

System Engineering of the Atacama Large Millimeter/submillimeter Array

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ABSTRACT

The Atacama Large Millimeter/submillimeter Array (ALMA) will be composed of 66 high precision antennae located at 5000 meters altitude in northern Chile. This paper will present the methodology, tools and processes adopted to system engineer a project of high technical complexity, by system engineering teams that are remotely located and from different cultures, and in accordance with a demanding schedule and within tight financial constraints. The technical and organizational complexity of ALMA requires a disciplined approach to the definition, implementation and verification of the ALMA requirements. During the development phase, System Engineering chairs all technical reviews and facilitates the resolution of technical conflicts. We have developed analysis tools to analyze the system performance, incorporating key parameters that contribute to the ultimate performance, and are modeled using best estimates and/or measured values obtained during test campaigns. Strict tracking and control of the technical budgets ensures that the different parts of the system can operate together as a whole within ALMA boundary conditions. System Engineering is responsible for acceptances of the thousands of hardware items delivered to Chile, and also supports the software acceptance process. In addition, System Engineering leads the troubleshooting efforts during testing phases of the construction project. Finally, the team is conducting System level verification and diagnostics activities to assess the overall performance of the observatory. This paper will also share lessons learned from these system engineering and verification approaches.

Keywords: System, Engineering, ALMA

1 INTRODUCTION

The Atacama Large Millimeter/submillimeter Array (ALMA) will be a premier tool for studying the first stars and galaxies that emerged from the cosmic "dark ages" billions of years ago. These objects now are seen at great cosmic distances, with most of their light stretched out to millimeter and submillimeter wavelengths by the expansion of the Universe. In the more nearby Universe, ALMA will provide a unique ability to study the processes of star and planet formation: unimpeded by the dust that obscures visible-light observations, ALMA will be able to reveal the details of young, still-forming stars, and is expected to show young planets still in the process of developing. In addition, ALMA will allow scientists to learn in detail about the complex chemistry of the giant clouds of gas and dust that spawn stars and planetary systems.

ALMA will be located at the Array Operations Site (AOS) at 5000 meters altitude on the Chajnantor plateau in northern Chile. Its main array will have fifty antennae, 12 meters in diameter, complemented by an additional compact array of four 12-meter and twelve 7-meter antennas. The 66 ALMA antennae can be arranged in different configurations, where the baseline between antennas can vary from 9 meters to 16 kilometers. The array will be able to probe the Universe at millimeter and submillimeter wavelengths (from 0.32 to 3.6 mm) with unprecedented sensitivity and resolution. The

observatory will be operated and maintained from the Operation Support Facility (OSF) at 2900m altitude some 30km from the center of the AOS.

International co-operation is integral to ALMA, whose current design has benefited from a merger of smaller arrays originally envisaged by each of the Executive partners, as explained below. The resulting collaboration spans continents to surmount considerable financial and technological hurdles, whilst also needing to address political and intercultural challenges. The international partners are Europe, Japan and North America, in cooperation with the Republic of Chile. ALMA is funded in Europe by the European Organization for Astronomical Research in the Southern Hemisphere, in Japan by the National Institutes of Natural Sciences (NINS) in cooperation with the Academia Sinica in Taiwan and in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC). ALMA construction and operations are led on behalf of Europe by ESO, on behalf of Japan by the National Astronomical Observatory of Japan (NAOJ) and on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI).

On the one hand, the technical requirements necessitate the use of state of the art technology - for example, the mixers that are at the heart of the radiometric receivers. On the other hand, the size of the Observatory with 66 antennae requires that the subsystem teams generate deliveries on a production line basis, not just one-off instruments. This is an unusual combination, which has required the adoption and dissemination of a strong system engineering approach based on the key principles of requirements flow-down and management, articulation and maintenance of system budgets, design and manufacturing reviews, requirement verification, formal acceptance reviews and a robust non-conformance handling process. Despite the relevance of the System Engineering discipline in a project of this magnitude, ALMA reinforced these efforts only at a very late stage of the Construction Project. The creation of the JAO System Engineering team and further enhancement of the team across the Executives happened only in the last three years. This paper summarizes the results of such effort.

