ALMA Project Book, Chapter 2.2

ALMA ENGINEERING SPECIFICATIONS

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Introduction

In this chapter we give a summary of the engineering specifications of all aspects of the ALMA project. The material is drawn from other chapters of this Project Book, but is collected here for convenience. This chapter is intended to be completely consistent with all other chapters of the book. If discrepancies are found, please notify the editors DTE or JWMB as soon as possible.

Tables of specifications

Table 2.1 ALMA Science Flowdown to Technical Specifications

Science Requirement and Examples	Technical Requirements Needed to Achieve
1. High Fidelity Imaging ● Imaging spatial structure within galactic disks; • Imaging chemical structure within molecular clouds; ❍ Imaging protostars in star formation regions	● Reconfigurable Array ● Robust Instantaneous uv-coverage, $N_{ant} > 60$ ● Precision Pointing, 6% of the HPBW ● Antenna Surface Accuracy RMS = 20 microns ● Primary Beam Deviations < 7% ● Total Power and Interferometric Capability ● Precise (1%) Amplitude Calibration ● Precise Instrumental Phase Calibration (<10 degrees rms) ● Precise atmospheric phase calibration (<15 degrees rms) with compensation using both fast switching and water vapor radiometry
2. Precise Imaging at 0.1" Resolution ● Ability to discriminate galaxies in deep images; ● Imaging protoplanets orbiting protostars; ● Imaging nuclear kinematics	● Interferometric baselines longer than 3 km ● Precise Instrumental Phase Calibration (<10 degrees rms) ● Precise atmospheric phase calibration (<15 degrees rms) with compensation using both fast switching and water vapor radiometry

3. Routine Sub-milliJansky Continuum Sensitivity • To enable imaging of the dust continuum emission from cosmologically-distant galaxies • To enable imaging of protostars and protoplanets throughout the Milky Way • To enable astrometric observations of solar system minor planets and Kuiper-belt objects	• Array site with median atmospheric transparency < 0.05 at 225 GHz • Quantum-limited SIS receivers • Antennas with warm spillover <5K, and aperture blockage <3% • Antennas of aperture efficiency > 75% • Wide correlated IF bandwidth, 16 GHz • Dual polarization receivers • Array collecting area, $ND^2 > 7000\ m^2$
4. Routine Milli-Kelvin Spectral Sensitivity • Spectroscopic probes of protostellar kinematics • Spectroscopic chemical analysis of protostars, protoplanetary systems and galactic nuclei • Spectroscopic studies of galactic disks and spiral structure kinematics	• Array site with median atmospheric transparency < 0.05 at 225 GHz • Quantum-limited SIS receivers • Antennas with warm spillover < 5 K, aperture blockage <3% • Antennas with aperture efficiency > 0.75 • Wide correlated IF bandwidth, 16 GHz • Dual polarization receivers • Array collecting area, $ND^2 > 7000\ m^2$ • Array collecting length, ND > 700 m
5. Wideband Frequency Coverage • Spectroscopic imaging of redshifted lines from cosmologically-distant galaxies • To enable comparative astrochemical studies of protostars, protoplanets and molecular clouds • To enable quantitative astrophysics of gas temperature, density and excitation	• Receiver bandwidths matched to the width of the atmospheric windows • Tunable local oscillator matched to the bandwidth of the receivers • Cryogenic capacity > 1 W at 4 K
6. Wide Field Imaging, Mosaicking • Imaging galactic disks • Imaging the astrophysical context of star formation regions • Imaging surveys of large angular regions • Searches for dusty and luminous protogalaxies • Searches for minor planets in the solar system • Solar astrophysics	• Compact array configuration, filling factor > 0.5 • Instantaneous uv-coverage that fills more than half the uv-cells, $N_{ant} > 60$ • Precision pointing, 6% of HPBW • Antenna surface accuracy 20 microns • Total power and interferometric capability • Precise amplitude calibration, 1% • Precise Instrumental Phase Calibration (<10 degrees rms) • Correlator dump time 10 msec • Capability to handle data rates > 100 Mbyte/sec

