Assembly, Integration, and Verification (AIV) in ALMA: Series Processing of Array Elements

Bernhard Lopez[1], Rieks Jager[1], Nicholas D. Whyborn[1], Lewis B. G. Knee[1,2], Joseph P. McMullin[3]
[1]Atacama Large Millimeter/submillimeter Array (Chile)
[2]NRC-Herzberg Institute of Astrophysics (Canada)
[3]National Solar Observatory (United States)

ABSTRACT

The Atacama Large Millimeter/submillimeter Array (ALMA) is a joint project between astronomical organizations in Europe, North America, and East Asia, in collaboration with the Republic of Chile. ALMA will consist of at least 54 twelve-meter antennas and 12 seven-meter antennas operating as an aperture synthesis array in the (sub)millimeter wavelength range. It is the responsibility of ALMA AIV to deliver the fully assembled, integrated, and verified antennas (array elements) to the telescope array.

After an initial phase of infrastructure setup AIV activities began when the first ALMA antenna and subsystems became available in mid 2008. During the second semester of 2009 a project-wide effort was made to put in operation a first 3-antenna interferometer at the Array Operations Site (AOS). In 2010 the AIV focus was the transition from event-driven activities towards routine series production. Also, due to the ramp-up of operations activities, AIV underwent an organizational change from an autonomous department into a project within a strong matrix management structure. When the subsystem deliveries stabilized in early 2011, steady-state series processing could be achieved in an efficient and reliable manner. The challenge today is to maintain this production pace until completion towards the end of 2013.

This paper describes the way ALMA AIV evolved successfully from the initial phase to the present steady-state of array element series processing. It elaborates on the different project phases and their relationships, presents processing statistics, illustrates the lessons learned and relevant best practices, and concludes with an outlook of the path towards completion.

Keywords: assembly, integration, verification, AIV, series processing, ALMA.

1 INTRODUCTION

1.1 Atacama Large Millimeter/submillimeter Array (ALMA)

ALMA is an international project to build and operate a large observatory that will make astronomical observations at millimeter and sub-millimeter wavelengths. ALMA's specified wavelength range is from 10 mm to 0.3 mm, corresponding to frequencies of approximately 30 to 950 GHz. Because these wavelengths are strongly absorbed by clouds and water vapor in the atmosphere, the instrument is located in the very dry Atacama region of northern Chile. The actual site is the Chajnantor plateau, which is at an altitude of 5000 meters above sea level.

The instrument is made up of an array of parabolic antennas that work together to form a single telescope. Despite the antennas being quite similar in appearance compared to those used for lower-frequency radio astronomy and for communications, they are specially designed to be extremely stiff and to have surface accuracies of better than 25 microns. There will be 12 dishes of 7-meter diameter, forming a close-packed array, and at least 54 dishes of 12-meter diameter. The 12-meter antennas can be moved around on the plateau to provide different configurations of the array, ranging in size from about 150 meters up to 15 kilometers.

1.2 Array Elements

An Array Element (AE) refers to an ALMA antenna with all instrumentation subsystems integrated. This distinguishes the antenna subsystem, i.e. the dish, structure, and its respective control mechanisms, from the fully equipped and integrated version. Array elements are the ultimate AIV project deliverables to the ALMA array.

1.3 Assembly, Integration, and Verification

Assembly, Integration, and Verification (AIV) is part of the construction phase of ALMA. The primary AIV tasks are to assemble and integrate the major subsystems into functional AE, establish their initial technical performance, and ensure they meet stated technical requirements. Considering the geographically widespread manufacturer locations and transportation restrictions, the final assembly and integration is performed at the Operations Support Facility (OSF). The OSF is located at an altitude of nearly 3000 meters above sea level and 30 kilometers distant from the Chajnantor plateau, to which the operational antennas are moved using special transporters. AIV is finished when the last AE is delivered to Commissioning and Science Verification (CSV) at the operations site.

