

Experience with the operation of the European ALMA antennas

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ABSTRACT

The 25 European antennas of ALMA were delivered by ESO to the ALMA project in Chile between April 2011 and September 2013. Their combined time of operation is already significant and allows us to draw conclusions regarding their ability to fulfil the original specification, in terms of both scientific performance and operational availability. In this paper, we will summarize the experience gained during the past five years of operation. We will characterize the performance of the antennas in routine operation and compare with the data obtained during acceptance testing. We will also describe the few technical issues experienced while operating at 5000m and the way in which these were treated during these first years of operation. We will evaluate the effective reliability obtained in service based on field data and draw some conclusions as to the way in which reliability and maintainability aspects were covered during the process which led to the final design of the antenna. We will discuss the smart use of software to handle redundancy in a flexible way and to exclude failed components without affecting overall antenna operability. The use of low-level diagnostics enabled by remote access allows us to shorten the trouble-shooting cycle and to optimise physical interventions on the antennas. Finally, the paper will cover Antenna maintenance manuals edited using an industrial interactive standard. It will be explained why this advanced and innovative concept has not achieved the success that was expected, and why the traditional form is preferred at the ALMA Observatory.

Keywords: European ALMA Antenna, performance, reliability, maintainability.

1. INTRODUCTION

25 high-precision 12 meters diameter antennas were assembled and commissioned at the Operation Support Facility of the ALMA Observatory in Chile by the AEM Consortium (Thales Alenia Space, France and Italy, European Industrial Engineering, Italy, MT-Mechatronics, Germany) between 2010 and 2013. After the commissioning, a formal Test Readiness Review was held to review the status of each antenna and to allow the start of the official acceptance testing phase. The acceptance testing phase has lasted a few months, per antenna, for the first three units, and it has progressively been shortened to a few weeks afterwards. Acceptance testing was based on a previously agreed verification program, in which achievement of performance had to be demonstrated starting from mechanical alignment and checks, proceeding to the functional verification of each individual subsystem. Once these were demonstrated, the verification of certain key performances associated to science requirements, like pointing and tracking on sky and measurement of the dish surface by means of holography scans followed.

The formal acceptance of the complete set of 25 antennas and their delivery to the ALMA Observatory took altogether approximately 30 months. While still in the process of accepting and delivering antennas to the observatory, in July 2011 the first unit was brought to the Array Operations Site (AOS) on the plane of Chajnantor^[1], located at 5000m above sea level. From that time on, there were antennas in the process of commissioning or acceptance testing in the AEM Consortium work area at the ALMA Operations Support Facility (OSF), at 3000m above sea level, other antennas were being equipped with front end and back end electronics at the OSF, and others were performing science observations in the harsh environment of the AOS. This event marked an important milestone for the ESO team in charge of the European Antenna construction and added a further step of complexity to the process of following-up the units in different stages of progress.

With antenna(s) at the plane of Chajnantor, it became soon clear that despite all reasonable effort during the lengthy and complex acceptance testing, there could be no substitution to the experience and validation which can be gained by

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operating in the real environmental and harsh conditions. Antennas at the AOS experience extreme (daily and seasonal) temperature variations, high wind and high solar radiation and finally reduced cooling due to low air pressure and density (50% of sea level). The effect of these extreme environmental conditions became evident in a short time and a few minor adjustment and retrofits were carried out. The ESO team made an effort in achieving the retrofitting of the antennas while still in the production process and as soon issues were discovered. This led to having antennas in various different design configurations and represented a major effort also on the side of the AEM Consortium, which showed a high level of cooperation on this matter.

The various retrofits and adjustments which proved necessary due to the extreme environment and also the long-term effects on the antenna will be described in details in Sections 4.1 and 4.2, respectively.

2. SPECIFICATIONS

2.1 Main Specifications

The specification of the ALMA antennas is rather comprehensive and is constituted by a compendium of interlinked requirement covering mechanical aspects, electrical aspects, safety, environmental conditions, interface requirements and operational requirements. For the purpose of this article we limit the discussion to two major sections.

(1) The first and most important section deals with all elements of performance directly or indirectly affecting the science capability of the ALMA interferometer, briefly called "system performance". It is crucial that these performances have to be obtained in the large range of environmental conditions typical of the Chilean desert at high altitude, and unusual for other observatories.

