Installation and Verification of High Precision Mechanics in Concrete Structures at the Example of ALMA Antenna Interfaces

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Abstract

For the ALMA interferometer at the array operation facility near San Pedro de Atacama at 5.000 meters asl 192 concrete antenna foundations had to be equipped with coupling points for 66 antennas. These antennas will be frequently moved between the foundations and placed on these interfaces without further adjustment.

To position the ALMA antennas with the required accuracy, high precision inserts need to be installed in previously casted concrete foundations. Very tight mechanical tolerances have to be applied to civil structures, with standard tolerances of not less than millimeters. This is extremely difficult considering the material (mortar and steel in a concrete slab) to be used and the environmental conditions on site. Special tools had to be designed and an installation and alignment procedure developed, tested and improved. Important was to have a robust process, which allows highest precision installation without major re-machining for approx 600 interface blocks. Installation material, which could cope with the conditions, was specially tested for these requirements.

The geometry of the interface and other parameters such as horizontal and vertical stiffness must be verified after the installation. Special metrology tools to measure reliable at micron level at high altitude had been selected.

The experience and knowledge acquired will be beneficial for the installation of any opto-mechanical device in civil engineering structures, such as telescope and dome track rails, but also in optical interferometer installations. Metrology requirements and environmental conditions in most of these cases are equally challenging.

Keywords: telescope foundation, high altitude, high precision installation, precision metrology equipment, opto-mechanical interfaces

Introduction

To install telescopes and their subsystems, civil structures mainly foundations need to be erected first. On and in these high precision interfaces are installed to mount the opto-mechanical systems. It can be distinguished between open and enclosed interfaces, although their installation appears mostly in the open air. For large telescopes the interface to the concrete peer often is the Azimuth track, which can either serve as base for a hydrostatic bearing, but can also be a track for a roller type bearing. For smaller, especially mobile telescopes, this interface often is designed as a kinematic mount with clamping facilities. A general description of these interfaces and their installation and verification shall be the topic of this manuscript. At the example of the installation of the foundation inserts for the ALMA antenna at the Array observation site the process will be explained.

The Atacama Large Millimeter/Sub millimeter Array (ALMA) is an advanced instrument with a 54 plus 12-antenna interferometer array. The ALMA Array Operation Site (AOS) will be sited in the Altiplano of northern Chile at an elevation of 5.000 meters (16,500 feet) above sea level and the ALMA Operations Support Facility (OSF) will be sited at an elevation of 2.900 meters (9,600 feet) above sea level in the vicinity of the AOS site near the village of San Pedro de

Atacama in the Second Region of the Republic of Chile in South America. The ALMA AOS site is the highest, permanent, astronomical observing site in the world.

As an engineering project, ALMA is a collection of 54 plus 12 precisely-tuned mechanical structures each weighing more than 100 tons, cryogenically cooled super conducting electronics, and optical transmission of data at terabit rates-all operating together and continuously. Antennas will be transported between foundations regularly. 192 foundations will be built for the 50 antennas of the main array and the 16 antennas of the compact array. Each foundation consists of a concrete pad with recesses for the precision antenna interfaces. The high precision inserts for the antenna interfaces will be mounted after the concrete pad has cured. Creep and settling of the concrete prevents high precision alignment and installation for 6 months after casting.

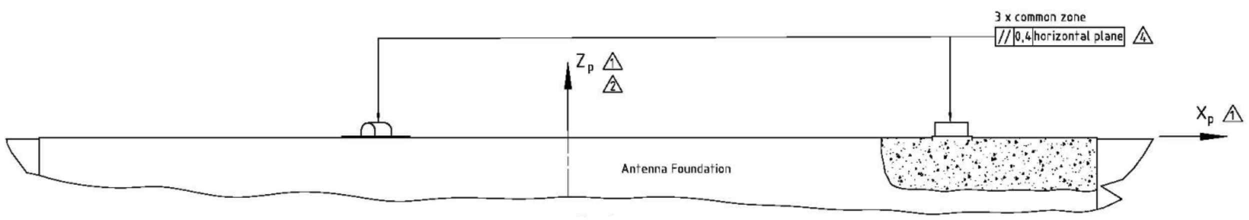
For assembly and technical commissioning of the antennas also in the base camp area 11 antenna stations are installed.