This paper will present the methodology, tools and processes adopted to system engineer a project of high technical complexity, by system engineering teams that are remotely located and from different cultures, and in accordance with a demanding schedule and within tight financial constraints. This paper covers the Construction phase of the project, which will end in September 2013.

2 SYSTEM ENGINEERING STRUCTURE

The organization of the System Engineering (SE) team reflects the overall ALMA project organization, with the three Executive partners supporting the Joint ALMA Observatory in Chile. The team is headed by the Project System Engineer in Chile, who holds responsibility for all System Engineering activities across ALMA, and reports to the JAO Construction Project Manager. The Project System Engineer directs the work of the System Engineering team, the System Verification team, the Documentation team, and the System Engineering Leads at the Executives, who in turn co-ordinate the local executive System Engineering resources including the Subsystem Engineers. This structure achieves a uniform System Engineering approach across ALMA.

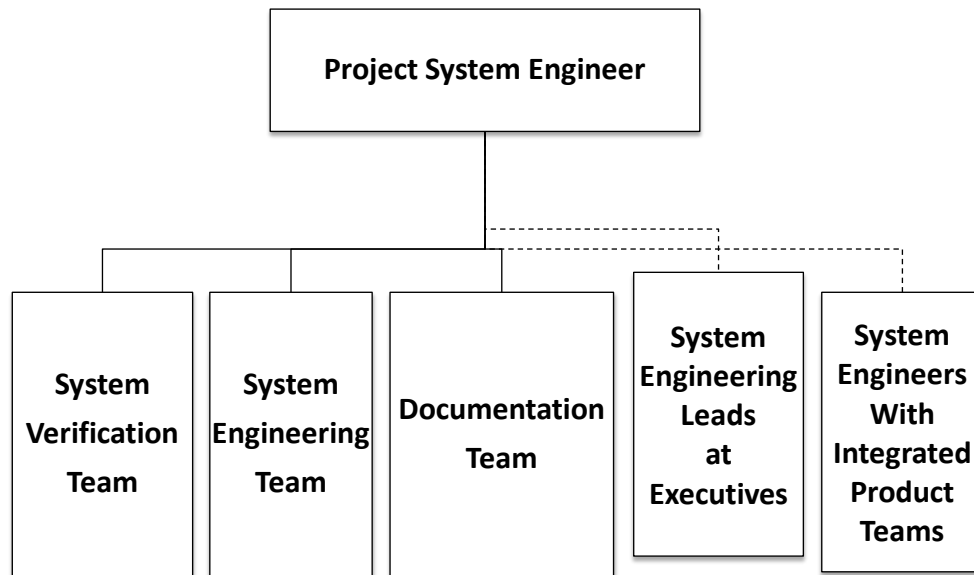


Figure 1. System Engineering organizational chart

3 SYSTEM ENGINEERING APPROACH

The role of the ALMA SE team is described in the following diagram. Elements in white are the responsibility of other groups within ALMA.