(2) The other relevant aspect for the present discussion is linked to the operability, availability and maintainability of the antennas, once again limited by the harsh conditions of the site.

Under point (1) we need to recall the following main specifications, to be fulfilled within the operating environmental conditions:

- Overall surface accuracy error: $< 25\mu\text{m}$ RSS (Root Sum Squared)
- Non repeatable Path Length error: $< 15\mu\text{m}$ RSS over three minutes
- Absolute Pointing error: < 2.0 arcsec
- Offset and tracking pointing errors: < 0.6 arcsec within 2 degrees and 15 minutes
- Fast switching error over 1.5 degree and 2.0 sec: < 0.6 arcsec
- On the fly mapping: scan at 0.05 deg/sec with error < 1.0 arcsec
- Solar observation capability

All these specifications, except the Path Length error, were individually tested on each antenna at the OSF at 3000m elevation above sea level. Some of those were confirmed at the AOS at 5000m as explained below. The Path Length error was only demonstrated in the framework of the acceptance of the first three units.

Under point (2) we need to recall the following requirements:

- System Level Mean Time Between Failure (MTBF): > 3 years
- Stability of Surface: to be maintained over 5 years, including transport

The specifications above are critical for the ALMA array, operating during day and night, always necessitating a minimum number of antennas operational, and with heavy limitations for human intervention at the antennas. Preventive and corrective interventions can only be performed during a limited number of hours per day and in good weather conditions. Readjustment of the primary reflector surface necessitates at the present time a relocation to the OSF where a holography transmitter and receiver is installed. Events of maintenance causing the relocation of the antenna from 5000m (AOS) to

3000m (OSF) have to be consider exceptional in nature due to the heavy cost and down time associated with such relocations.

3. SURFACE PERFORMANCE AT AOS

The main contributors to the surface accuracy are the primary reflector panel manufacturing and mounting accuracy, the gravity error caused by the changing elevation of the reflector, and the thermal deformation caused by change in the bulk temperature of the structure and the panels. Other elements also playing a role in the overall surface accuracy are the manufacturing and thermal errors in the subreflector, and ageing effects. One major unknown was represented by possible changes in the surface accuracy caused by the transport between 3000m and 5000m, the heavy temperature cycling experienced at the AOS and the change in atmospheric pressure. For the transport, all possible precautions were taken both in terms of damping the vehicle ("antenna transporter") to avoid shaking along the 35km mountain road and in terms of design of the panel supports ("panel adjusters") equipped with irreversible mechanisms to avoid any inadvertent movement. The panels, being constituted by closed electroformed panels glued on an Aluminium honeycomb were all equipped with a special Gore-Tex valve allowing equalization of inner and outer pressure.