7. Submillimeter Receiving System • Measurement of the spectral energy distribution of high redshift galaxies • Chemical spectroscopy using CI and atomic hydrides • Determination of the CII and NII abundance in galaxies as a function of cosmological epoch	• Array site with median atmospheric transparency < 0.05 at 225 GHz • Quantum-limited SIS receivers • Antennas with warm spillover < 5 K, aperture blockage <3% • Antennas with aperture efficiency > 0.75 • Precise Instrumental Phase Calibration (<10 degrees rms) • Precise atmospheric phase calibration (<15 degrees rms) with compensation using both fast switching and water vapor radiometry
8. Full Polarization Capability • Measurement of the magnetic field direction from polarized emission of dust • Measurement of the magnetic field strength from molecular Zeeman-effect observations • Measurement of the magnetic field structure in solar active regions	• Measure all Stokes parameters simultaneously • Cross correlate to determine Stokes V • Calibration of linear gains to <1%
9. System Flexibility • To enable VLBI observations • To enable pulsar observations • For differential astrometry • For solar astronomy	• Ability to phase the array for VLBI • Sum port on the correlator for external processing • Sub-arraying, 4 subarrays simultaneously • Optics designed for solar observations

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Calibration Requirements

The precision imaging to be attained by the ALMA will be achieved through accurate calibration. The types of calibration are summarized in Table 3.1.

Table 3.1 ALMA Calibration Requirements.

Pointing	0.6" absolute
Primary Beam	2-3%
Baseline Determination	0.1 mm
Flux Calibration	1% absolute flux accuracy goal
Phase Calibration	0.15 radian at 230 GHz
Bandpass Calibration	10000:1 to 100000:1
Polarization Calibration	10000:1
Single Antenna Calibration	Employed

Antenna Specifications

The ALMA radiotelescope is currently planned to consist of a goal of 64 antennas, each of 12 m diameter. In this chapter we outline the general requirements for the antennas and the detailed specifications can be in the contract for the prototype antenna (NRAO, 2000) and in the Interface Control Documents (ICD, 2000) which are part of the contract. The principal requirements for the antennas are shown in Table 4.1.

Table 4.1 ALMA antenna principal performance requirements.

Configuration	Elevation-over-azimuth mount, Cassegrain focus
Frequency range	30 GHz to 950 GHz
Precision performance conditions	Nightime: wind 9 m/s Daytime: wind 6 m/s and sun from any angle
Reflector surface accuracy	20 microns rms, goal; 25 microns rms, spec
Pointing accuracy, rms	0.6 arcsec (offset, 2 deg in position and 15 min time), 2.0 arcsec (absolute)
Fast switching (settle to 3 arcsec pointing)	Move 1.5 deg in position in 1.5 seconds
Phase stability	15 microns rms
Close packing	1.25 dish diameters (15.0 m) between azimuth axis
Solar observing	Allowed
Transportability	Transportable on a rubber-tired vehicle

The antennas will be designed and built by one or more commercial companies. Prototype antennas are being built for the US and European ALMA partners by Vertex Antenna Systems LLC (Santa Clara, CA) and European Industrial Engineering (EIE) (Mestre, Italy) respectively.

Receiver Specifications

The document *Specifications for the ALMA Front End Assembly* (latest version) contains the detailed specifications. Portions of this have been approved by the AEC. The main specifications are:

- Frequency coverage: from 31.3 to 950 GHz in 10 bands (see Table 5.1)
- simultaneous reception of two orthogonal polarizations
- receiver noise between 6 and 10 times $h\nu/k$ over 80% of the band, with a goal of achieving 3 to 8 times $h\nu/k$, depending on the band
- IF bandwidth 8 GHz total per polarization
- observations at one frequency at a time (no dual frequency obervations)
- inclusion of a water vapour radiometer using the 183 GHz line for phase correction.

For details, see the full *Specifications for the ALMA Front End Assembly* (latest version).

Table .1 – Frequency bands for ALMA

Band	from (GHz)	to (GHz)
1	31.3	45
2	67	90
3	89*	116
4	125	163
5	163	211
6	211	275
7	275	370

8	385	500
9	602	720
10	787	950

* change to 84 GHz has been proposed

LO specifications

The LO subsystem also forms part of the array master clock, in cooperation with a computer of the monitor-control subsystem. It does this by providing an interface to an external time scale (currently GPS) and by measuring the difference between external time and array time. Measures of time larger than 48 msec are obtained in the MC system by integration. Further details are given in the LO chapter.

