma.
14 The panel members included: Steve Beckwith (MPIfA), Jim Crocker (Lockheed-Martin), Thijs de Graauw (ESTEC), Peter Dewdney (DRAO), Tom Phillips (Caltech), and Jean Turner (UCLA).
15 Van Citters' letter is Appendix A of the CAA report.
16 The CAA report, *The Atacama Large Millimeter Array – Implications of a Potential Descope*, can be found at https://nap.nationalacademies.org/download/11326.
17 The NCMR report, known as the "Hartill Report" may be found at NAA-PVB, ALMA, ALMA: The Story of a Science Mega-Project. https://science.nrao.edu/about/publications/alma.
18 The MOU (unsigned copy) for the Taiwan-American Program in Radio Astronomy (TAPRA) can be found at NAA-NRAO, ALMA, ALMA Multi-Institutional Agreements. https://science.nrao.edu/about/publications/alma.
19 Dickman's presentation can be found at NAA-PVB, ALMA, ALMA: The Story of a Science Mega-Project. https://science.nrao.edu/about/publications/alma.
20 Bement's memorandum can be found at NAA-PVB, ALMA, ALMA: The Story of a Science Mega-Project. https://science.nrao.edu/about/publications/alma.