Atacama
Large
Millimeter
Array

ALMA Commissioning and Science Verification Plan

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Change Record

Version	Date	Affected Section(s)	Change Request #	Reason/Initiation/Remarks
A	2004-02-28			Initial version
B	2004-09-03	All		Redraft incorporating comments from R. Lucas, D .Emerson and M. Holdaway.
C	2006-09-07	All		Complete rewrite, incorporating interfaces to AIV, rebaselining and trilateral ALMA. Included estimates of schedule and manpower.

Table of Contents

1 Description

1.1 Purpose

This document provides an overview of the commissioning and science verification phase of the ALMA project. It describes the scope of the activity, including its relation to Assembly, Integration and Verification and to Operations. It also gives an outline of commissioning activities, concentrating on the period up to Early Science. Staffing, resources and support required from Operations and construction IPTs are also considered briefly.

1.2 Definitions

Assembly, Integration and Verification (AIV) is a construction activity led by the JAO Project Engineer. The primary AIV tasks are to assemble and integrate the major ALMA sub-systems into a working system, establish its initial technical performance and ensure it meets stated *technical requirements*. AIV will then continue until all antennas are accepted from the contractor, outfitted and integrated into the array. It includes single-antenna activities (e.g. fitting out of antenna) as well as system-wide activities.

The purpose of the **Commissioning and Science Verification (CSV)** activity is to test and optimize the elements of the ALMA system (e.g. an antenna, new correlator mode, receiver or software component) and to ensure that its meets the *scientific requirements*. It is led by the JAO Project Scientist. The CSV phase starts when the mode or component is handed over by AIV and ends with acceptance on behalf of the ALMA operation.

The CSV phase is currently defined to begin with the handover of a verified 3-element interferometer from AIV to CSV. This marks the transfer of responsibility from PE to PS, but there is a significant overlap in personnel and techniques.

The principal outputs of CSV are:

- operational procedures and documentation for operation of ALMA as a science facility, including end-to-end data management.;
- reports documenting as-built performance, exceptions, recommendations for improvement and test data, including
- a verification matrix showing the performance of ALMA as measured against the science requirements.

Throughout the commissioning and verification, the CSV team will devise and accumulate software scripts and procedures for the ALMA operation, test procedures and data, reference observations and reduction scripts. The aim is to maintain complete as-built documentation for the commissioned modes for operations and commissioning staff as well as users. Extensive use will be made of the archive, both astronomical and monitor data.

Commissioning and Science Verification are carried out by the same team, but are differentiated as follows:

Commissioning covers initial testing, interaction with AIV and other construction IPTs to identify and resolve faults, optimization, training of Operations staff and documentation.

Science Verification (SV) is an end-to-end test of an ALMA mode done using a science project proposed by a user who may be outside the CSV team. It is part of the activity of the team, done to verify and document the performance of a particular mode. It is an incremental activity, as new modes will be added continually. It tests the end-to-end system, from proposal submission to final science. Data are made public immediately after quality assurance is complete.

ALMA Public Images (API) are large-scale projects whose primary intention is to convince the wider community and general public of the value of ALMA. They are produced as part of the SV process. [1]

Early Science (ES) is defined in this document to be the first operation of the array for observations proposed by users in response to a full, open call for proposals. The capabilities of the array will be restricted at this stage. The call for proposals is necessarily issued well in advance of the start of Early Science

The present document provides an overview of commissioning and science verification in Chile. It does not cover activities at the ATF, except to make recommendations about training of the CSV team. It is primarily concerned with the period up to Early Science, but the principles proposed have continuing application.

Proposal management, except for the special case of science verification, is not part of CSV.

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[1] These definitions of Science Verification and ALMA Public Images were agreed by the ASAC at its October 2005 meeting.

2 Related Documents and Drawings

2.1 References

ALMA-00.00.00.00-002-H-PLA	ALMA Operations Plan
ALMA-10.04.00.00-001-A-PLA	ALMA Project Plan
ALMA-90.02.00.00-004-A-SPE	First Science Configurations
VLT-PLA-ESO-10000-0937	Very Large Telescope Commissioning Plan
	VLT Science Verification Policy and Procedures
	ALMA Operations Budget Update (Version A6)
ALMA-80.04.00.00-005-B-SPE	ALMA System Technical Requirements

2.2 Abbreviations and Acronyms

AIV	Assembly, Integration and Verification
CSV	Commissioning and Science Verification
ES	Early Science
ESDP	Early Science Decision Point
SV	Science Verification
WVR	Water vapour radiometer

2.3 Glossary

3 Planning assumptions

3.1 Location

The CSV team will work primarily at the OSF, with significant participation from SCO and specialists located elsewhere. Work at the AOS is not anticipated except under special circumstances.

3.2 Equipment available

The assumptions of this plan are that receivers for the following bands will be available when the antennas are handed over for commissioning:

3	84 - 119 GHz
4	125 – 163 GHz
6	211 - 275 GHz
7	275 - 370 GHz
8	385 – 500 GHz

9 602 - 720 GHz

The first few (TBD) antennas may lack Bands 4 and 8. In addition, water vapour radiometers are assumed to be mounted on all antennas.

The plan includes ALMA-J and ALMA-B antennas. It is anticipated that at least the first 3 and possibly all 4 of the ALMA-J 12m antennas will be used for initial interferometric commissioning using the ALMA-B correlator. Continuum total-power commissioning will be primarily with these antennas. When the first ACA 7m antennas and the ACA correlator arrive, the ALMA-J 12m antennas will be used increasingly for ACA commissioning, but will retain their total-power role.