Table 1: Specification Summary

Item	Specification	Goal (if different)
Frequency Range, 1st LO	1st LO: 27.3 to 938 GHz (see Table 2) 2nd LO: 8-10 and 12-14 GHz	
Output Power	1st LO: band dependent (see Table 3) 2nd LO: +10dBm ea. to 2 converters.	100 µW
Sideband Noise, 1st LO	10 K/µW	3 K/µW
Amplitude Stability, 1st LO	.03% <1s; 3% between adjustments	.01%; 1%
Phase Noise (>1 Hz)	63 fsec (18.9 µm)	31.4 fsec (9.4 µm)
Phase Drift (<1 Hz)	29.2 fsec (8.8 µm)	6.9 fsec (2.1 µm)
Tuning step size, maximum	On the sky: 250 MHz SIS mixer 1st LO: 500 MHz	
Subarrays with independent tunability	TBD (3 or more)	5
Simultaneous different sky frequencies	1 per subarray	
Time for frequency change, maximum	Within .03% (freq switching): 10 msec Otherwise: 1.5 sec	1 msec 1.0 sec
Repeatability	1. Phase-unambiguous synthesis 2. Stability specs apply across frequency changes.	

LO Output Power

The local oscillator must provide adequate mixer drive power for both HFET and SIS based receivers. A conventional balanced mixer used in a millimeter-wave HFET front-end requires approximately 5 mW of LO power. However, 20 mW may be required if a sideband-separating mixer follows the low noise HFET amplifier.

Chapter 7, Table 3: First LO Power Requirements

ALMA Receiver Band	LO Tuning Range [GHz]	Type of Receiver Front-End	Number of SIS Junctions	Minimum Required Mixer Power	Required Power at Input of -20 dB Coupler of SIS Mixer	Required Power at LO port of an Image -Reject & Balanced Mixer	LO Power Specification of 50% Over Worst-Case
1	27-33	HFET	---	5 mW	---	10 mW	15 mW
2	71-94	HFET	---	5 mW	---	10 mW	15 mW

3a	101-104	HFET	--	5 mW	---	10 mW	15 mW
3b	101-104	SIS	4	0.10 µW	10 µW	0.40 µW	15 µW
4	137-151	SIS	4	0.15 µW	15 µW	0.60 µW	23 µW
5	175-199	SIS	4	0.26 µW	26 µW	1.06 µW	39 µW
6	223-263	SIS	4	0.46 µW	46 µW	1.84 µW	69 µW
7	287-358	SIS	2	0.21 µW	21 µW	0.84 µW	32 µW
8	397-488	SIS	2	0.40 µW	40 µW	---	60 µW
9	614-708	SIS	2	0.42 µW	42 µW	---	63 µW
10	799-938	SIS	1	0.37µW	36 µW	0.73 µW	54 µW

In the worst-case scenario where only single-ended, two-port SIS mixers are used, a waveguide or quasi-optical LO coupler, having a coupling factor of -20 dB, will be required to combine the LO and RF signals appropriately. The LO power required at the input of the coupler is also given in Table 3. However, if a balanced mixer can be utilized, the LO power is supplied via a separate LO port on the mixer thus rendering the coupler unnecessary. Column #7 in Table 3 lists the power requirements for a balanced mixer configuration that is both image separating and balanced. The last column is a suggested *specification* per RF band based upon a 50 percent overhead for the worst-case conditions. The LO power *goal* will be 100 µW per band to ensure adequate power to overcome losses within the mixer block.

The Downconverter

In each ALMA antenna there will be two Downconverter modules, one for each polarization, and the two inputs to each module will carry upper and lower side-band signals. A block diagram of the Downconverter is shown in Figure 9.1.1 and the specifications are in Table 9.1.1 The input and output noise power spectral power distribution will be nominally flat over the passband as given in the specifications. The Downconverter will take the wideband 4 - 12 GHz input signals received from the front end subsystem and produce four output signal channels each with a passband of 2 - 4 GHz suitable for bandpass sampling at by the digitizers, which are clocked at 4 GS/s