2 PROJECT PHASES

2.1 Phased Planning and Progressive Elaboration

Considering the initial level of unknowns, an expected duration of more than five years, and dependencies of future project phases on previous milestones, the AIV project lifecycle was and is developed using phased planning and progressive elaboration. Phased and iterative planning in rolling-wave style allowed concentrating on the imminent project needs while keeping the future, high-level milestones in sight. Progressive elaboration adequately reflected the reality as project details became available and unfolded only with time.

This approach allowed for an early start of AIV activities, for continuous refinement of the processing requirements and activities, and for flexible project adaptation to varying boundary conditions over the years. As a result different project phases evolved progressively, each consequence of its specific context and the goals pursued at that time. The resulting phases are presented in more detail in the following sections.

Considering the clear scope there was little risk of scope creep related to this phased planning approach. Nevertheless, the downside was a proliferation of interim solutions at the early project stages before definitive implementations became accessible. Overall, it is believed that a phased planning and progressive elaboration technique can be a pragmatic choice when preparing for and executing series processing of array elements.

2.2 Initial Preparation and Processing Pilot Phase

After project initiation and a first planning round where baselines for budget, internal organization and staffing, procurement processes, and communications were laid, preparations of the site infrastructure and procurement of equipment and tools were pursued. At the beginning strong interactions with the Integrated Product Teams (IPTs) developing the various sub-systems were crucial as it allowed to start with the first processing activities, it helped to progressively develop the detailed processing requirements, and it allowed for knowledge transfer to the up-ramping AIV team.

The initial organizational structure was a functional one, with AIV an autonomous group within the Joint ALMA Observatory (JAO). Incorporation of area experts, continuous hiring efforts and staff training allowed for an increasing availability of a skilled work force. The initial approach towards array element series processing was established as team-focused, i.e. several technical teams would exist and each team would perform activities on an AE through its whole workflow. This approach aimed to achieve ownership of the processing responsibilities by the respective teams, and also allowed for simplified estimation of staffing level requirements. Nevertheless, with more experience acquired, and considering the 8-days on/6-days off shift system used for working at the OSF, the team-focused approach quickly changed into a task-focused approach where different technical teams would work on specific processing tasks rather than on specific AEs.

This phase lasted roughly two years (2008-2009), it featured the processing of the very first array elements, and it culminated with the establishment of a 3-antenna interferometer at the AOS. The latter milestone had been an important project schedule driver, and its accomplishment demonstrated that "ALMA works" and also marked the start of Commissioning and Science Verification (CSV) activities [1].

2.3 Transition towards Series Processing

This phase was marked by efforts to transition from the initial path-finding, and often event-driven, way of working towards a routine, efficient and predictable series processing approach.

An important change of context arrived with the ramp-up of Operations preparations, including the related staffing needs and the potential synergies between the AIV group and the up-ramping Department of Technical Services (DTS). An initial attempt at synergy was made by establishing an engineering pool: a limited pool of shared staff that could be assigned totally or partially to either AIV or DTS groups on a 3-monthly basis. However, this approach could not solve the underlying problem that Operations positions were more attractive to staff considering their longer-term perspective, thus AIV started to lose key people when DTS hiring started to ramp up. Consequently, it was decided to merge the AIV and DTS departments into a single ALMA Department of Engineering (ADE). AIV then became a project within ADE, managed via a strong matrix structure, as illustrated in figure 1. Funding agency requirements of keeping construction costs separated from operations were addressed by a detailed, task-based separation performed at the management level. Even though there were important indirect costs related to the merge and some things that could have been done better, this approach proved with time to be workable and effective.

Another key aspect that marked this phase was the focused effort made on stabilizing all possible underlying variables, e.g. maximizing the availability of infrastructure, achieving adequate stock levels of spare parts, establishing a stable software platform, ensuring permanent key staff coverage on site, et cetera. Here also a detailed infrastructure risk assessment and analysis was performed, and high-risk exposure cases identified and handled as appropriate. Examples of mitigation actions were: procurement of spares, focused staff training, and equipment upgrades or procedural improvements.

When mission critical technical equipment was set up, modified, or commissioned, participation of area experts has been sought. This maximized the probability of success and minimized risks related to improper handling, operation, or the lack of specific knowledge. Considering the complexity of the array element processing, having had all controllable variables as stable as possible allowed to effectively focus on and address the remaining, unavoidable processing issues.