ALMA Antenna Interface Design

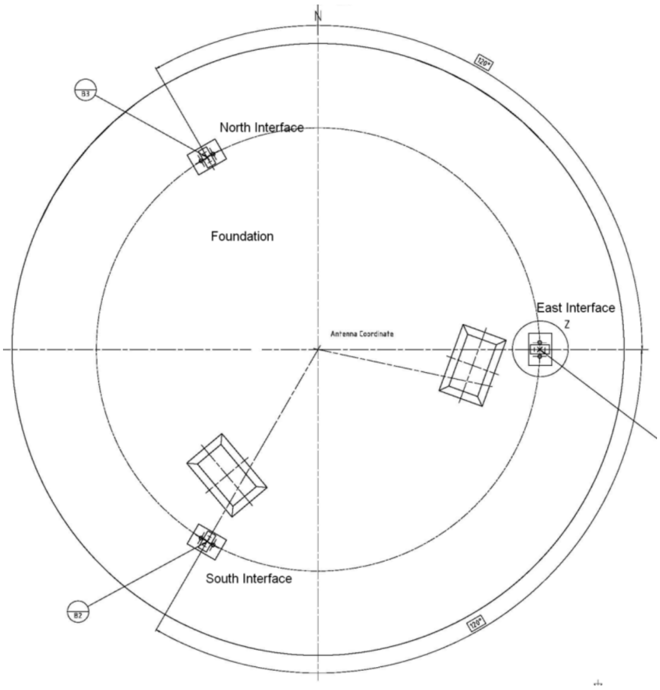
The interface between the ALMA antenna and its foundation consists of three steel blocks, embedded with high precision into recesses of a previously casted concrete slab. It works as kinematic mount in Y- shape, which allows mounting the antenna in different thermal state.

Based on the following requirements the detailed design of the anchoring system was developed:

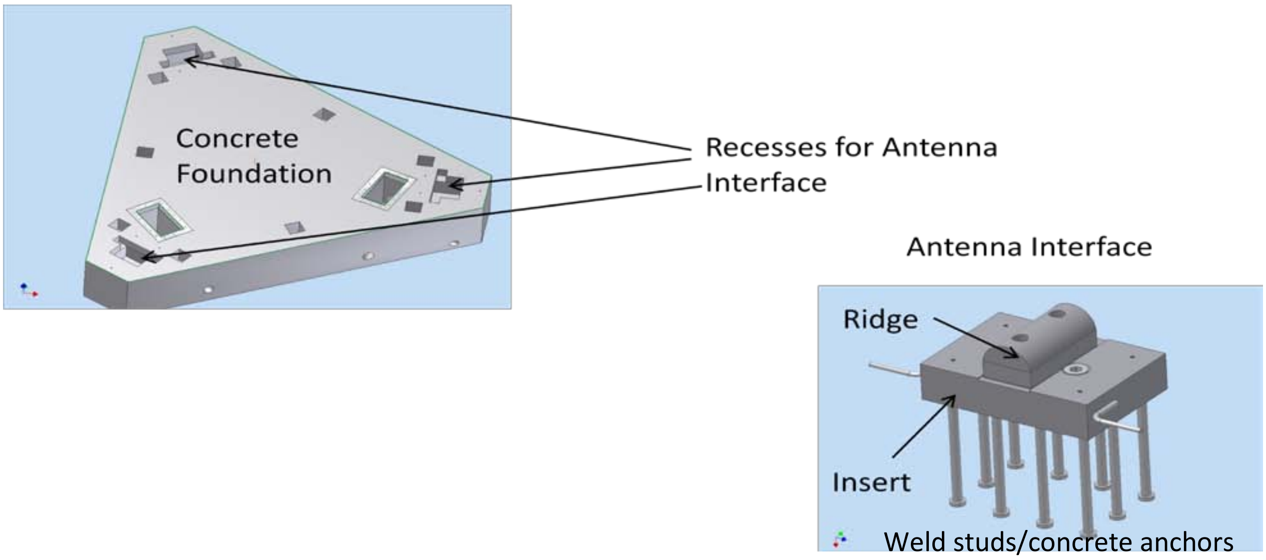
Requirement	Value/Tolerance
Global position of interface center in the array	Circle of ∅50 mm in the closest configuration of the array
Rotation of interface against Astronomical North	0.2 Degree
Horizontality of interface/verticality of the Az axis	Local horizontal plane with 0.4 mm tilt/± 10”
Local Tilt of interface block	100 µm/meter