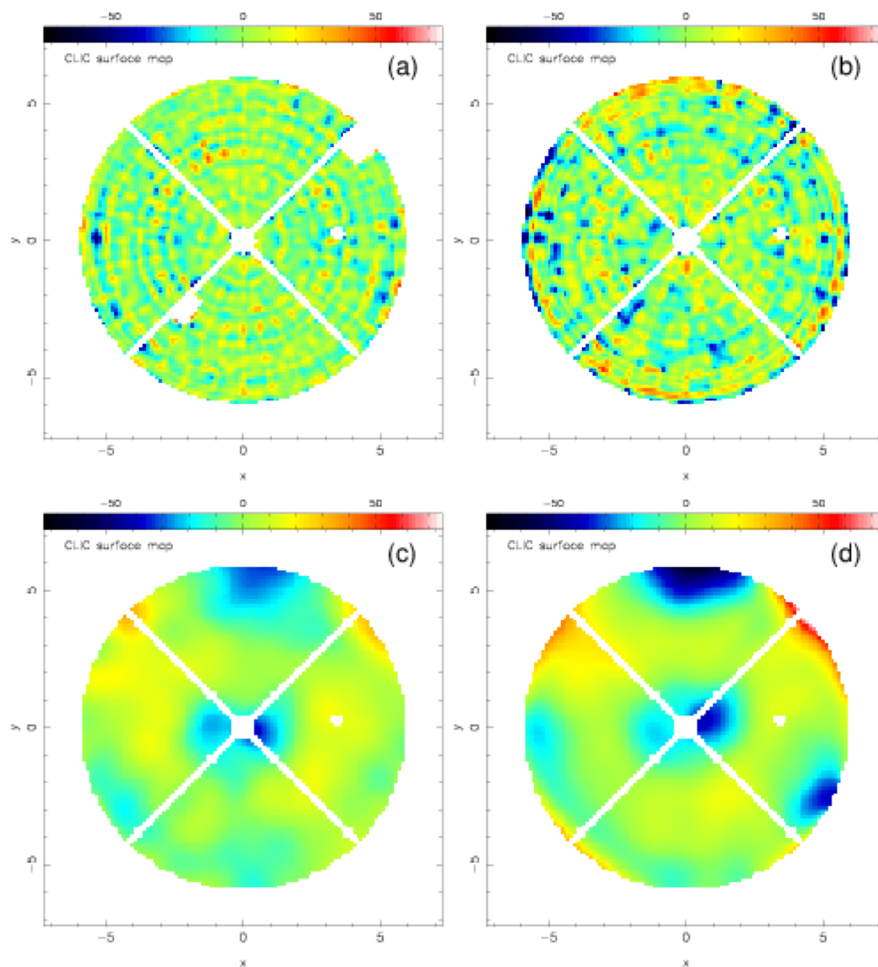


Figure 1: Surface maps derived from holography. (a) primary surface of DA41 after setting at the OSF. (b) as (a), but after two years of operation at the AOS (the same thermal and gravitational model has been applied in both cases). (c) Surface map of DA41 for the full optics (primary and secondary) derived from astrophotography at 230GHz. (d) as (c), but for antenna DA43.

The setting of the primary reflector is done using near-field holography^[2] at the OSF. A dual receiver with a reference horn operating at a frequency of 104 GHz is used and the measurement accuracy is specified to be $<10\mu\text{m}$ rms: in practice, measurement reproducibility was in the range 2 - 4 μm . An example of a measurement of the primary surface just after setting is shown in Fig. 1(a). The residual rms error is 10.9 μm . We have rather little evidence on the evolution of the small-scale surface errors with time, since very few antennas have been returned to OSF for tower holography so far. The best data are for the first antenna, DA41, where measurements after two years operation at AOS show only a slight degradation (to 13.7 μm ; Fig. 1b), primarily in the panel-scale structure. This would not be enough to take the entire optical system out of specification.

The technique used to measure the antenna surfaces at the AOS is interferometric holography^[3] or astrophotography, in which antennas are scanned in a raster or star pattern across a bright quasar, while one or more other elements of the array act as an amplitude and phase reference. This has the advantage that it tests the entire optical system over the full range of operational conditions, including temperature and elevation, but has limited spatial resolution ($\approx 1\text{m}$ on the primary surface). Examples of astrophotography surface maps are shown in Fig. 1(c) and (d). The measured rms errors are 11.3 and 13.1 μm , respectively. Even after allowing for the unmeasured small-scale surface errors, these antennas are both well within the 25 μm specification. Note, however, that the residual large-scale error patterns are very similar for these antennas. This is true in general for all of the European antennas, with a few having significantly worse residuals of the same general form. It seems likely that the consistent residual pattern results from the combination of an incorrect thermal bias introduced during the initial setting and an imperfectly known holography feed-horn correction. The errors are stable in time, temperature and elevation (at least to a first approximation), so the next step in optimization will be to correct the large-scale errors in the surface using astrophotography data from AOS.

4. OPERATIONAL ASPECTS

4.1 Retrofitting at 5000m caused by environmental conditions

Shortly after the first units were brought to the AOS at 5000m, a number of mostly minor issues were discovered. Various malfunctions occurred which could be easily solved by changing some parameter settings, fixed during commissioning, and by some initial retrofitting. The first two elements which demanded an investigation were:

- The setting of the thermostats in the electronic cabinets. These settings were intended to protect the equipment against under-temperature and over-temperature events. However, it was found out that the behaviour (hysteresis and set point offset) of the hardware at 5000m was sensibly different than at 3000m for reasons not completely understood. An offset was introduced in all protective thermostats to allow uninterrupted operation of the antennas, also in consideration of the seasonal changes experienced at the AOS.
- A problem of condensation in the electrical cabinet containing the controls of the drive system. This cabinet has a large horizontal exposed surface. We detected water condensation on the internal ceiling of the cabinet during the wettest months of the year, and also after snow had accumulated on the cabinet. The issue was cured with a retrofit improving the top thermal insulation of the cabinet. A first test version was implemented as a proof of concept, and later all antennas were retrofitted accordingly.

