ALMA Assembly, Integration and Verification: Overview and Work Plan

SYSE.85.01.00.00-001-A-PLA

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1 Overview and Context

This document describes the guiding principles and organization for the Assembly, Integration and Verification (AIV) phase in the realization of the ALMA array telescope.

The work of the AIV phase brings and assembles together in Chile the major subassemblies into an array telescope, it verifies that the array telescope meets specification and interfaces, and it hands the product over to the Project Scientist for Commissioning and for Science Verification. Development and delivery of the major subassemblies, as defined in RD 05, are the responsibility of the development IPTs under resource management of the regional executives. This document seeks to clarify the interaction and responsibilities between AIV and the development IPTs and those between AIV and commissioning. In that AIV will happen during a period in which operations capabilities are also coming on line, this document also seeks to clarify the interaction and responsibilities between AIV and operations.

The ALMA observatory passes through five distinct phases on the journey from a scientific case and justification to an operating observatory. These phases, although overlapping each other in schedule, have different characteristics and objectives. The five phases are

   a)  System Design Phase, in which a) the funded science case is expressed as a set of technical requirements, b) an overall design architecture is developed and is partitioned into subassemblies and development tasks (including software components), c) technical specifications, interface control documents and statements of work are prepared for each subassembly and development task, and d) the work distributed among the IPTs.

   b)  Development Phase, in which each of the subassemblies or development tasks are completed and verified by the IPT developers to meet the ICDs and specifications. In the context of this AIV document, Prototype System Integration is a part of the Development Phase and happens prior to the start of AIV in Chile.

   c)  Assembly, Integration and Verification Phase, in which a) the verified subassemblies are brought together at the observatory site, b) integrated into an array, and c) verified by the Project Engineer to meet the stated requirements,

   d)  Commissioning Phase, in which verified array telescope is used by the Project Scientist to validate, to exercise, and to measure the characteristics of, the observing modes into which the array would be placed to perform the stated science objectives, to demonstrate that the array meets its high-level science requirements, to document and train operations staff, and to confirm the end-to-end availability of the observatory, from proposal preparation to final data distribution.
e) Demonstration Science, in which the user community is engaged in demonstrating the ability of ALMA to produce science. Demonstration Science phase, although distinct in objectives from Commissioning, will broadly run concurrently.

In the previous description, the words array and telescope synonymously refers to the hardware, software and infrastructure at the OSF and AOS that, as a system, gather astronomical data and produce raw data files. The word observatory is used to encompass all services and processes seen by the scientific user and provided by ALMA to enable scientific investigation. An Observatory includes the ALMA array telescope, the operation of the telescope, any ALMA-provided proposal preparation and submission tools, any ALMA-provided post-processing capability, archives and data analysis support. The word antenna in the following sections is used to describe one relocatable element of the array, and as such includes the integrated assembly of antenna structure, mount, subreflector and ancillary systems, front end and back end electronics.

The remainder of this document will examine the AIV Phase within the above context.
2 Reference Material

2.1 Applicable Documents List (ADL)

The following documents, of the exact issue shown, form part of this document. In the event of conflict between the documents referenced here and this document, this document shall take precedence.

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2.2 Reference Documents List (RDL)

The following documents provide reference material to this document.

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2.3 Definitions, Abbreviations and Acronyms

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<td>AIV</td>
<td>Assembly, Integration and Verification</td>
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<td>ATF</td>
<td>Antenna Test Facility</td>
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<td>FE</td>
<td>Front End</td>
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<td>FEIC</td>
<td>Front End Integration Centre</td>
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<td>ICD</td>
<td>Interface Control Document</td>
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<td>Integrated Product Team</td>
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<td>JAO</td>
<td>Joint ALMA Office</td>
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<td>LO</td>
<td>Local Oscillator</td>
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<td>M/C</td>
<td>Monitor and Control</td>
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<td>OSF</td>
<td>Operations Support Facility</td>
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<td>PAI</td>
<td>Preliminary Acceptance In-House</td>
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<td>TB</td>
<td>Technical Building</td>
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<td>ZD</td>
<td>Zenith Distance</td>
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3 AIV Objectives and Philosophy

The objectives of the AIV work are:

a) to assemble, integrate and verify the telescope within a managed process which delivers predictable progress commensurate with the antenna delivery schedule, at least overall cost and risk,

b) to deliver to the Project Scientist for commissioning, a telescope which meets the stated specifications,

c) to deliver to Operations an operable and maintainable telescope, including training, documentation and procedures, and

d) to ensure that subassemblies received from the IPTs are of uniform and high quality, and to maintain that quality standard through the AIV process.