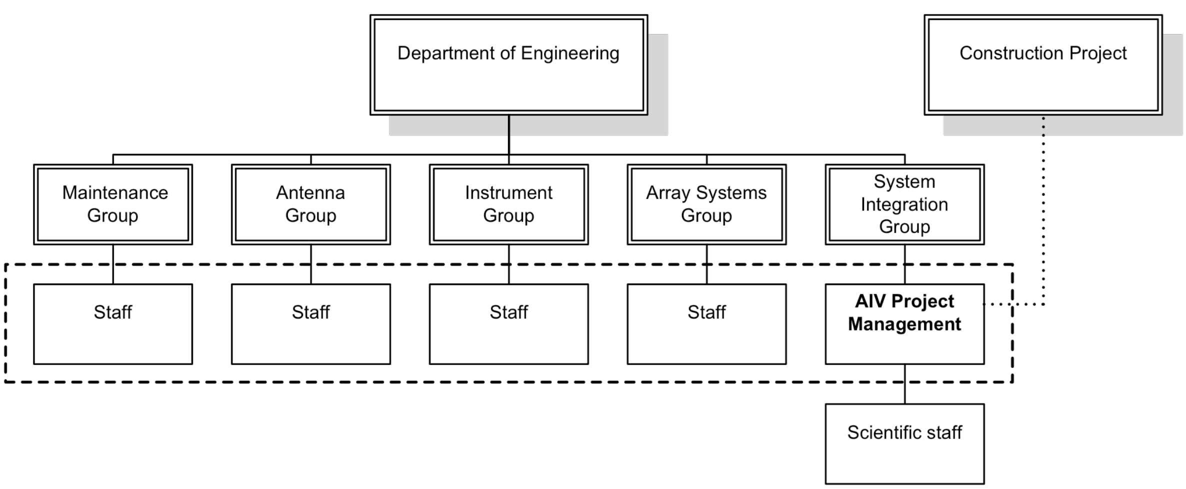

Figure 1. AIV project management via a strong matrix organizational structure.

During this phase the staffing plan was reviewed from scratch considering that by then a lot of statistical information was available for detailed analysis. Consequently, staffing numbers and roles were adjusted, and the AIV budget was aligned accordingly. Energy was put into achieving a fully staffed organization [2] in order to be prepared for the upcoming steady-state series processing workload.

Regarding the transition towards routine processing, it was also necessary to change the staff's mindset: staff had to move from event-driven activities towards repetitive routine tasks. Here the development of detailed procedures, and the enforcement of their precise application, helped to steer this transition. On the other hand, the contemporary increase of upgrade and corrective maintenance tasks related to the already delivered AEs introduced new challenges in diagnostics expertise and front-line support.

Interactions with the Systems Engineering [3] group were tightened, and processes related to acceptances, non-conformances, and upgrades or retrofits were tuned and improved. Also, first steps towards a more systematic quality management approach were undertaken, resulting in preparations for internal quality audits and further efforts on completion of all AIV procedures. But, efforts on quality management might have started too late to become effective already for the earlier processing stages. It is believed that a thorough review of quality management at the initial preparation phase might have been an asset in order to maximize its impact on the highest possible number of processed AEs.

The described transition occurred over a period of roughly one year (2010), and while processing eight additional array elements, i.e. at an average pace of 0.7 AEs/month, tracking the limited supply rate.

2.4 Steady-state Series Processing

By early 2011 infrastructure, staff numbers and competence levels had been established in order to support a processing throughput of 1.4 AEs/month, and efforts were underway to increase this to the ultimate target of 2 AEs/month by September that year. Capacity for up to six array elements in different stages of the workflow related to the AIV 4-station processing model [4][5] had been generated.

