7

Contentious Matters

"Necessity never made a good bargain."

Benjamin Franklin

The ALMA Board had to contend with a number of important and difficult issues which occupied much of the time in their meetings and the voluminous exchange of documents and emails that preceded the meetings. The partnership agreement between Europe and North America came up first. Next, the entrance of Japan into the ALMA partnership required long discussions over what Japan would bring to ALMA and the corresponding value of those contributions. Then there were the legal issues around the negotiations to secure the site. The procedure for the purchase of the 12 m antennas, the largest item in the budget, needed to be defined. Other sticky wickets to work through included the precise location of the ALMA headquarters in Chile and which of the partners would employ the local staff.

Bilateral ALMA Agreement

The MOU establishing the ACC was not a legally binding agreement. Even so, the NSF had agreed to let the ACC manage the ALMA activities in Phase 1 – design and development. But by the start of 2003, Phase 2 – construction – was about to begin. Adding to the urgency, as has been mentioned in the previous chapter, the MOU had expired at the end of 2002. Fortunately, the ACC had been busy for months refining draft agreements. If the final agreement was to be legally binding, it needed the blessing of the US State Department. Making the agreement an international treaty had been ruled out as that would have taken years to conclude. After review, the State Department pronounced the draft agreement as legally binding in an international court. The

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final draft was approved by the ALMA Board in its meeting on 24–25 February 2003 at NSF headquarters in Arlington, Virginia. On 25 February 2003, the Bilateral ALMA Agreement[1] was signed by representatives of the two partners: Rita Colwell, NSF Director, for NSF and the National Research Council (NRC) of Canada and Catherine Cesarsky, ESO Director General, for ESO, and Spain.[2]

The deliverables required of the parties to the Agreement were specified in the WBS that had been negotiated by Bob Brown, Masato Ishiguro, and Dick Kurz. The WBS was integral to the Agreement, as it committed the partners to delivering specific components. It included a schedule and total cost, as well as the management structure shown in the previous chapter as Figure 6.1. ALMA was to be completed by 2012 for a total cost of $552M (FY2000 US$) divided equally between Europe and North America. The distribution of the work packages went beyond establishing equal cost to the partners. The total risk was also balanced, giving each partner equal amounts of risk and contingency funds. It is ironic that the WBS, project schedule, and cost summary, all key elements of the Agreement, are in annexes. The body of the Agreement is largely concerned with rules of procedure, who owns ALMA, intellectual property rights, settlement of disputes, and the like.

Implementation of the WBS by the Executives would be a tremendously complex undertaking. As both mundane and challenging implementation matters arose, Pat Donahoe (AUI) and Ian Corbett (ESO) recognized that some sort of formal agreement between the Executives would be necessary to address a wide range of matters: protocols to be followed when interacting with Chilean authorities, issuance of contracts, relations with the Joint ALMA Office (JAO), the hiring of both local and international JAO staff, liability matters, common approaches to health, safety, security policies and procedures, and financial reporting. These and other matters were negotiated by Donahoe and Corbett and incorporated in a Bilateral ALMA Management Agreement,[3] signed on 31 July 2006 by Ethan Schreier, President of AUI, and Catherine Cesarsky, Director General of ESO. The management agreement proved essential to establishing commonly shared approaches to solving existing and future management challenges during ALMA construction and early operations. The Trilateral ALMA Agreement, discussed next, contains a requirement that all three Executives sign a similar management agreement covering operations.

Japan Joins ALMA

Following the 13 October 2000 ACC meeting in Paris, the Japanese government funded design and development work for the hardware contributions anticipated when Japan would eventually join ALMA. At first, the proposal was

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for Japan to become a full and equal partner. Accordingly, NAOJ contracted with the Mitsubishi Electric Co. (MELCO) for a 12 m prototype antenna. But it later developed that the funds Japan could provide would be approximately two-thirds of that required to match the US and ESO shares. This severely limited the number of 12 m antennas Japan could provide. However, the proposed compact array of twelve 7 m antennas, optimized for submillimeter operation, would provide a valuable and unique addition to ALMA. The offer to build additional receiver bands was also attractive, as ESO and US could only afford to build four bands out of the 10 that they had envisaged. The importance of having Japanese industry benefit from Japan joining ALMA played a role. For example, Japan proposed contributing a signal correlator for the compact array, presumably to be built by the Fujitsu Corporation, even though the correlator to be built for the large array had the capacity to handle all 66 antennas. The value of these options and the extent to which Japan would buy into the ALMA infrastructure were questions to be answered. As mentioned in the last chapter, the ALMA Board appointed a liaison group that held eight face-to-face meetings, with teleconferences in between, to arrive at a recommendation that satisfied the ASAC priorities and fit within the available funds. In August/September 2004, Arden Bement (NSF), Catherine Cesarsky (ESO), and Yoshiro Shimura (NINS) signed an agreement[4] formalizing Japan's entrance into ALMA, under Article 11 of the Bilateral ALMA Agreement, in exchange for what was called "Enhanced ALMA." Under the terms of the agreement, Japan would contribute $180 million (FY2000) to ALMA. The work packages included four 12 m antennas; a compact array of twelve 7 m antennas; equipping the entire array with Bands 4, 8, and 10 receivers; and a correlator for the compact array. This gave Japan a 25 percent share in ALMA. The agreement was amended twice, in June 2005 to extend deadlines,[5] and in June/July 2006 to recognize the collaboration between Japan and the ASIAA of Taiwan for the construction of Enhanced ALMA.[6] The ALMA Board also adopted an official statement describing ALMA. The most recent (2022) version of that statement is illustrative of the complexity of ALMA:

> *The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership of the European Organisation for Astronomical Research in the Southern Hemisphere (ESO), the U.S. National Science Foundation (NSF) and the National Institutes of Natural Sciences (NINS) of Japan in cooperation with the Republic of Chile. ALMA is funded by ESO on behalf of its Member States, by NSF in cooperation with the National Research Council of Canada (NRC) and the Ministry of Science and Technology (MOST) in Taiwan and by NINS in cooperation with the Academia Sinica (AS)*

in Taiwan and the Korea Astronomy and Space Science Institute (KASI). ALMA construction and operations are led by ESO on behalf of its Member States; by the National Radio Astronomy Observatory (NRAO), managed by Associated Universities, Inc. (AUI), on behalf of North America; and by the National Astronomical Observatory of Japan (NAOJ) on behalf of East Asia. The Joint ALMA Observatory (JAO) provides the unified leadership and management of the construction, commissioning, and operation of ALMA.

Figure 7.1 In the front (from left to right): Tim de Zeeuw (ESO Director General), Katsuhiko Sato (NINS President), and F. Fleming Crim (NSF Assistant Director) on behalf of France Córdova (NSF Director) representing the three partners at the ceremony and signing the Trilateral ALMA Agreement for Operations. In the middle row (from left to right): Phil Puxley (Program Director, NSF), Masahiko Hayashi (Director General of NAOJ), Hideyuki Kobayashi (Deputy Director of NAOJ), Satoru Iguchi (East Asia ALMA Project Manager, NAOJ), Yuko Nagasaka (Translator, NAOJ). In the back row: Jim Ulvestad (Division Director, NSF), Rob Ivison (ESO Director for Science), Junichi Watanabe (Deputy Director General of NAOJ), Tsuyoshi Sasaki (Head of Administration, NAOJ), Shin-Ichiro Asayama (NAOJ Chile), Nikolaj Gube (Deputy Head Legal and International Affairs, ESO), and Takao IIzawa (Head of Administration, NINS). Credit: ALMA/ESO/AUI/NINS, CC BY 4.0.