A limited number of correlator modes will be supported initially, starting with those tested at the ATF and commissioned in an order based on scientific priorities and equipment availability. The default modes used at the ATF are as follows:

Table 1: ATF correlator configurations

Bandwidth	Single polarization	Dual polarization	Full polarization
2 GHz	256	128	64
128 MHz	2048	1024	512
31.25 MHz	8192	4096	2048

Note that the ALMA correlator will support some modes (e.g. 4-bit) not available at the ATF. The full capability of the Tunable Filter Bank (TFB) is assumed to be available.

Further details, as well as the requirements for back-end, correlator, computer hardware and software vary over the commissioning programme, and are outlined below.

3.3 Initial antenna configurations

Initial commissioning will be done with the first antennas in a close-packed configuration in order to keep baselines short and minimize atmospheric phase errors. The first 3 antennas will form the innermost triangle of the configuration proposed in “First Science Configurations”. Antenna 4 will initially be positioned close to the first 3, and will then be moved out to a distance ~200m to allow initial evaluation of atmospheric phase errors. Antennas 5 and 6 will complete one of the outer triangles. Very limited reconfiguration will occur during early commissioning.

3.4 Commissioning phases

The early AIV and CSV activity in Chile falls naturally into six phases, leading up to Early Science. These are:

1. single antenna at the OSF;
2. single-baseline interferometer at the OSF;
3. single antenna at the AOS;
4. single-baseline interferometer at the AOS;
5. close-packed array (antennas 1-4);
6. early science array.

The first four activities are included in AIV; the last two are part of CSV.[2] Thereafter, there will be ongoing CSV tasks leading up to full science operations.

3.5 Early Science

The precise definition and start date of Early Science are currently under discussion, but it is anticipated that that a formal call for proposals and the start of Early Science will both occur in 2010. As a result of rebaselining, changes to the antenna delivery schedule and the formation of the trilateral ALMA Project, many of the planning assumptions inherent in previous discussions of Early Science and Commissioning are now incorrect. In particular, the rate of handover of antennas to the CSV team has greatly increased, and the amount of equipment to be commissioned is significantly larger, including two additional receiver bands and the ACA 12m and 7m antennas. The long period required for the first formal proposal call also required a decision on the modes to be offered for Early Science to be made very soon after the start of CSV, before adequate knowledge of system performance could possibly be acquired.

For these reasons, the present document describes a model in which the delay between the start of commissioning and that of Early Science is significantly longer than the 12 months anticipated previously. The specific model is neither definitive nor formally approved, but is consistent with:

1. current Operations planning;
2. the bottom-up analysis of time required for commissioning as given below and
3. the recommendations of the ASAC (at least qualitatively).

The specific straw-man performance assumed for ALMA at the start of Early Science is as follows:

1. At least 16 antennas fully commissioned (there are likely to be more in the process of being integrated into the array, or with partial capability).
2. Receiver bands 3, 4, 6, 7, 8 and 9.
3. Interferometry in single-field or mosaic mode.
4. A significant (TBD) range of correlator configurations, including use of the Tunable Filter Bank.

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[2] In addition, there are preparatory activities at the prototype interferometer in Socorro.

5. Circular and linear polarization, although not high-fidelity mosaics.
6. Single-dish operation in mosaic (position- and beam-switched) and on-the-fly modes, including the ability to combine with interferometric data.
7. At least two subarrays operational simultaneously.

Clearly, trade-offs are possible between capability and time-scale.

It is assumed that further dedicated commissioning activities will be interleaved with science operations from the start of Early Science, and that both will be scheduled in relatively long periods (>1 week), as described in the Operations Plan. At this point it is likely that a test subarray will be used to allow integration of antennas into the array in parallel with normal observing.

3.6 Milestones

The CSV and Operations Plans are tied to major construction project milestones. Of these, the most important for commissioning are:

Table 2: Milestones

Code	Description	Increment on CSV (months)
2bl	Single-baseline interferometry at OSF	CSV - 7
Ant-1A	Antenna 1 AOS checkout	CSV – 6
3ant-A	Antenna 3 AIV move to reference pad A1	CSV – 1
CSV	Start AOS 3-antenna interferometry for CSV	
EDSP (old)	Decision point for Early Science	CSV + 3
EDSP (this document)	Decision point for Early Science	CSV + 12
ES (old)	Start of Early Science (EDSP + 10months)	CSV + 13
ES (this document)	Start of Early Science (EDSP + 8 months)	CSV + 20
16ant	16 antennas available for CSV	CSV + 15
32ant	32 antennas available for CSV	CSV + 30

It is currently anticipated that CSV will start in 2008Q4.

4 AIV Tests

This section briefly outlines the tests which are scheduled to be carried out as part of the AIV programme. Although not formally part of commissioning, they are closely related, and provide an opportunity for the CSV team to gain familiarity with the system.

4.1 Prototype Interferometer

It is important that the CSV team gains experience with the components of the ALMA system before moving to Chile, so they should participate in tests with the prototype interferometer in Socorro. Although many of the components (including the software) are prototypes, this is sufficiently similar to the final system that significant time will be saved during commissioning in Chile. Activities include, but are not limited to:

- Optical pointing
- Holography
- Radio pointing
- Basic interferometer operation
- Tests of calibration procedures
- Initial calibrator survey

The feasibility of training a significant fraction of the CSV team of at the ATF is open to question, and it will probably be more effective for a small number of members of the Science IPT to work with the PSI team at the ATF and then to train the remainder in a more formal way off-site.

