9

Construction and Inauguration

“Keizoku wa chikara nari (Persistence pays off)”

Japanese proverb

No telescope of the scale of ALMA had ever been built on a site as high as 5,000 m above sea level. Working effectively in the thin atmosphere with only 50 percent of the oxygen available at sea level would require special equipment and procedures. Furthermore, the site was remote, lacking even the most basic necessities such as roads, water, and electricity. The components of ALMA[1] were manufactured in far-flung facilities in Japan, North America, and Europe. As they arrived at the site they needed to be inspected, installed, tested, and transported as outfitted antennas to final locations. Much of the work was repetitive. Fifty-four 12 m plus twelve 7 m antennas all received the same set of electronics. It was a massive task that required determination and focus, despite the repetition. It all had to happen by the inauguration, scheduled for 2013.

Groundbreaking

The ALMA groundbreaking ceremony was held on 6 November 2003, attended by representatives from all the partners. After the observance of a Pachamama (“Mother Earth”) ground blessing ritual conducted by a local shaman and a prayer by Padre Ibar Astudillo Godoy, parish priest in the Cathedral of Antofagasta, the group shown in Figure 9.1 posed for a photograph to record the event. Riccardo Giacconi, President of AUI, gave a speech[2] that highlighted the major observatories of modern astronomy, on the ground and in space. He ended his remarks by thanking the host country: “*I would like to end by thanking our host, Chile, for joining us in this noble voyage of discovery and making this enchanted land the home for some of the most important of these great enterprises.*”

Figure 9.1 Some of the groundbreaking representatives. Left to right: Bob Dickman, Eduardo Hardy, Fred Lo, Massimo Tarenghi, Catherine Cesarsky, and Daniel Hofstadt. On the concrete block in the foreground are the remains of the Pachamama ceremony. Courtesy of Ineke Dickman, reproduced by permission.

Basics

Roads – In the early days of exploration and testing, the ALMA site was reached by one of three routes. One could drive up the road to the Jama Pass, Route 27, and either take the cutoff to Cerro Toco and then down to the site, or drive further, around Cerro Toco and Cerro Chajnantor, to Pampa la Bola, where the Japanese would install two submm telescopes, and thence back west to the site. The third option was to drive directly east from Route 23, starting at a point between San Pedro and Tocanao, straight up to the site on a mining road that led to an abandoned sulfur mine on Cerro Negro. Which of these routes would ALMA use to transport antennas from their assembly point to the high site? Using state highways would save the cost of road construction. But it would require permits and police convoys to ensure safety as the transporters, moving at 10 km/h, would tie up traffic. This option was judged to be unworkable. Instead, a road was built roughly along the track to Cerro Negro from Route 23 to a site at 2,900 m elevation where the antennas were to be assembled and from there to the Array Operations Site (AOS) at 5,000 m. The Operations Support Facility (OSF), would be the location of lodging for contractors and

ALMA staff, cafeterias, a building for the assembly of the North American antennas, and the large OSF technical building, which would house offices, electronics laboratories, and an array control center. At the AOS, 175 antenna pads needed to be built and connected by roads. Road construction began in 2004 and was completed and accepted in March 2013.

Electrical Power – The Chilean national power grid does not reach San Pedro, so the possibility of connecting to a source of power in the village was not possible. Initially, diesel power generators were leased and installed at the OSF. The diesel fuel came from a refinery in Concepción, over 2,000 km south of San Pedro. It was rumored that during construction there were five fuel trucks on the road going to or from ALMA at any given time. The plan was eventually to connect ALMA to the national grid by constructing towers and high voltage lines to carry the power from Calama to San Pedro and then to ALMA. The cost for this turned out to be far more than had been budgeted. An alternative was to purchase generators to replace the growing set of rental units. This occurred in 2011, quite late in the construction. ALMA now runs on a 5.7 MW Taurus 60 turbine generator by Solar Turbines, a Caterpillar company, that burns liquified petroleum gas (LPG), but can be converted to burn diesel fuel. A standby unit is ready to take over in case of a failure. And a third unit is available to be deployed as a standby when one of the units is undergoing maintenance. At the 2,900 m elevation of the OSF one of these units can only generate 3.75 MW of power. The power plant is shown in Figure 9.2. Electrical power is a significant item in the ALMA operations budget. Sixty percent of the power is used to run the antennas, mainly the refrigerators that cool the receiver electronics to 4 K, with the balance used by the OSF. A crew of nine people is required to operate the power station and maintain the 27 kV transmission grid, daily, around the clock.

Security – It is impossible to fence off the huge area on which ALMA sits. But access other than through the main entrance is limited by the natural terrain to all but the most adventuresome. The entrance to the OSF from Route 23 is secured by a guard house near the highway. It is still possible to access the high site using the mining road that goes along Cerro Toco from Route 27 (the road used to make the first site search visits). Also, one can access the site from the Japanese telescopes at Pampa la Bola behind Cerro Chajnantor. And, of course, one can simply drive cross-country in a four-wheel drive vehicle, working one's way to the high site, as was done in the early days of the site exploration. But unwanted visitors can be spotted by a network of 16 security cameras or by ALMA staff working on the site. Even so, the high site is enormous and there have been a limited number of incidents of vandalism.

Figure 9.2 The ALMA power plant built by TSK Elektronica y Electricidad S.A. The plant uses Taurus 60 gas turbine generators, by Solar Turbines. The three 60,000 L fuel tanks on the right side of the photograph store diesel fuel; an additional three tanks, not visible, store 200,000 L each of LPG, enough to run ALMA for three days. Credit: ALMA/ESO/AUI/NINS, CC BY 4.0.

Safety – The ALMA safety program has its roots in the early site search for the MMA. As the search progressed toward higher and higher sites, the question of safety at high elevations arose. Dr. John West, an expert on high-altitude medicine, was hired as a consultant. In 2006, the NRAO safety officer, Jody Bolyard, spent a year in Chile writing the ALMA safety program. It was based on his experience with the MMA search and Dr. West's advice. There are three main functions of the safety program: training, inspections, and accident mitigation. The incidence of accidents is limited by rigorous training, alcohol restrictions on site, and the establishment of protocols for dangerous procedures.

The two unfortunate accidental deaths that occurred during ALMA construction were both the result of drivers losing control of their vehicles. Alcohol is restricted at ALMA, and drivers are given a breathalyzer test on entering the site. Another safety issue is fire, which is difficult to fight at high elevations due to the limited availability of water and the stressful conditions for the fire fighters in the thinner air. ALMA has trained volunteer firefighters who are well equipped to deal with blazes that might occur. To mitigate the effects of high elevation, workers at the high site use supplemental oxygen, as do the transporter drivers. All visitors to the high site carry oxygen canisters, either in a specially equipped backpack or handheld. The air in the building that houses the correlators is enhanced in oxygen content. In case of emergency, so-called Gamow Bags are available should someone suffer high-altitude pulmonary or cranial edema. Victims can be sealed in the bags which are then inflated to sea-level pressure and transported to a hospital. Fortunately, they have never been used.