The Trilateral ALMA Agreement[7] between ESO, NSF, and the NINS was signed in Tokyo, Japan, on 15 December 2015. The new agreement provided the framework for the long-term *operation* of ALMA over the next 20 years. The meeting attendees posed for a photograph, shown in Figure 7.1, to record the event. It had taken more than 12 years since the signing of the Bilateral ALMA Agreement to reach this point.[8] The Management Agreement previously concluded between ESO and AUI was updated in the Trilateral ALMA Management Agreement[9] signed on 17 November 2016 by Ethan Schreier, AUI President; Tim de Zeeuw, ESO Director General; and Masahiko Hayashi, NAOJ Director General.

Wandering the Road from Nobeyama to ALMA

The road from Nobeyama to ALMA was not straight. After working 10 years with solar radio interferometers at Toyokawa Observatory, I moved to the Tokyo Astronomical Observatory of the University of Tokyo in 1980 and started working as a leader of the construction of the Nobeyama Millimeter Array (NMA). I started the design work at Toyokawa before moving to the Nobeyama Radio Observatory (NRO). Since I had no experience in non-solar radio observing and aperture synthesis, the design work was completely new to me.

In November 1972, I had attended the Symposium on the *Collection and Analysis of Astrophysical Data* held at NRAO Charlottesville. After the meeting, I visited various observatories in the world to see the radio interferometer systems at Stanford University, Caltech Owens Valley, NRAO Green Bank, Mullard Observatory (UK), and Westerbork Observatory (The Netherlands). Travelling alone around the world helped me gain an international perspective in my life. The insights I gained from this visit were applied to the design of the NMA. The first aperture synthesis observations with NMA were made at 22 and 115 GHz in 1984 and 1988, respectively. Around 1983, I realized that a larger millimeter wave interferometer would be needed in the future, and began to study the basic concept of the Large Millimeter Array (LMA), which later became the Large Millimeter Submillimeter Array (LMSA).

While I was the NRO Director, between 1990 and 1996, I worked very hard to make the LMSA plan a reality. As a first step, in 1992, I visited Chilean sites for the first time with Naomasa Nakai and Ryohei Kawabe in collaboration with SEST/ESO. The same year I organized IAU Colloquium 140 at Hakone, Japan, with Jack Welch as co-chair, to discuss the status of

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the operating millimeter and submillimeter arrays and the future plans for larger arrays. At this conference, I sensed a great deal of interest in future international cooperation in larger arrays. With a tailwind for international cooperation, Roy Booth and I proposed the establishment of the Millimeter-Submillimeter Array Working Group at the Kyoto URSI General Assembly in 1993. These activities were followed by lively discussions of cooperation between MMA and LMSA starting in 1994.

The most shocking event in my life with ALMA was the signing of the MOU toward a joint project between NRAO and ESO. It happened in June 1997 when I visited NRAO Charlottesville to discuss the antenna design with Peter Napier and Jeff Kingsley. Paul Vanden Bout, then NRAO Director, invited me to his office and told me that the MOU was signed on that day by him and Riccardo Giacconi. It was very surprising message for me, because I was told beforehand by Bob Brown that an official signing would not happen in the meeting. For me, it was like having my bride stolen before the wedding. Anyway, after various twists and turns, the projects of the three parties, Japan, North America, and Europe, were finally unified to ALMA.

In 2007, I decided to step down from the ALMA-J Director and joined the JAO as a lead test scientist to work for the Assembly-Integration-Verification (AIV) group. At that time, I was the first and only Japanese staff member. I could work with many Chilean engineers under the leadership of Joe McMullin. Working with the Chilean staff as well as the US and European staff was a great pleasure for me and made my 16-month stay in Chile very enriching. In February 2009, I returned to Tokyo for my retirement from NAOJ. As I was very eager to see the first fringes from ALMA, I decided to visit Chile again in November 2009. During my visit, I was attacked by a high fever and cough and was admitted to a hospital in Calama. After staying at the hospital three days, my medical condition miraculously recovered and I was able to return to work at ALMA. I saw the first fringes at Band 9 just one day before I left Chile.

I feel very happy that I was involved in various aspects of the ALMA project, such as initial planning of LMSA, site surveying, budget request preparation, international negotiations, and the AIV work in Chile (Figure 7.2).

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Figure 7.2 Masato Ishiguro with some members of the AIV team at his going-away party. Left to right: Joe McMullin, Dick Sramek, Fernando Gallardo, Masato Ishiguro, Johnny Reveco, Cristián Maureira, Camilo Menay. Credit: M. Ishiguro, used by permission.

Site Negotiations

The process of obtaining a concession to the Chajnantor site was discussed in the previous chapter. Here we address some legal issues that occupied the ALMA Executives, still only two at the time when the site was negotiated. Both were eager to obtain a concession from the Chilean government that allowed the construction and operation of ALMA on the Chajnantor site. At the same time, both were concerned with the legal terms and conditions that a concession agreement might entail. The legal standings of ESO and AUI in Chile were and still are very different, and the concession would need to be consistent with both without compromising either. ESO is an international treaty organization, similar to CERN or the United Nations. Its Convenio with Chile is based on that of the United Nations Economic Commission for Latin America and the Caribbean. ESO interacts with Chile at the level of the Ministry of Foreign Affairs. ESO has an ambassador called the ESO Representative to Chile. Not compromising its existing legal standing was critical to ESO, with

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its substantial investments in the La Silla and Paranal Observatories. AURA was also watching from the sidelines, concerned that its agreement with Chile for the Cerro Tololo Inter-American Observatory (CTIO) not be adversely impacted by the ALMA negotiations. The same was true for the Carnegie Institution of Washington and its Las Campanas Observatory (LCO). At that stage, AUI was established in Chile on the same basis as AURA and Carnegie, through an agreement with U. Chile under Law 15172.

As already noted, the slow pace of the negotiations for the site was of sufficient concern to the ALMA Board that a working group was appointed to expedite matters. It was intended to provide better communication with the board and allow individual group members to undertake coordinated assignments. For example, arrangements were made to have the German ambassador to Chile urge the Ministry of Foreign Affairs to act, and for the American ambassador to Chile to speak to the governor of Chile's Region II, where the ALMA site is located. There was plenty of time to review the proposed terms of the agreements with the agencies of the Chilean government that were involved, and the board provided substantial feedback to the negotiators. Daniel Hofstadt and Eduardo Hardy, ESO and AUI Representatives in Chile, respectively, were critical in pushing the process along. In the end, the Ministry of Foreign Affairs decided that the ESO Convenio did not need to be replaced. It could cover ALMA in addition to the other ESO observatories, and an agreement to that effect was signed. AUI was granted the same rights and privileges as ESO under Law 15172. The entire process was finally concluded in late 2003 in a contract with BN giving the ALMA Executives the use of the ALMA site for 50 years.

Contracting for the Antennas

The 12 m antennas that made up most of the array constituted the largest item in the ALMA budget, estimated to be $228 million or 41 percent of the original budget cited in the Bilateral ALMA Agreement. Accordingly, the process of selecting a contractor to provide these antennas was very carefully constructed. The intent of the North American and European partners was to select a single design from a single contractor for the production of the entire array of 64 antennas, choosing the design that met the specifications at the best price. A motivation for a single design was that an array with multiple antenna designs incurs greater maintenance costs: more spare parts, increased training for antenna mechanics, multiple antenna control systems, and the like. In addition, different antenna designs could introduce different systematic errors into specific observations, such as polarization. Having a single design was a laudable goal, but as it turned out, one doomed to failure.

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Specifications – As a first step in antenna procurement, bids were solicited for prototype antennas which would be tested to verify their compliance with the specifications. To meet ALMA's science goals, the 12 m antennas needed to go beyond the state-of-the-art. No antennas of this size and precision had ever been built. The reflecting surface needed not only to be of exquisite accuracy, but also to maintain that accuracy as the antenna changed direction on the sky. The ability to point in a given direction with very high accuracy, and to change pointing direction quickly, was needed as well. The resulting specifications addressing these points and many more were developed over many years, beginning with those for the MMA, LSA, and LMSA.