Temperature variations had also a number of undesired effects:

- The torque limiters protecting the elevation and Azimuth stow pin axes had to be retuned because at lower temperatures the systems were encountering a time out, due to the increased friction in the system.
- The alignment of the Hall sensors of the drive system had to be modified because of saturation issues caused by stronger magnetic field of drive magnets at the low temperatures of AOS.
- The elastomeric caps protecting the screws of the reflector panel adapters had to be re-engineered and manufactured. In fact, the original shape and material was found to be unable to resist the environment at AOS. Caps were falling off after few weeks of operation at the AOS.

Apart from these relatively innocuous effects, one more serious issue was detected during the first Chilean winter. It was found that the calibration volume of the antenna, in which the radiometer, the water vapour radiation measurement system

and the calibrating arm are located, were operating outside their specified temperature limit, and that under certain conditions the risk of getting some of the moving elements stuck was considerable. The European Antenna was counting on achieving the specified temperature by means of a controlled air flow from the receiver cabin of the antenna. However, the volumetric performance of the fans, coupled with the reduced thermal capacity due to the rarefaction of the air, was not sufficient to bring enough heat to cover the heat losses by dissipation and radiation through the central hole. This was cured by using local heaters and by adding an extraction fan, to improve the air flow and therefore the thermal capacity in the calibration volume.

The reduced thermal capacity of the rarefied air was also at the origin of a couple of other issues:

- Damages of a plastic cable duct inside one electrical cabinet. The low thermal exchange due to the reduced air density originated some local hot-spots in the proximity of one heater causing the deformation of the closest cable duct. This was solved by moving the heater, increasing the gap between heater and cable duct.
- Malfunctioning of the encoder interpolation boards. To avoid stratification of the air in presence of the heaters in the cabinets containing the Azimuth and Elevation Encoder interpolation boards, miniature fans had to be installed in order to avoid localized overheating of the electronics.

We also experienced an issue with the LCD screens of the Antenna Control Units. Some monitors have shown cracks of the glass protecting the LCD panels, due to internal air pressure and their sealing for standard outdoor use. All monitors were retrofitted in order to allow pressure equalization between the internal parts of the monitor and the atmosphere.

4.2 Other issues at 5000m

For other components, the environmental conditions of AOS had an effect that became evident after several months.

Electronic problems became evident after a few months of operations on three antenna subsystems: Sub Reflector Mechanism, Inclinometers, and Power supplies for Metrology system and Sub Reflector Mechanism. The final root cause has not been fully understood but is most likely related to the effect of high altitude to some electronic components.

An issue that adversely affected the maintainability is the quick deterioration of the batteries (UPS, and Fire Alarm). Despite the fact that all electrical cabinets are maintained actively at the optimal temperature range for batteries and electronics, the replacement is needed with a periodicity of 2 years instead of the expected 4 years. This may depend to the local temperature rise of the batteries banks which may not be sufficiently cooled due to the reduced air thermal capacity at AOS. Although the UPS system used in the European antennas, is a rugged (for marine use) model, the conditions at AOS are beyond the environmental range to be expected in normal or marine application.

Finally, we would like to mention an issue that affected the surface of the secondary mirror. During the final inspections after 2 years of operation of some European Antennas, corrosion has been detected on the surfaces of the sub-reflector. The problem was investigated in depth by the AEM consortium^[4] and the root cause was identified. The corrosion problem is caused by atmospheric conditions triggering unexpected chemical reactions on the surface of the antenna sub-reflectors. The proximity of active volcanoes and the presence of corrosion activators such as Nitrates (NO₃), Sulphates (SO₄), Chlorides (Cl) and their combinations with Sodium (Na), Calcium (Ca), Potassium (K) on the soil together with the high wind and occasional heavy rain, create favourable conditions for chemical reaction on the Aluminium (5083 H111) surface finished with Alodine 1200s. This issue seems to be one of the classical cases where a product is designed according to an incomplete specification. In fact, the ALMA environmental specification did not consider the possibility of corrosion resulting from aggressive chemicals emitted by active volcanoes in that region. For this reason, this problem was not treated in terms of warranty with the supplier, and will have to be treated at a later stage, when more insight into the deterioration rate will allow to take a sensible decision.