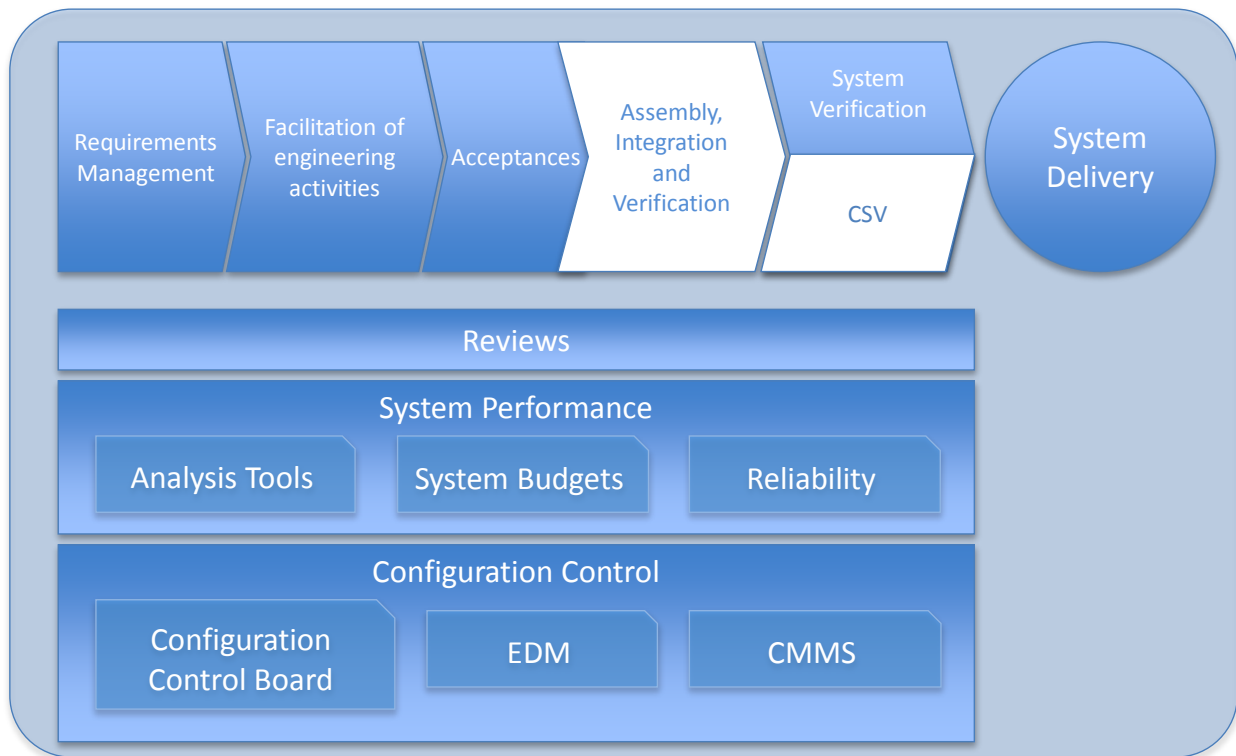


Figure 2. System Engineering flow

The chart shows on top the flow of System Engineering activities that begin with requirements management. During the design and development phases of the subsystems of ALMA, the team facilitates the resolution of technical conflicts and performs trade-offs. The completion of the System Engineering activities comes with System Verification. Commissioning and Science Verification^[1], and delivery to Scientific Operations. The entire work flow is supported by a number of technical reviews of subsystems. System Engineering uses analysis tools to analyze the system performance. Strict tracking and control of the system technical budgets allows System Engineering to ensure that the system operates within required limits. Reliability is continuously monitored to ensure the sustained performance of the system. In order to ensure that a proper configuration control is implemented, the documentation team supports SE with a document management system and processes.

4 ANALYSIS AND MANAGEMENT OF REQUIREMENTS

The technical and organizational complexity of ALMA requires a disciplined approach to the definition, implementation and verification of the ALMA technical requirements. A standard aerospace approach to requirements management is used within ALMA. The top level technical requirements (Level 2) are contained in the ALMA System Technical Requirements Document, and are in turn derived from the top level scientific goals of ALMA (Level 1). From the

System Technical Requirements, all lower level technical requirements (Levels 3 and then 4) are further disseminated across the different subsystems, including interface requirements, in a univocal and hierarchical manner. Maintaining a consistent dependency between requirements, from the start of the project until the system verification tests, is key to the success of the project. The use of DOORS to manage the requirements was considered, but was later abandoned due to the introduction of the tool at a very late stage of the development. Instead, requirements are managed through documentation configuration control. The high number of Interface Control Documents (ICD) is managed using ICD diagrams that show the relevant interface documents superimposed in the links between elements of the Product Tree. These diagrams proved to be a simple, effective and easy to visualize tool for the management of ~150 ICDs.

5 CONFIGURATION CONTROL AND INFORMATION MANAGEMENT

Since ALMA is a large collaboration between international partners, efficient configuration and documentation management are essential to facilitate communication among geographically dispersed stakeholders, to ensure quality of hardware and software, and to allow equipment to be understood and maintained throughout the lifetime of the array. Indeed, the high level ALMA Project Plan stipulates implementation of a process for configuration management.