1 Interface Section View



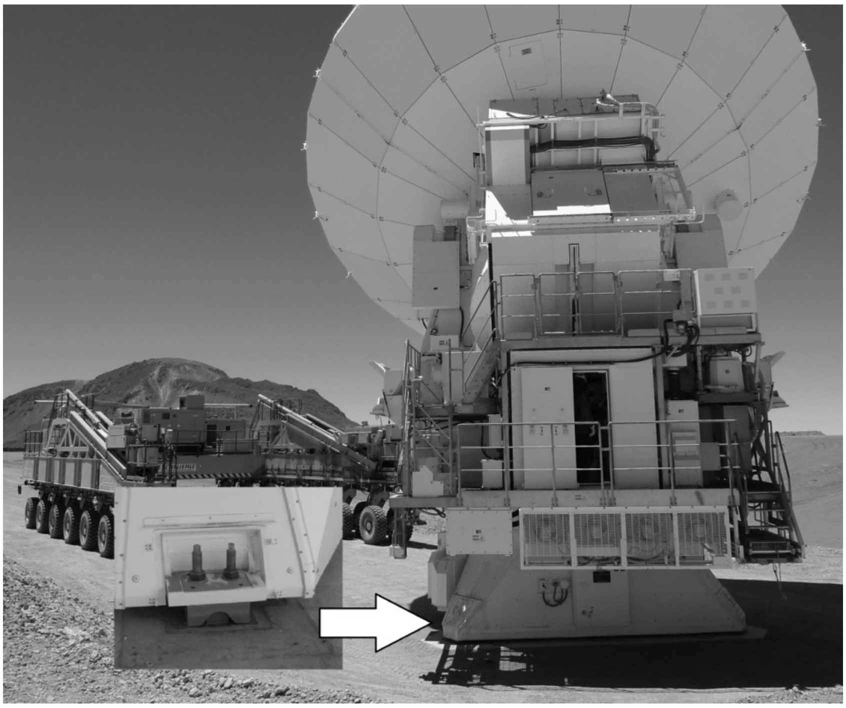
2 Top view of the foundation interface



1 Foundation Recesses and Steel Inserts with Interfaces

For embedding the three inserts into the recesses of the concrete slab, they need to be positioned and aligned. Once having the steel blocks stable in place, the recess is being filled with mortar, a grout material of either cementitious or Epoxy base. To achieve the required position accuracy, stability and verticality of the Azimuth Axis of the antenna on the foundation, tight tolerances must be applied. For each individual insert block the local tilt with respect to the normal horizontal plane is 100 micron/meter. The plane defined by the three interface blocks must be parallel to the normal horizontal within 400 micron. As a fallback solution if the alignment goal could not be reached, the possibility for rectification was foreseen. The upper part of the interface, the ridge, can be removed from the insert and be machined on a mill or flat bed grinder.

For the installation of the antenna on the pad it is important to have also the embedded insert in the correct position and orientation

