Atacama
Large
Millimeter
Array

ALMA System Technical Requirements

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Change Record

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1 Overview

This document summarizes the technical requirements of the ALMA telescope at the system level. These are the parameters that determine the overall performance of the telescope. For the most part, no attempt is made here to derive or justify the values given, but references to other documents are provided where possible. Only the basic 64-element array is covered; the Atacama Compact Array is not included.

The requirements are given in Table 1 and its accompanying notes. For a few critical items, additional data and discussion are given in the following sections.

2 Delay/Phase Error Limits

As discussed in [2], section 3.1.1.2, variations in the instrumental phase cause two effects: loss of coherence and thus of sensitivity is caused by fluctuations faster than the elementary integrating time (which we take to be 10 sec or less); and errors in the phase of the calibrated visibility measurements are caused by fluctuations on longer time scales, up to the length of a full calibration cycle (which is expected to be typically 60 to 300 seconds, but sometimes as long as 1000 sec). The required performance is difficult to quantify, partly because it depends on the observing and calibration techniques used.

The requirements here (Nos. 151, 152, 451, 452 in Table 1) are based on the idea that the limitations caused by the instrument should be smaller than those caused by the natural environment at least 95% of the time. For this purpose, we consider that the natural limits are those imposed by the residual delay fluctuations of the troposphere after all available corrections have been applied. Statistics of the tropospheric fluctuations at the Chajnantor site are available from more than six years of site testing [11]. The effects of corrections from rapid phase referencing to a nearby calibrator (fast switching) combined with instrumental phase calibration have been studied in simulations [12], and these results are the main basis of the requirements in Table 1. The total instrumental error, which is the rss of the part due to the structure and the part due to electronics, is equal to the corrected tropospheric error under 5th percentile conditions. For further discussion see [2] and [12].

For the fast fluctuations, it is currently predicted that corrections based on water vapor radiometry alone will produce residuals about the same as with fast switching alone. In practice, a combination of the techniques is likely to be used.

Table 1: Requirements Summary

Req No.	Parameter	Value	Sci. (1).	Notes Refs.
	Antennas			
110	Number of antennas	64	100	
120	Antenna diameter	12 m	100	
130	Aperture efficiency, min.	0.45 at 675 GHz		21
140	Pointing error, max.	0.6 arcsec, relative to reference source within 2 deg	260	
151 152	Delay error due to structure	rms, non-repeatable, drift, over 300sec <13 fsec. rms deviation from 10 sec average, short term <38 fsec (see also section 2.0 of this document)		20
161 162	Subreflector nutation	4 antennas only 5 arcmin throw in 20 msec (switching freq up to 10 Hz)		5
	Receiving Signal Path			
210	Frequency coverage	31.3—950 GHz, all atmospheric windows; see Table 3	010	2
220	Receiver noise temperature, max.	See Table 3.	160	22
231 232	1st mixer sideband ratio	>10 dB, SSB and 2SB. <3 dB, DSB.		
233	Front end structure	HFET SSB, SIS 2SB, or SIS DSB by band as listed in Table 3. All 2SB FE output to the BE both sidebands simultaneously.		
240	IF range	4—12 GHz		
250	Total instantaneous IF bandwidth	8 GHz (minimum) in each of 2 polarizations		
311 312	Digital signal transmission	Repeatable latency with no loss of samples. Bit error rate $<10^{-6}$.		
 411 412	Tuning range and resolution	Any sky frequency may be placed at any: baseband frequency within ±10% of digitized BW IF within ±10% of IF bandwidth		14
420	Independently tunable subarrays	4	390	
431 432	Frequency changing time, max.	1.5 sec (<0.1 sec desired) 10 msec for .03% or less (single dish mode only)	050	9
441 442 443 444	Phase switching	180° and 90° in 1st LO; sign reversal after digitization Walsh functions, 64 orthogonal by antenna Cycle time .016 sec Synchronization within 1 μsec		3 [3]
450	Phase ambiguity	All frequency synthesis unambiguous		
321 322	Digitization	2 GHz nominal channel bandwidth 8 levels (3 bits), uniformly spaced, at 4 GSa/sec		
323 324 325	Sampling clock	Variable phase for fine delay, < 1/8 sample accuracy. Common to all channels at an antenna. Synchronization with correlator to within 10μsec.		4 [4]
451 452	Delay errors (all electronics)	Max rms change in 300 sec (drift): 22 fsec **TBC** Max rms deviation from 10 sec average (noise): 65 fsec. See also section 2.0. See Table 2 for allocation among sub-systems		20
261 262 263	Gain stability: Allan standard deviation of ΔG/G	< 1.0e-3 at . 0.05 to 0.5 sec for all antennas < 1.0e-3 at 100 sec for all antennas < 4e-4 at 0.05 to 0.5 sec (for 4 antenna optimized for total power) 0.707 of each of these three requirements are allocated BE and FE sub-systems.		6 [7]
264	Differential gain and phase stability between channels of a polarization pair	1.e-3 amplitude and 0.06 degree phase at 300 sec **TBC** allocation to FE and BE are each 0.707 of this value	320	23
271 272	Gain flatness, each baseband channel (2 GHz nominal)	Effective b.w. due to anti-aliasing filter > 90% of nominal. Max. pk-pk variation across channel due to all other components, any tuning: 6 dB. This requirement is allocated 3 dB to BE and 3 dB to FE sub-systems.		 7, 25