An on-site ALMA rescue squad with paramedics is trained to handle accident victims. Victims can quickly be treated in the ALMA Polyclinic, which has offices on-site at the OSF technical building, residencia, and at the AOS. The rescue squad is also ready to help with accidents at the other astronomical facilities in the Science Reserve as part of a good neighbor policy. The record of accidents at the ALMA site is gratifyingly low, given the hazards and the number of ALMA staff and contractors that inhabit the workplace. Since safety is such an important concern, trainings are regularly offered to ALMA staff on topics such as high-altitude first aid, fire and emergency preparedness, and off-road driving.

Water – Although the Atacama Desert is a very arid region, it does rain. Total precipitation on the ALMA high site, largely in snow, is equivalent to 10–30 cm of water annually. There is an abundance of ground water at lower elevations that has flowed down from snow melt at higher elevations. This water is close to the surface in the oases like San Pedro and other villages at the base of the Andes. It is used for irrigation but is not recommended for human sustained consumption due to its arsenic content. It is thought many of the health problems of the indigenous Atacamaño population result from their consumption of arsenic-laced water. ALMA buys water from San Pedro, transported from the village by truck to the OSF. ALMA uses about 75,000 L of water per day. This may seem like a lot of water until one realizes that it must supply: a hotel with 120 guests expecting to eat meals, shower, and enjoy clean linens; the central OSF building and other facilities; and for cleaning antennas, transporters, and other equipment of accumulated dust. An additional 100,000 bottles of drinking water are purchased annually. Waste water is processed in a treatment plant. The processed gray water is used to keep down dust on the roads and construction sites. Excess gray water is safely discharged into the environment.

Communications – A mechanism for transferring data from the high site to the world at large was needed from the earliest days of site exploration and study. Initially, the site study data were simply downloaded to a storage device, magnetic tape at first and then compact disks. These were retrieved every few months by Angel Otárola and express shipped to Simon Radford for analysis. This brute force method was supplemented by an Inmarsat satellite phone link which allowed for daily data downloads. During ALMA construction, a microwave link to Calama was established, where a connection to the internet was available.

For the massive amounts of data from ALMA, an optic fiber connection was required, connecting ALMA to San Pedro and thence to Calama and Antofagasta. The fiber connection was installed by Silica Networks in 2014 as part of the first project of the ALMA Development Program, the ongoing program whereby

ALMA is improved and enhanced with new equipment. Silica Networks was unable to charge for ALMA's use of the fiber until it received government approval, a process that took many years while ALMA enjoyed free service.

The Silica link allowed ALMA to connect to the existing data system through northern Chile that came from a 2010 European investment known as EVALSO (Enabling Virtual Access to Latin American Southern Observatories), which was made in partnership with Red Universitaria Nacional (REUNA) in Chile. EVALSO was designed to enable faster connection for ESO's facilities at Cerro Paranal and Armazones, where the ELT would be constructed. In 2012, ALMA signed an MOU with REUNA to transport data from Antofagasta to the JAO in Santiago, where it is redirected to the various regional centers. Beyond the Santiago metropolitan region, it is the responsibility of the ALMA partners to transport the data to the three ALMA Regional Centers (ARCs), where copies of the data are stored in addition to the archive at the JAO. ALMA data are sent to Europe via ESO's established network. In the case of North America, data travel via Brazil to the Florida International University[3] (FIU) in Miami where they connect to the US National Research and Education Network backbone for further transport to the North American ARC in Charlottesville. The data take a longer journey to the East Asian ARC, following the same path as the North American data to FIU and connecting there via the fiber optic carrier Internet2 to Tokyo.

High Site

Antenna Pads – The fifty-four 12 m antennas can be moved into numerous distinct configurations by utilizing the 175 antenna pads. There are an additional 16 pads for the Japanese compact array and four 12 m antennas. The pads incorporate kinematic mounts whereby the placement of an antenna on the pad always results in the antenna sitting in the exact same location. Clamps tie the antennas to their pads to secure them against high winds. Power is supplied to the antenna through cables that connect the pads to the generators at the OSF. The signal received by an antenna during observing is transmitted to the OSF via optic fiber cables running to each pad. The pad connections required a significant amount of trenching, a challenge in the abrasive, volcanic earth. As an example of what can go wrong, a simple purchasing error resulted in the connections from power transformers to 51 antenna pads to be in noncompliance with the grounding standard specified by the antenna manufacturers. Rewiring these pads was necessary to maintain the antenna warranty. It was impossible to dig up the faulty power cables without damaging the fiber optic cable. The solution was to bury an additional ground wire as deep as possible. This was done hydraulically, using heated water to cut a trench.

Figure 9.3 ALMA antenna transporter *Otto* carrying the last antenna, built by AEM, to the high site to join the array. Credit: ESO, CC BY 4.0.

Antenna Transporters – Being able to relocate antennas to different pads and generate distinct configurations, some with vast separations between antennas, is a vital function for interferometry. It makes possible observations with higher angular resolution, that is, greater detail in the images obtained. Moving the antennas closer together provides greater sensitivity to extended emission from a source. ALMA does not have fixed configurations. The 12 m antennas can be spaced as needed for the scientific goals of projects, from a minimum separation of 15 m to a maximum of 16 km, in what is known as a dynamic array that is changing, sometimes daily, throughout an observing cycle. Each 12 m antenna weighs approximately 100,000 kg, so moving one about requires a very special transporter; ALMA has two such custom-designed transporters, shown in Figure 9.3. Each is 20 m long by 10 m wide by 6 m tall, weighs 260,000 kg, and has 28 independently steerable tires. To learn to drive a transporter one must take a six-month course, and only a few critical employees are so equipped. The drivers use supplemental oxygen while driving to stay alert at elevation. Each transporter has two 500 kW diesel engines that only deliver 320 kW in the thin air at 5,000 m elevation. The engines are supplied fuel from two 1500 L tanks. Electrical power is supplied to an antenna from the transporter during a move. This keeps the refrigerators running that cool the receiver electronics and allows the antenna base to be driven to the proper orientation when it is being placed on a pad.[4] The transporters live in a hangar at the OSF when they are not in use. A second shed on the high site is available for overnight shelter if necessary. The transporters are named Otto and Lore, the given names of the Scheuerle's, who own the company that made the transporters, Scheuerle Fahrzeugfabrik GmbH, of Pfedelbach, Germany. In December 2007, the transporters were loaded onto a barge to be shipped down rivers and canals to Antwerp, Belgium, and then by ship to Antofagasta, Chile. They were then unloaded and driven to the ALMA site in a convoy that occupied the city street and highway lanes in both directions. The trip was made possible with the assistance of the Carabineros.

Buildings

Operations Support Facility – The OSF is the complex of facilities required to operate ALMA. It is located in a 1 km^2 area owned by the ALMA partners at an elevation of 2,900 m, midway between the valley floor and the high site. The main facility is the 7,000 m^2 Technical Building, shown in Figure 9.4, that contains offices, laboratories, the array control center, and emergency services. It dominates the OSF in a central location. The architect, Fichtner GmbH & Co, Germany, gave the building a sleek, modern design that blends into the landscape. The construction contractor was the consortium Vial y Vives and Mena y Ovalle, Ltda, of Santiago, Chile. Design work began in November 2003, construction on 10 August 2006. The building was completed in 2008, but outfitting continued for two more years as activities ramped up.