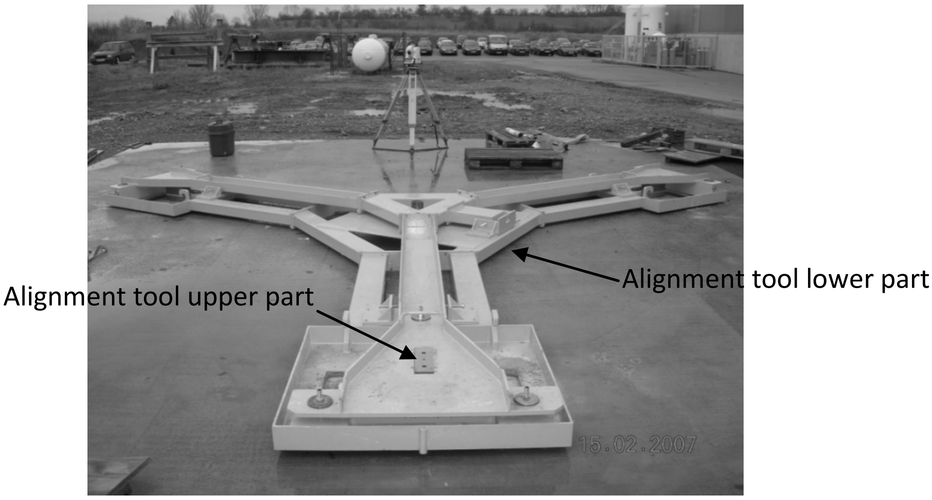


2 Antenna Installed on foundation with Interface detail

Tools and Materials

Alignment and Installation Tool

To meet the design requirements for positioning and alignment accuracy an interface alignment tool was designed. The structure consists of two parts, upper and lower half. While the lower part is fixed to the concrete with anchor bolts, the upper part, which carries the inserts and ridges during adjustment and holds them during grout curing, is used to fine adjust the interface to the correct position (center and North are marked on the foundation), and finally the height of the three inserts within 400 micron and the local tilt of 100 micron/meter of each embedded plate are adjusted. The advantage of this tool is that with its lateral stiffness the position of the three inserts relative to each other is well defined and fixed. No care needs to be taken to align the plates wrt each other. As the ridge, which defines the interface with the antenna has a rotational degree of freedom, the angular adjustment of the inserts is not critical and can be performed visually. Before moving to Chile with the equipment, a procedure was developed and tested during a trial installation in Germany.



3 Interface Alignment Tool

As the installation sequence per pad was estimated with 4 days with only one tool the pure installation time would be 2 ½ years, not considering rest and bad weather periods. Therefore three tools were built.

Metrology tools

Not only for the installation of the interfaces were metrology tools required but also for the verification of the installation result and other parameters, such as the stiffness of the whole foundation. For the geometrical measurements and verification the following equipment was used.

1. Industrial Total Station

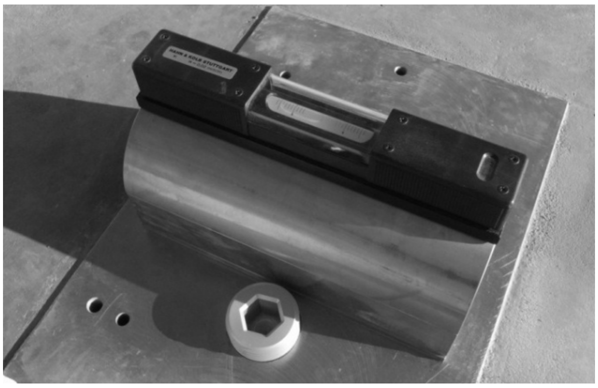
The main metrology tool is a Leica industrial total station, similar to a theodolite, but with an additional distance measurement and therefore a full 3D coordinate measuring system. It fulfills the necessary accuracy requirements for the tight installation tolerances, is robust enough for the harsh outdoor use under extreme conditions (low temperature, humidity, dust). In addition this instrument allows creating local coordinate systems, and measure positions within these coordinates, a function, which was used in part of the array where the absolute position tolerance for the interface center was a circle of 5o mm.

Angular measurement
Standard deviation
per ISO17123-3, 1 ʃ 1) 0.5“ (0.15 mgon)
Units of measurement 360° sexagesimal, 400 gon
360° decimal, 6400 mil
Data storage and interfaces
PCMCIA memory card
RS232 programmable interface
Motor and fine drives
Fine drives Coarse/fine, motorised, infinite,
slip coupling
Motor
Speed of rotation 45 °/s (50 gon/s)
Positioning accuracy 0.8” (0.2 mgon)
Temperature range
Working –20° C to +50° C (–4° F to +122° F)
Storage –40° C to +70° C (–40° F to +158° F)
Point accuracy (total RMS H***1 ʃ) 2)*** δ 0.3 mm (0.012”)
at 20 m (65 ft) measuring volume
Distance measurement *(integrated in the TDM5005 and TDA5005)*
Standard deviation (absolute) 1 mm + 2 ppm (0.04” + 2 ppm)
per ISO17123-4, 1 ʃ over the entire measurement range
Typical distance accuracy
at 120 m (365 ft) measuring volume3)
Reflective tape ± 0.5 mm (0.02”)
Corner cube reflector ± 0.2 mm (0.008”)
Units of measurement m, mm, feet, inch
Display 0–5 decimal places, dependent
(smallest selectable unit) on the selected unit
Reflectors (selectable) Prisms, Corner Cube Reflectors CCR
(1.5“ diameter), Leica reflective
tapes, 360° prisms
Measurement range with CCR
(dependent on atmospheric conditions) 2 to 600 m (6 to 1’900 ft)
Measurement range with reflective tapes
(dependent on target size) 2 to 180 m (6 to 600 ft)
ATR – Automatic Target Recognition *Integrated in the TDA5005*
Tracking speed lateral (linear) 3 m/s (10 ft/s)

[1]

2. Precision Water Level

To measure the local tilt a high precision tooling water level, normally used for alignment of precision machine tool and turbine shafts, is being used:

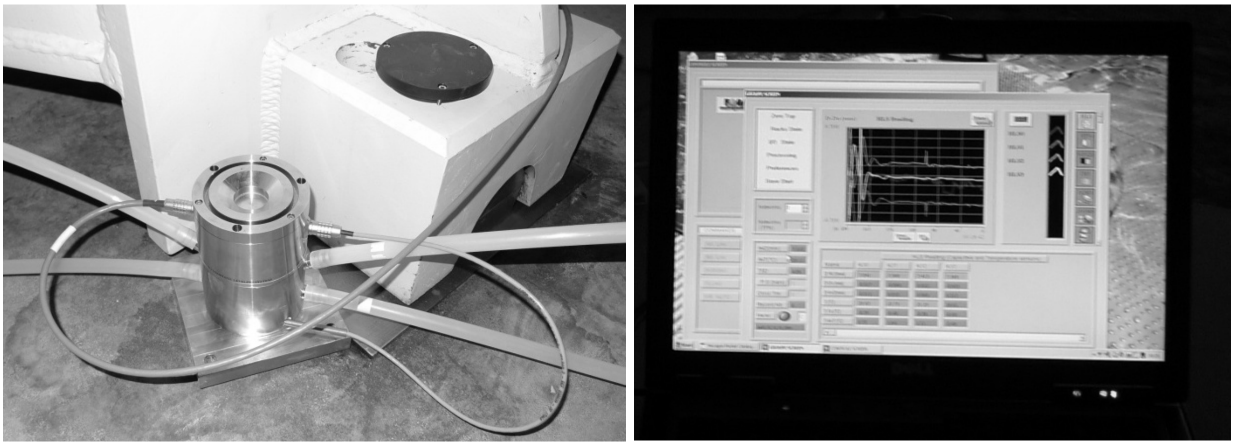


With a resolution of 20 micron/meter sufficient accuracy of the instrument is assured to verify the tight tolerances of the ALMA installation. However this tool normally is used in a stable and temperature controlled environment. When used at the construction site for installation and verification utmost precaution had to be applied.

3. Hydrostatic Leveling System

For the stiffness verification a precision hydrostatic level system was applied (see chapter Quality Control and Verification. This tool consists of 4 small vessels with capacitive sensors on top, which are interconnected by hoses. With the sensors level differences in the micron range can be measured, the signals are converted in an electronics rack and via RS232 interface transmitted to a laptop with the measurement software.

- Global accuracy: 5 µm
- Repeatability: 2 micron
- Range: 5 mm



4 Hydrostatic Level Sensor and Control Screen

4. Laser Detector (Laser Trac™)

To measure small movements without mechanical contact a laser detector was used. This laser with a CCD allows to measure movements of several microns, however this instrument is extremely sensitive to sun and wind exposure and therefore best results for outdoor measurements can only be achieved during night time.

5 Laser Detector CCD installed on Interface block

Materials used

To embed the steel insert in the concrete foundation recess, a non shrinking mortar must be used. Two types of this material (grout) were available.

- Cement Based
- Epoxy Type Grout

The cement based grout has the following properties

+ Cheap
+ Easy to process
+ Higher Young Modulus
+ Can be installed at low temperatures, and material does not need to be prepared
– Longer curing time
– Higher tendency for cracking

While the Epoxy material has the following properties

+ Fast curing
+ No cracking, higher positive expansion
+ Higher probability of failsafe installation
– More expensive
– Material must be preconditioned before application
– Young modulus too low

After using cementitious grout for all foundations in the base camp area, a test installation at the high site has shown that Epoxy grout is necessary as the faster curing time has great advantages for the stability of the aligned setup and therefore direct proportional better installation results, which lead to the avoidance of rectification.

Although the nominal compression modulus (Young's modulus) of the product "Five Star DP Epoxy grout" is too low, an independent test [2] had shown that the material reaches our specifications to 90% for the compression modulus. This was approved by the ALMA project and the decision was taken to use mostly Epoxy grout Five Star DP. Only during the summer period with higher temperatures, less problematic to reach the specified tolerance, cement grout was used to reduce installation costs, in about 30% of the foundations.

On the cost side, the ratio between Cement based material and Epoxy is approximately a factor of 7. However considering the high installation manpower cost per day, it is definitely worth to safe the time due to faster curing, which justifies the higher material expenses. The additional benefit is the better accuracy achieved with Epoxy material, which saves the rectification costs and such very expensive machine hours in a precision workshop.