4.3 Reliability

The reliability of the ALMA array antennas is of fundamental importance for scientific observations. The observatory has to count on having a considerable amount of operational antennas in order to achieve the specified sensitivity. In addition, there are some cases where the lack of reliability causing a failure, also require a human intervention at high altitude or,

even worse, a relocation of the antenna to the Operations Support Facility (OSF). The latter causes an antenna to be out of service for a minimum of a few days.

To ensure high reliability, a severe specification of a MTBF larger than 3 years/antenna has been specified. When we are dealing with reliability in a contractual environment, it is of paramount importance to characterize the concept of failure. The specification has defined as *failure*, the occurrence of an event that required one or more of the following:

- a) The need to bring the antenna to the OSF;
- b) A loss of one movement axis not recoverable within 2 hours for 2 people;
- c) A pointing degradation to worse than 5 arcseconds;
- d) A loss of stability of the temperature in the receiver cabin (and consequently the receiver);
- e) Inability to operate the sub-reflector mechanism;
- f) A failure of the UPS.

The aforementioned definition of failure has been adopted not only for ensuring clarity in a contractual environment but also for avoiding that simple malfunctions, which would have effectively allowed continuing observation – although with degraded performance – would have caused the interruption of antenna operation.

Although ALMA operation does not foresee any intervention during night time, it was not distinguished between correctable failures of type b) occurring during day or night, because this would have been very difficult to account for. It is clear that a failure occurring during the night may cause potentially more than just 2 hour of observation time loss.

For the purpose of meeting the specification, the designer could use different strategies, including selecting specifically highly reliable or redundant components. In the case of the European ALMA antennas a mixture of both strategies was used. For instance, the drive system is made of a distributed system, therefore intrinsically redundant. Each individual drive is commanded via a CAN Bus and is accessible remotely via the network. The malfunction of individual drives can be detected and the affected node is automatically excluded waiting for a later human intervention. Only the failure of multiple nodes entails a shutdown of a system and therefore should be counted as a failure. One could consider that because the antenna meets the pointing performances also in the presence of wind of up to 8 m/sec, strictly speaking a failure of the wind metrology could be discarded for the computation of the failures. However, being the inclinometers also part of the alignment checks on the antenna foundations, their failures have been accounted in the following discussion.

The reliability has been checked collecting failure field data at two different points in time.

The first computation of the reliability has been performed towards the end of 2012^[5]. At that time, 13 antennas had been delivered and they have accrued a total operation time sufficient to start an investigation, although partial in nature.

The total cumulative time of operation of the antennas was approximately 10 years, without taking into account that, before delivery, each antenna had been operating during commissioning and testing for a period averaging 4 months/antenna. ESO has used a web based tracking system (JIRATM) expressly developed in-house for this task in order to record issues occurring after provisional acceptance of the antenna. As typical in the case of the start of operation of a new system, a number of issues of different nature surfaced in relatively short time. To avoid polluting the computation with initial problems, ESO decided to exclude from the analysis any software issue (once detected it can be solved or patched), any human factor issue (attributable to insufficient knowledge of the system), wrongly tuned/ commissioned components, and finally any hardware issue which once analysed has triggered a retrofit at design level. Once this analysis has been performed the average MTBF in the field has been computed at app. 1.2 years, and therefore sensibly less than the one specified. The subsystem experiencing the largest number of faults was the HVAC system, followed by the Antenna Control Unit (ACU). We shall remind that contractually the MTBF had to be proven by the supplier only at analysis level, so that ESO did not pursue contractually this issue, beyond the request for repair under warranty obligation. Much more ESO put an effort to review and implement with the supplier any desired retrofits (some of those described above).