4.2 Antenna acceptance

The CSV team should also participate in test and evaluation of the antennas at the OSF, again with the primary aim of gaining experience prior to operation at the AOS. Specific activities prior to acceptance are:

- Pointing tests with the optical telescope
- Holography
- Antenna motion tests

4.3 Single-antenna AIV

The aim of the commissioning process for the first antenna is to verify that the individual antenna and receivers meet their specifications for continuum observations.

Equipment available:

Antenna 1
Nutator (Note: if this is not available, then some alternative switching device will be required for continuum radiometry. An alternative method for pointing experiments would be to use line sources, which would require the full back-end and correlator).
Optical pointing telescope
Receivers (at least one band, preferably all four)
Back-end to include IF total-power detectors
Hardware and software to allow single-antenna operation

An outline of the test programme is as follows:

4.3.1 Basic operation of antenna and receivers

- Band 3
- Higher frequencies in turn, as allowed by the lower site

4.3.2 Focus and collimation

- Measure best focus by offsetting subreflector and maximizing signal.
- Check focus stability
- Measure dependence of focus and collimation on elevation and temperature

4.3.3 Surface accuracy

- There are no plans at present to measure the surface of a single antenna by astronomical test at OSF, but phase-retrieval holography could be considered.

4.3.4 Pointing calibration

- Note: this assumes continuum radiometry, hence the requirement for the nutator.
- Develop initial pointing model based on the initial model derived with the optical telescope. Initially, use Band 3 continuum.
- Check dependence of pointing model coefficients on environment (solar loading, temperature as measured by sensors, tiltmeters, …..).
- Collimation offsets for all bands. Variations and stability.
- Test metrology equipment supplied by antenna manufacturer and evaluate the need for additional measurements and incorporation into the antenna control system.
- Verify blind pointing accuracy
- Verify offset pointing accuracy (not to full accuracy)
- Verify step reponse; tracking stability under various wind conditions

4.3.5 Primary beam

- Measure beam map, large enough to include the first few sidelobes, for all available bands.
- Test stability and dependence on elevation of main beam gain and width, sidelobe pattern and sky/ground noise.

4.3.6 Gain calibration

- Perform tipping scans to characterize the atmosphere and assess changes of system noise due to varying ground pickup, receiver attitude etc.
- Observations of planets etc. as primary flux standards; flux transfer to quasars in total-power mode.
- Test amplitude calibration system and characterize receiver gain and system noise as functions of elevation.

4.4 Single-baseline interferometer at OSF (AIV)

Equipment available:

Antennas 1 and 2, on closely-separated pads
Front ends
WVRs
Local oscillator
Back-end
Test correlator
Software for analysis of single-baseline interferometer data

4.4.1 Basic operation

- First fringes (band 3 initially; then higher frequencies).
- Check correlation efficiency by observing point sources in continuum and spectral-line modes; compare results for total-power and interferometry. aControl of gain (programmable attenuators)

4.4.2 Antenna location (delay) calibration

[This assumes an accurate geometric and neutral atmosphere delay model]

- Measure phase slope across the band.
- Track a source in hour angle to remove phase wraps.
- Confirm using global solution using observations using a grid of sources distributed over the sky.
- Test stability.
- Test accuracy of replacement of antenna on pad..

4.4.3 Pointing, focus, transverse focus, primary beam profile

- Refine interferometric test procedures developed at the ATF.
- Pointing; optimize pointing patterns (5-point, Az-El, …)
- Focus
- Transverse focus
- Primary beam

4.4.4 Surface

- Measure low-order surface deformations using interferometric holography (Band 3: sensitivity?)
- Check variations with elevation, etc. Check for consistency of derived surface errors with radiometric measurements of aperture efficiency.

4.4.5 Local oscillator coherence

- Measure common-mode phase errors
- Measure independent phase errors
- Derive calibration procedures

4.4.6 Water-vapour radiometers

- Basic functional tests.
- Compare measurements from WVRs to assess precision and reliability.

4.5 Single antenna at AOS (AIV)

Antenna checkout at AOS, repeating OSF tests with the addition of higher frequencies.

4.6 Single-baseline interferometer at OSF (AIV)

Repeat of single-baseline interferometer tests at AOS, but with production correlator.

5 Commissioning tests required before Early Science (CSV)

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The activity numbers given in this section correspond to the table entries in Section 6.

5.1 Close-packed array

Equipment available:
As for single-baseline interferometry, but adding
Antennas 3, then 4 on pads close to the initial two
Software for antenna-based calibration and imaging
Band 3 only, initially

Table 3: Close-packed array commissioning activities

1.1	Band 3 compact array	Images of simple fields (one or more point sources) Spectral resolutions as tested at the ATF Assess phase and gain stability
1.2	Basic array and antenna calibration procedures	Interferometric pointing Focus and transverse focus Antenna location Delay
1.3	Initial complex gain solutions	Measure close phase (3 antennas) Measure closure amplitude (4 antennas) Evaluate baseline-dependent (closure) errors Initial assessment of dynamic range
1.4	Initial bandpass calibration	
1.5	Initial temperature and flux-scale calibration	

5.2 Early Science Array

Table 4: Mode commissioning descriptions

2.1	Band 3 1km baselines	Imaging tests with a range of spectral resolutions, source complexity, brightness, in single-field interferometric mode Dynamic range Reproducibility Noise level
2.2	Band 4	As above
2.3	Band 6	As above
2.4	Band 7	As above
2.5	Band 8	As above
2.6	Band 9	As above
2.7	Band 3 long baselines	As above
2.8	Mosaics	Optimize sampling grid and pattern Optimize sampling speed Test reproducibility with different antenna combinations Test addition of total-power data
2.9	Polarization	Measure instrumental polarization on unpolarized calibrator Test reproducibility of measurement
2.10	Formal verification	Covers a series of tests using the verification matrix described in Section 8 below, with target numbers scaled to the number of antennas available for Early Science.