Special Conditions and Challenges of the ALMA Antenna Mechanical Interface Installation

To apply grout some basic thermal requirements must be fulfilled, a temperature level of minimum 13 Deg C must be maintained over at least 24 hours to allow a successful installation. High precision installations however require even more stable conditions and thermal control. The tolerances given for this installation can normally only be achieved under indoor and controlled conditions. Certainly temperature variations of up to 20 degrees during the alignment and curing process do not allow installations at micron level. Therefore it was necessary to assure the maximum stability. This could be achieved by designing a protected environment (thermally insulated shelters) and thermal control to the maximum extent possible. This was implemented at the Llano de Chajnantor at more than 5.000 meter asl and severe conditions like cold nights, strong radiation during daytime and heavy winds together with precipitation, mostly as snowfall. This thermal control is part of a specially developed and strictly followed installation procedure, which was first tested under normal conditions and by first experience adapted to the special requirements of a high altitude work site.

6 thermal shelter for the insert installation

As the following photo shows, building thermal shelters alone is not sufficient, also heating systems need to be installed to maintain a controlled environment. This includes power reliable power generation at 5.100 meters.

9 thermal shelter with alignment tool covered with snow

The diameter of the three insert center points from the center of the tool is approximately 6 meters. Considering a delta T of 20 deg C during the curing time of the grout for the inserts will cause a thermal expansion/shrinkage of 10^{-5} m/(m*deg)*20 deg*6 meter= 1.2 mm. This thermal deformation applied to a structure fixed to the concrete pad will cause buckling, which does not allow achieving the required installation tolerance. Goal was to reduce this effect as much as possible by maintaining the temperature inside the shelter during the 24 h curing period of the grout as stable as possible. As only limited active temperature control was possible through the thermometers of electrical heaters, a great part of the alignment success depended on the experience of the site staff.

Quality Control Verification of the Installation

Regular Inspection of Instruments

Crucial for the high precision installation is the reliable measurement of the total station, which was used at the limits of its accuracy. Despite the high efforts a yearly re-certification was executed at the manufacturer's premises.

Not resulting in a formal certificate but giving a reliable re-calibration was the regular adjustment of the precision water level on a plane surface.

Due to limited usage and high complexity of re-calibrating for the further precision metrology equipment this service was not executed during the 2 years of its usage. However one sensor of the Hydrostatic leveling system had to be sent to the manufacturer after measuring results were in doubt.