The key specifications were:

- Reflector Surface Accuracy: 25 µm with 20 µm goal
- Absolute Pointing Accuracy: 2 arcsec over the entire sky
- Offset Pointing Accuracy: 0.6 arcseconds within a 2 degree radius
- Fast Switching: 1.5 degree move in 1.5 s, with a 3 arcseconds peak pointing error
- Path Length Accuracy (Non-Repeatable): 15 µm
- Path Length Accuracy (Repeatable): 20 µm

These specifications are to be satisfied under all azimuth and elevation angles of the antenna and all environmental situations, in particular, wind of 6 m/s by day and 9 m/s at night, as well as full solar illumination from changing directions.

To illustrate two of the above key specifications, consider that an antenna was required with a 12 m diameter reflecting surface that deviates from a perfect parabola by no more than 20 micrometers (µm), which is about one-third the diameter of an average human hair or about the size of a human white blood cell, averaged over the surface. This specification allows observing at frequencies up to 950 GHz (0.32 mm in wavelength). The antennas must also be able to point by dead reckoning to any direction on the sky with an accuracy of 2 arcseconds, approximately 1/14th of the smallest angle that can be perceived by the human eye.

NRAO/AUI received several proposals on 30 June 1999 to design and build a prototype. The proposal evaluation was done using standard procedures. A Contract Selection Committee (CSC) was appointed, chaired by Bob Brown. Business and Technical Evaluation Committees ranked the proposals on their respective merits, without any knowledge of likely cost, and reported their findings to the CSC. The CSC then made a final ranking and opened the price.

The proposal from Vertex[10] was judged by the CSC to be superior to the others. ESO and NAOJ followed their own procurement procedures, in the end selecting different contractors. North America purchased a prototype antenna from Vertex, Europe from the European Industrial Engineering Consortium[11] (EIE), and Japan from the MELCO. The contract with Vertex with a price of $6.1 million was signed on 21/22 February 2000. The fact that the Vertex contract[12] is over 200 pages long indicates the detail and specificity needed to state the very large number of requirements. The purchase orders for all three prototypes contained identical technical specifications.

Prototype Antenna Testing – The three contractors delivered their prototypes, shown in Figure 7.3, to NRAO's VLA site in New Mexico for testing. There the testing team could use the extensive VLA infrastructure to advantage. The VLA site is only 2,120 m above sea level, compared to 5,000 m for the ALMA site, but it is sufficiently high and dry much of the year for testing of an antenna at modest (3 and 1.2 mm) wavelengths. On the other hand, wind at the VLA site and its poor optical "seeing" (the atmospheric effect that makes stars twinkle) would make the tests of antenna pointing accuracy difficult. The Vertex prototype was first to be available for testing in March 2003. Testing of the prototypes from Vertex and EIE was done by the Antenna Evaluation Group (AEG), a joint working group of engineers and antenna experts from Europe and North America who were appointed to test both

Figure 7.3 The ALMA prototype antennas (left to right): Japan's, North America's, and Europe's. Credit: NRAO/AUI/NSF, CC BY 3.0.

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the Vertex and EIE antennas. The AEG began with the Vertex antenna immediately after its assembly. The EIE prototype, carried to the Albuquerque airport in an Airbus Beluga, could not be tested by the AEG until January 2004. The MELCO prototype arrived in May 2003 and was assembled by a small army of engineers and technicians by September 2003. Japan conducted tests of their MELCO prototype separately, as Japan was not yet an official partner in ALMA. The testing program was to have been completed by 1 June 2004, but the late delivery of the antennas, especially the EIE antenna, forced testing of the antennas to run later.

The AEG had the opportunity to test and compare two prototypes with very different designs. Vertex had designed an antenna that pushed conventional techniques to the limit by incorporating carbon-fiber-reinforced plastic (CFRP) in a few key elements. EIE used far more CFRP. Both designs had insulated steel bases and yokes (the "forks" that support the elevation "tipping" structure). But EIE built the receiver cabin at the antenna's secondary focus entirely from CFRP, whereas Vertex made theirs from insulated steel. The reflecting panels for both antennas are supported by a Backup Structure (BUS) made from CFRP. Vertex connected the cabin to the BUS with an Invar[13] ring to limit thermal expansion, whereas EIE used CFRP throughout. The reflecting panels were also very different in the two designs. Vertex made machined aluminum panels, etched to produce a surface that would scatter solar radiation and prevent overheating at the secondary focus. EIE electroformed nickel skins on accurate molds, glued them to thick aluminum honeycomb cores, and coated them with a thin layer of rhodium to scatter solar radiation. The prototypes had radically different drive systems: Vertex used a conventional gear drive and EIE a direct drive system with permanent magnet linear motors. The resulting EIE design was lighter at 80 metric tons than the Vertex design at 108 metric tons.[14] The tests pitted an upgraded conventional design from Vertex against an *avant garde* design from EIE. Which would be better?

A major AEG task was adjusting the reflecting surface panels to form a parabola with the specified accuracy of 20 μm. As delivered, the surfaces were smooth to 80 μm, four times worse than the desired accuracy. Topographic images of the surfaces, obtained by a holographic technique, showed where adjustments in the surface panels needed to be made. By repetitively iterating between making slight adjustments and follow-up holographic images, the surfaces could be set to the final accuracy. Both prototypes satisfied the specification. The same was true for the pointing accuracy, both prototypes meeting this requirement, as well as for many other tests. One design was occasionally slightly better in some specifications and the other in other specifications, but both designs appeared to satisfy the ALMA requirements. The AEG issued a report[15] on 28 May 2004. A complete description[16] of the testing program and results was published later by the AEG leadership. A report of the results[17] of the tests by the Japanese team showed that the MELCO design met the key ALMA specifications, although the testing program given in the report appears to be somewhat less extensive than that of the other two prototypes. All three of the prototypes seemed to be qualified for the ALMA large array. One nagging issue remained that would lead to more testing. The structure of the Vertex prototype did not deform under changing gravitational loads as it should have according to computer models.[18]

Prototype Destinies – After the Japanese astronomers learned that their funding to join ALMA would be less than what was hoped for, it was clear that only four 12 m antennas could be afforded in addition to the compact array of 7 m antennas, new receiver bands, and correlator. The prototype would be one of these four and MELCO would manufacture three more. The North American partners judged the cost of moving the Vertex prototype to Chile to be more than that of a new antenna. They had no other viable use for it and NSF declared it to be surplus property. Proposals were solicited by NSF from would-be owners. Two proposals were received. One was from a team at the University of Arizona, led by Lucy Ziurys, a leading astrochemist. Had they won, the Vertex prototype would have replaced the old NRAO 12 Meter Telescope, which Arizona had acquired as surplus property in 2000. But the alternate proposal was selected. It came from a partnership between the ASIAA of Taiwan and the Smithsonian Astrophysical Observatory, with principal investigators Paul Ho and Roger Brissenden, respectively. They planned to place the antenna first at Thule Air Force Base and later at the NSF's Summit Station on the high ice sheet (3,200 m elevation) of Greenland. That would make it the northernmost millimeter wavelength telescope on the planet, at an ideal location for a future element of the Event Horizon Telescope (EHT), which would later image the super massive black holes at the center of the galaxy M87 and our own Milky Way. Initially disappointed, the Arizona team went on to acquire the EIE prototype, which was moved to Kitt Peak from the VLA site in 2013, where it continues to operate today.