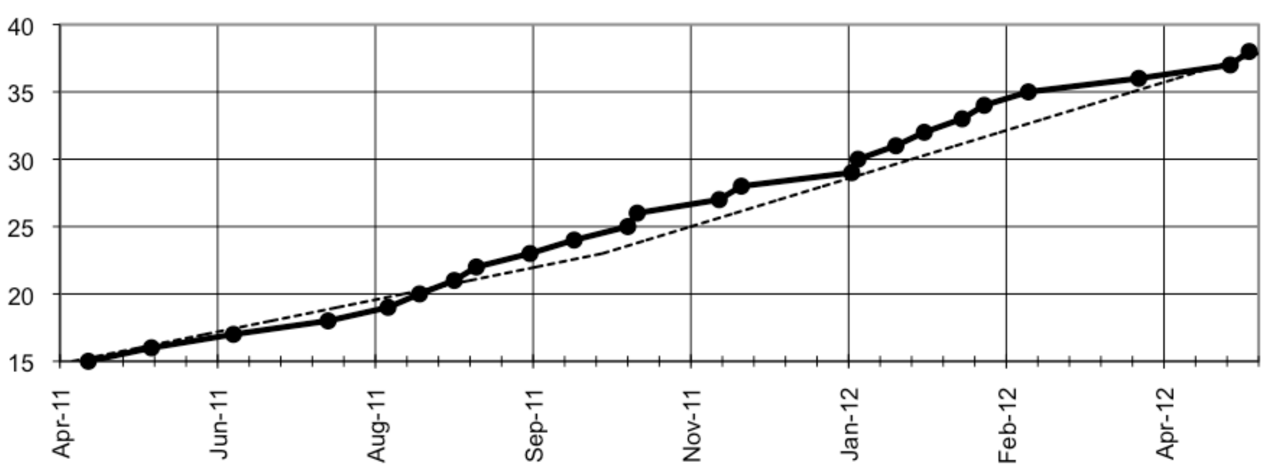

Figure 2. Actual vs. reference (dotted line) delivery dates of array elements in the period May 2011 – May 2012.

Figure 2 shows the reference processing schedule and the actual progress accomplished during this phase. As can be seen, the targeted throughput rates were achieved and even exceeded, so sometimes allowing for schedule contingency building up. However, also in this phase the main schedule driver for integration is the sub-system suppliers' deliveries. To a lesser extent technical failures, incidents, or bad weather episodes have had an impact on the series-processing schedule, but can usually be absorbed by the individual AE schedule contingencies.

In case of longer lasting repairs or trouble-shooting campaigns an AE would be isolated, meaning its priority would drop and the next antenna would use its slot. Later on the AE would re-enter the processing line as capacity opens up, thus avoiding an impact on the whole processing line.

During steady-state series processing schedule risks are being monitored periodically and mitigation actions are triggered when potential impasses are identified. In some cases external IPT staff or contractors are able to fill in specific resource gaps; in other cases shipments would be expedited in order to avoid or minimize schedule slips. As problems with the supply chain or with acceptance testing could potentially delay the whole production schedule enough budget contingency is kept in order to be able to effectively and quickly address risks as soon as they are identified, assessed and analyzed.

As part of the risk assessment, schedule simulations showed to be a useful tool to evaluate the impact of different scenarios. Even when risk monitoring required significant attention in the early stages of this phase it became less and less relevant as tests became automated, more competent staff became available in house, and the IPTs' deliverables production stabilized so increasing stock levels at the OSF. An area of permanent concern is the limited availability of spare parts at the site as many of those were supposed to be delivered only at the end of the respective production lines. With hindsight it would have been an asset to plan for progressive deliveries of spare parts during the earlier construction phases, so allowing for effective corrective maintenance and reasonable lead times.

Series processing activities' scheduling is maintained on three, interacting levels: long-term, project-wide planning performed by the ALMA project management office [6]; a medium-term schedule for the AIV project; and weekly short-term plans applying a success-oriented approach in order to allow for effective and efficient use of the available resources. The latter does not consider relevant schedule contingency in order to avoid unnecessary idle times, but does consider and illustrate detailed dependencies between the different activities. Per-group to-do lists are extracted and distributed in order to provide additional information for the functional line managers with respect their groups' overall workload.