Figure 9.4 An aerial view of the OSF. Credit: ESO, CC BY 4.0.

Figure 9.5 The AOS Technical Building. The arches in the foreground are vehicle shelters. The large shed in the background to the right is the transporter shelter. Credit: ESO, CC BY 4.0.

AOS Technical Building – The supercomputers, known as correlators, that combine the signals from the array antennas to form an image are housed in the main building at the high site, one for the large array of 12 m antennas and one for the compact array of 7 m antennas. The technical building also houses the electronics that synchronize the antenna receivers in time, the so-called "local oscillator" system. The 5,000 m elevation imposes special requirements. Heat generated by correlators and associated electronics must be dissipated by a refrigeration system designed to operate in thin air. The air in the building is charged with supplemental oxygen to allow technicians to function normally in servicing the equipment. The building is the highest in the world with this level of technical activity. An adjacent shed provides cover for transporters should they need to stay at the AOS. The building was designed by the international architectural firm M3 and built by Constuctora Tesca Con.Pax S.A. of Santiago, Chile. It is shown in Figure 9.5.

Residence Hall – During construction, ALMA staff and contractor employees were housed in separate, temporary residences, each with its own cafeteria. On 23 February 2015, ground was broken for the ALMA Residencia. In Massimo Tarenghi's dream for this "hotel," it was to bridge a ravine, with a swimming pool built into the ravine below. His hope was to build something at least as stunning as the Residencia at ESO's Paranal Observatory. Sadly, there were

Figure 9.6 The ALMA residence hall provides living accommodations for up to 120 staff members and visitors along with a cafeteria, and a variety of venues for exercise and relaxation. Credit: ESO, CC BY 4.0.

insufficient funds to realize this vision. The more practical residencia, shown in Figure 9.6, that was built has an excellent design that was created by the Finnish architectural firm Kuovo and Partanen. The Chilean firm Rigotti and Simonovic, Arquitectos, adapted the design to local standards. The residence hall was built by the consortium AXIS LyD Construcciones Ltda, consisting of Constructora LyD S.A. and Axis Desarrollos Constructivos S.A., two Chilean companies that had extensive experience in constructing residential buildings in the challenging environment. The residence hall can house up to 120 employees and visitors. OSF employees work on the *sistema de turno*,[5] a well-established program in Chile of rotating shifts whereby they are at the OSF for five days and then are at home for two days, or for positions that require continuous duty, at the OSF for eight days and home for six days. Many employees commute to the OSF from long distances, as far as Santiago and beyond. ALMA provides for their transportation from specified pick-up points and for their room and board. The residencia provides amenities for its guests that help maintain physical and mental health outside of work hours: a swimming pool, gymnasium, and sauna.

Antenna Assembly Building – The contractor for the North American antennas, General Dynamics Satcom Technologies (Vertex), wished to assemble them in a controlled environment, out of the weather. Accordingly, a large building, shown in Figure 9.7, was erected at the southwest corner of the OSF for that purpose. Four antennas could be assembled simultaneously in the building, the work aided by lift buckets and an overhead gantry. An additional three antenna pads are located outside the building to store finished antennas. The downhill side of the building has huge doors, large enough to allow a transporter loaded with an antenna to pass through. The building has proven to be extremely useful in ALMA operations for antenna and transporter maintenance, justifying the decision not to remove it once the North American antennas had been assembled. It has, however, been an item of controversy with the local residents, particularly, those living in the village of Toconao, directly below the site. The source of the controversy is an illustration of unexpected consequences. When first constructed the building did not have doors; it was open, facing Toconao. The temporary electric power generators in use at that time had to be run with a power load. Running without a load caused breakdowns. So the lights on the OSF site were left on all night, whether or not they were needed, including those in the antenna assembly building. This spoiled the night view of the mountains above Toconao, the tranquil scene the residents were accustomed to seeing replaced by one dominated by the maw of a harshly illuminated building interior. The eventual installation of the doors helped considerably.

Joint ALMA Office – As was described in Chapter 7, the ALMA Observatory offices are housed in a building on the ESO campus in Vitacura, Santiago. The building provides office space for administrative and scientific/technical staff, meeting rooms, and an auditorium. An underground garage can hold 150 cars, shared with ESO next door. The location is secure and in a pleasant neighborhood,

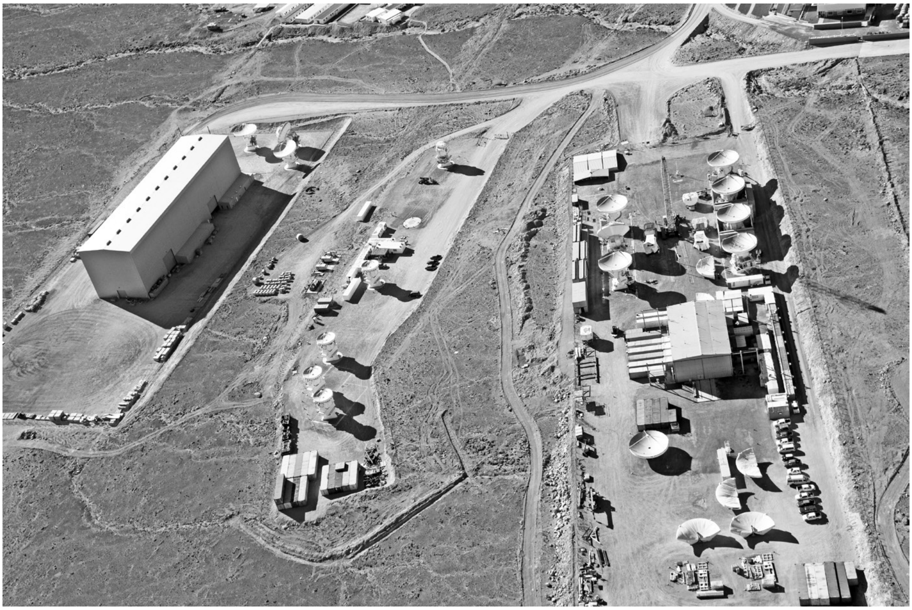

Figure 9.7 The Vertex antenna assembly building is on the left. Three North American antennas can be seen stored on the outdoor pads. The MELCO assembly area is in the center, where four of the antennas for the Atacama Compact Array (ACA) can be seen. The AEM assembly area for the European antennas is on the right, where seven antennas appear to be complete and more reflecting surfaces are being assembled. Credit: ESO, CC BY 4.0.

close to the Vitacura Municipal Center and the expansive Parque Bicentenario nestled along the Mapocho River. Activity at the JAO has steadily increased since operations began. For example, the arrays can now be operated from a control room extension there.