Notes

1. These activities include optimization of data-reduction algorithms (e.g. phase interpolation, optimum use of WVR data, imaging and deconvolution).
2. Optimization of on-line blanking and flagging is included (e.g. tracking error, LO out of lock, subreflector out of position, ….)

Table 5: observation calibrations

3.1	Phase calibration	Characterize phase fluctuations by long observations of point sources

		Characterize decorrelation due to fast atmospheric fluctuations Evaluate fast switching using groups of closely-space calibrators. Check dependence on: Flux density Separation Atmospheric conditions Frequency Optimize cycle time Evaluate WVR phase correction Conversion to phase Dependence on conditions Dependence on frequency Adequacy of atmospheric model Limitations (ice particles, …) Optimal combination of WVR and fast switching
3.2	Instrumental phase transfer between frequencies	Test for slow and fast switching Optimize sampling, cycle time, flux density of calibrator
3.3	Calibrator surveys	Aim is to develop efficient methods of locating fast-switching calibrators around a given target, rather than to survey the whole sky. Survey pre-selected sources from CLASS, SUMSS, ATCA, etc. at Band 3, then higher frequencies Develop criteria for finding calibrators suitable for fast switching or instrumental phase transfer
3.4	Refinement of temperature and flux-scale calibration	Investigate potential primary amplitude calibrators Assess relative and absolute calibration accuracy Optimize use of dual-load calibration
3.5	Refinement of bandpass calibration	
3.6	On-axis polarization calibration	Develop techniques to calibrate D-terms and position angle Assess calibration stability Search for unpolarized and polarized, but stable standard sources

Notes:

1. The calibrator survey also provides a good opportunity to soak-test the array and assess reliability in routine operation.

2. The intention of the calibrator surveys is not to cover a significant portion of the sky accessible to ALMA, but rather to develop reliable methods of locating good fast-switching calibrators using existing surveys.
3. The refinement of temperature and flux scale activity includes research on absolute flux calibration.
4. Polarization commissioning does not include the use of the quarter-wave plate in Band 7. The need for this should be assessed after initial tests.

Table 6: Antenna and array calibration procedures

4.1	Pointing	Optimize interferometric pointing calibration Monitor global rms pointing accuracy Measure dependence of pointing terms on temperature, etc. Optimize offset pointing calibration and verify accuracy on astrometric calibrators
4.2	Focus and transverse focus	Calibrate dependence on elevation and temperature for all antennas Assess stability
4.3	Primary beam Surface errors from interferometric holography	Determine individual primary beams for all antennas Measure stability and dependence on elevation Check surface deformation as a function of time and elevation (low-order)
4.4	Check receiver feed setting and beam squint	Should have been set up by AIV
4.5	Antenna location calibration	Verify calibration procedure and measurement accuracy Check stability
4.6	Delay calibration	Stability Dependence on band
4.7	Local oscillator coherence	

Notes
1. These activities all include monitoring of the stability of calibrations with time and environmental conditions such as temperature.
2. The activities required to integrate an antenna into the array and to characterize its performance after a move are included in this Table.

Table 7: single-dish commissioning

5.1	Observing modes	Mosaic with position switching Mosaic with beam-switching On-the-fly Autocorrelation

		Continuum total power Frequency switching
5.2	Calibration	Temperature and flux scale Cross-calibration of interferometric and total-power flux scales Polarization Compare beams determined in total power and interferometrically

Notes:
1. These activities will be carried out in parallel with those for interferometry, primarily using the ALMA-J 12m antennas.
2. Many of the antenna calibrations are best carried out interferometrically and are not given separately here.

ACA commissioning table to be added here.

6 Schedule and task durations

This section takes the tasks identified in Section 5, estimates their durations and incorporates them into a draft schedule leading up to Early Science.

Warning: the estimates given in this section, whilst based on a reasonably complete list of tasks and some experience, are very preliminary and must be refined given feedback from tests at the ATF and OSF.

6.1 Description

The following tables divide commissioning into major activities and give an approximate incremental schedule. There is (inevitably) a high degree of parallelism, as verification of observing modes depends on refinement of calibration procedures, and conversely.

All activities include the production of associated documentation.

6.2 Modes

Table 8: Schedule for mode commissioning

	Activity	Duration (days)	Start (months)	End (months)
1.1	Band 3 compact array	35	CSV	CSV + 3
2.1	Band 3 1km baselines	10	CSV + 3	CSV + 5

2.2	Band 6	20	CSV + 5	CSV + 12
2.3	Band 7	20	CSV + 6	CSV + 13
2.4	Band 4	15	CSV + 7	CSV + 14
2.5	Band 8	25	CSV + 8	CSV + 15
2.6	Band 9	25	CSV + 9	CSV + 16
2.7	Band 3 long baselines	5	CSV + 9	CSV + 16
2.8	Mosaics	20	CSV + 16	CSV + 18
2.9	Polarization	20	CSV + 17	CSV + 19
2.10	Verification against science requirements	10	CSV + 19	CSV + 20
Total		230		

Notes

1. The long duration for 1.1 (Band 3 compact array) reflects the fact that much new software will be tested for the first time at this stage.
2. The schedule suggested for Bands 4, 6, 7, 8 and 9 is indicative only. A pragmatic arrangement based on the availability of working receivers and on weather conditions will need to be adopted.
3. The boundary between this activity and observation calibration is fuzzy: the intention is for the Modes table to reflect the time required to verify system performance once calibration procedures are in place.
4. Activities up to Band 9/CSV + 16 refer to single-field interferometry.
5. The mosaic activity includes addition of total-power data.
6. Science Verification is **not** included in this Table.
7. Long-baseline tests (>1 km) are anticipated from roughly CSV + 9 in all bands, hence the additional activity for Band 3.
8. End-to-end tests are included, mostly towards the end of the period.