Table 1 (continued)

Req No.	Parameter	Value	Sci. (1).	Notes Refs.
281 282 283 284	Gain matching among antennas	±1 MHz tolerance on –3 dB freqs. 1.2 dB max difference of slopes. ±0.5 dB deviation from average magnitude, after removing exponential slope. ±4° deviation from average phase after removing linear slope.	8	[8]
	Detection and Correlation		10	
 511 512 513	Analog total power detectors On each baseband channel (2GHz): On each IF channel (8 GHz)	 Accuracy 1% of full scale (after linearity correction). Sampling interval 2 msec at >90% efficiency (>1.8 msec effective integration time). Not used for astronomy; for engineering monitoring only. Requirements are in BE sub-system requirements		 24
520	Digital filtering	32-subchannel filter bank, programmable bandwidth		11
521	Quantization	At antenna, first quantization, 8-level (3b); at correlator ,4-level (2b) at full bandwidth or 16 levels (4b) at reduced bandwidth.		
530	Spectral resolution	< 6 kHz	030	12
541 542	Correlator output rate	16 msec integrations and readout interval, all baselines. 1 msec integrations and readout, autocorrelations only. 128M complex correlations per second.	240	13
	General			
610	Archive writing rate	>40 MB/sec for correlation products, >60 MB/sec total.		15
615	Monitor / Control	All Line Replaceable Units with an AMB node shall be self identifying to the ABM.		
617	Reliability	The MTBF for each LRU shall be > 5 years **TBC**		
621 622 623	Water vapor radiometers	Installed on all antennas Path length correction noise (rms) < .01w + 10 µm Sampling rate <1 Hz. Divergence from observing beam < 10 arcmin.		 16
631 632 633	VLBI support	Array shall be usable as a single station (phased up) Real-time phasing up required only for bands 1—6. Sum output available for any subset of antennas.	380	27
460	VLBI support	Common mode phase fluctuations: Allan std dev, frequency < 1e-12sec/T for 0.1 sec < T < 100 sec. **TBC**		17
470	Absolute frequency accuracy	1 part in 10^{11}		18
481 482	Array time	Maintained within 10 µsec of TAI. Difference from TAI known to within 100 nsec.		19
490	RFI Protection	The shielding effectiveness of the antenna receiver cabin shall be 20 dB at 12 GHz		
492	Fiber optic cable	The fiber optic cable (LO, DTS & M/C) length from the AOS Technical Building to an antenna station shall be < 15 km		26