Antennas

ALMA's 66 antennas are its most expensive, mechanically complex, and visible components. They were fabricated in distant facilities around the world, far from Chile, by three different companies in four different designs to exacting specifications. Formal quality assurance (QA) procedures were established to ensure that each antenna with all its sub-components would actually work as specified. These procedures also applied to the signal correlators and their associated electronic systems, and to site construction of roads, buildings, and utilities. The larger the project, the greater the importance of QA. ALMA never had enough. As is typical for a large project, the ALMA quality assurance procedures had names and acronyms.

Preliminary Acceptance In-house – To ensure that nothing faulty was shipped from its place of fabrication, every deliverable from an IPT was tested by a PAI team prior to being sent to the ALMA site.

Provisional Acceptance On-site – The PAS team was the component of the JAO responsible for accepting the deliverables by checking that nothing had been damaged during shipment, before assembly and integration into working telescopes. The PAS team was also responsible for inspecting and accepting the construction work on the ALMA site. The JAO was severely understaffed at the beginning of construction. Pressure to complete the integration of electronics and make the antennas ready for observing meant that provisional acceptances were issued by the hard-pressed PAS group, reserving the right to make a final inspection and acceptance later. For example, the roads on the site had been in use for years before a final inspection occurred. This led to a conflict with the contractor over who was responsible for bringing the roads up to specifications. It was only one example of contract and warranty disputes that cost the ALMA Executives a great deal of time and effort to resolve. The contractor that constructed the outdoor antenna pads at the OSF provided another example. To allow for water to run off, they were to have a two percent slope from the center to the pad edge, that is, a slope of 2:100. For the first of these pads, the contractor misread this specification in the drawings as 2 degrees, a slope that is nearly twice as large. The first time an antenna was placed on one of these pads, it teetered on the tip of the concrete cone.

Assembly, Integration, and Verification – The AIV team was the component of the JAO responsible for assembling a functional antenna, that is, equipping an antenna with the electronics systems that made it into a telescope, making sure the systems worked together, and confirming that their functionality met specifications. The AIV team had to work closely with IPTs responsible for fabricating and delivering the systems to fix problems and work out bugs.

Commissioning and Science Verification – The CSV team of the JAO was responsible for making test astronomical observations with a completed antenna, verifying that it was ready for service in the array. The CSV team was strongly supported by the AIV team. Initial observations with a new telescope, so-called "first light" observations, often reveal unexpected results that prompt a variety of tests that may lead to still others. The activity can become a somewhat interrupt-driven seat-of-the-pants exercise with some appearance of disorganization. If this was true of the CSV team, perhaps it was so because the tasks were conducted by astronomers, who typically are less management oriented than engineers, and the team was battling against time in order to get to the real science as quickly as possible. Throughout, the CSV team also tested new capabilities and investigated any issues that arose with data acquisition. What counts is that ALMA works as specified, for which the team, led by Richard Hills, deserves immense credit. Following Cycle 0, and as ALMA approached full operations, the CSV team successfully morphed into a team known as Extension and Optimization of Capabilities (EOC).

Vertex Antenna Assembly – The following description of this process focuses on the North American antennas, for which the authors had access to the most extensive documentation. The North American antenna components and materials are shown in Figure 9.8. Vertex was the contractor for the antennas and these components came from its different facilities and subcontractors: the Invar[6] cone, cabin, azimuth structure, and pedestal were shipped from the Vertex plant in Kilgore, Texas, after being fabricated in Mexia, Texas; the CFRP components – Backup Structure (BUS) and quadrapod support legs – from Airborne in The Hague, The Netherlands; the reflecting panels from Zrinski AG in Wurmlingen, Germany; and the machined aluminum subreflector from CPI Vertex Antennentechnik (VA) in Duisburg, Germany.

The delivery schedule for all the antennas was specified in their contracts. The first of 25 Vertex antennas arrived at the OSF on 24 April 2007 and the last was completed and accepted on 16 November 2012. The first of 25 AEM antennas arrived about a year later in 2008. The AEM delivery schedule was faster paced to make the 2012 goal of having all the 12 m antennas accepted. With only 16 antennas, MELCO enjoyed a somewhat more relaxed schedule for delivery, easily meeting the 2012 deadline. Re-assembly and testing of the antennas was a learning process. For example, the first Vertex antenna took about 434 days to reach acceptance. After that, the time required dropped steadily to 184 days for the last antenna. It should be noted that several antennas could be in assembly at the same time. The Vertex building had four assembly pads; AEM and MELCO had multiple assembly pads as well.

The activity prior to shipment for the Vertex antennas was located in two places. In a Vertex facility in Kilgore, Texas, the mild steel components and INVAR cone were fitted together. Before attaching the azimuth structure to the pedestal, cabinets for the main power distribution system and uninterruptible power supplies were installed in the pedestal, along with the azimuth cable wrap, a mechanism to prevent cables going to the receiver cabin from binding when the antenna moved in azimuth. Air-conditioning equipment was installed in the receiver cabin prior to attachment of the INVAR cone. Two access platforms were assembled and test fitted to the assembly. Then the required cabling and piping were installed. All exposed steel and INVAR surfaces were covered with closed-cell foam insulation and then a layer of aluminum cladding. Finally, the drive system was tested. While the North American Antenna IPT monitored the assembly and testing particularly closely for the first antennas, the process was truly a world-wide affair.

After completion of factory acceptance testing, the assembly was placed horizontally on a heavy steel pallet or skid and wrapped for shipping. The package came to be called the “Blob.” Its size and weight were comparable to, if

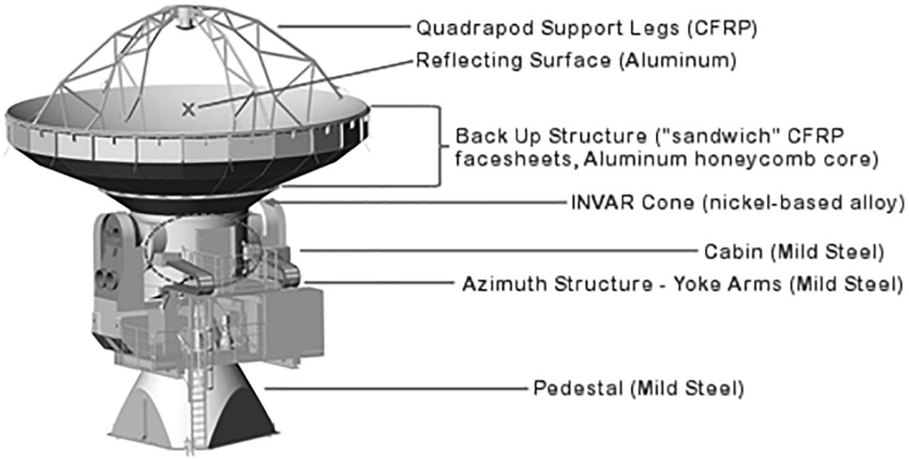

Figure 9.8 Diagram of the subassemblies of the North American antenna indicating the materials from which they were fabricated (CFRP is the acronym for carbon fiber reinforced plastic). Credit: Art Symmes; NRAO/AUI/NSF, CC BY 3.0.

somewhat less than, those of a diesel locomotive. The load traveled on a high-capacity flatbed trailer to the port of Houston, Texas, where it was loaded onto a cargo ship for shipment to Antofagasta, Chile. After being placed on a different skid and again on a flatbed trailer, the Blob headed to the OSF, filling all lanes of the city streets and highways along the way. As with the antenna transporters, the Carabineros provided traffic control and security for the convoy. Two 20 ft shipping containers with the access platforms and air conditioning equipment accompanied the Blob. The entire trip from Kilgore to the OSF took about four weeks.