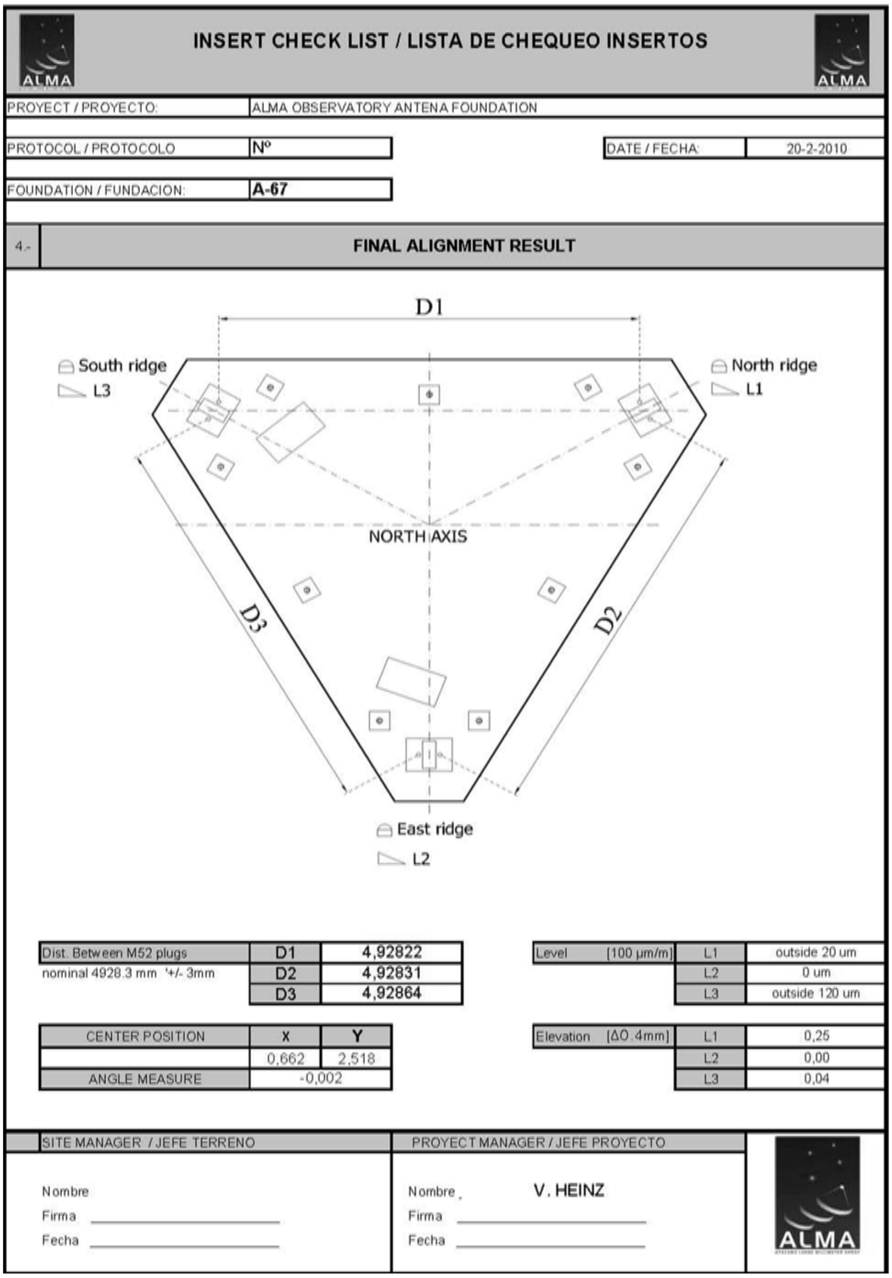
Documentation archiving, CIDL

All project documentation was properly archived and logically structured. For redundancy purposes and general access the storage and release process was organized as follows:

During execution of work and before final acceptance of the installation, local copies and a backup on a shared drive were used to save the documents, once released for general access the package was uploaded to the ALMA documentation server. The complete documentation and its configuration control was handled through a Configuration Item Data List (CIDL)

Verification measurements and protocols

To hand over the installation to the ALMA project verification measurements were executed and registered. These protocols, part of the data package, contain the checklist for the correct and complete installation, the geometrical measurement values, and temperature logs for each individual foundation.



INSERT CHECK LIST / LISTA DE CHEQUEO INSERTOS

PROYECT / PROYECTO:	ALMA OBSERVATORY ANTENA FOUNDATION
PROTOCOL / PROTOCOLO	Nº
DATE / FECHA:	20-2-2010
FOUNDATION / FUNDACION:	A-67

4.- FINAL ALIGNMENT RESULT

Dist. Between M52 plugs	D1	4,92822
nominal 4928.3 mm '+/- 3mm	D2	4,92831
	D3	4,92864

Level [100 µm/m]	L1	outside 20 um
	L2	0 um
	L3	outside 120 um

CENTER POSITION	X	Y
	0,662	2,518
ANGLE MEASURE	-0,002	

Elevation [ΔO.4mm]	L1	0,25
	L2	0,00
	L3	0,04

SITE MANAGER / JEFE TERRENO	PROYECT MANAGER / JEFE PROYECTO
Nombre	Nombre V. HEINZ
Firma	Firma
Fecha	Fecha