6.3 Observation calibration

Table 9: schedule for commissioning of observation calibration

	Activity	Duration (days)	Start (months)	End (months)
1.3	Initial complex gain	10	CSV	CSV + 3
1.4	Initial bandpass	5	CSV	CSV + 3
1.5	Initial T/flux scale	5	CSV	CSV + 3

3.1	Phase calibration: fast switching and WVR optimization	50	CSV + 3	CSV + 12
3.2	Instrumental phase transfer between frequencies	10	CSV + 5	CSV + 12
3.3	Calibrator surveys	35	CSV + 6	CSV + 18
3.4	Refinement of T, flux scale calibration	15	CSV + 3	CSV + 9
3.5	Refinement of bandpass calibration	15	CSV + 3	CSV + 9
3.6	On-axis polarization calibration	5	CSV + 17	CSV + 19
Total		150		

Notes

1. The schedule suggested after CSV + 3 is again notional: it makes sense to interleave activities depending on progress, weather conditions etc.

6.4 Array calibration

Table 10: schedule for commissioning of array calibration

	Activity	Duration (days)	Start (months)	End (months)
1.2	Basic array calibration	10	CSV	CSV + 3
4.1	Interferometric pointing	15	CSV + 3	CSV + 19
4.2	Focus and transverse focus	15	CSV + 3	CSV + 19
4.3	Primary beam and surface accuracy using interferometric	20	CSV + 3	CSV + 19

	holography			
4.4	Receiver beam squint	5	CSV + 3	CSV + 19
4.5	Antenna location calibration	20	CSV + 3	CSV + 19
4.6	Delay calibration	5	CSV + 3	CSV + 19
4.7	LO coherence	5	CSV + 3	CSV + 19
Total		95		

Notes:

1. Most of these activities are necessarily in parallel because they are required whenever an antenna is integrated into the array.

6.5 Single-dish commissioning

Table 11: schedule for single-dish commissioning

	Activity	Duration (days)	Start (months)	End (months)
5.1	Modes	40	CSV	CSV + 16
5.2	Calibration	20	CSV	CSV + 16
Total		60		

Notes:

1. Single-dish commissioning is expected to proceed in parallel with interferometric commissioning, using a second subarray. Durations are therefore not added, but additional staff are required.

6.6 ACA 7m array commissioning

To be added.

Notes:

1. ACA commissioning is expected to proceed in parallel with that of the 12m array, at least initially, using a separate subarray. Durations should not be added, although additional staff are required.
2. At some point, probably not before Early Science, cross-correlation of the ACA and 12m array will be commissioned, at which point the schedules interact.

6.7 Commissioning milestones

Many of the commissioning activities are in parallel, so there are fairly few major milestones. The most important of these are tied to the main phases of the commissioning programme, as follows:

1. Start of Commissioning and Science Verification on handover of verified 3-element array at AOS.
2. Compact array commissioned. Short-baseline array of 4 antennas functional in Band 3, continuum.
3. Successful test with baselines up to 1 km in Band 3.
4. 16-antenna array verified formally against science requirements.

6.8 Array operational efficiency

In order to achieve the aims of the CSV programme within the available time, it will be necessary to operate the array continuously whenever possible. In particular, night-time operation will always be required. Scheduled interruptions to commissioning will occur as a result of ongoing AIV activities and scheduled maintenance. Failures which stop all work until they are fixed will be inevitable, especially in the early stages. It is difficult to assess the level of interruption, but for the moment we assume an average level of 20%, presumably ramping down from a high value at the start of CSV, to include scheduled and unforeseen events.

6.9 Time allocated for Science Verification

We make an initial estimate of 10% for the fraction of time allocated to Science Verification (including ALMA Public Images), as described in Section 9.

6.10 Total time required

The total time required for the commissioning activities in Tables 7 – 9 is 475 days. With the numbers assumed for SV and operational efficiency, the total time required for the programme outlined in this Section would be 617.5 days or 20.6 months. Given that the time estimates are extremely rough at present, this is in adequate agreement with the schedule given in the Operations Budget.

7 Staffing

7.1 Management

The commissioning team will be led by the Project Scientist and will consist of technically qualified astronomers. Technical support will be provided by AIV, construction IPTs and Operations. The principles underlying the staffing of the CSV team are to take maximum advantage of expertise available within all of the regional communities and to involve Operations staff from the start as full members of the team. To quote the ALMA Operations Plan:

> '*The key concept of ALMA Operations development is the early recruitment of operations staff and the integration of these people into AIVC activities.* Thus, core operations staff (i.e. astronomers, engineers, technicians, computing/IT support and operators) can be involved in the verification and/or creation of the operations and maintenance procedures developed by the AIV and Commissioning teams. Such integration has the additional advantage of fostering team building by minimizing an 'us and them' attitude between Construction and Operations teams.'

The current model for CSV staffing is completely dependent on the close involvement of Operations staff.

The commissioning team will be drawn from a wide range of groups, including:

1. The Project Scientist and commissioning scientists (JAO).
2. Science IPT staff on rotation from Europe, NA or Japan or on mission to Chile for longer periods.
3. Staff on rotation from the EU, NA or EA ARCs.
4. External staff seconded from other home institutes (universities, observatories etc.).
5. Ad hoc specialists involved in specific projects.
6. Staff working remotely on analysis of commissioning data.
7. Astronomers and system scientists from the Division of Science Operations.