Notes to Table 1

1. Related scientific requirement number, where applicable, from [1]. Only the significant digits of the requirement number are quoted.
2. Band edge frequency choices are explained in [2], section 2.2, and in [5].
3. See [2] sections 3.1.1.4, 4.3, 4.5; and [3].
4. See [2] sections 3.1.5, 4.5; and [4].
5. Number of nutators set by budget.
6. The spec of 1e-3 at 100 sec allows an rms calibration error of up to 0.1%. Further discussion is given in [6] and detailed background analysis is given in [7]. A spec of 6e-5 at .05 sec would make gain fluctuation noise equal to thermal noise at 7 GHz effective bandwidth.
7. Quantization leads to a loss of SNR compared to an analogue correlator. A 2-bit quantization leads to 0.88 efficiency and 3-bit quantization leads to 0.96 efficiency. The efficiency in the ALMA system is probably better than the product of these two numbers. However, departure from a flat bandpass shape leads to additional loss in SNR. It is estimated that a 6 dB slope across the 2 GHz bandpass will lower the efficiency in the low end channels by an additional 0.97. This loss due to quantization noise needs to be verified by simulations (due end of 2004). An additional requirement based on spectroscopic sensitivity is under study. Until these studies are complete, a deviation of 6 dB p-p is the system level requirement.
8. Matching provides for <0.2% error in complex gain solutions from interferometric calibrator observations. This is sometimes called "closure error." For details see [8].
9. The basic frequency changing time is chosen to match the antenna pointing settling time for fast switching. However, for calibration of the instrumental phase difference using a single source, faster frequency changing is desirable. The 10 msec time for small frequency changes is intended to support single-dish frequency-switched spectroscopy, and thus it does not require that accurate phase tracking be achieved at the new frequency within 10 msec.
10. The actual design of the ALMA correlator provides for a wide range of modes and features. Here we consider only the most important requirements. A detailed mode table will be part of the correlator subsytem's specification document (in preparation).
11. The filter bank is described briefly in [2], section 2.6.1, and more fully in [9]. The correlator is also required to operate in a mode that bypasses the filter bank.
12. The requirement here matches the scientific requirement for .05 km/sec resolution at the lowest observing frequency. Achieving the finest resolution may require using reduced bandwidth and/or processing a single polarization. In the current design, a channel spacing of 3.8 kHz (satisfying the requirement) is achieved by processing one polarization channel per quadrant at 31 MHz bandwidth, or an aggregate bandwidth of 125 MHz for all quadrants. By using all quadrants to process the same channel, the resolution can be 4 times smaller or all polarization products can be formed but the total bandwidth is then 31 MHz.
13. The minimum readout interval is limited by the data rate, and is available only by limiting the bandwidth or spectral resolution or number of baselines. At the finest resolution, the minimum readout interval for all baselines is 512 msec.
14. Observing frequency selection involves a combination of 1st and 2nd LO tunings. Details are given in [2] section 3.1.1.3.
15. The required archiving rate is 4% of the maximum correlator output rate. Although this requirement is not covered in [1], it is considered adequate for the anticipated science [10].