Production Antennas – Even though the testing of the prototype antennas was not complete, on 17 December 2003, NRAO/AUI and ESO issued a call for proposals to build up to 32 antennas each. Each Executive's call contained identical statements of work which were jointly developed in conjunction with the JAO. Each Executive had its own business terms and conditions which were required by their respective laws, policies, and procedures, and which would also give rise to pricing differences. The proposals were due on 30 April 2004 with pricing valid until 31 October 2004. The goal was to procure antennas of a single design that satisfied the performance specifications at the lowest possible price. The joint process established to review proposals and select a contractor is shown in Figure 7.4. The process is similar to that followed by NRAO for selecting a prototype antenna contractor, but it takes into account the different contract terms and conditions between AUI/NRAO and ESO. The Proposal Receipt Teams (PRT) open the proposals, secure and seal the prices, and confirm that the proposals are generally responsive. Then the proposals, without prices, are sent to the Joint Technical Evaluation Team (JTET) and in the case of NRAO/AUI, the Business Evaluation Team. The results of JTET evaluation were sent to the ESO Contract Award Committee (CAC) and to the AUI/NRAO CSC which also received a report from the Business Evaluation Committee (BEC). After that step, the standard procedures of each side are followed.

The overall goal of both contracting processes, as confirmed by the ALMA Board on several occasions, was for each side to procure the same antenna design. However, after extensive, and sometimes intense, discussion between the Executives and by the ALMA Board over the preceding years, the process also allowed for the possibility of acquiring different designs.

ESO limited its call for tender (CfT) to *qualified European* companies, where *qualified* meant the company had successfully passed ESO's Preliminary Enquiry Process. NRAO/AUI did not require that proposals came from US companies. However, NRAO/AUI did limit participation by the following language in the RFP:

> *This solicitation specifically reserves the right to award the production antennas to the successful prototype Contractor. Participation in the AUI antenna procurement is limited to those Proposers/entities that have made a substantial contribution to either the AUI or the ESO prototype antenna.*

Proposals were received from Vertex, and a consortium[19] consisting of Alcatel Space France, European Industrial Engineering S.r.L., MAN (AEM) on the US side, and from the European subsidiary of Vertex – Vertex Antennentechnik (VA), Alenia Space Italy, and AEM on the European side, consistent with the above requirements. The proposals were opened on 3 May 2004 in a teleconference between ESO, NRAO/AUI, and the ALMA Director. At this point, an enormous effort[20] began that involved nearly 30 meetings and negotiations on the US side alone. The proposal receipt committees checked that the proposals were responsive, sealed the prices, and passed the proposals to the JTET, and on the US side to the BEC, for review. The JTET and Antenna Technical Working Group (ATWG) reports[21] went to the Contract Selection/Assessment Committees. After extensive study, the NRAO/AUI CSC gave both proposals under their review comparable scores with respect to specifications and general business

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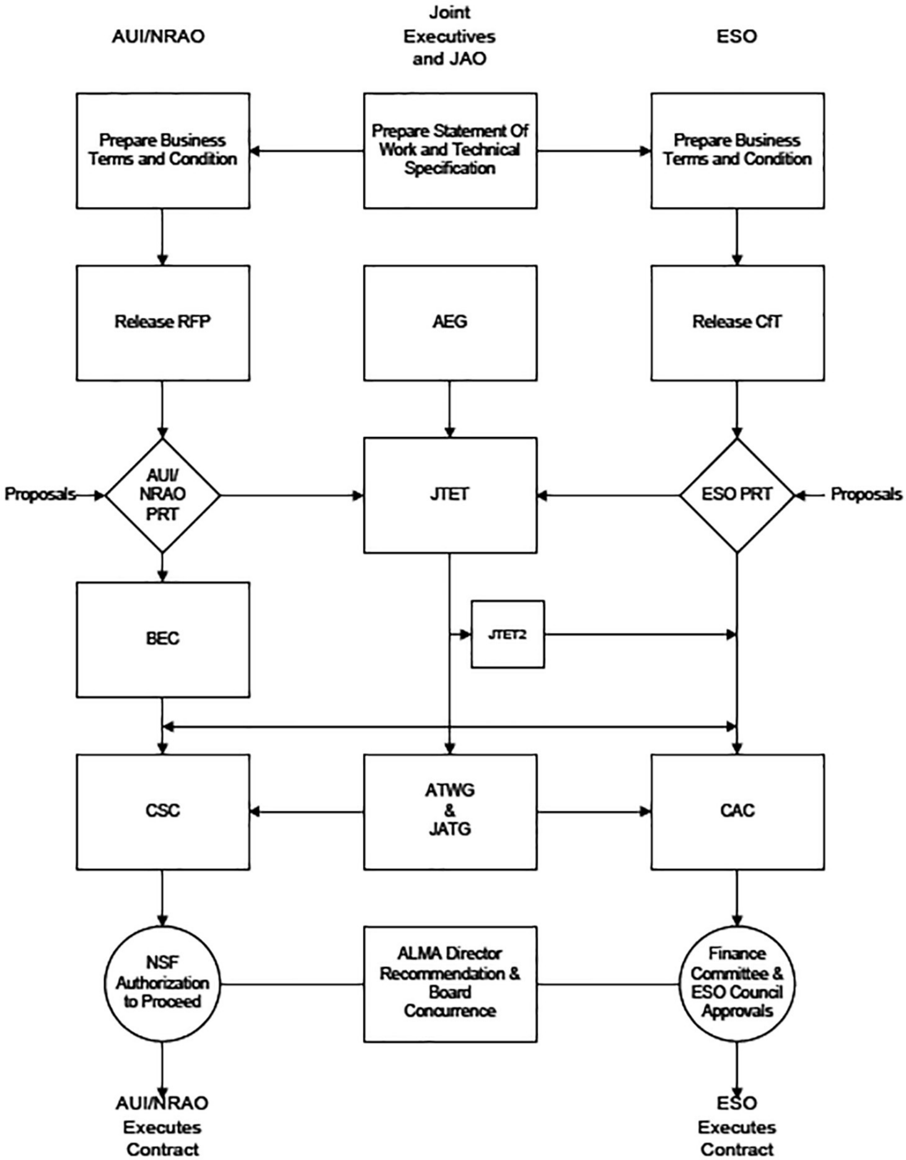

Figure 7.4 The flow chart for joint evaluation of antenna production proposals and the selection of a contractor. The acronyms are: Request for Proposal (RFP), Call for Tender (CfT), Antenna Evaluation Group (AEG), Proposal Receipt Team (PRT), Business Evaluation Committee (BEC), Joint Technical Evaluation Team (JTET), Contract Selection Committee (CSC), Contract Award Committee (CAC) Antenna Technical Working Group (ATWG), and Joint Antenna Technical Group (JATG). Credit: NRAO/AUI/NSF, CC BY 3.0.

qualifications. However, in addition to a significantly higher price, the CSC noted that AEM proposal had several shortcomings: instead of a fixed price, the price was indexed for inflation without a cap; the proposal did not contain a design for the specified common transporter interface; and AEM made numerous exceptions to NRAO's contract terms and conditions. AEM was informed on 29 August 2004 in a letter[22] from Bill Porter, NRAO Business Manager, that they would no longer be considered by the US side unless negotiations with another vendor failed. In a further exchange of letters, AEM confirmed the continued validity of its price through 31 October 2004.

Although the CSC had judged the Vertex proposal to be superior to AEM's, the review had raised a number of questions to be asked of Vertex. These were addressed in a series of three meetings between Vertex and NRAO: on 27–28 July 2004, to discuss a myriad of proposal details; on 18–19 August 2004, to discuss more proposal details and pricing; and on 6 October 2004 to review and understand the revised offer pricing submitted by Vertex on 8 September 2004. Even though the price was the lowest received in a competitive bidding process, it was more than double the amount budgeted for antennas in the Bilateral ALMA Agreement. The main reason for the difference was the dramatic increases in the prices of steel and oil, the latter being the raw material for CFRP. Changes in the design of some elements and the cost of providing an assembly building, lodging, meals, and utilities at the OSF added to the increase as well.