Configuration Control procedures in ALMA moderate the change request process, providing a method for proposing and implementing changes while preserving the integrity of the final product. This defines a means of formally requesting a change, a process for analyzing the technical, performance and schedule impacts of the proposed change, and a process for communicating the change request decisions.

Any proposed change that would affect performance requirements, scope, budget and/or schedule is assessed by a Configuration Control Board (CCB). The Configuration Control Board is chaired by the ALMA Project Manager. The CCB is also comprised of the Project System Engineer, serving as secretary, and additionally includes the Executive Project Managers, ALMA Project Scientist and ALMA Product Assurance Manager. The CCB directly reviews and approves/rejects Change Requests and Requests for Waivers that have significant technical and budgetary impacts within the ALMA System. Other Document Approval Requests that are presented to the CCB include ICDs between subsystems, as well as top-level specifications, requirements and procedures.

The design, manufacturing, handover and maintenance process for ALMA equipment has produced many thousands of other critical engineering and administrative documents and data throughout the various portions of the project. Documents outside the scope of the Configuration Control Board are approved internally by Integrated Product Teams (IPT), following ALMA documentation procedures and standards. The System Engineering Documentation Team is responsible for collecting and organizing deliverable information in an Electronic Documentation Management (EDM) system, classifying documents according to Document Tree numbering, classifying subsystems according to Product Tree numbering, and facilitating appropriate peer review, approval and archival of information.

Configuration management throughout ALMA is supported by the EDM system, which contains forums and directories for discussion, authorization and storage, along with workflow processes, a document number database, and a search engine. The System Engineering Documentation Team maintains this system and database of documentation as a deliverable product from Construction to Operations, processing, disseminating and preserving ALMA's collaborative knowledge.

6 SYSTEM BUDGETS

System Engineering holds responsibility for the compilation and update of the key technical budgets across the project, including system level radiometric performance and optical signal attenuation. Although performance budgets are most relevant to the scientific operation of ALMA, other budgets such as for Electrical Power play a critical role. Original estimates of needed power levels were made when the design of the Observatory hardware was not finalized. This initial estimation of power need (plus margin) was used for performing tradeoffs between accessing the Chilean utility network versus local generation, both at the AOS and the OSF. Factors such as derating of performance due to altitude of course needed to be taken into consideration. From this analysis, generation of onsite power at the OSF was considered the best

option. The initial power budget assumed a 55 kVA average power demand per antenna, and a 75 kVA peak allowance. Combining with the Technical Building and OSF loads gave an initial power budget of 7 MVA and 6.7 MW, which were used for the Permanent Power System specification.

The power budget now has two distinct applications. The first application is to determine the average power demand, so that fuel usage and cost estimates can be made for operation. The second application is to estimate the transient peak power demand. Quantification of both the steady state and transient peak power demand are needed to properly configure and size the system, so that power quality can be maintained.

The dominant peak demand comes from the antenna Fast Switching Mode, wherein the antennae are moved rapidly between the source and a calibrator. When used in the fast switching mode the peak power consumed by the antenna is approximately double its average power consumption. This required that a Flywheel system be installed to handle these large repetitive short duration peak power transients from the antennas, in order to maintain power quality. The duty cycle and duration of this peak power, together with losses in the flywheel system, will add approximately 10% to the average power load of the antennas, giving an average antenna power demand of ~ 2 MVA when the array is fully in operation. Other transients come from the cycling of air conditioning and heating equipment, the air compressor for the oxygenation system, and other similar loads within the support infrastructure.

The average power demand for the OSF and AOS is currently estimated to be 4 MW, with 1 MW for the OSF, 1 MW for the AOS Technical Building, and 2 MW for the Antennae.