16. Here δL is the uncorrected rms fluctuation in atmospheric delay and *w* is the condensed water vapor depth along the line of sight. The requirement matches the current WVR specification, which applies to fluctuations about the 5 min average, and at constant air mass.
17. The common mode phase stability is intended to match that of a typical hydrogen maser oscillator over this time range. VLBI coherence times may be only a few seconds at 230 GHz due to the atmosphere. Real time phasing up of the entire array at higher frequencies is doubtful, but it might be possible for a few antennas.
18. This absolute accuracy is easily obtained with Rb cavity oscillators or H-maser oscillators; in fact, a factor of 10—100 better is possible.
19. This requires resetting array time to TAI about every 12 days if the absolute frequency requirement is just met. Knowledge of the time difference is needed only for VLBI, and it is easily provided by a simple GPS receiver.
20. The delay repeatability (structure) and phase drift (electronics) apply over any 300 sec interval, taken to be the length of a complete instrumental calibration cycle. It is desirable to meet this requirement over longer intervals so as to allow longer calibration cycles; a goal is 1000 sec. The delay drift in time for the antenna structure only applies to the differential change over a 2 degree change in antenna pointing.
21. This corresponds to a Ruze efficiency of 0.61 (the theoretical value for a surface error of 25 microns rms at 675 GHz), along with feed and spillover efficiency of 0.75.
22. Maximum receiver temperatures are SSB, and apply over at least 80% of the specified RF frequency range of each band. They are set equal to Nhf/k + 4K, where *f* is the maximum frequency in the band, *h* and *k* are the usual constants, and *N*=6 for bands 1…6, *N*=8 for bands 7 and 8, and *N*=12 for bands 9 and 10. Values are given in Table 3.
23. Finalizing the technical requirement is awaiting analysis of the scientific requirement.
24. A CRE is in process to increase sampling rate to 2 kHz with >99% efficiency.
25. The BE and FE system pre-production prototypes are being built to a less stringent specification. The system specification given here will be reviewed after evaluation of this hardware.
26. The fiber cable length to four stations (212, 214, 215, and 216) may be at or slightly exceed the 15 km limit. In the detail network design, a best effort will be made to keep these cable lengths less than 15 km.
27. For VLBI support, only the basic hooks for access to delay-adjusted samples are provided on connectors on the correlator backplanes. There is no phasing-up software, no data acquisition terminal, and no hydrogen maser frequency standard in the project plan.

The allocation of errors between the structure and the electronics is somewhat arbitrary, with 25% of the squared error allowed for the structure. Further allocation among major elements of the electronics is given in Table 2.

Table 2: Preliminary Allocation of Instrumental Delay/Phase Errors

Component	Sq. Err. Fraction %	Short term rms (fsec)	Drift rms (fsec)
First LO	50	53	17.7
Second & Third LOs	5	17*	5.6*
Signal Path (FE and IF/BB)	20	34*	11.2*
Subtotal for electronics	**75**	**65**	**22**
Structure	25	38	13
Total instrumental error	**100**	**75**	**25 TBC**

* For 2nd and 3rd LOs and for the IF/BB part of the signal path, these values should be understood to apply at 950 GHz.

The meaning of these requirements must be understood in the context of the assumed observing scenarios. Consider three cases:

1. Two-frequency fast switching. A phase calibrator is observed at a different frequency from the target source, with the calibrator observations rapidly interspersed between target source observations. This is repeated with a cycle time T_1 of about 10 to 20 sec. A separate observation of a calibrator at both frequencies is then made to determine the difference of instrumental phases between the two frequencies. This is done less often, with cycle time $T_2 >> T_1$. See [12] for more details.
2. Single frequency fast switching. Again, phase calibrator observations are rapidly interspersed with target source observations at cycle time T_1, but with both at the same frequency.
3. No fast switching. A phase calibrator is observed at interval T_2, and at the same frequency as the target.

The requirements are based primarily on simulations of Case 1 with $T_1 \cong 20$ sec and T_2=300 sec [12]. Notice that, for this case, the drift requirement over 300 sec applies only to the *difference* in instrumental delay between the two frequencies; any drift that is common to both is not important. The fast calibrator observation simultaneously removes the tropospheric delay fluctuations and the common part of the instrumental phase. In Case 2, the tropospheric correction and full instrumental calibration are performed together. There is only one frequency so no common-mode cancellation can occur, but drift is important only for intervals ~T_1. If the *differential* drift requirement is met at T_2, then it might be met at T_1. In Case 3, the calibrator observation cannot remove most of the tropospheric fluctuations and serves mainly to calibrate the instrumental phase. It applies only if the tropospheric effects are negligible or have been corrected by other means (e.g., WVR measurements). Then the instrumental phase drift at the single frequency is important at interval T_2. This is probably the worst case. To summarize, the drift requirement applies at 300 sec intervals (and preferably longer) to *both* the delay change at a single observing frequency and the change in the delay difference between two observing frequencies.