All the antenna components above the INVAR cone were assembled in Duisburg, Germany, at VA. The BUS of an antenna is made up of plates that consist of aluminum honeycomb sandwiched between CFRP sheets. The aluminum reflecting panels are mounted to this structure. The rigidity of the structure was tested by applying specified bending loads and measuring the deflection. After testing, the structure was disassembled and packed for shipment. All the pieces fit together with location pins and were labeled with barcodes to ensure an exact duplicate re-assembly in Chile. Shipment required two 40 ft shipping containers for the BUS panels and three 20 ft shipping containers for the reflecting panels, support legs, and subreflector. The trip to Antofagasta required six weeks.

When the first Vertex antenna arrived at the OSF in 2007, the assembly building was not finished yet, so assembly began on an outdoor pad. Subsequent antennas were assembled indoors. Assembly was the responsibility of the contractor, with the NA Antenna IPT monitoring the workmanship and testing. The two groups cooperated in resolving problems as they arose. One example of such a problem arose with the first antenna. The closed-cell foam insulation installed in Texas expanded in the thin air by 50 percent. A different foam proved satisfactory. Another unanticipated problem caused by the environment was the crystallization of the fluid in the antenna inclinometers at the low temperatures on the high site. This was discovered after an antenna spent a winter on the high site. Switching the fluid in the inclinometers of all the antennas solved the problem.

The NA Antenna IPT then conducted optical pointing observations to develop a pointing model for the antenna. The model, unique to each antenna, makes small corrections to the angles measured by the encoders on the azimuth and elevation axes. In the course of this, the Antenna IPT was initially puzzled by an effect well-known to geophysicists – vertical at the OSF on the side of the mountain is not the same as on the high site on top of the mountain, but is tipped slightly, the downward end pointing a little towards the mountain. They had not observed the "deflection of the vertical" effect at the prototype test facility which was located on a broad, flat plain. And the effect is not present on the Llano de Chajnantor where the AOS is located. This exercise was the first opportunity to use the antenna drive system and numerous bugs were found and corrected by the contractor.

The contractor had set the reflecting surface to an accuracy of 35 μm using photogrammetry, a technique that involves taking pictures of the surface from several angles to obtain a three-dimensional image. The antennas then received extensive testing of mechanical alignments, servo system performance, and general satisfactory compliance with specifications. The Antenna IPT made holographic observations to set the reflecting surface to an accuracy of 20 μm. Holography is a technique that involves observing a fixed transmitter at a large variety of angles to obtain an error map of the reflecting surface.

The NA Antenna IPT served as an interface between the contractor and the AIV group, supporting the AIV group in solving little problems and bringing in the contractor for warranty issues. Nick Emerson from the IPT and Lutz Stenvers from VA conducted operation and maintenance training sessions for the AIV group. Figure 9.9 shows an assembled antenna, ready for its electronics.

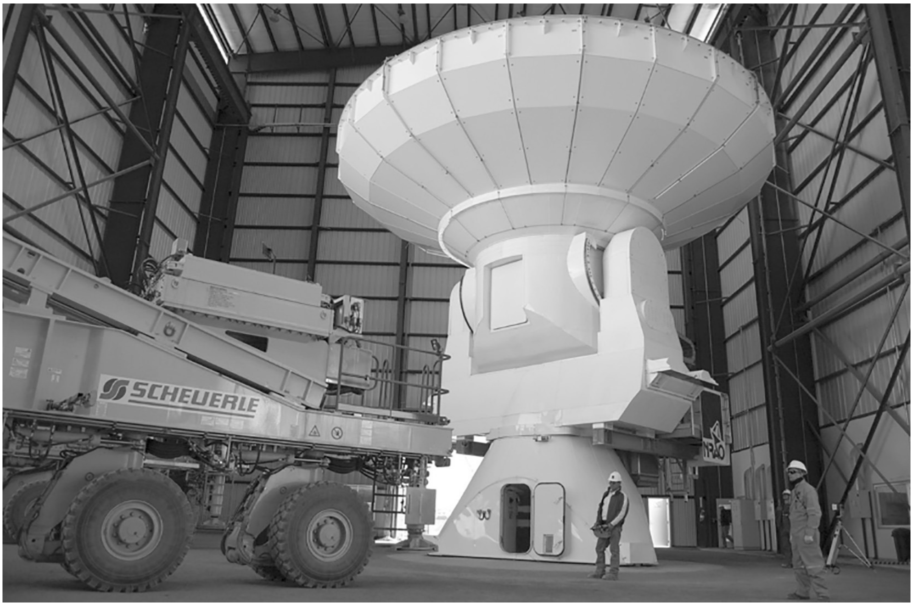

Figure 9.9 An antenna, ready for its electronics, being loaded onto a transporter. It is shown in the antenna assembly building, built by Vertex for assembly of its antennas. Credit: Art Symmes; NRAO/AUI/NSF, CC BY 3.0.

Memories of Roles in ALMA/NAOJ

NAOJ formally joined ALMA two years late, and at that time the specifications for the interfaces between ALMA antennas and other subsystems were advanced. When I participated in the ALMA transporter meeting in 2004 September, I asked to modify the antenna clearance with the ALMA transporter. At first, ALMA Director Massimo Tarenghi refused the request. I explained that the interface change did not affect EU or NA antenna design and the request was eventually approved. After that, Stefano Stanghellini, Jeff Zivick, and I, with ALMA Project Manager Tony Beasley, enjoyed improved communications on antenna interface and specification issues. Things went better after that.

NAOJ ALMA project overcame several challenges by the work of several individuals: Junji Inatani led the antenna engineering discussion with MELCO on details to fulfill the stringent specifications. NAOJ ALMA project manager, Satoru Iguchi was responsible for the schedule and costs and argued with MELCO. I led the verification team with Kouichiro Nakanishi to make the verification plan and procure measurement instruments, including the holography system.

These efforts saw the first three ACA 12-m antennas arrive at OSF in 2007 September on schedule. In the initial holography measurement, the thermal deformation of the dish was larger than predicted. After examining numerous holography maps with temperature data, NAOJ identified the cause. MELCO improved the insulation of the receiver cabin and yoke structures and NAOJ finally demonstrated that the ACA 12-m antenna met the ALMA surface specification. We conducted verification measurements on pointing, surface, path length stability, and servo performance for months. The antenna was accepted as the first ALMA antenna in the acceptance review of December 2008 and moved to the JAO OSF pad the following month. The NAOJ ALMA project were very happy over this accomplishment and I think this was due to the individual strengths of the team members of the NAOJ ALMA project even under difficult circumstances.