The expectation is that there will be both experienced astronomers and engineers and junior staff, the latter being more likely to be seconded from and/or to move to Operations. The involvement of outside astronomers will be carefully managed: there will occasionally be good reason for experienced people to join the commissioning team for shorter periods, but they will always work for the team in some capacity.

The management of such a diverse and potentially distributed team will not be straightforward. It will depend crucially on good interpersonal communications and effective high-bandwidth computer and video links. It is anticipated that one of the PS or the two commissioning scientists will be in daily charge of CSV, on a rota basis. The relationship between the PS and Project Engineer is vital to effective commissioning: a daily meeting between the scientist in charge of commissioning, the engineer running AIV and the key operations staff will be essential to ensure rapid feedback on fault diagnosis and effective sharing or resources.

The relationships between the PS, the regional project scientists and the Head of Science Operations are also crucial to the success of the process. In essence, the HSO must provide the infrastructure within which the CSV team can function, together with a large fraction of its staff.

The number of people making short trips to Chile for commissioning must be severely restricted: it is not worthwhile educating such people unless they can contribute effectively in the longer term (there will be ad hoc exceptions to this rule at the discretion of the PS). This applies to Science IPT and ARC staff, as well as to external scientists.

As a general rule, external scientists should be able to commit to a minimal period of 3 – 6 months in Chile. ALMA should issue a Request for Letters of Interest in Commissioning Participation as far in advance as possible (>1 year, preferably) to allow external participants to arrange (e.g.) sabbatical leave. In any case, external scientists must be aware that they are part of a managed team and that they will be assigned specific tasks and goals by the PS. Under no circumstances will astronomers whose prime motivation is the acquisition of their own observations be supported by the commissioning team.

7.2 Required staffing profile

In order to estimate the required staffing for the main commissioning period to Early Science (CSV – CSV + 20) we split the tasks as shown in the Table below. We follow the Operations Plan in applying a factor of 2.4 to account for the turno system, regardless of whether staff are based in Santiago or in one of the Executives, except for the management positions (PS + 2 commissioning scientists).

Description	Number	Shifts	Total (including turno factor)
Duty scientist	1	2	5
Observing calibration	2	1	5
Antenna and array calibration	2	1	5
Single-dish	1	1	2
Modes, imaging,documentation, SV	3	1	7
Management	3	1	3
ACA	3	1	7 (from CSV + 12)
Total			27 (CSV to CSV +12) 34 (CSV + 12 to CSV + 24)

This does not include the effort required to accept and check out new antennas, which is provided by the AIV test scientists (4 initially); thereafter by Operations at a level TBD.

7.3 Current staffing profile

Staffing relevant to CSV from the current construction and operations budgets is anticipated to be as shown below. The start and end dates are as of August 2006, and will in reality be tied to construction milestones – some changes are suggested. Note that this list does not include array operators, technical support et al.

1. JAO

Project Scientist (2007Q1 – 2012Q3)
Commissioning Scientist E (2007Q1 – 2009Q4)
Commissioning Scientist F (2007Q1/2 – 2009Q4)

Note: the start dates for the commissioning scientists would allow them to gain experience at the ATF, but the end dates do no fully cover the main commissioning period. 2008Q1 – 2010Q4 would be a better fit to the requirements.

2. NA Science IPT

NA Project Scientist (→ 2010Q4)
NA Instrument Scientist (→ 2010Q4)
NA Person D (2006Q2 – 2009Q4)
Calibration Leader (2006Q2 – 2009Q4; then transfers to Operations)
Imaging Leader (2006Q2 – 2009Q4; then transfers to Operations)
PDRAs as in rebaselined budget

Person D: move 1 year later?

3. EU Science IPT

EU Project Scientist (→ 2010Q4)
EU Instrument Scientist (→ 2010Q4)
EU Person D (2006Q2 – 2009Q4)
PDRAs as in rebaselined budget

Person D: move 1 year later?

4. JP Science IPT
(Dates need to be checked)

JP Project Scientist (→ 2010Q4?)
JP Instrument Scientist (→ 2010Q4?)
JP Person D (2008Q1 – 2010Q4?)
JP PDRAs (Say 2 x 0.5 → 2010Q4?)

5. Division of Science Operations (DSO)

The following positions are currently anticipated in the Operations Staffing Plan.
Head of Science Operations (2006Q4 →)
Science Programme Manager (2008Q1 →)
4 Programme and Data Management (PDM) Astronomers (2008Q2 →)
(see below for transfers from AIV)
4 Programme and Data Management (PDM) Astronomers (2009Q1 →)
5 Programme and Data Management (PDM) Astronomers (2010Q2 →). 2 of these are transfers from NA Science IPT.
4 Systems Astronomers (2008Q2 →)

The roles of the PDM and Systems Astronomers in full operation are outlined in the Operations Plan. The latter are expected to become the 'JAO system ultra-experts, providing advice and assistance to operations and development teams through the Observatory and the ALMA user community.' This is effectively a continuation of commissioning, and it is reasonable to expect the systems astronomers to be fully devoted to commissioning initially. The other members of the PDM group will have significant responsibilities for operations support preparation in the period immediately before Early Science.

PDM fellows are hired too late to contribute to the main commissioning period, but are included in the summary table below.