When Early Science observations started in September 2011 it became clear that Operations activities would have to be assigned increasing levels of priority. In order to allow for control and dynamic adjustment of priorities weekly meetings were established where stakeholders would agree on a priorities baseline for the next seven days. Coordinators would then use this baseline in order to keep the day-to-day activities in line with the overall project priorities. We believe that this pragmatic approach demonstrated its effectiveness within the context of an organizational matrix structure.

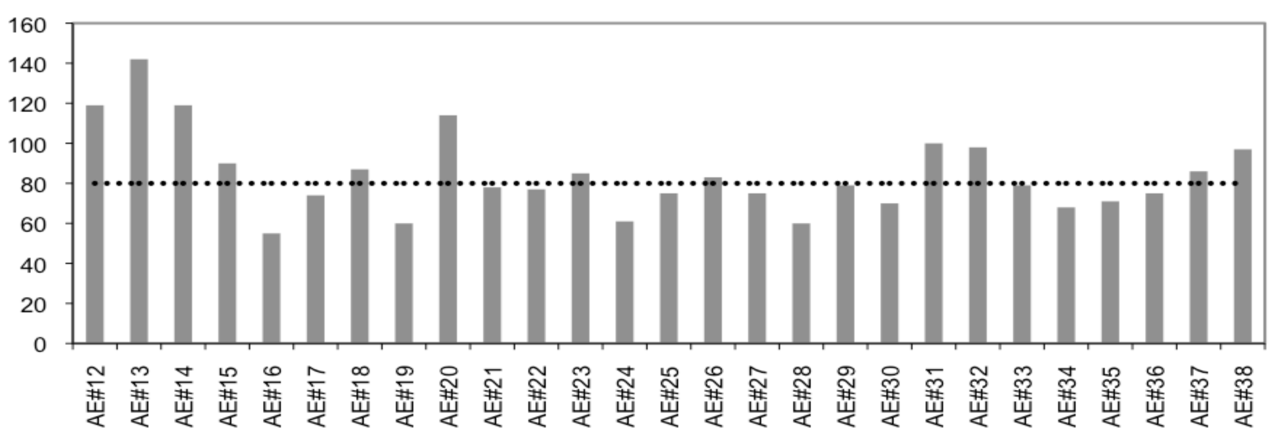

Figure 3. On-time performance indicator of the steady-state series-processing phase.

Quality of workmanship, but also project indicators like on-time performance and opened vs. closed non-conformances, are being monitored and controlled together with the Product Assurance and Systems Engineering groups. As an example, figure 3 shows the processing on-time performance achieved in the period February 2011 till May 2012: while the overall processing duration initially exceeded the target of 80 days it could usually be met from array element #16 on.

In general, the concept of continuous improvement was pursued as an underlying quality principle, meaning that whenever technical, performance, or process issues are identified these would be analyzed and, if applicable, corrective actions defined and implemented.

During the first eight months of this phase AIV delivered a total of 11 AEs at an average throughput pace of 1.4 AEs/month. Due to the acceleration and stabilization of subsystem deliveries at that point the throughput was increased to the target level of 2 AEs/month, allowing for processing of 16 additional array elements in another 8-month period. At the time of this publication AIV has accomplished 58% of its scope with the delivery of 38 out of the 66 ALMA array elements to the AOS.

2.5 Path towards Completion and Closing

The outlook for the remainder of this year is to keep up routine series processing and carefully monitor and control related variables, including subsystem delivery schedules and risks. When approaching 75% of completion another iteration of the staffing and budget plans is anticipated. In preparation for the closing phase of the AIV project the status of annex deliverables like e.g. verification reports, procedures, and hand-over of test equipment is being reviewed and resources are assigned in order to ensure timely readiness. It is expected AIV to conclude towards the end of 2013.

3 CONCLUSIONS

The AIV project follows a four-phases life-cycle in order to accomplish series processing of ALMA array elements: initial preparations and processing pilot phase; transition towards series processing; steady-state series processing; and a closing phase. These project stages represent a progressive elaboration of the series processing approach, and combined with phased and iterative planning this technique helped AIV to achieve deliveries on schedule and on budget. Figure 4 illustrates these phases in combination with the effectively accomplished delivery schedule and relevant ALMA milestones. Note that the project management processes have not been detailed as considered implicit to each stage.