I served as the chair of the ACA 7-m antenna Preliminary Design Review in September 2008. The design adopted a steel BUS with fans stabilizing the BUS temperature. The reviewers were initially concerned about such an unusual approach to meet stringent ALMA surface specification of 20 µm. The review panel finally accepted that design since MELCO showed the detailed supporting analysis. In closing remarks, I said that the ACA

7-m antenna would make history. Later, the holography measurements demonstrated that the 7-m antenna had the best surface accuracy of better than 5 µm. Further, the antenna achieved very small thermal deformation despite of relatively large temperature variations.

I was fortunate to have a unique and exciting experience in an extremely large international project. I appreciate my colleagues, especially Koh-Ichiro Morita who passed away just after the ALMA early science started.

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The process just described was in broad outline similar to the European and Japanese antennas, and the three efforts, somewhat incredibly, converged on time to form the final array at the Chajnantor Plateau.

Electronics

An optical telescope forms an image using mirrors and lenses; a radio interferometer via electronics. ALMA's electronics fall into four major systems: receivers, local oscillator, intermediate frequency, and correlator. Together, ALMA's electronics systems represent a multitude of parts: wires, cables, integrated circuits, resistors, capacitors, inductors, micro-processors, fiber optics, power supplies, digitizers, oscillators, lasers, connecters, refrigerators, and cooling equipment, that were built into systems in laboratories around the world to be fitted onto the antennas in Chile. Electronic systems were the third largest fraction of the ALMA budget, essentially tied with the cost of developing the site at 15 percent of the total cost.

Receivers – The signals received by radio telescopes are extraordinarily weak, and ALMA enjoys no exception in that regard. The signals they detect are measured in Janskys (Jy), a unit[7] named after Karl Jansky, who was the first to discover radio waves from a non-terrestrial source. A cell phone on the Moon transmitting 1/4 W has a signal strength of 1 Jy. Modern radio telescopes routinely detect signals that are only a micro-Jansky (µJy) in strength, 10 million times weaker. For ALMA to do so at millimeter and submillimeter frequencies requires receivers that define the state of the art. The key components that make this possible are superconductor-insulator-superconductor

(SIS) junctions and high electron mobility transistors (HEMT). At NRAO, the SIS junctions and their mixers were designed by Tony Kerr and Shing-Kuo Pan, and the junctions were fabricated on silicon wafers under a cooperative arrangement with a laboratory at the University of Virginia run by Arthur Lichtenberger of the Electrical Engineering Department. HEMT transistors were obtained by NRAO as part of a wafer purchase by JPL. Although room temperature HEMT amplifiers are in relatively common use, the cryogenic-cooled amplifiers designed by NRAO's Marian Pospieszalski outperform them all. His designs are based on a model[8] he developed for cooled HEMTs. They are in use throughout radio astronomy and were key to the success of NASA's Wilkinson Anisotropy Probe. In all but the lowest frequency ALMA receivers, the radiation gathered by the antenna is focused on a SIS junction where it is mixed with a reference frequency to produce a difference called the intermediate frequency. (For the lowest frequency ALMA receivers, the SIS junction is unnecessary.) The intermediate frequency is then amplified by a HEMT amplifier and digitized for transmission to the AOS Technical Building. The SIS mixers are tunerless, that is, they do not require the motor-driven mechanical tuning stubs of previous mixers designs. This feature is crucial to the reliability of the mixers; mechanisms cooled to cryogenic temperatures are prone to failure.

Each ALMA antenna can host up to ten receivers for the detection of radiation in ten bands of the millimeter/submillimeter spectrum. The initial allotment was only eight bands. Bands 1 and 2 are being implemented at the time of writing this book. The bands are matched to the high transparency "windows" in the atmosphere at the ALMA site. Table 9.1 lists the characteristics and fabricator of each receiver band.

The SIS junctions must be cooled to 4 K (−269 C or −592 F) and the HEMT amplifiers to 15 K, to achieve the performance goal of noise generated in the receiver itself to be no more than three times the limit imposed by quantum physics. To accomplish this, the receivers are built into cartridges that are housed in a cryogenic enclosure and cooled by a closed-cycle helium refrigerator. Figure 9.10 shows a pair of Band 6 receiver cartridges and a cryostat with Bands 3–10 installed. Observations can only be made in one band at a time for a given antenna array. The antenna subreflector tilts slightly to direct the signal beam to the selected receiver. The receiver cryostats are installed in the antenna using a modified airplane catering truck and special handling gear.

Local Oscillator System – The local oscillator system[9] is basic to setting the exact frequency of observation. A reference frequency for the receiver mixers is sent from the AOS Technical Building to the antennas via optical fiber as

Table 9.1 *Receiver characteristics*

Band	Frequency (GHz)	Detector type	Partner: fabricator
1	31–45	HEMT	East Asia: ASIAA-led international team: NAOJ, HIAA, NRAO, U. Chile
2	67–90	HEMT	Europe: under consideration
3	84–116	SIS	North America: HIAA (with NRAO SIS mixers)
4	125–163	SIS	East Asia: NAOJ
5	163–211	SIS	Europe: SRON under contract from ESO
6	211–275	SIS	North America: NRAO
7	275–373	SIS	Europe: IRAM under contract from ESO
8	373–500	SIS	East Asia: NAOJ
9	602–720	SIS	Europe: SRON under contract from ESO
10	787–950	SIS	East Asia: NAOJ

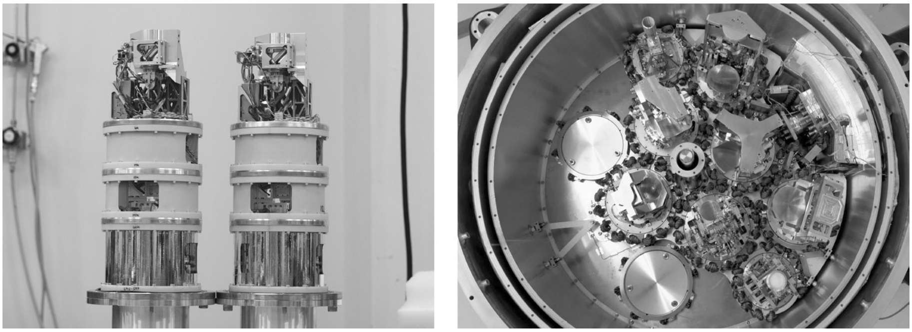

Figure 9.10 Left panel: A pair of Band 6 cartridges. The three temperature tiers are separated by two insulating fiberglass cylinders, from 4 K at the top, to 15 K, to 77 K. Right panel: Cartridges for Bands 3–10 installed in the cryo-container. Credit: ALMA/ESO/AUI/NINS, CC BY 4.0.

the difference between two laser frequencies. It is in the range 27–142 GHz. (For the higher frequency receiver bands, this difference must be multiplied by factors of 3, 7, or 9.) The phase stability required for the local oscillator system is very high, and elaborate mechanisms are employed to ensure that the electrical length of the optic fiber does not change. Antenna motion, for example, can stretch the fiber. Changes are monitored and corrected in real time. The early development of this system was part of the design and development program of the MMA, done at NRAO's Tucson site by John Payne and Larry D'Addario.