The philosophy adopted to meet the above objectives includes following elements:

a) Subassemblies are formally verified to meet their functional and performance characteristics, as far as is possible, before being shipped from the developer IPT,

b) The ATF is used as a test range to verify riskier system level characteristics and to test system level control and analysis software: together these are a work package known as Prototype System Integration (P-SI). Note that the environmental conditions at ATF are different from those in Chile, and that hardware at P-SI, although similar to that of the telescope, will not be complete nor identical to that in Chile.

c) The functionality and performance of the telescope, as well as the ability to operate and diagnose problems on the antennas remotely, must be tested as completely as possible at the OSF prior to relocating telescope hardware to the more hostile AOS environment. In general this means a thorough test of the system as far as can be achieved using the first two antennas in the OSF environment, after which the test capability can be diminished to relocate unique hardware as needed to the AOS.

d) Procedures which will be used to test and verify elements of the telescope at the AOS are developed and exercised at the OSF prior to the period of rapid deployment of antennas. In effect, the antenna work at the OSF will become the advance training field for the phase in which antennas are deployed rapidly.

e) Sufficient capacity (in staff, antenna pads, test equipment) must be available at OSF and AOS that individual problems can be taken out of the queue of antenna integration process, and addressed without causing the workflow to back up behind them.

f) Operational procedures for fault tracking, scheduled maintenance, inventory control, etc. will go into use early in the AIV phase. Further, operations staff will be used to perform routine procedures such as moving and operating antennas during AIV so that they can become trained and familiar with these procedures and can ensure they are correctly documented.
g) The telescope, or elements of the telescope, shall be formally verified to meet their functional and performance characteristics before being handed over to the Project Scientist. In practice some characteristics are best verified during Commissioning rather than during AIV, in which case acceptance would be provisional, and the AIV team would continue to support the resolution of problems uncovered during Commissioning.
4 Standards and Principles of work

The following standards and principles are those which we expect to adhere to during the AIV phase of work. Any individual agreements captured in the Level 1 Statements of Work which differ from what is described here take precedence.

4.1 Acceptance: Flow, and Software Responsibility.

For the purposes of ownership responsibility, every deliverable made from a Level 1 work package (RD 05) are considered to be formal deliveries to the observatory: both those delivered to the observatory in Chile, and those destined to form part of another work package before ultimate delivery to the observatory. For cases where one work package provides equipment to another work package (for example the BE’s digital receivers to the Correlator IPT) the equipment will be taken through formal provisional acceptance by the observatory and then deemed furnished by the observatory to the second work package. In practice the unit would most often ship directly from the first to the second work package once provisional acceptance has been achieved. Once furnished, the second IPT is the custodian of the equipment and responsible for its security, insurance and subsequent shipping costs, but not responsible for any maintenance or rework costs of the furnished unit. It is clearly necessary in such cases for the receiving IPT to participate in the PAI process so that they are satisfied that the product they will take custody of meets their ICD and has all associated documentation and software needed to make it safely operable by the receiving IPT.

In ALMA, the assignment of operational software and hardware to different IPTs create a slightly more complex situation during acceptance. It is the responsibility of the hardware developer to develop associated unique software requirements, and to ensure embedded software is meeting software interfaces as well as both unique and general software requirements. The hardware developer is also responsible for developing higher level control algorithms and test routines which exercise or test the hardware via the defined interface, and which may be implemented with third-party software such as LabView. The software IPT is responsible to provide M/C software which, in addition to meeting its own requirements, provides the same higher-level functionality and meets the same agreed ICD as that developed by the hardware IPT.