6. NA ARC

Scientist 1 (2007Q3 →)
Scientist 2 (2008Q4 →)
both half-time in Chile during commissioning

7. EU ARC

Astronomer 3 (2008Q2 →)
Astronomer 4 (2008Q4 →)
both half-time in Chile during commissioning

8. EA ARC

Astronomer 3 (2008Q4 →)
Astronomer 4 (2010Q2 →)
both half-time in Chile (second only just relevant for commissioning)

9. AIV Test Scientists

4 test scientists are initially working within the AIV team on antenna verification. They transfer to Operations to become the Science Programme Manager and three of the first four PDM astronomers in 2008Q2, at which point their duties are also absorbed into Operations.

Table 12: Summary of staff requirements

	2006	2007	2008	2009	2010	2011	2012
SciIPT	13.25	14.0	21.0	15.5	11.0	1	1
Ops	0.25	2.0	9.0	15.0	21.5	24.5	28.0
ARC	0.0	0.25	1.5	2.5	3.0	3.0	3.0
Total	13.5	15.25	31.5	33.0	35.5	27.5	31.0
Required	2 (ATF)	6 (ATF)	20	27	34	TBD	TBD

The average number required in 2008 covers the need for a rapid ramp-up towards the end of the year, when the full complement of 27 staff is needed at the start of CSV and the need to hire some staff early for training. The Staffing numbers are only just adequate in 2009, bearing in mind that Operations needs to provide scientific support for checkout of new antennas (replacing the AIV test scientists) as well as activities not directly related to CSV. In 2010, the numbers are currently inadequate for two reasons: the additional CSV load represented by the ACA, which arrives before commissioning of the 12m array is complete, and the need to prepare for Early Science, which inevitably reduces the number of staff available from Operations.

Staff requirements for commissioning after the start of Early Science have not been analysed yet, but the staffing plan for construction does not provide manpower from Science IPT in that period, leaving the burden solely on Operations (except for the project Scientist).

7.4 Support

Support and close collaboration will be required from:

- Non-astronomer Operations staff (array operators; maintenance engineers; IT support; etc.)
- AIV (normally the first contact in case of problems with newly installed equipment).
- Construction IPTs.
- Computing IPT. Particularly close collaboration will be required, especially for the real-time systems but also for data analysis and with the SSR scientists.

One effective way of organizing effective liaison would be for AIV to allocate a duty systems engineer and Computing a duty software engineer, both to act as initial points of contact for problem triage and solution.

8 Verification Matrix

A primary goal of commissioning is to verify that ALMA meets its science requirements. In order to verify this formally, we follow the standard methodology of verification by **D**esign, **A**nalysis, **I**nspection and **T**est. During commissioning, we are concerned primarily with the last of these. The verification matrix given below is derived from Table 4 of the ALMA Scientific Specifications and Requirements, indicating those requirements which must be verified by test. Some of the requirements should have been checked during AIV but should be re-tested during observing as part of a full system test.

Level-1 science requirements 1 (detection of CO or CII line emission from a normal galaxy at z = 3); 2 (imaging gas kinematics in protoplanetary disks at 150 pc) can clearly only be tested with the full array and 3 (precise imaging at 0.1 arcsec resolution) can only be tested with the full array. A number of the derived science requirements also refer to the full array, but we can define appropriately scaled versions for smaller numbers of antennas. This is noted in the table.

Almost all of the requirements to be verified by test are band-dependent. Most also depend on the individual sub-systems (antennas, receivers) in use. Some (noted explicitly in the table) depend on the atmosphere and need to be carried out under a range of conditions.

Column 1: Science requirement number
2: Brief description (see ALMA Scientific Specifications and Requirements)
3: Test outline or alternative verification
4: Whether there is a dependence on number of antennas

SR	Description	Test	N dependence
10	Bands	Design	
20	Tunability	Select representative range of frequencies in all available bands and check that tuning is correct.	No
30	Spectral resolution	Design	
40	Intraband tuning	Retune between pairs of frequencies in the same band and verify that time taken < 1.5s Check that frequency switching takes <10ms	No
50	Interband tuning, second band ready	Check that it is possible to retune to any frequency in a band which is on standby in <1.5s	No
60	Interband tuning, second band unready	Check that it is possible to retune to a new frequency in a different band in <15 minutes	No
70	Spectral dynamic range	Observe sources with strong and weak lines separated by a small frequency interval and check detectability of line at 10000:1 level. Observe source with weak line (emission or absorption) and strong continuum and check line detectable at <1000:1	Yes (quantify) .
75	Image dynamic range	Observe bright, point-like source (e.g. 3C273). Self-calibrate and measure noise level; check detectability of faint structure nearby.	Yes
80	Flux sensitivity	Measure noise level on blank field/faint source. Check reproducibility of faint source detections.	Scales as $[N(N-1)]^{-1/2}$
90	Site	Design	
100	Antennas complement	Design	
110	Antenna surface	AIV will establish small-scale surface accuracy with tower holography. Interferometric holography to measure larger-scale surface errors; stability and variation with elevation.	No
150	Aperture efficiency	Test on astronomical sources of known flux density.	No
160	System	Measure noise level	No