In all cases, the short term requirement refers to the rms deviation from the 10-sec average. It thus encompasses all time intervals shorter than 10 sec. The drift requirement refers to the rms of the difference between 10-sec averages taken at intervals of 300 sec.

These requirements are given as rms variations of delay, in time units. For the structure and for the RF signal path, this refers to variations in the actual path delay. For the first LO, it is the phase error divided by the LO frequency. For later LOs and for the IF and baseband signal paths, it should be converted to phase by multiplying by 950 GHz.

3 Gain Stability

The gain stability requirements (Nos. 261, 262) are based primarily on the studies reported in [7] and the testing method in [6], and they are stated in terms of the 2-point Allan standard deviation of the fractional gain variation $\Delta G/G$. The .05 sec time interval corresponds to fast nutation of the subreflector, and 0.5 sec corresponds to on-the-fly mapping, both in single-dish total power mode. The adopted value of 4e-4 for the four total power antennas is far worse than is desirable in this mode, since it reduces the effective bandwidth from about 7 GHz to 175 MHz per polarization. It is claimed that better performance is not practical.

Tentatively, and somewhat arbitrarily, these requirements are allocated equally to the Front End components and the “back end” components (downconverter, baseband processor, 2nd LO, digitizer) of the signal path. On the assumption that gain fluctuations in FE and BE are independent, 0.707 of the standard deviation is allocated to each. These allocations should be re-examined after field experience with complete prototype systems is obtained.

Table 3: Band-Dependent Requirements

Band No.	Frequency Range GHz	*Max. Rcvr. Temperature* K	Front End Type	IF *Range* GHz
1	31.3-45.0	17.0	HFET, USB	4-12
2	67—90	29.9	HFET, LSB	4-12
3	84—116	37.4	SIS, 2SB	4-8
4	125—163	51.0	SIS, 2SB	4-12
5	163—211	65	SIS, 2SB	4-12
6	211—275	83	SIS, 2SB	4-12
7	275—373	146	SIS, 2SB	4-8
8	385—500	196	SIS, DSB	4-12
9	602—720	419	SIS, DSB	4-12
10	787—950	551	SIS, DSB	4-12

Notes: Band 7 - receiver noise temperature limit from 370 - 373 GHz will be < 300 K.

This document is based on an earlier document “System-Level Technical Requirements” ALMA-80.04.00.00-D by Larry D’Addario which is now obsolete. I appreciate the large and conscientious effort by Larry in establishing the top level requirements for ALMA.

4 REFERENCES

[1] *ALMA Scientific Requirements,* document ALMA-90.00.00.00-001-A-SPE
[2] *System Design Description,* ALMA-80.04.00.00-002-C-SPE - draft
[3] L. D'Addario, "Fringe tracking, sideband separation, and phase switching in the ALMA telescope." ALMA Memo 287, February 2000.
[4] L. D'Addario, "Notes on delay tracking for ALMA: resolution and tolerance." Memo dated 2003-02-08, BEND-50.00.00.00-002-A-GEN.
[5] A. Wootten *et al.*, "Frequency band considerations and recommendations." MMA Memo 213, 1998-May-28.
[6] L. D'Addario, "Gain stability testing for front end and back end assemblies." Memo dated 2003-07-14, SYSE-80.10.00.00-003-A-SPE.
[7] L. D'Addario, "Gain stability: requirements and design considerations." ALMA Memo 466, 2003-May-22.
[8] L. D'Addario, "Passband shape deviation limits." ALMA Memo 452, 2003-Apr-09.
[9] B. Quertier *et al.*, "Enhancing the ALMA correlator performances with a second generation correlator digital filter system." ALMA Memo 476, 2003-Aug-27.
[10] A. Wootten, private communication.
[11] L. D'Addario and M. Holdaway, "Joint distribution of atmospheric transparency and phase fluctuations at Chatnantor." LAMA Memo 801, 2003-Nov-11.
[12] M. Holdaway, “Simulation of atmospheric phase correction combined with instrumental phase calibration using fast switching.” LAMA Memo 803, 2004-Jan-23.