7 ANALYSIS TOOLS

The System Engineering team has created its own analysis tools, to facilitate system trade-offs. The ALMA System Performance Analysis Tool predicts the system performance of ALMA through a combination of modeling and experimental data on subsystems. The analysis tool consists of calculation programs compiled by Matlab, together with a database. A graphical user interface easily allows users to perform calculations for various parametric conditions. The performance database can be updated via a web browser, such that authorized persons can maintain the database remotely. Eleven calculators are available to date, including for calculation of system noise temperature, beam pattern, aperture efficiency, and amplitude stability. The tool can further be used to assess the quality of observations as the results can also be obtained from actual measurements of the subsystem elements.

(a) Beam Calculator

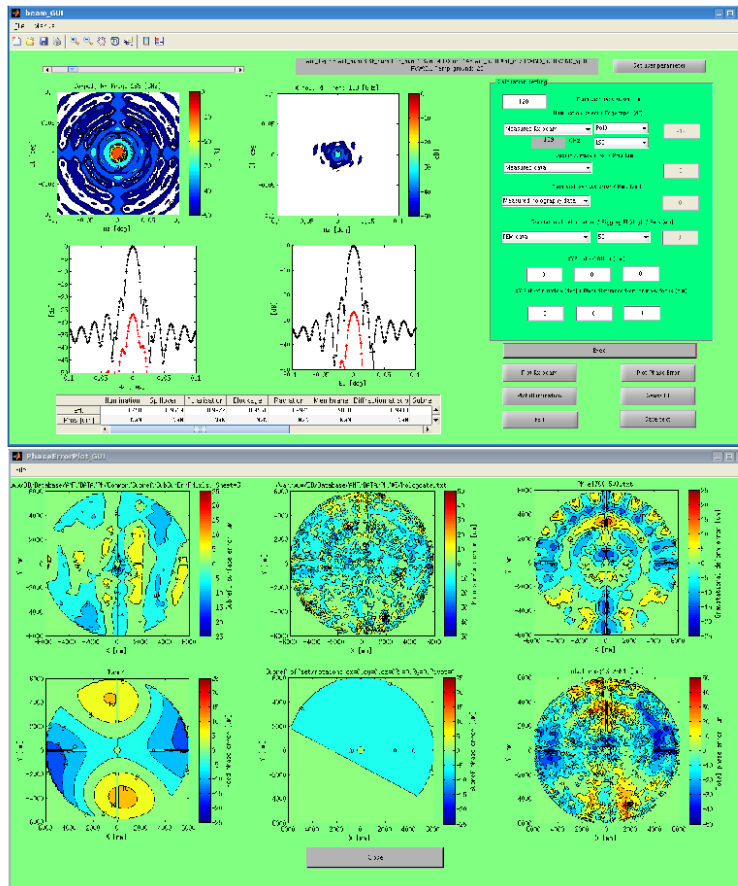


Figure 3. Example of system performance analysis tool Beam Calculator, showing the expected beam pattern which is calculated from various error contributions. Bottom figure corresponds to the contributions, e.g., subreflector surface errors, panels adjustment errors on the main reflector, gravitational deformation, phase error, etc.

(b) System noise calculator

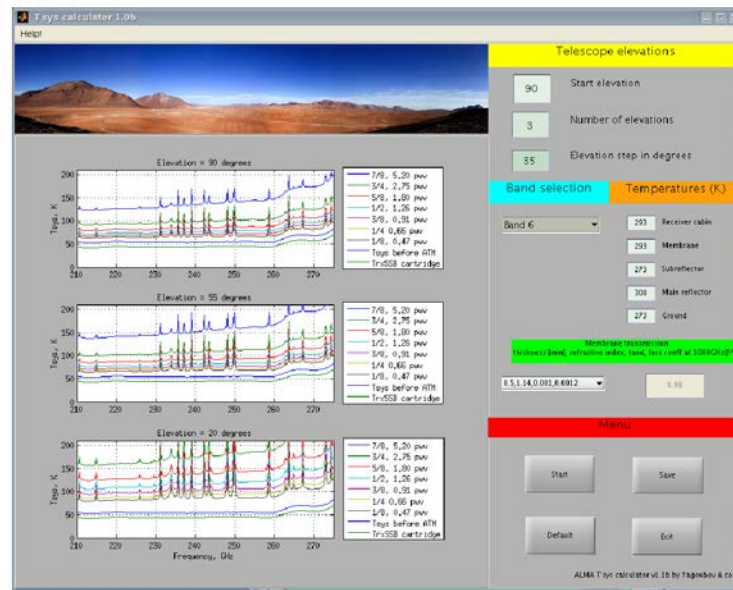


Figure 4. Example of system performance analysis tool System Noise Calculator; the noise temperature is calculated from models of transmission loss in the antenna and atmosphere etc, as well as receive noise temperature measured at lab.