To ensure careful coordination of the antenna procurements on both sides of the Atlantic, a series of four meetings were held over the summer and autumn of 2004 at the Heathrow (7 July and 24 August 2004) and Dulles (2–3 August and 29 November 2004) airports. These were high-level meetings with the Director General of ESO, the President of AUI, and the NRAO Director in attendance. The meetings also included the ALMA Director and ALMA Project Manager. The first three meetings were routine, with each side reporting to the other on its plans and activities. But the fourth meeting was intensely confrontational. The ATWG could not certify from their examination of the AEG prototype test results that the Vertex antenna would meet specifications.[23] As has been mentioned, the concern was the failure of the structural computer model provided by Vertex to accurately predict the measured deformation of the antenna under varying gravitational loads. Bob Dickman pressed the group to contract with Vertex for the production antennas anyway, motivated by the rapidly rising cost of commodities and confident that the technical issues would be solved. In fact, NRAO/AUI had *already* requested NSF permission to do this on 14 September 2004. The ESO delegation was strongly opposed to Dickman's proposal. They considered ignoring the lack of conclusive test results to be wildly imprudent. The meeting nearly fell apart. In the end, Dickman relented and it was agreed that a new testing campaign would be conducted. A new team, the JATG, would review the previous testing and make new tests as required to resolve the technical issues. The JATG team comprised participants in the earlier testing plus additional experts.

The main problem was eventually traced to an error in the holography software. Although smooth to the required accuracy, the surface was not set to a perfect parabola but one that had a superimposed "donut" shape. The error was discovered by Robert Lucas[24] from IRAM in examining the results of a simple test. The distortion was just barely detectable in the photogrammetry measurements that had been made previously. Once holographic measurements and surface setting had been accomplished with the software error corrected, a consistent set of all the test results was obtained. This testing took time and the report was not given to the ALMA Board until April 2005. The final report[25] of the JATG certified both prototypes as meeting specifications:

> *Based on all available data and the ATF testing done by the AEG and the JATG, it is the consensus view of the JATG that both prototype antennas meet the ALMA antenna specifications under direct consideration (surface accuracy at all elevations, all-sky absolute pointing performance) under the environmental conditions encountered during the testing, and that the production antennas based on either design can also be expected to meet these specifications.*

Based on this information, the NRAO/AUI CSC recommended that authorization again be sought from NSF to execute a contract with Vertex. Rapidly rising commodity costs were driving the price of the antennas up and there was heavy pressure to buy the antennas as quickly as possible. The authorization[26] to purchase was sought from NSF on 15 April 2005. The request provided pricing covering the common antenna design as well as the scenario under which ESO would procure its antennas of a different design. The request, as modified on 5 May 2005 in response to some NSF questions, put the NSF into an extremely difficult position. The results of the re-baselining effort to assess the cost to complete ALMA, discussed in the next chapter, were not yet in, but it was already clear that a substantial increase in the ALMA budget would be required if the project was to continue. NSF was far from identifying the additional funding required to support the escalating costs of the project.

At ESO the process had apparently come to the same conclusion. As a result of contract selection coordination activities between AUI/NRAO and ESO prior to, and in the margins of, the ALMA Board meeting of 5–6 April 2005 in Pasadena, California, it was becoming clear that ESO was moving toward choosing VA, the German subsidiary of Vertex. At the meeting, Cesarsky told the Board that she planned[27] to submit the Contract Award Committee's recommendation to the Finance Committee (FC) by 15 April and that if her proposal was approved at the 10–11 May meeting of the FC, it could be ratified by the ESO Council at its 6–7 June meeting. At its May meeting, the FC approved the selection of Vertex Antennentechnik, and authorized ESO to begin negotiations. However, as it turned out, the FC also decided[28] it needed assurance from Council that ESO could afford to pay for its entire share of the ALMA project.

The ESO Council was scheduled to affirm the affordability of ALMA in its 6–7 June meeting in Helsinki, but the German delegation would not support the resolution without evidence that the costs would not escalate even further. The German position was supported by a majority of the Council members.[29] The recommendation to the FC to approve the purchase of antennas from VA had been greeted with consternation by some of the Council members. Most importantly, national interests were expressed in the meeting by the Italian delegation. They complained about the way the procurement was being conducted. At one point in the meeting, there was a threat to take Italy out of ESO if the contract did not go to AEM.[30] Indeed, Piet van der Kruit, Council President, recalled "*I was in a very sad mood and was very concerned that the whole ALMA project would come to an end.*" The meeting ended by passing a resolution confirming ESO's commitment to ALMA and that it would purchase its antennas on a sound financial basis.

The 21 June 2005 ALMA Board meeting at Den Haag, Netherlands was a crucial point for the ALMA project. In addition to Dickman who was the NSF representative, NSF also sent to the meeting Wayne Van Citters, Astronomy Division Director, Judy Sunley, MPS Deputy Assistant Director, and Mike Turner, the NSF Assistant Director for MPS, upon whose desk AUI/NRAO's antenna approval request was sitting.

Turner believed in what he called "transformational science." By that he meant science that transformed a discipline, opening up new avenues and directions of research. Turner was convinced that ALMA would produce transformational science. Waiting until the anticipated cost reviews were complete would result in even higher antenna costs. A pre-publication copy of a report[31] from the National Academies of Science, Committee on Astronomy and Astrophysics had been transmitted to the NSF in June 2005. It concluded that although none of the three Level-1 Science Goals could be reached with a 50-antenna array, transformational science was still possible and the project deserved continued NSF support. If an increased project budget were not approved, the project would die and the contract would be canceled. But if increased funding were realized, all would be well. He was persuasive in arguing the case with NSF upper management.

At the meeting, the North American representatives presented two resolutions from the AUI Board of Trustees: one which urged NSF to approve the AUI contract for the North American antennas and another in which they welcomed "*ESO Council's reaffirmation of its strategic commitment to ALMA and encouraged ESO along with the ALMA Director and the ALMA Board to take all necessary steps to ensure the success of the project*." Massimo Tarenghi, the ALMA Director, urged the Board to endorse the US purchase of antennas to avoid further delay and cost increase. During a break in the ALMA Board proceedings, Turner and Sunley met with Ethan Schreier (AUI President), Fred Lo (NRAO Director), Anneila Sargent (AUI and ALMA Board member), and Pat Donahoe (AUI Secretary) and after quickly assessing the risks and rewards of authorizing the procurement Turner made what he termed "*a bold move*" to authorize the NSF ALMA Board representative to vote in favor of the motion to proceed with the award of the AUI/NRAO contract with Vertex. The ALMA Board then reconvened and gave its formal approval.[32] On 11 July, AUI/NRAO signed a contract with Vertex. The results of the JAO's revised project budget would be available in September and it was hoped that ESO could proceed to a purchase of VA antennas soon after that. It looked like ALMA would have a homogeneous array of antennas. But this was not to be.

The FC and ESO Council decisions to effectively delay the award of the VA contract meant that ESO had several choices[33] with respect to their CfT, the principal ones being: terminate the CfT and do nothing, issue a totally new CfT, or simply extend the existing CfT for as long as the end of the calendar year. The first choice would kill the ALMA partnership and was unthinkable. ESO chose to ask their vendors to extend the pricing validity of their proposals until 30 September 2005, but did not specify a date by which the vendors could submit any further revisions to their proposals, a fact that would come into play later.

From the beginning, there had been considerable pressure on ESO to select the AEM proposal. As early as late September of 2004, the previous year, Cesarsky had been invited to a meeting[34] with the Italian Minister of Science in which he urged her to sign a contract with the French-Italian consortium. On 28 October 2004, letters[35] had been received from the Italian Minster of Education, Universities, and Research, and from Piero Benvenuti, the head of the Istituto Nazionale di Astrofisica and senior spokesman of the Italian

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astronomical community. Both letters expressed concern on the process of the procurement. As noted above, in the meantime, the Italian members of Council had continued to question the validity of the selection process, and AEM had begun to send fax messages to Council members and to attempt to reach them by phone.[36] In the face of all this and to her great credit, Cesarsky was resolute in her commitment to buy a single design.