The acceptance process, then, would be as follows:

a. The Hardware IPT will achieve provisional acceptance on-site of the hardware and embedded software prior to shipment, with tests and functional checkout performed with the hardware under the control of third-party (e.g. LabView) software.
b. The software IPT (supported by the hardware builder) will then take control of the hardware, and when able to demonstrate a M/C software module meeting requirements and performing the same functionality checkout as demonstrated in a. above, would have that software module provisionally accepted.

c. The hardware and associated M/C module can be shipped to Chile and are registered in the configuration management system.

For the above process to flow smoothly it is clearly necessary for the hardware developer to give early access to the software IPT so that the M/C software can be exercised and debugged prior acceptance tests.

4.2 Acceptance: Standards for the Array

Just as system engineering standards will be applied during the acceptance process for subassemblies, a similar process will be used for the integrated array. In the period prior to the start of AIV, qualification matrices, test plans and test procedures will be developed which address the observatory-level requirements of the array. These documents, once approved, capture exactly what qualification method, what test and what pass-fail criteria are to be used to demonstrate that the array meets the requirements enunciated in the Science Requirements, Technical Requirements and the Calibration Plan. In many cases final proof of meeting a requirement can’t be had until the commissioning phase of work, in which cases a suitable criteria for Conditional Acceptance will be sought to mark the conclusion of AIV. The objective is that when an antenna or assembly of the observatory is released to the Project Scientist for commissioning, it has either met the stated requirements enabling the science, or there is reasonable confidence through component tests that the requirements will be met during Commissioning.

4.3 Configuration management, functionality checks and fault tracking during integration.

Important processes that enable efficient and predictable progress during the integration phase are the use of a) configuration management, b) functionality checks, and c) a fault tracking database. It is anticipated that IPTs will make use of similar processes during their integration phase. The elements of these processes are:

a. Hardware revision number, along with associated release of control software and test routines and configuration documents, shall be tracked in a configuration management database. Any updates to any of those three elements must be verified to be working properly with the other two elements before being put into service. It must be possible to quickly revert to any earlier stable version of software or test routine.
b. Functionality tests are developed for each level of the hierarchical build of the observatory: from modules through subassembly (developed at the IPTs) through assemblies and systems (developed at P-SI and AIV). These tests exercise that the unit under test is functioning correctly, and should give confidence that it is probably also performing correctly. Tests should confirm all hardware functionality (e.g. signals and voltages are in normal range), software functionality (e.g. correct response to commands and correct response to exceptions), and confirm correct operation of all instrument or personnel safety features (e.g. limit switches function correctly and are positioned correctly, all interlocks work). During AIV, every time hardware is installed, disturbed or reconfigured (e.g. moved and re-cabled, serviced, etc.) it shall be run through its functionality tests and results logged.

c. A formal fault tracking system will be used to log, and to track the resolution of, all faults found during the AIV process.

d. The AIV process proceeds in a methodical and hierarchical way, with testing of each added subassembly to achieve its correct operation before larger buildup of the assembly occurs.

4.4 Capturing process for subsequent integrations.

To be able to process antennas rapidly, AIV will need to carefully plan and automate as far as possible the integration and test work for the series run of antennas. The work of doing this preparation is scheduled to happen largely during the integration and test of the first antenna, during which a longer period is available on the antenna delivery schedule.

The integration and of the first two antennas, while conducted in a formal planned manner, is expected to still be a highly interactive and flexible process as the team copes with bringing together new systems in a new work environment. With the experience of that integration, workplans will be revised and punchlists developed so make the integration of subsequent antennas as methodical as can be achieved. The AIV teams will use on-line database software to track the steps of integration, as well as to capture and associate test results with process control points and hardware identifiers. It should be possible for one team to seamlessly hand off a partly-integrated antenna to another similarly-trained team, and have a uniform set of data and test results for all systems regardless which team(s) worked on them.

While the framework of this database will be developed prior to the start of AIV, detailing and testing it will be done during the integration of the first antennas.

We also anticipate taking advantage of the first antenna’s integration to identify any components (brackets, ducting, cables, lines, etc.) which can be measured, mass-
produced off site and made available for subsequent antennas, thereby reducing the time to perform the integration on those later antennas.