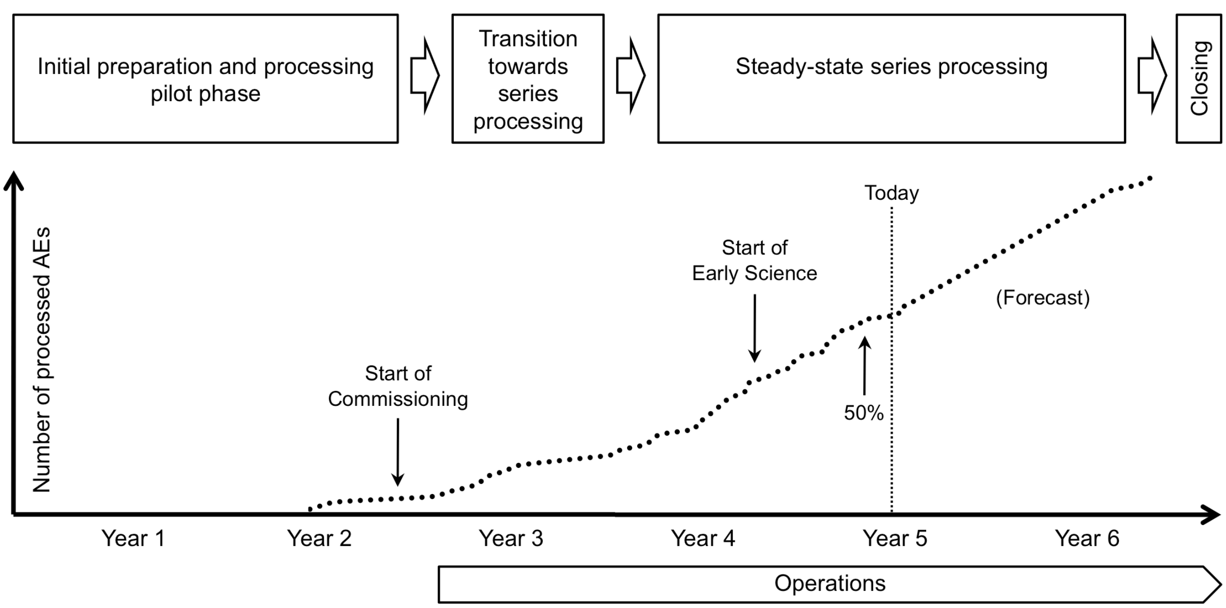

Figure 4. The four-phases life-cycle of the ALMA AIV project.

The first phase aimed at preparations and on demonstrating that assembly, integration, and verification of array elements could be engaged. Here progressive elaboration and phased planning helped to focus on short-term results while keeping the long-term project milestones in sight.

The transition phase then concentrated on further improvement of processes, leveling of staffing and competences, and stabilization of infrastructure, among other aspects. Here the investment in stabilization of all possible underlying variables, including associated risk management, paid off as later on attention could be given to the remaining, unavoidable processing issues. Related to quality management, with hindsight it would have been an asset if related efforts had started much earlier than effectively pursued, i.e. during the prior preparation phase. An organizational change of AIV from a functional into a strong matrix structure, embedded within a single organization, allowed coping with up-ramping operations activities, and proved to be workable and effective.

In steady-state series processing the main schedule driver is the delivery pace of the different subsystems; specific faults, incidents, or bad weather events can usually be absorbed by the individual array element's schedule contingency. Permanent monitoring of and timely reacting to schedule risks is considered a crucial aspect in this phase. Due to coexisting construction and operations tasks a mechanism for periodic reviews of priorities was established that helps to maintain effective matrix organization.

Even if there are many opportunities for improvement it is believed that the presented project phases and practices have demonstrated by now their effectiveness for ALMA. At the time of this publication the AIV project has successfully integrated, verified and delivered 58% of the array elements to ALMA. Completion is expected towards the end of 2013, after an overall project duration of six years.

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This paper is dedicated to the memory of our ALMA colleague Professor Koh-Ichiro Morita.

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