Regrouping, van der Kruit, Cesarsky, and Corbett envisioned a plan[37] which consisted of holding a meeting of the ESO Committee of Council (Council's "executive committee" – CoC) on 16 September 2005 at which the CoC would discuss the status of the antenna procurement, and then a 29 September 2005 combination CoC/Council meeting to address the affordability determination that had been requested by the FC in its May meeting. If approved by the Council, then Cesarsky would send her recommendation to the Finance Committee for approval at its October meeting.

In preparation for this sequence of events, ESO sought proposal clarifications from VA and the AEM consortium. On Tuesday, 13 September 2005, VA submitted bid clarifications to ESO of its firm fixed price and business terms and conditions, and pointed out that although their current proposal was already compliant with ESO's requirements regarding the amount of work that was to be done in Europe, it would be working later in the month to determine whether this allocation could be further improved. VA also extended its price validity to 31 October 2005. On Thursday, September 15, the AEM Consortium submitted to ESO clarifications of its firm fixed price bid and extended the validity of its price to 31 October 2005. On Friday, 16 September, the CoC met and the contract situation was discussed at length. Then came a surprise – on Tuesday, 20 September, AEM submitted another revised firm fixed price proposal which significantly reduced their previous pricing. The timing of the revised bid was striking. As the President of the ESO Council at the time put it,[38] "*It is not clear why this occurred at this particular time, but it did happen after the Committee of Council meeting where it was stated that if things would remain as they stood, Vertex would win*." The next day ESO declared[39] that the bidding process had ended and Cesarsky sent her AEM award recommendation to the Finance Committee for consideration at its upcoming October meeting. The AEM bid was now lower than the bid from VA and Cesarsky had no choice but to recommend that AEM receive the contract.

In the meantime, on 8 September 2005 the JAO had released its estimate of the cost to complete the project, upon which Cesarsky had prepared a paper that demonstrated the affordability of ALMA, consistent with ESO's long-range plans, assuming Spain would join ESO.[40] At the 29 September 2005 combined CoC/ESO Council meeting the paper was discussed and thus the affordability question that had been initially raised by the FC in May. The Council then affirmed the affordability of ALMA,[41] and also directed the FC to continue with its proceedings with respect to awarding the antenna contract. On 5 October 2005, the FC approved the negotiation and award of a contract to the AEM Consortium.[42]

This decision to award the contract to AEM instead of VA was a totally unexpected result, at least to most outside observers. Ever since, there has been speculation on both sides of the Atlantic that confidential information was leaked to AEM. Although it certainly fits the circumstances, we can cite no evidence that it happened. The Vertex price for the US antenna purchase was public. AEM could have modified that price for European contract requirements and other calculable differences and then submitted a bid that was lower. Perhaps "Euro-fever" ran high at AEM and they submitted a very low bid on which they were willing to take a loss. The mystery remains. ESO signed a contract with AEM on 7 December 2005 for the purchase of 25 antennas.[43]

Following the FC's antenna decision, on two occasions, VA wrote to ESO[44] raising what VA viewed as violations of fundamental formalities in the procurement process including ESO's lack of establishing a common deadline for final price submissions. In late October 2005 Ethan Schreier, AUI President, received a letter[45] from VA which cited the procedures that ESO had followed and proposed that ESO should hold a public bid opening to once and for all eliminate any perception of possible misconduct. Similar letters were sent to NSF. VA also proposed that AUI vote against the award of the contract at the upcoming ALMA Board meeting. Schreier discussed the situation with Turner, who, while sharing his disappointment in the ESO decision, was also extremely concerned about the upcoming external cost review of the JAO's estimate to complete the project, the result of which might pose an existential threat to ALMA. In the end, NSF and AUI concluded that voting against the award of AEM contract had the potential of further destabilizing the project. At the November 2005 meeting in Santiago, Ian Corbett took pains to review[46] the actions at ESO in great detail, the implication being that, following a completely above-board process, ESO was compelled to take the lower priced bid. It was in all probability true, but some in the United States delegation were left with an uneasy feeling that in the future they should be wary in their dealings with their counterparts at ESO. The ALMA Board also extensively discussed the ESO decision's implications of proceeding with two antenna designs. In the end, the Board concurred with the ALMA Director's recommendation that ESO proceed with the issuance of the antenna contract.

NSF commissioned an ALMA Delta Cost Review (ADCR) to assess the additional costs resulting from the selection of two different antenna designs. It met on 26 January 2006 at NSF and concluded[47] that the cost to the project of a mixed array of 50 antennas was $8 million more than the original budget for a homogeneous array. Relative to the total budget for antennas, this was a small amount, but it did represent the price of about one antenna. However, this was exclusive of the increased antenna costs to the United States that came from Vertex spreading its non-recurring costs over 25 antennas rather than 50. The hit on operations was estimated to be a 10 percent increase. These extra costs, seemingly significant in themselves, were not that large compared to the overall budget and the huge scientific payoff that was to come.

The original Vertex contract price was indexed for inflation and capped at $183,000,000 prior to any modifications. The cost of the Vertex antennas after all modifications was $183,113,889, an increase of less than one-tenth of one percent.[48] The final cost of the AEM contract was never released. Contrary to the widespread fear that an array of two different antenna designs would be costly to ALMA operations, in ten years of experience the expense has proved to be much less than the ten percent estimated by the ADCR.[49] The impact on scientific results, specifically in the area of polarization observations, has turned out to be well managed by the data analysis software. However, at the time, the decision to buy a second design for the European antennas took a toll on trust between certain individuals at ESO and NRAO/AUI. There were two contentious issues yet to be resolved: the location of the JAO and the employer of the JAO's local staff. Fortunately, the shared goal of realizing ALMA overcame personal differences.

Local Staff Employment

Every JAO employee is legally employed by one of the ALMA Executives, either ESO, NAOJ, or AUI. The JAO staff take programmatic direction from the ALMA Director while matters of compensation and other terms of employment remain with the legal employer. The JAO staff is divided into two categories: Local Staff (LS) and International Staff (IS). These categories are not original to ALMA; they have always been used by ESO, AURA, and Carnegie. As originally implemented, an IS position was one requiring job skills that were not available in the Chilean labor market. By agreement among the Executives, IS positions were allocated to ESO, NAOJ, or AUI depending on the nature of the position, budget availability, and the desire to achieve an equitable balance of such positions among the Executives. The resolution of who would be the legal employer of the LS, constituting the overwhelming majority of JAO staff, would take years to resolve. A wide range of options was considered, including having each Executive hire its *pro rata* share. This was judged to be too complicated and it was decided that there should be a single employer. Would that be ESO

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or AUI? (This issue arose before Japan joined ALMA; Japan showed no interest in employing the LS after it joined.)

From the outset, ESO had made it clear that it did not want to hire the LS, but rather proposed a third alternative – outsourcing the employment of the LS. Under this arrangement ESO and AUI would form a jointly owned Chilean corporation to hire the employees and handle labor relations. It would *per force* be subject to Chilean labor law and the jurisdiction of Chilean courts. From AUI's perspective, this hiring arrangement posed several problems, chief among them was that such an arrangement could serve to undermine the status of the other US observatories in Chile, namely CTIO and LCO, specifically, that it might lead to curtailing their immunities. ESO also proposed that the LS be outsourced to an existing Chilean company, one that would not be owned by AUI and ESO. However, AUI had substantial reservations about whether outsourcing the LS employment to a totally independent company might be viewed by Chilean authorities as an illegal arrangement. AUI's position was that the only satisfactory hiring arrangement would be that AUI hire the LS. Following the practice at AURA and Carnegie, AUI would follow Chilean labor law even though it was not obligated to do so.