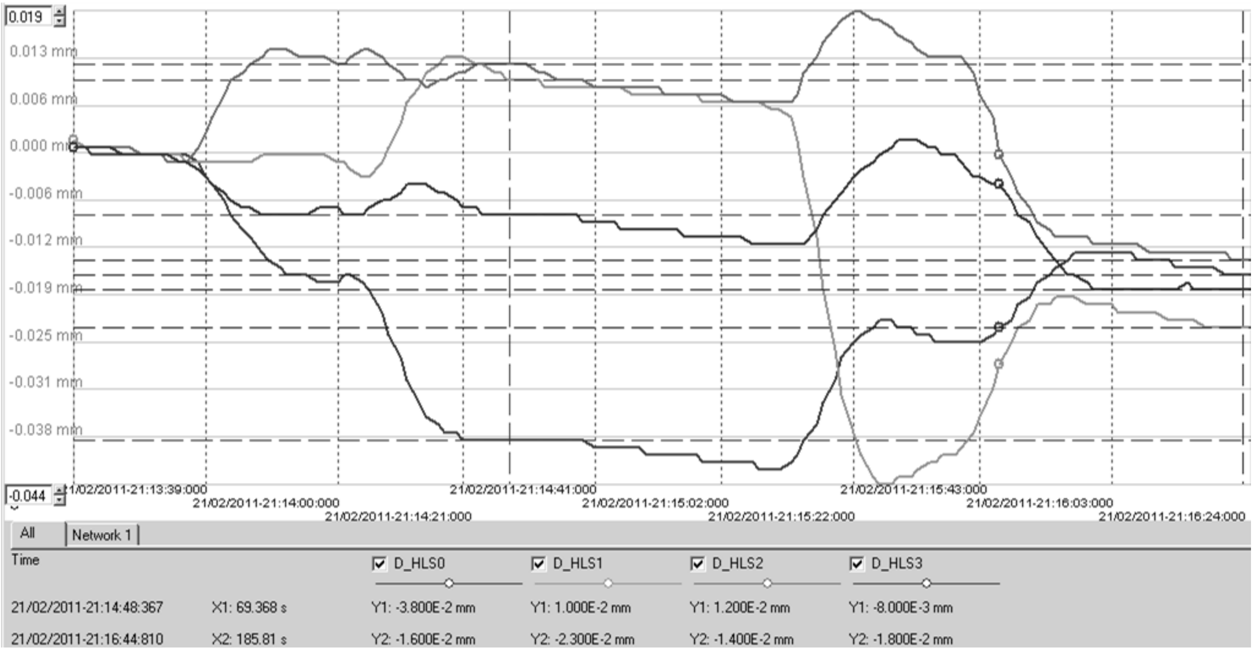
7 Extract from verification protocol

Stiffness tests of whole foundations

One important requirement for the finished antenna foundation is the stiffness, which has a direct impact on the eigen-frequency of the antenna system and thus its performance. To verify compliance a complete test for vertical and lateral stiffness was developed and executed. For this test it was necessary to load the foundation with a load as big as possible and to measure the deflection. This was achieved by loading the foundation with a dummy mass, which was also used to test the antenna transporter and which represents an exact antenna interface with the antenna weight. For the measurement two systems were used, the hydrostatic level and the laser detector. For vertical movements the high precision level has proven to be most suitable. With its accuracy it was sufficiently precise possible to measure the expected movement of 35 micrometer. One reference sensor was installed as far away as possible from the foundation and the other three were connected to the antenna. While lowering down and lifting the dummy the relative movement between reference and foundation sensors, was recorded. Due to the sensitivity of the system it is very susceptible to temperature drifts, which can easily be eliminated from the measurement result, because tests have shown that they are very similar for all sensors

8 Antenna dummy before lowering down on foundation with Sensors installed

The results of various tests had shown that the foundations did not reach the specified stiffness of 13 GN/m. As a consequence of this result the soil was analyzed and The actual soil stiffness was much lower than assumed in the FE analysis. With the new value for the soil stiffness the measured values could be confirmed with the CAD/FEM model.



Typical Hydrostatic Level Data Record

Other precision interfaces for Telescopes and their Subsystems

Paranal Unit Telescope tracks

9Telescope Azimuth Track with Hydrostatic Bearing

AT plate mounts

10 Paranl Auxiliary Telescope Mounting Plate, Enclosure, Alignment tool

VLT Interferometer Delay Lines and Mirror Mounts

Summary

The outfitting of almost 200 antenna foundations for the ALMA project with antenna fixation and coupling devices had shown that with the correct preparation, procedures, strategies and equipment, very demanding alignment results under extremely severe environmental conditions can be achieved. The experience gained from this project is very valuable for further large astronomical installations. While the design of the antenna interface allows later rectification to reach the tolerance, other systems will not have the same possibility and the initial installation must be carried out with utmost precision to reach the tight tolerances required for opto-mechanical systems. Strict quality control and verification during installation are required to reach the alignment goal. The metrology equipment used for the ALMA foundations and the associated processes can easily be adapted to different interface installations with similar requirements and tolerances.

Lessons learned:
Do not underestimate extreme geographical and climatic conditions; the required time to achieve a good result is significantly longer than at lower altitude and decent temperature. Alignment work, having low and changing temperature and workers wearing thermal protection clothes, becomes much more difficult. All materials and equipment change properties and behavior under the Chajnantor conditions. Sufficient Instrument checks and calibration must be carried out to assure the required precision.

References

[1] Leica datasheet for the Industrial Total Station TDA 5005

[2] Dictuc Test results from the Five Star compression modulus qualification test