The reliability has been numerically checked after 2012 in June 2014^[6], after all antennas were delivered. At that time there were still approximately half of the antennas in the warranty period which demanded a good bookkeeping of the intervention performed. The integrated time of operation of the antennas at that time was approximately 35 years. A total of 213 faults had been recorded, of which approximately 25% could be ascribed to reliability issues. The rest of the faults could be ascribed to software or firmware, to human factor, to hardware design still in the process of retrofitting, and to

initially defective or deteriorated components. In a few cases, a Jira ticket had been opened without a clear link to a fault. In terms of ascribing the faults to the antenna subsystems, one can state that HVAC, mechanisms and electrical installations were constituting approximately 80% of the faults. Under mechanisms, one must include the drive for the main axes and for the sub-reflector hexapod system. The new analysis of the MTBF has been based on the Bayesian methodology, therefore using the initial data of 2012 as starting point for computing the new MTBF. In this case the computed MTBF with a confidence level of 90% ranges between 1.27 and 1.93 yrs. A point estimate would provide an MTBF of 1.54 yrs. It can be noted that the MTBF has surely increased between 2012 and 2014, but not as much as expected, and within a reasonable confidence level of 90%, it still does not meet the initial specification. As expected, the trend confirms that reliability of the antennas has increased with time, but more data would be needed to confirm that the finally achieved reliability has reached the order of magnitude demanded. After the warranty has expired, ESO has interrupted the classifications of the faults and during routine operations the same level of tracking is not done, therefore making further analysis more cumbersome.

The two other aspects of the specification linked to the availability of the antennas are linked to preventive and corrective maintenance. At specification level it was decided not to take into account the access time to the antennas, because of the varying travel time from OSF to the antenna at 500 m as well as the uncertainty associated with the conditions at the high site. Also, this is beyond the control of the antenna supplier. For this reason, at contractual level the specification was verified on the basis of a) the preventive intervention list, b) the computed reliability, and c) a verification in the field of the effective intervention time announced in the maintenance manual for each maintenance procedure. After the antennas were delivered there was an attempt to verify during operation the MTTR (Mean Time To Repair), but the analysis of the data did not provide usable result in view of confirming the specification, not least in view of the difficulty to separate operational constraints encountered in the field and in various cases associated to limitation of access, due to prohibitive atmospheric conditions.

4.4 Maintainability & redundancy

During the design phase and later during commissioning and acceptance, a lot of effort was invested in the maintainability aspects. This effort went beyond the traditional design care and involved safety, access to antenna devices and components, illumination, comfort for the user carrying out maintenance, ease of assembly/disassembly, etc. The fact that antennas had to be maintained by personnel ergonomically limited due to the geographical altitude was always kept in mind. Maintenance by replacement of “Line Replaceable Units” (LRUs) was considered and the mass of the LRUs was kept under control. Jigs were designed for the case of replacement of heavy LRUs.

More important is to note that the European antenna was designed and built also with hardware redundancy, software dynamic automatic management of failures and remote low level accessibility to most of the active components.

It is worth mentioning an example. The direct drive system^[7] of the European Antenna is composed of 14 motor winding sectors (10 in Azimuth and 4 in Elevation) made up of 2 independent segments each and by 3 Hall sensors. Each of the 28 segments is commanded by a driver. The redundancy concept at hardware level (2 independent redundant CanOpen lines, 2 independent Power Lines) allows safe parking of the Azimuth and Elevation axes with only half of the motor segments in operational status in view of maintenance. In addition, the software of the Antenna Control Unit is capable to exclude and ignore automatically up to two defective Azimuth drivers and one defective Elevation driver while still keeping the antenna operational and in its full performance range. The software would try to recover the failing drivers when the antenna is not used. In case of unsuccessful recovery, the error log informs the engineers about unresolved issues. A similar approach is also implemented for the Elevation and Azimuth encoder system, having redundant reading heads.

Remote access to the antenna controls is also a fundamental aspect that improves the maintainability of the system and allows more comfortable working conditions for the maintenance crew, minimizing the time of interventions at AOS. The engineers and technicians can connect via Ethernet protocol to several devices of the antenna like the main UPS, the Antenna Control Unit, the Sub-Reflector Mechanism controller, and the Encoder System. These features not only help increasing directly the availability of the antenna park for science (often the issue discovered at night time can be fixed or patched immediately via remote control) but also contribute to minimize the time spent for corrective maintenance at AOS (engineers and technicians can already troubleshoot and identify some possible root causes of the issues while inquiring from the OSF) increasing indirectly the availability of the antenna for science.