After years of haggling over details, consulting lawyers, and exchanging letters and emails, ESO concluded that their proposal was going nowhere. Immediately after ESO announced its decision on the antenna contract, Ian Corbett and Pat Donahoe met[50] privately in Chicago in early October 2005 to develop a process that would, once and for all, decide how the LS would be hired. They agreed to utilize the Disputes Provision of the ALMA Agreement to elevate the matter to the NSF Director and the ESO Council President. On 10 January 2006, ESO Council President, Richard Wade, accompanied by Monnik Desmeth and Laurent Vigroux, met at NSF in Arlington, Virginia with NSF's Mike Turner, representing the NSF Director, Wayne Van Citters, and Judy Sunley to settle the matter. NSF and ESO acknowledged the complexity of issues surrounding the matter, and that each side had genuine concerns about each of the Executives' preferred options. At the conclusion of the meeting, a recommendation was made to have AUI hire all LS for the JAO. The result was not a surprise to either AUI or ESO because Corbett and Donahoe had done extensive backchanneling over previous months to achieve this outcome. AUI was directed to prepare an ALMA Local Staff Implementation Plan. The plan[51] was approved by the ALMA Board at their June 2006 meeting in Santiago.

Unions are strong in Chile, particularly so in the north where there is a long history of union activism in the mining industry. The vast majority of ALMA workers are unionized. Initial relations between the ALMA union and AUI were good and a contract was successfully negotiated in 2010. In 2013, the

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union did call a strike and ALMA ceased operations for a brief period until an agreement on a new contract was reached. Since then, labor relations have been less confrontational, with contract renewals in 2015, 2018, and 2020 reached without strikes. Worker compensation in Chile is periodically indexed for inflation. As a result, union demands are more focused on working conditions and benefits. In 2019 a second union was organized, mostly comprised of employees in Santiago and managers and supervisors at the ALMA site. AUI has never invoked its immunities, instead choosing to follow Chilean labor law and appearing in labor court when sued. As a result, ALMA enjoys overall good labor relations that prevail at CTIO and LCO, as NSF hoped would happen. An outstanding example of ALMA's commitment to its employees occurred during the height of the COVID-19 pandemic when everyone was paid even when no one was allowed to come to work and astronomical observing was shut down.

At the time of this writing in 2022, there were 214 LS employees. The IS employees were distributed as follows: 11 working for AUI, 16 for ESO, and eight for Japan. As new skills became available in the Chilean labor market, Chilean applicants began to be awarded IS positions, and six had been successful by 2022. Also working on ALMA are the staffs of the Executives in Santiago: 20 at AUI, 10 in the Japanese office, and a similar number at ESO.

ALMA Headquarters Location

The location of the JAO, also known as ALMA's Santiago Central Office (SCO), was an equally thorny issue to resolve. It made economic sense to build it on land available in ESO's Santiago facility,[52] not to mention its location in an attractive, upscale area of Santiago called Vitacura. However, AUI was eager to display itself in Chile as an equal ALMA partner with ESO and feared that locating the JAO at ESO would make ALMA look like just another ESO observatory. Riccardo Giacconi, AUI's president, was particularly opposed to a location at ESO's headquarters in Chile. AUI explored several alternatives to the ESO location, including contacting U. Chile regarding locating the building on the Cerro Calan Observatory site on the east side of Santiago.

In an 11 May 2004 letter[53] from the ESO Director General, Catherine Cesarsky to Bob Dickman at NSF, ESO formally offered to construct the SCO building on ESO's Vitacura site. Conscious of NSF's and AUI's views about ALMA being viewed as an ESO initiative, rather than an international collaboration, the letter specifically stated that, while a specific site within the ESO property could not be identified in the absence of a definitive design, the building would have "… *an address and entrance separate to*

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those of ESO buildings." Little progress was made toward a definitive decision about the building's location until the 6–8 April 2005 meeting of the ALMA Board when it endorsed[54] a paper jointly prepared by AUI, ESO, and the JAO which outlined a series of actions to be undertaken based on the premise that the ESO proposal of the Vitacura location was the preferred alternative. The ALMA Director was tasked to undertake actions which would result in a final decision which would be subject to separate ALMA Board approval. However, no more progress occurred during the next six months largely due to the activity surrounding the antenna procurement decisions and the hiring arrangement for JAO local staff.

Events which would result in a decision picked up momentum as a result of the 10 January 2006 meeting between NSF and ESO Council representatives who not only recommended that AUI should hire the JAO LS but also recognized the benefits of the offer of land at the Vitacura site for the location of the Santiago building. At its 22–24 March 2006 meeting, in Kyoto the ALMA Board officially recognized the tradeoff made by the NSF/ESO Council delegation between the ALMA building site and LS employment, and approved the selection of ESO's Vitacura site as the location for the ALMA Headquarters building, noting that implementation should be consistent with ESO's 11 May 2004 letter to the NSF.[55] As a result of joint efforts to identify specific locations within the ESO site, three potential locations were identified. Two locations were on the north side of the property away from ESO's main entry gate, with the third location immediately adjacent to the main entry gate. From AUI's and NSF's perspectives, the least preferred location was by the ESO main gate because it blurred the important point that ALMA not be viewed as an ESO enterprise, but rather as an international collaboration. Nevertheless, in November 2006, ESO Council approved the site by the main entrance as the "*best location*" for the ALMA building. This decision was met with considerable dismay by NSF and AUI because they thought that ESO Council failed to appreciate the depth of their concern. Over the next year as the detailed building design process evolved, ESO stated that it was impractical to establish a separate entrance. On 8 March 2007, NSF Director Arden Bement formally accepted the offer of the Vitacura site in a letter[56] noting that, "*ESO, the JAO, and NSF are working together to secure architectural designs consistent with the need for ALMA to have an image in Chile as a separate international collaboration with its own distinct identity.*" The conditions in ESO's 11 May 2004 offer letter to NSF citing that the facility would have a separate entrance and address were never fulfilled. But on the bigger issues of economics, convenience, and surroundings, the location of the building is a success. The SCO is shown in Figure 7.5.

Figure 7.5 A view from the north of the SCO (ALMA Headquarters) on the ESO compound in Vitacura, Santiago. The lawn separates SCO from the ESO building, out of the image to the right. The small building to the right leads to an underground parking garage between the two buildings. Credit: ESO, CC BY 4.0.

Notes

1 A draft of the Bilateral ALMA Agreement can be found at NAA-NRAO, ALMA, ALMA Multi-Institutional Agreements, Box 3. https://science.nrao.edu/about/publications/alma.

2 Spain would join ESO on 16 February 2006.

3 The Bilateral ALMA Management Agreement can be found at NAA-NRAO, ALMA, ALMA Multi-Institutional Agreements, Box 4. https://science.nrao.edu/about/publications/alma.

4 The agreement bringing Japan into the ALMA partnership can be found at: NAA-NRAO, ALMA, ALMA Multi-Institutional Agreements. https://science.nrao.edu/about/publications/alma.

5 The first amendment can be found at NAA-NRAO, ALMA, ALMA Multi-Institutional Agreements. https://science.nrao.edu/about/publications/alma.

6 The second amendment can be found at NAA-NRAO, ALMA, ALMA Multi-Institutional Agreements. https://science.nrao.edu/about/publications/alma.

7 The Trilateral ALMA Agreement can be found at NAA-NRAO, ALMA, ALMA Multi-Institutional Agreements. https://science.nrao.edu/about/publications/alma.