4.5 Training and Post-Delivery Support.

In general, it is expected that the development IPTs will heavily support the installation and integration of the first one or two models of their deliverables, with the AIV team learning from the IPTs during that period and taking on subsequent installation and integration. Details of level of support and share of work for each work package are captured in the Level 1 SOWs (see RD 05) and in RD 06.

Training should include the following elements:

a. AIV will, whenever possible, place an AIV team member temporarily within the IPT for the last months of hardware integration and test. It is anticipated this team member would move from AIV on to the operations staff at an appropriate time. *(note that due to budget pressure, the funds available for advance training is restricted and we may not be able to take as much advantage of this form of training as we would like)*

b. The IPT shall lead the installation of the first units at the observatory, which is done in cooperation with the AIV team, and thereby pass on practical knowledge on the operation of the unit.

c. The IPT will give the AIV and Operations teams a formal short course in the design and maintenance of their equipment, accompanied by the user, operation and service manuals.

d. Sufficient quantity and quality of documentation is delivered from the development IPTs that, with the assistance of remote or on-site support as needed from experienced IPT members, the depth of AIV staff training need not be onerous.
5 Workflow

The details of AIV and also of Commissioning are developed in RD05, which is the source for the AIV area within the Integrated Product Schedule. Here we present a broad overview and explanation of work detailed in RD05.

For planning purposes, the AIV work has been organized into four distinct areas. The first is that of establishing AIV support infrastructure at the OSF and the AOS. Second is the work of receiving, integrating and testing all common technical capability. Third, and often happening concurrently with the previous area, we have the work of receiving subassemblies for the first two antennas, integrating them and qualifying the integrated design. Last, and largest, is the production work of processing and delivering all remaining antennas to the commissioning team.

Each of these areas is discussed in more detail below.

5.1 Observatory support infrastructure

In the initial phase of work, infrastructure needed to perform AIV are installed and/or qualified. The infrastructure expected to be in place include buildings, on-site roads and vehicles, computer support infrastructure (network, telephone, videocon, switches and routers, servers), power, site monitoring, safety services, logistic support, warehousing, holography tower(s), prototype correlator and RF test sources, technical configuration and maintenance database(s). During this phase the AIV will outfit the technical labs in preparation for the first subassembly deliveries. Also during this phase, support vehicles should be delivered and accepted: the antenna transporters and the FE service vehicle. In almost all cases, the work of installing and checking out the above services is provided by the source IPT.

5.2 Qualification of common technical capability

This phase of work qualifies all the common technical capability: that is, hardware and software which participate in an astronomical observation, but which are in common to many or all antennas. In most of these cases too, the work of delivering, installing and checking out these services is provided by the source IPT.

These subsystems include the core ALMA software system installed initially at OSF and later extended to AOS, weather stations (OSF and AOS), correlator, central LO, control room equipment, antenna pads.
5.3 Qualification of first two antenna interferometer

One of the more exciting times in this project will be when the first, and a few months later the second, production antennas are delivered by the contractor, integrated into telescope elements and tested on the sky. The work of integrating and testing the first two antennas is shared between the delivering IPTs and the AIV team, with much of the work and knowledge in installing and checking out a subsystem provided by the IPT, while the AIV team learns about it. The delivering IPTs are expected to participate heavily during this phase, both on-site in installing equipment and providing training, and remotely in helping resolve technical problems.

The work undertaken prior to delivering the antennas to the AOS has three objectives. It strives to qualify, as far as is possible, the design of the antenna – both as a single total-power unit and as an element of an interferometer. It also serves to establish and exercise the procedures which will be needed by the integration teams during the production phase. Finally, it develops and exercises procedures which will be used to test the antennas once they arrive at the more hostile AOS. For that latter reason, the OSF checkout during this phase will use, as far as is possible, the same control room, network, data reduction, etc. that operators will use when controlling an AOS antenna: it is as much the software, procedures, infrastructure and training which are being exercised as the telescope performance.