Intermediate Frequency System – The intermediate frequency system transmits the received signal from the antennas to the correlator in the AOS Technical Building. The signals are digitized at the antennas by high-speed analogue to digital converters (ADCs) before being transmitted on optic fiber cables. An ADC samples the incoming signal 4 billion times per second and delivers a digital output giving the strength of the signal as one of eight levels, encoded in three bits. The ADCs utilize 0.25 µm chip technology developed by STMicroelectronics.[10] Alain Baudry, of the University of Bordeaux, led the team that developed these ADCs, under contract from ESO.

Correlators – The soul of a radio interferometer is its correlator. ALMA has two correlators,[11] a large one for the array of 12 m antennas and another for the ACA, now named the Morita Array.[12] The purpose of the two correlators is the same but their architectures are different. The correlator for the large array is of a conventional architecture whereby signals from all possible pairs of antennas are multiplied ("correlated") to calculate what are called "visibilities." A mathematical operation called a Fourier Transform, performed later in another computer, then produces an image from the visibilities of the object that was

Figure 9.11 View along the rack fronts of one quadrant of the correlator for the 12 m antenna array, located in the ALMA Technical Building at 5,000 m above sea level. Credit: ALMA/ESO/AUI/NINS, CC BY 4.0.

observed by incorporating information about their amplitudes and phases. The correlator for the Morita Array performs these functions in the reverse order, Fourier transforming the data streams before correlation. The Morita Array correlator[13] was designed and built by the Fujitsu Corporation in cooperation with the NAOJ.

The correlators operate at blinding speed. For example, the large array of 50 antennas has 1,225 unique pairs for which the visibilities are calculated by the correlator billions of times per second. The correlator can be considered to be a supercomputer, capable of ~100 trillion arithmetical calculations per second, but it is a very single-minded supercomputer, only capable of this one function. It contains 135,000 integrated circuits on 3,000 printed circuit cards. These consume about 150 kW of power. The heat generated is dissipated by chilled air circulating through the electronics. A supply of spare integrated circuits is available to replace failed units. There are plans to build a new, even more, capable correlator in the coming years.

The correlator[14] for the large array of 12 m antennas was built in the NRAO Central Development Laboratory. It was designed by Ray Escoffier and the project was managed by John Webber as head of the laboratory. The correlator was built in four sections or quadrants, each delivered in succession to the AOS Technical Building and installed by a team led by Rich Lacasse. The first quadrant is shown in Figure 9.11. It was the only major ALMA deliverable to be completed at a cost below the original budgeted amount.

Software

One of ALMA's major software packages is a real-time operating system that controls the array. Large projects often experience cost overruns and delays to completion with their software requirements. This was not the case with ALMA, where the software deliverables only needed a modest budget increase of nine percent to meet their deadlines. Of course, software is never really finished. As the real-time system began to be used, bugs were subsequently revealed and repaired. The rate at which bugs appeared tapered off in time, but improvements to the system continue. The Computing IPT was led by Brian Glendenning. Any of a number of data reduction applications may be used to process ALMA data and produce images. The Common Astronomy Software Applications (CASA) package is one. AIPS, GIPSY, and MIRIAD are other examples. CASA, developed by NRAO, was chosen for the ALMA data reduction pipeline (and for other radio telescope pipelines as well). The pipeline processes

ALMA data automatically, producing so-called reference images that are available via the ALMA Science Archive (ASA). These can be analyzed and published as is, or processed further by the user.

Local Benefits of ALMA

Under the terms of the concession agreement with the government of Chile, ALMA pays for the use of its site. There are three annual payments to make: one to Bienes Nacionales (BN) for rental of the access road, one to CONICYT (now Agencia Nacional de Investigación y Dessarollo, or ANID) for the development of astronomy in Chile, and one to Region II for the benefit of the local communities, principally, the village of San Pedro de Atacama, which includes several other villages in its governance. The average annual amount since the first payments in 2004 is a total of roughly $1 million, divided roughly in half for ANID with the remainder split between BN and Region II. The funds paid to ANID, together with the 10 percent share of observing time on ALMA, along with similar arrangements with the large optical observatories in Chile, have had a profound effect on the Chilean astronomical community. Astronomy departments are now flourishing at universities throughout Chile. ALMA maintains close contact with this community, teaching courses, organizing scientific meetings, and, up to the time of this book, welcoming over 100 interns and postdocs to activities at the JAO headquarters in Santiago. In addition, ALMA has reinforced the education of a larger cadre of technically savvy engineers and astronomers. Although the payments were requirements that emerged from lengthy negotiations for access to the ALMA site, it has been gratifying to see the positive results of the investments. A supportive local community is a great benefit to ALMA.

The ALMA Region II Fund supports social and economic development in San Pedro de Atacama and its sister communities. Projects to be funded are selected by a panel that reviews all submitted proposals. The panel members are the Governor of Region II, the Regional Secretary of Social Development and Family, the Mayor of San Pedro de Atacama, and the President of the Atacameño Community of Toconao. Projects that have been funded range from the small, a tourist map, to the large, equipping a first-aid and dental health center. Science education in the local community is a priority for ALMA. Volunteer time together with funding for teachers and physical improvements to the schools in Toconao have raised the students' scores in national standardized tests. The school in this small, remote village has ranked in the top 100 in Chile. Plans are being made for a science museum in San Pedro de Atacama with a planetarium.

Figure 9.12 The Estancia Barrio ranch has been restored as a museum by ALMA. It lies above the OSF in the elevation band that supports vegetation. Credit: Carlos Padilla; ALMA/ESO/AUI/NINS, CC BY 4.0.

Respect for the local culture has been a hallmark of ALMA's relations with its community. Care has been taken to include religious leaders, officials, and prominent citizens in important events. ALMA has also helped in the preservation of Atacameño's cultural heritage. Working with the Chilean Museum of Pre-Columbian Art, ALMA is investigating the origin and purpose of the "Saywas," archeological mounds of stone that may possibly predict astronomical events through the shadows they project as the sun rises. Figure 9.12 shows the restoration of an "Estancia," a shelter used by local shepherds who grazed animals in the area. It lies in the zone of vegetation above the OSF where the dew is sufficient to support plant growth.

The *Universe of Our Elders* is a 19-page preview[15] of a book to be published on conclusion of a joint ethno-astronomy study conducted by the Universidad Católica del Norte, the Archeological Museum Le Paige in San Pedro de Atacama, and ALMA. The goal of the project is to recover the vision of the Universe held by the inhabitants of the valleys and salt flats below the Andes from San Pedro de Atacama to Ollagüe on the Bolivian border.