Additionally, a Risk Analysis Tool has been developed to identify the subsystems of the Observatory that pose the greatest technical risk to achieving adequate performance at System Level. The tool is based on a Hierarchical Functional Model, which is an abstract model of the Observatory hardware. The model incorporates propagation of the effect of "functional failures", thereby allowing a straightforward identification to be made of Single Point Failures for the entire Observatory, or failure scenarios and the related technical impact. The tool then associates an estimated "probability" or "likelihood" parameter to the loss of functionality of each of the subsystems. Multiplication of the impact by the probability gives the "risk" associated with each of the Observatory technical parts. The Risk Analysis Tool and the Hierarchical Functional Model are built in a top-down fashion such that they can be easily scaled or detailed up to the level necessary for the analysis of the risks.

8 REVIEWS

All subsystems are subject to the normal aerospace review process that reflects the design and manufacture cycle; these include the preliminary design review, critical design review, and manufacturing readiness review. For each of the major such subsystems, the System Engineering team chairs the technical review and co-ordinates the preparation of the review with the delivering party. Such activities include definition of the submitted documentation package, assessment of the maturity of the design including interfaces, detailed technical discussion with the product engineers to pre-emptively address technical concerns, and co-ordination with the Safety Department for assessment of equipment and human safety. The System Engineering team also participates in lower-level reviews throughout the project, either as formal members of the Review Panel, or as Observers. In all cases, the focus of the review is technical, with a final recommendation made to the Decision Making Authority (usually the Project Manager for the delivering Executive), who then assesses these recommendations in view of schedule and budgetary considerations and works with the senior management team to define and authorize the actual response by the project.

9 SYSTEM BLOCK DIAGRAM

System Engineering maintains the ALMA System Block Diagram comprising two types of information. First is system level design information, including but not limited to the configuration of the main signal path, the assignment of

functions to major subsystems, interconnections among major subsystems, locations of major assemblies, and some (but not all) parameters such as frequencies, bandwidths, and signal levels. Information in this category is determined by System Engineering, and controls the ALMA design. The second type of information is subsystem design information, sufficient to provide a clear understanding of the telescope's functioning, including some subsystem design parameters. Information in this category is based on documented design decisions of other integrated product teams at the delivering Executives.

10 CO-ORDINATION WITH INTEGRATED PRODUCT TEAMS

The System Engineering team co-ordinates a number of special projects requiring input from many sources of expertise across the project. An example is the implementation of an alarm system for the entire observatory, aiming to cover the entire Array and also the infrastructure, which together have tens of thousands of housekeeping monitor points. A requirements-based approach starts with close cooperation and knowledge transfer with the product engineers for every module, in order to define trigger and response requirements along with alarm reduction rules to provide meaningful route cause analysis in case a failure triggers a cascade of alarms. These requirements are incorporated into the array and infrastructure software, and then go through the normal process of verification and validation. The end goal will be to have dashboards for each major subsystem and also for the system as a whole. This in turn will support the execution of a correct response in case of a failure, and also support diagnostic activities (because all such information is archived and can be analyzed after a failure) and longer term trend analysis (by looking at deterioration with time of the performance of subsystems, in order to ensure that maintenance is planned before a failure actually occurs).

11 ACCEPTANCE OF DELIVERIES

One of the critical roles of the System Engineering Team is leading the acceptance of hardware deliverables at the Observatory, on behalf of the ALMA Director. The System Engineering Team also provides support for the software deliverables. A successful acceptance requires close co-ordination between the delivering Executive(s) and the Observatory staff in Chile. Once a subsystem has been manufactured, it is subject to verification tests, which are designed to evaluate whether technical specifications and requirements have been met. As is normal engineering practice, such verification is through inspection, review, analysis and/or test.