Bearing in mind the need to be flexible during this phase, as things aft gang agley, the baseline plan takes the first and then the second antennas through the following steps:

a) The antenna performance is characterized. This includes setting the surface, measuring optical pointing, servo performance, robustness after moving the antenna, installing nutator.

b) The ALMA equipment is added to the antenna. The cabling will be installed and terminated (subsequent antennas will be cabled up by the contractor, terminated by ALMA), FE and BE installed, systems checked out to be functional in total-power data from the control building, $T_R$ measured.

c) Total power tests are made of the antenna. These include gain calibration, beam profiles, radio pointing, solar linearity and loading, and some early measure of surface performance vs ZD: out of focus maps or beam cuts on astronomical sources.

For the first antenna, this work is planned to take almost all the 10 months needed for the gestation of a second antenna. Once that second antenna is available, it will go through a condensed and much more rapid series of the above steps. Once the second antenna has reached a similar state of development, both antennas move on to the following step.
d) Interferometric functionality tests of the antenna pair. In this step, we will confirm autocorrelation of each antenna using a weak artificial line source, get fringes from the antenna pair, confirm fringe tracking, measure phase stability, confirm reasonable efficiency, and measure the surface of the antennas using sky holography.

e) Move the antennas to AOS, and move central LO to the AOS TB. The correlator, on its current and successful schedule, will already have been installed at AOS TB many years before. It will probably be necessary to brush away the cobwebs from it and try to remember where that startup checklist was last seen.

f) Confirm antennas are still functioning properly, and measure pad characteristics. This includes pad-based electrical source impedance and pointing measurements, confirming LO and digital transmission are robust, confirming beam profiles remain the same, sweeping for interference from the TB or antenna equipment. Many of the total power tests can be repeated, for example a measure of T_{sys} is now possible in every band. As much as possible these tests are conducted from the OSF. And finally,

g) Verification of 2-element interferometer. In this last set of checks before starting commissioning, we would again get fringes, confirm LLC and phase tracking are functional, confirm WVRs are functional and within reasonable ranges, measure that phase and amplitude stability are as expected, interferometric pointing and focus, ensure on-the-fly mapping and fast switching are functional.

In the background, and as described in the next section, antennas 3 and 4 will already have been substantially processed, taking advantage of knowledge and experience from the first two. It is anticipated that antennas 3 and 4 will be ready within weeks of the first two.

h) Hand antennas over to the Commissioning team, and support resolution of problems they uncover.

5.4 Processing Production Antennas

From antenna 3 onwards, processing of antennas takes place in structured a manner structured akin to an assembly line.

Antennas, assumed to be arriving with an initial 31 day delivery period and accelerating later in the delivery schedule, are taken through four integration stations S1 through S4 before being handed over to the Project Scientist for commissioning. Each station performs a restricted set of the tasks performed on the first two antennas above, taking advantage of the philosophy that one need only repeat measurements on each antenna for qualities which need to be characterized (e.g. T_{sys}), adjusted (e.g. surface shape),
properties related to safety, characteristics which are marginal and challenging or properties which may have changed as a result of any process change by a supplier. It is expected that with experience many of the performance tests will be skipped during AIV, accepting the informed risk that occasional flaws will be delivered to Commissioning and will be identified and rectified later.

The first station S1, located at one of the inner OSF pads, deals with testing the antenna structure itself. In particular, the team at this station would install the holography receiver, move to the dedicated holography pad, perform surface holography and set the antenna surface. Optical pointing tests are performed at this station, either at the holography pad or one of the other outer pads. When the surface is set satisfactorily and mount control is performing correctly the antenna is returned to the home S1 pad, the holography receiver can be removed and nutator installed. If necessary (although not planned at the time of writing) photogrammetric measurement of the surface shape as a function of zenith distance would be performed at S1.

The distribution of antenna acceptance tests between the contractor and the ALMA station S1 are still being consolidated; the detail of the above description will evolve.
The team at the second station S2, located at a different inner OSF pad, installs onto the antenna and tests ALMA-provided equipment. They terminate contractor-laid cabling, install the FE subsystem and antenna-based BE racks. They would clean and run up the cryogenic system, install the LO fibre wraps and LO fibre. Once equipment is installed, the S2 team verify the correct functionality of the integrated antenna by means of control from the OSF control building. The S2 team is also responsible for performing post-shipment tests on arriving FE and BE subsystems at the OSF labs.