Finally, the European antenna was designed to allow certain preventive and corrective maintenance via remote connection and the use of software routines. Preventive maintenance tasks that can be performed remotely from the OSF are: lubrication of the Sub-Reflector Mechanism, Azimuth and Elevation friction checks, tiltmeter alignment check, and antenna balancing check around elevation (the antenna has direct drives). The manufacturer also developed ad-hoc hardware and software for bridging Ethernet and CanOpen protocols. This allows the engineers to troubleshoot and parametrize each individual active component of the drive system from their desks at OSF.

A remote restart device is also mounted in the antenna. In case of power outage, the antenna is able to restart remotely, without human intervention, also in case of drained UPS battery.

4.5 Maintenance Manual

The maintenance manual of the European ALMA antenna was prepared and edited following the S1000D standard. Specific information can be found in [8]. This standard is common in the aeronautic industry but represents an innovation in the astronomic field. ESO had great expectations when commissioned the Antenna Maintenance manual in S1000D standard. The standard was felt to be mature when selected and with the desired features to ensure accessibility, consistency and uniformity of the full information.

The first years of operations indicated however that the standard S1000D was not the best solution for documenting the antenna maintenance activities in the complex environment of the ALMA Observatory. The expected ease of access to the information was not obtained under several aspects. It turned out that the Maintenance Manual produced with this standard has limitations in terms of software requirements, not being available to Linux and OSX users. Additionally, in the environment of the Array Operation Site at 5000m, consulting the screen of a laptop for open-air maintenance activities has been considered by the users not optimal due to reasons of:

- Poor readability caused by strong illumination
- Short battery lifetime of the laptops due to low temperatures
- Limited portability of the manual in confined space
- Poor usability of the keyboard for consultation when the user is heavily dressed and protected against wind and cold.

The complexity of the antenna maintenance did hamper the uniformity of the level of information in the manual. The impossibility of installing the Antenna Manual on a single server and make it available to the users in the field, severely limited the interesting feature of an interactive manual where users may add in the manual notes and comments useful for co-workers.

In addition, the relatively short lifecycle of the ALMA maintenance manual and the maintainability of the manual itself inside the organization was underestimated. The maintenance procedures need to be constantly modified responding to the experience gained in field and the feedback of the engineers. The substitutions of components due to reliability issues or simple obsolescence require also regular revisions of the manual (new components may need different maintenance or simply the references to the component inside the manual shall simply be new updated).

In this context, an Antenna Maintenance Manual developed with a traditional word processor would have been a conservative and less elegant solution but it would have allowed in-house maintainability of the document without impacting good maintenance practices.

5. CONCLUSION

As expected, the first years of operation of the antennas at 5000m showed some deviations between a few performances obtained at design level and tested at 3000m and the same performances as verified at 5000m. The positive aspect is that the scientific performances have either been specifically confirmed at 5000m or there has been no indication whatsoever that they are not fulfilled.

The analysis of technical aspects shows a possibly slight different scenario. First of all, a number of retrofits had to be implemented, none of those major in nature, but when taken together constituting a major industrial effort for the supplier

(AEM Consortium) which had to handle antennas in various configurations, operational stages and locations, still keeping the delivery schedule of the overall antenna park under control. (ESO is very grateful to AEM for their excellent reactivity on this aspect). The need of further tuning by ESO after the warranty expiration has been however very minor. Overall it has to be said that the technical results are very positive. Despite the use of only commercial items (the program could not afford to have aerospace qualified components), the design and the associated prototyping activities of the antenna systems resulted in a solid telescope well adapted for its use at 5000m. Regarding the reliability and the other operational aspects of the maintainability, ESO is confident that despite not fully meeting the specification in 2014, further analysis and a systematic treatment and characterization of the issues will allow to show that the expected reliability is achieved, approximately five years after the start of operation of the antennas. In terms of maintainability, a positive note is that until now only three antennas were brought back to the OSF for corrective maintenance. Surface checks by holography on the antennas returned to the OSF have confirmed the good stability of the surface. A possible lesson learned can be the one of the subreflector, where a missing item in the specification led to the production of a key item (subreflector) with a life which in the field is surely shorter than the one originally demanded.

Overall it is noted that the procurement of the European antenna has been a success and that after five years of operation the antennas are proven to fulfil their scientific objective and their technical scope. The program has been possible thanks to the effort of many, and surely the supplier, always engaged in producing a state of the art product.

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