The performance of every system of the ALMA array will be subject to verification firstly at the location it is manufactured. The criteria defined for acceptance is applied from this early stage, and cover several aspects. The as-built status needs to be documented, highlighting any differences from the design baseline. Test and inspection results are assessed with reference to the technical specification and interface requirements, making use of the compliance matrices that are prepared for every module or subsystem that is to be delivered. Any non-conformance reports and requests for waivers need to have a clear path towards approval and closure. The completeness and correctness of the Acceptance Data Package documentation is assessed; such a documentation package includes a Configuration Item Data List, Internal and external Interface Specifications, verification plans and procedures, verification (e.g. test) reports, shipping and handling plans, and operation and maintenance manuals. If no major blockers are found with performance verification, authorization is given for shipping of the subsystem to Chile.

Once the subsystem is at the Observatory facilities, it undergoes a second range of verification tests. The criteria to be used for such tests are exactly the same. For systems that require complex on-site integration, deployment and commissioning, such as the Antennae, Central Local Oscillator and the Correlator, the on-site verification tests are exhaustive. For line replaceable units that can be tested at a lower level of integration, a more limited set of tests is performed, in essence to ensure that the deliverable survived shipment. Formal acceptance by System Engineering releases antennae and their subsystems to the Assembly, Integration and Verification teams^{[2], [3]}.

This acceptance process applies not just to the array subsystems, but also to the site infrastructure, which includes the employee camps, buildings, antenna final assembly and test infrastructure, the power generation and distribution network, and the fiber optic road networks. In all cases, an acceptance certificate is issued which extends transfer of ownership from the delivering Executive to all three Executives, on behalf of the Observatory.

Given the large number of products delivered to the Observatory, and the commonality of many subsystems across 66 antennae, the acceptance review process has evolved over time. As the maturity of the delivered products increases, and we gain confidence in their actual performance at the site, this allows future acceptances to focus on key parameters rather than being exhaustive. As such, the acceptance process becomes manageable and realistic given available resources.

12 NON-CONFORMANCE PROCESS AND MATERIAL REVIEW BOARDS

The need for Non-Conformance Reports (NCR) and Requests for Waivers (RFW) was foreseen in the early definition phase of the project, in line with normal practices for technology development and deployment programs. However, formal processes for handling NCR's were not defined until the construction was already well advanced. This oversight led initially to a somewhat confused mix of ad hoc approaches implemented by different groups. However, this has now converged into a 3-tier approach at the Observatory.

The lowest level corresponds to faults encountered during array operations. These are generally handled directly by engineering staff, without any formal System Engineering or Product Assurance involvement other than monitoring for signs of a systemic problem.

The middle level corresponds to non-conformances detected during verification testing at array element level, or related to deviations from procedures, etc. All such NCR's are formally managed by a System Engineer (for technical leadership) and a Product Assurance representative (for co-ordinating the process). A Material Review Board is convened, comprising the necessary technical expertise to assess the fault. The Material Review Board reviews the available information pertaining to the issue and directs the investigation towards resolution of the problem. During the investigation, the Material Review Board can elect to raise an NCR status to major if the nature or extent of the problem warrants it. When the investigation is completed the Material Review Board decides the disposition with respect to the NCR (e.g. repair, use as-is, etc) and where necessary assigns follow-up corrective actions to avoid a recurrence of the problem.

The highest level corresponds to major NCR's related to system-level non-conformances or issues affecting multiple units such as design faults. Investigation into these problems is managed through Material Review Boards which are expanded to include representatives of the Executives. The progress of these investigations is reported at a bi-weekly project meeting attended by the subsystem leads from the Executives.