8 For a history of Japanese millimeter interferometry from NRO to ALMA, see Ishiguro, Chiba, and Sakamoto (2022).

9 The Trilateral ALMA Management Agreement can be found at NAA-NRAO, ALMA, ALMA Multi-Institutional Agreements. https://science.nrao.edu/about/publications/alma.

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10 The ownership history of Vertex is complex. CPI Vertex Antennentechnik GmbH originated as the Antenna Division of Friedrich Krupp AG in 1968. Krupp AG, together with MAN, built the Effelsburg 100 Meter Telescope. Its counterpart in the United States, the 100 m Robert C. Byrd Green Bank Telescope, was built by Radiation Systems Inc. (RSI). In 1994, RSI was acquired by COMSAT, Inc., which was in turn acquired by Lockheed Martin in 1999. In 2000, RSI was sold by Lockheed Martin to Tripoint Global, a company held by the Thyssen-Bornemisza Group, which had acquired Vertex Antennentechnik (VA) in 1999. In 2004, General Dynamics bought both companies from Tripoint Global and merged RSI and VA into a division called Vertex Satcom Technologies. In 2019, long after ALMA construction was complete, Vertex Satcom was acquired by CPI, Inc. We ignore the series of buyouts and takeovers in this account, referring to the US company as Vertex and using VA for its European subsidiary.

11 ESO's contract for the purchase of a prototype antenna was originally placed with a consortium consisting of European Industrial Engineering, S.r.l. and Costamasnaga. Following the bankruptcy of Costamasnaga, the contract was amended in December 2003 by ESO, recognizing the reorganization of the consortium with Alcatel Space as the leader. We refer to the prototype contractor as EIE.

12 The purchase order for the Vertex prototype antenna can be found at NAA-NRAO, ALMA, ALMA Design and Construction, Box 1. https://science.nrao.edu/about/publications/alma.

13 Invar is a steel alloy with a high content of nickel and a very low coefficient of thermal expansion.

14 The Vertex and AEM (EIE) production antennas weighed 97.7 and 89.5 metric tons, respectively, both meeting the limit set in the antenna specifications of 100 metric tons.

15 *Evaluation of the ALMA Prototype Antennas Report (Executive Summary)*, dated 28 May 2004, can be found at NAA-AUI, Projects, ALMA. https://science.nrao.edu/about/publications/alma.

16 Mangum, J.G. et al. (2006) give a full report on the North American/European prototype testing program and its results.

17 Ukita, N. et al. (2004) present the results of the tests of the Japanese prototype.

18 Mangum, J.G. et al. (2006). See the Executive Summary, Figure 6.13.

19 The Alcatel Space France, European Industrial Engineering S.r.L., MAN (AEM) consortium changed in July 2005 to become Alcatel Alenia Space France, European Industrial Engineering S.r.L., MT Aerospace. This occurred when the MAN Technologie subsidiary of MAN was sold to form MT Aerospace. This happened after the JTET report of 15 June 2004; the acronym remained the same.

20 The US process of proposal review leading to the selection of a production antenna contractor is described in the ALMA Antenna Procurement Summary of 15 April 2005. It can be found at NAA-AUI, Projects, ALMA, Box 5. https://science.nrao.edu/about/publications/alma.

21 The JTET report can be found at NAA-AUI, Projects, ALMA. https://science.nrao.edu/about/publications/alma.

22 Porter's letter to AEM can be found at NAA-PVB, ALMA, ALMA: The Story of a Science Mega-Project. https://science.nrao.edu/about/publications/alma.

23 The ATWG reports of 29 September can be found at NAA-NRAO, ALMA, ALMA Advisory and Coordinating Committees, Box 4. https://science.nrao.edu/about/publications/alma. The addendum of 17 November 2004 can be found at NAA-PVB, ALMA, ALMA: The Story of a Science Mega-Project. https://science.nrao.edu/about/publications/alma.

24 A memorandum by Robert Lucas reporting his discovery of the error in the holography software can be found at NAA-PVB, ALMA, ALMA: The Story of a Science Mega-Project. https://science.nrao.edu/about/publications/alma. A thorough description of the holography technique, including the proper near-field correction, and its application to the ALMA prototype antennas was published by Baars et al. (2007).

25 *ALMA Joint Antenna Technical Group (JATG) Test Results, 2005* can be found at NAA-AUI, Projects, ALMA, Box 5. https://science.nrao.edu/about/publications/alma.

26 The letter to NSF requesting approval of the purchase of production antennas from Vertex can be found at NAA-AUI, Projects, ALMA, Box 5. https://science.nrao.edu/about/publications/alma.

27 Our account of the production antenna procurement events at ESO draws heavily from the memoir of Piet van der Kruit, *Five and a Half Years in ESO Council*, pp. 77–95. It can be found at NAA-PVB, ALMA, ALMA: The Story of a Science Mega-Project. https://science.nrao.edu/about/publications/alma.

28 Ibid., p. 87.

29 Ibid., p. 88.

30 Ibid., p. 88.

31 The report is available at http://nap.naptionalacademies.org/11326.

32 P. van der Kruit, *Five and a Half Years in ESO Council*, p. 93.

33 Corbett's memorandum, *Antenna Procurement – Options, 7 June 2005*, can be found at NAA-PVB, ALMA, ALMA: The Story of a Science Mega-Project. https://science.nrao.edu/about/publications/alma.

34 P. van der Kruit, *Five and a Half Years in ESO Council*, p. 78.

35 Ibid., p. 86.

36 Ibid., p. 91.

37 Ibid., p. 94.

38 Ibid., p. 95.

39 NAA-NRAO, ALMA, ALMA Board Meetings.

40 P. van der Kruit, *Five and a Half Years in ESO Council*, p. 94.

41 A copy of the Council resolution can be found at NAA-PVB, ALMA Series, ALMA: The Story of a Science Mega-Project. www.nrao.edu/archives/items/show/38359.

42 P. van der Kruit, *Five and a Half Years in ESO Council*, p. 94.

43 Ibid., p. 94

44 The letter VA sent to ESO can be found at NAA-PVB, ALMA, ALMA: The Story of a Science Mega-Project. https://science.nrao.edu/about/publications/alma.

45 The letter to E. Schreier from R. Vardeman can be found at NAA-PVB, ALMA, ALMA: The Story of a Science Mega-Project. https://science.nrao.edu/about/publications/alma.

46 The minutes of the ALMA Board meeting of 5 November 2005 can be found at NAA-NRAO, ALMA, ALMA Board Meetings.

47 The ALMA Delta Cost Review Report can be found at NAA-PVB, ALMA, ALMA: The Story of a Science Mega-Project. https://science.nrao.edu/about/publications/alma.

48 The total cost of the North American 12 m antennas can be found in the release of claims located at NAA-PVB, ALMA, ALMA: The Story of a Science Mega-Project. https://science.nrao.edu/about/publications/alma.
49 Beasley to Vanden Bout, private communication.
50 Donahoe to Vanden Bout, private communication.
51 The ALMA Local Staff Implementation Plan can be found at NAA-NRAO, ALMA, ALMA Board Meetings.
52 A report on the options and costs of various locations in Santiago for the JAO offices was prepared by the JAO. It can be found at https://library.nrao.edu/public/memos/alma/misc/ALMAU_2.pdf.
53 Cesarsky's letter to Dickman can be found at: NAA-PVB, ALMA, ALMA: The Story of a Science Mega-Project. https://science.nrao.edu/about/publications/alma.
54 The minutes of the ALMA Board meeting 6-8 April 2005 can be found at: NAA-NRAO, ALMA, ALMA Board Meetings.
55 The minutes of the ALMA Board meeting 22-24 March 2006 can be found at NAA-NRAO, ALMA, ALMA Board Meetings.
56 Bement's letter can be found at: NAA-PVB, ALMA, ALMA: The Story of a Science Mega-Project. https://science.nrao.edu/about/publications/alma.