	temperatures		
170	IF bandwidth	Design	
190	Quantization losses in correlator	Analysis	
200	Data accuracy	Design	
210	Dynamic scheduling	Verify dynamic scheduling algorithm	No
220	High fidelity	Observe fields with bright, complex emission on various scales. Fidelity very difficult to verify; reproducibility, off-source noise level and obvious artifact level are surrogates.	Yes!
230	Total power	Design	
235	Nutators	Design	
240	Integration time, correlation	Design/analysis	
245	Integration time, total power	Design/analysis	
250	Configuration	Design/inspection	
260	Pointing	Verify reference pointing using calibrators with astrometrically known positions.	No
270	Primary beam	Measure using interferometric holography. Check stability, dependence on elevation for all bands.	No
280	Antenna location	Solve for antenna locations. Repeat test at intervals and measure residuals from original solution.	Yes (accuracy of solution)
290	Phase correction	Measure phase stability using combination of fast switching and WVR to observe a (bright) point source using phase calibrators at different separations and a range of brightnesses. Weather, baseline-dependent.	Yes (accuracy of antenna phase solution)
300	Amplitude fluctuations	Measure amplitude fluctuations on a bright point source (essentially as requirement 290)	Yes
305	Amplitude fluctuations	Analysis/laboratory test	
310	Signal measurement	Design	
320	Polarized flux error	Residual for an unpolarized source after instrumental calibration <0.1% of I.	Yes ($N^{-1/2}$)

330	Polarization position angle	Check reproducibility <6^{o} for a stable source. Standards?	Yes
345	Relative polarization channel stability	Analysis/laboratory test	
350	Calibration	Establish consistency of absolute flux calibrators to better than 5%	Yes
360	Solar	Design/analysis	
370	Phased array	Design/analysis (not yet implemented)	
380	VLBI	Design/analysis (not yet implemented)	
390	Subarrays	Design. Verify use in practice.	
400	Ease of use	Opinion poll?	
410	Software tools	Inspection	
420	Data reduction	Test cases	

This verification matrix will form the basis for a set of formal verification tests (each with a detailed test procedure) to ensure that ALMA meets its science requirements. Criteria will be developed for arrays of various numbers of antennas and used to assess the performance of the array as it grows.

9 Science Verification

9.1 Purpose

The goals of SV are:

- Test end-to-end operation of one or more ALMA modes using a range of different targets
- Test reduction tools
- Provide feedback to the CSV team and Operations staff
- Offer to users first-grade science data from a new mode of ALMA and involve them in prompt scientific exploitation
- Demonstrate the potential of the mode to a wide community
- Foster an early scientific return

9.2 Prerequisites

Each mode should be debugged and verified by the commissioning team before the SV phase, so that *the test is expected to succeed*. There are obvious dangers to the ALMA project if SV is scheduled prematurely. The responsibility of deciding whether to offer a mode for SV rests with the Project Scientist.

The following prerequisites apply to all bands, continuum and those spectral line modes selected for early science, using appropriate observing modes. Before a mode is released for science verification, it must be fully commissioned and documented, and the array performance must be assessed as meeting the appropriate subset of science requirements, modified appropriately for the number of antennas. Quantitative criteria include:

Image sensitivity in a given integration time
Image fidelity (dynamic range, reproducibility, comparison with results from other arrays)
Astrometric accuracy
Spectral dynamic range

9.3 Procedure for Science Verification

The SV plan for a mode is developed by a SV team. This will include but is not limited to members of the core CSV group. They will involve members of the community via an open call for ideas. The SV team will be responsible for selection of a small number of proposals according to the following criteria:

- Scientific interest
- Pushing the array close to its limit (consistent with technical feasibility at the time)
- Resulting in a complete dataset suitable for prompt exploitation.

Following the 2005 October ASAC recommendation, *scientific* review of SV proposals should include an international proto-TAC or advisory group with a wide range of scientific interest, but the process must remain fast and responsive to changing project priorities.

On completion of observing (possibly in multiple configurations), data reduction and quality control, the data (raw and reduced, together with scripts and documentation) will be made public.

The duties of the SV team are:

- Develop and pre-select SV projects, with the aid of an outside advisory group.
- Prepare and verify scheduling blocks.
- Maintain SV web pages, which should describe the SV plan well in advance of observations and list the data as they become public.

- Reduce and perform quality checks on the data.
- Deliver the data to users on request
- Provide information about and assist users with exploitation of the data.

9.4 ALMA Public Images

ALMA Public Images (API) are large-scale projects whose primary intention is to convince the wider community and general public of the value of ALMA. As noted by the ASAC, these are important to show progress in construction, particularly to funding agencies. The need to make such images as early as possible is in conflict with the difficulty of imaging with a small number of antennas, but if a few fields are selected in advance and observed repeatedly with different early configurations, good results should be obtained.

A second round of API observations could occur immediately before the start of Early Science in the programme proposed here.

10 Commissioning and Science Verification after Early Science

The process of science verification must continue as the array evolves. In addition, there are many new tasks, of which the following is an incomplete list.

10.1 Antenna configurations
- All antennas in all science configurations
- Procedure for adding a new antenna; use of a test subarray
- Reconfiguration
- Subarray management

10.2 ACA
- Complete commissioning of the 7m array
- Cross-correlation of ACA and 12m array both for calibration and high-sensitivity operation.

10.3 Bands
- Additional bands (5, 10)

10.4 Correlator modes
- All continuum modes
- All spectral-line modes

10.5 Polarization
- Mosaics (including measurement of leakage beams)
- High-accuracy linear (QW plate, Band 7), if required

10.6 Pipeline
- Exercise on full range of frequencies, array configurations, correlator modes, sources,

- Test and improve pipeline heuristics

10.7 Dynamic scheduling

- Optimization based on observing experience
- Rules for run-time selection of integration time, calibration strategy, etc. based on conditions.

10.8 New observing modes

- Very large mosaics
- Combination with ACA and single dish
- On-the-fly mapping
- Solar
- Pulsar
- VLBI
- Refined calibration procedures for all modes, deriving a matrix of anticipated accuracies and precisions.
- Interferometric on-the-fly mapping