Figure N: OSF location of AIV stations
The third station, S3, is located at one of the outer pads where the antenna can have access to the sky. At this station the antenna is given an operational shakedown to ensure that systems on the single antenna are working correctly before delivering it to the AOS. Tests include solar loading tests, solar linearity tests, functionality of on-the-fly mapping and data acquisition, fast switching, subreflector position vs ZD, samples of beam profile vs ZD, radio pointing. After checkout at S3, the antenna will be moved to S4 at the AOS.

Station S4 is any known calibrated pad at AOS, and although the antenna will be located at that station the crew performing this work will largely be located at the OSF. The objective of this station is to confirm the antenna remains properly functional after its trip up the road, and to ensure it operates as a member of an interferometer array. Tests here include checking pointing, checking autocorrelation is working correctly, quick sweep for interference, confirming cross correlation with another antenna is functional, measuring beam profile at the highest frequencies, ensuring WVR is functional and amplitude cal devices are functional and measuring Tsys.

When checkout at S4 is complete and qualification results are approved by the Project Scientist, the antenna is handed over for Commissioning.

It is anticipated that the routine work of processing antennas through stations S3 and S4 will be taken over by Operations staff after the first few antennas have been processed by AIV staff.
6 Staffing Plan for AIV

6.1 Organization

Following is a tentative plan for the organization of the AIV staff. Shown are the initial two integration teams which would be in place during the first year of AIV. A third and fourth team are planned to be added in time to be trained are ready to process the rapid arrival of antennas.

The team is divided as follows:

Configuration Control team:
- Based at SCO, regular work week.
- Provides support for document management and configuration control of hardware and software.
- Develop the AIV database described earlier.
- It is anticipated this team will be fully staffed for about 18 months at about the time of the first antennas, the diminishing to one or two persons during steady state.

Integration teams:
• Based at OSF, scheduled on turno, nominally 8/6 during the production phase but other schedule scenarios are possible before production phase.
• Initially one team would handle infrastructure and common technical capability, the other team would handle first antenna. Eventually both move onto antennas. A third and fourth team are added at about the start of rapid antenna delivery (currently that is nominally antenna #2) to maintain throughput in processing the antennas.

Testing Lead Scientist:
• Small team of instrumental scientists and engineers, based at SCO, regular work week.
• Augmented by staff borrowed from the IPTs (perhaps remote participation?) in the work up to Early Science, then diminish to 1 or 2 people.
• Responsible for analysing results as needed, developing performance test processes and data reduction for tests which will be repetitive, reviewing and signing off on results from the integration teams.

6.2 Staffing Actions

A policy for hiring local staff in Chile is still under development at the Regional Executives. The following description assumes one of the possible hiring models: that both Executives directly employ the local staff stationed in Chile.

AIV staff, while reporting directly or via chain of command to the JAO, are provided by the two executives in a manner similar to that used in matrix management. In addition to the line managers shown here, each person should have a personnel manager to whom they report in their respective executive, for human resource activities such as staffing, promotion and performance appraisal.

The AIV staff will be made up to the maximum extent possible of local staff. International staff will be used in cases where it is clear that suitably trained and experienced individuals for a particular post cannot be recruited locally.

AIV staff will be engaged by either executive upon request by the JAO, assuming the cost of that staffing action is within the budget assigned to AIV. In general, it is the intention to engage a very small number of AIV staff early (one or two persons, on site 12-18 months before commencing AIV) to prepare detailed planning. The early staff would also help to recruit the next, larger, wave of AIV staff as the approaching work demand becomes evident and deliverables imminent (on site or at IPT about 6 months before start of major AIV work).
It is anticipated that some of the Operations staff will be recruited from the trained AIV staff, especially in technical management, technical maintenance and software areas.

7 Interface with Operations

Details on the assumptions for what Operations will provide in support of the AIV effort are found in RD07. Broadly, the major items expected from operations are all normal-pattern vehicles, all maintenance, staff for Integration Stations 3 and 4 from antenna #8 onward.