Figure 9.13 Chilean President Sebastián Piñera (left) speaking at the ALMA inauguration after being introduced by ALMA Director Thijs de Graauw (right). The screen shows astronomer Antonio Hales on the high site waiting for the command to put the array in motion and begin ALMA operations. Credit: ESO, CC BY 4.0.

Inauguration

ALMA construction was completed on schedule and in time for its inauguration on 13 March 2013. It was a grand affair held at the OSF and attended by more than 500 guests. The guest of honor was Sebastián Piñera, President of Chile, shown while giving his speech in Figure 9.13. In his remarks he said:

> *One of our many natural resources is Chile's spectacular night sky. I believe that science has been a vital contributor to the development of Chile in recent years. I am very proud of our international collaborations in astronomy, of which ALMA is the latest, and biggest outcome.*

After his address, President Piñera ordered the start of ALMA operations by signaling via direct video link to ALMA scientist Antonio Hales, who was on the high site. Upon getting the green light, Hales contacted the ALMA Control Room via radio and requested that the array be set in motion, pointing the antennas to the center of the Milky Way, all to the theme music from *Cinema Paradiso*. It brought tears to some eyes.

There were many other dignitaries in attendance, including Jorge Molina Cárcamo, the governor of Region II at the time of the negotiations for the ALMA site, and Sandra Berna, the mayor of San Pedro de Atacama. The inauguration posed some vexing protocol issues, but such matters are all in a day's work for ESO which solved them in time for the event. One concerned the flags that fly in front of the OSF Technical Building. It was important that they all be of the same size. Massimo Tarenghi managed to locate and buy them in time. There was also an issue with Taiwan, which Chile does not recognize. The Taiwanese flag was not flown, given the many official Chilean government representatives.

A distinguished attendee of no political office, but held in high esteem by the many astronomers who had come to San Pedro de Atacama over the years, was Tomás Pobleta Alay ("Don Tomás"). His hotel, La Casa de Don Tomás, had hosted astronomical visitors for over twenty years, among them those coming for ALMA and APEX, the Submillimeter Receiver Laboratory group at the Harvard CfA, the Princeton University and Caltech groups studying the cosmic background radiation, and the Cornell University group looking to build a submillimeter telescope on Cerro Chajnantor. Don Tomás was more than welcoming, often entertaining guests at his home. At the

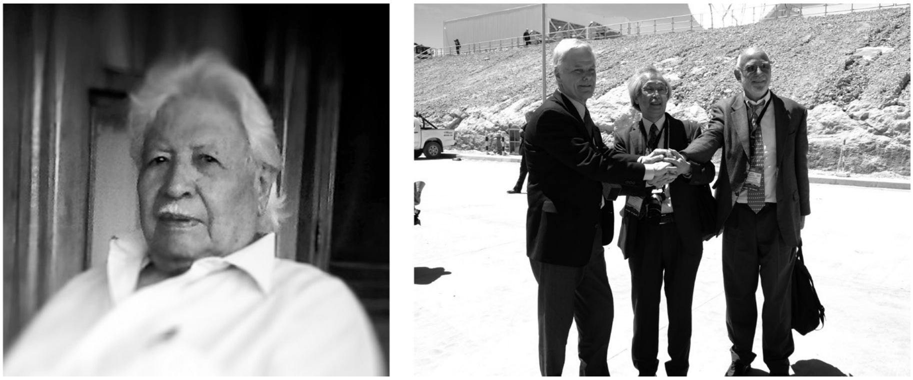

Figure 9.14 Left panel: Tomás Pobleta Alay, owner of La Casa de Don Tomás and friend of astronomy. Right panel: A three-way handshake at the ALMA Inauguration. Left to right: Dick Kurz, Masato Ishiguro, and Bob Brown. All three were critical to the establishment of the division of effort among the ALMA partners in the Bilateral and Trilateral ALMA Agreements. They also played important roles in their own communities – Europe, Japan, and North America – in furthering ALMA and managing the project. Credits: (Left) Paul Vanden Bout; NRAO/AUI/NSF, CC BY 3.0; and (Right) Courtesy of Tetsuo Hasegawa, reproduced by permission.

inauguration, he was eager to shake hands with the President, with whom he shared political views. Figure 9.14 shows a portrait of Don Tomás in the left panel.

And there were those at the inauguration who had conceived, promoted, sought funding for, and built ALMA over decades. For them, it was the realization of a dream and a highly emotional event. Figure 9.14, in the right panel, shows three of these individuals, the project managers/directors from the three ALMA Executives in a three-way handshake.

Notes

1 A summary technical description of ALMA can be found in Wootten and Thompson (2009). See also Iguchi et al. (2009) for a description of the ALMA Compact Array (ACA).

2 The full text of Giacconi's speech can be found at: https://library.nrao.edu/public/memos/alma/misc/ALMAU_3.pdf.

3 The contract from Santiago to FIU was made in agreement with AURA, taking advantage of their established path pertaining to optical telescope initiatives – present, and future – in Chile. Data transport via FIU is coordinated by NSF initiatives known as AmPath and AmLight.

4 To see an antenna transporter in action, watch the videos The ALMA Transporter Garage, www.youtube.com/watch?v=DBu9k1eq4HU, and Hauling an ALMA Telescope, www.youtube.com/watch?v=Ss0bxoLsOUs.

5 The section of the ALMA Operations Plan describing the *Sistema de Turno* in more detail can be found at: https://safe.nrao.edu/wiki/pub/ALMA/ARCinCSVrules/ARCinCSV.pdf.

6 Invar is an alloy of 36 percent nickel and 64 percent iron that is known for its low linear coefficient of thermal expansion. It has about 10 times less linear thermal expansion per degree Celsius than steel. Invar stands for invariable, in reference to this quality. The Invar cone in the Vertex antennas helps shield the reflector BUS from thermal distortions in the receiver cabin.

7 The Jansky is defined as 10^{-26} W m^{-2} Hz^{-1}.

8 The European Microwave Association awarded Pospieszalski its Pioneer Award in recognition of the impact his HEMT model has had on the field of microwave engineering.

9 ALMA's photonic local oscillator system is described by Shillue et al. (2012).

10 A technical description of the ALMA ADCs has been given by Recoquillon et al., in ALMA Memo #532 https://library.nrao.edu/public/memos/alma/memo532.pdf.

11 The performance highlights of the two ALMA correlators are discussed by Baudry et al. (2012).

12 The Morita Array is named for Koh-Ichiro Morita, a distinguished Japanese scientist and JAO staff member who tragically died from a head injury received during a mugging near his home in Santiago on 12 May 2012.

13 A technical description of the Morita Array correlator was given by Abe, Tsutsumi, and Hiyama (2014).

14 A technical description of the ALMA large array correlator was given by Escoffier et al. (2007).

15 The preview of *The Universe of Our Elders* can be found at: https://almaobservatory.org/wp-content/uploads/2016/11/alma-etno_2013.pdf

See also a brochure (in Spanish) describing the ALMA Fund at: www.almaobservatory.org/wp-content/uploads/2022/07/Informativo-Fondos-ALMA-2022.pdf.