Currently, the JIRA bug and fault reporting system from Atlassian is being used to document and track NCR's, with segregation between the different levels of NCR. As ALMA moves into full operations, we are reviewing the implementation of these processes. The goal is to tailor the processes for dealing with frequent operational faults that occur and are expected, given the increased quantity of hardware and software deployed. The key requirements for the operational problem reporting system are as follows. A simple problem reporting form is needed, to gather all required information to enable the engineering staff to set an appropriate priority and initiate the problem investigation. There must be a way to match the problem to previous faults with similar symptoms and ultimately the same root causes, and thus speed up the process to identify the root cause. There is a need to provide astronomers and other staff with an up-to-date status of the array, showing which antennae have unresolved problems associated with them. A mechanism is needed to provide senior managers at the Observatory with the tools for overseeing and managing the problem handling process. Finally, operational variables must be selected and combined to compute various key performance indicators, for optimization of maintenance processes.

13 SYSTEM VERIFICATION

System verification is one of the key activities of System Engineering in ALMA. Its role consists of providing verification of the System Technical Requirements, such that the astronomical observations can be conducted with a comprehensive knowledge of how well the technology does what it is supposed to do. The verification strategy

addresses each requirement on an individual basis. Almost half of the 108 system level technical requirements can be verified without dedicated observations, either because the relevant elements are checked at a lower level of integration, or because the required feature is guaranteed by design. In such cases, it is necessary simply to collect relevant data and provide a suitable report. Verification of the majority of other requirements is through Observatory level testing. The workflow then extends from definition of the detailed verification procedure, to the preparation of the software script which controls the antennae to perform the necessary observations, to negotiation of access to the Array for the observation, to collection and analysis of the resulting data, and generation of reports that present the level of compliance to the original requirement. This process of verification at system level sometimes highlights flaws in the design, manufacturing or integration. One example is the identification of spurious signals in the spectra, in order to ensure these are not mistaken for spectral emission/absorption lines from astronomical sources.

14 CONCLUSION

We have presented an overview of the system engineering methodology and tools implemented in ALMA. The simultaneous technological complexity and size of the project, and the multiple delivering parties, have presented major challenges towards that system engineering process. Nonetheless, the Early Science program of ALMA, with a limited number of operational antennae, has demonstrated that ALMA already delivers cutting edge science.\

A number of valuable lessons have been learned. The need for a strong presence of System Engineering at the start and throughout a project is evident. The imposition and oversight of system engineering into all technical areas is mandatory in order to ensure that there is a consistent approach adopted by *all* technical teams. This includes the software development and delivery process. Great emphasis must be placed and maintained on formal requirements, including interface control between subsystems. Balance must be sought between rigour and pragmatism, with understood and acceptable levels of technical risk, when managing the process of formal acceptances of thousands of deliverables to the Observatory. Adequate time and resource must be devoted towards verification activities at system level, which might involve several groups across the Observatory, but which must be led by system engineering. The constant tension between increasing scientific capability versus reaching closure on technology development requires that system engineering be satisfied with the bare minimum performance that is needed to be compliant with requirements.

The development of strong intercultural links is paramount: this greatly facilitates the technical activities by reducing miscommunication and strengthening the collaborative capabilities of the team. Working in an effective manner with partners across the world requires a combination of initial face-to-face discussions together with the technical capability for remote follow-up: most meetings with Observatory staff take place via video connections to the Executive partners. As such, system engineers must maintain an appropriate level of travel between the Observatory, the administrative office in Santiago, and the technical facilities in North America, East Asia and Europe.

It is hoped that some of these lessons learned might be valuable not just for other new high-technology astronomy projects such as SKA, but also taken up on a more routine basis by projects that use existing technologies. For example, Chilean infrastructure projects generally do not implement Systems Engineering to the extent that ALMA requires; their approach is mainly based on Project Management best practices, wherein planning and budgeting efforts allow monitoring of contracts, whilst elements such as requirements definition, configuration control, systems analysis, incremental verification and proper documentation management are simply not well developed.

ACKNOWLEDGEMENTS

The liaison role of system engineering with ALMA staff across the project has meant that we have benefited enormously from the efforts of hundreds of people within Chile and at the Executive partners. We are deeply grateful to them for their assistance.

This paper is dedicated to the memory of Professor Koh-Ichiro Morita, much appreciated colleague and former Lead System Verification Scientist.

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