Table 9.1.1 Specifications for Downconverter

DOWNCONVERTER MODULE

SPECIFICATIONS for ALMA CONSTRUCTION

Reference: Block Diagram, Document # ALMA06002KX0002

*** indicates interfaces**

Number of modules	142 (2 x 64 antennas plus 14 spares)
***Inputs from front end**	
Number of inputs per module	Two: USB, LSB (upper and lower sidebands)
Frequency range, nominal	4-12 GHz or 4-8 GHz
Power level within any 2 GHz bandwidth when the antenna temperature is 290K	-40 +/-3 dBm, less loss of coax and connectors between front end outputs and module inputs (3m of phase stabilized Andrew FSJ1P-50A ¼ inch diameter, attenuation = 2.4 dB @ 12GHz)
Variation of power spectral density vs. frequency (flatness)	<+/-1.5 dB across the nominal frequency range

Headroom when the antenna temperature is 290K (see definition)	>20 dB
***Inputs from Second LO (LO2)**	
Number of inputs per module	Four (A, B, C, D), independently tunable
Frequency range	8.0-14.0 GHz nominal; frequency LO2 > frequency input
Power level	+13 +/-1 dBm
Power level of spurious frequencies	<-70 dBc, except <-40 dBc for 2nd harmonic
***Outputs to digitizers**	
Number of outputs per module	Four (A, B, C, D)
Frequency range	2 - 4 GHz nominal
Power level	-TBD +/-TBD dBm plus loss of coax and connectors between output and input to digitizer module
Headroom when the antenna temperature is 290K	>20 dB
LO2 spurious and leakage at outputs	<(power level -40 dB) for all combinations of frequencies of LO2-A, -B, -C, -D

Throughput from front end inputs to outputs to digitizers	
Input S_{11} reflection magnitude 4 – 12 GHz	<-20 dB (VSWR < 1.22) to minimize spectral ripples
Input noise figure 4 – 12 GHz	< 10 dB (2 610K); SP_{DC} < -164 dBm/Hz << SP_{FE} = -133 dBm/Hz
Image rejection	>20 dB
Filter, 4-12 GHz nominal bandpass for total power detection	passband <4.0 GHz and >12.0 GHz at -1 dB, max ripple +/-0.5 dB; stopband 3.5 GHz and 12.5 GHz at < -20 dB, 0-3.0 GHz and 13.0-18 GHz at < -40 dB

Filter, bandpass image reject	(may be revised after re-analysis of spurious mixer responses)
4-8 GHz nominal	passband <4.1 GHz and >8.4 GHz at -1 dB, max ripple +/-0.5 dB; stopband 4.0 GHz and 8.6 GHz at < -10dB, 0-3.0 GHz and 10-18 GHz at < -40 dB
8-12 GHz nominal	passband <7.6 GHz and >12.0 GHz at -1 dB, max ripple +/-0.5 dB; stopband 7.4 GHz and 12.4 GHz at < -10 dB, 0-6.0 GHz and 14-18 GHz at < -40 dB
Filter, outputs A, B, C, D (may be revised after re-analysis of mixer and digitizer spurious responses)	passband <2.1 GHz and >3.9 GHz at -1 dB, max ripple +/- 0.5 dB; stopband 0-2.0 GHz and 4.0-12 GHz at < -20 dB
Passband amplitude ripple	<1.0 dB peak-peak
Passband deviation from linear phase	<40 degree peak-peak
Gain stability	<0.1 dB peak-peak over 1 minute, <0.5 dB peak-peak over 60 minutes
Phase/delay stability	<10 degree peak-peak over 1 minute, <40 degree peak-peak over 60 minutes
Headroom[1] when the antenna temperature is 290K	>20 dB
Crosstalk (inverse of isolation) among any input and any unconnected output	>40 dB rejection
Attenuators in input path 4-12 GHz	
Steps	1 +/-0.3 dB
Range	>30 dB
Phase variation vs. attenuation	<20 degree peak-peak over attenuation range 0-20 dB
Deviation from linear phase vs. frequency 4-12GHz	<20 degree peak-peak over attenuation range 0-20 dB

Attenuators in output path 2 - 4 GHz	
Steps, nominal	0.25 +/-0.15 dB over attenuation range 0-20 dB
Range, nominal	>30 dB

Phase variation vs. attenuation	<10 degree peak-peak over attenuation range 0-20 dB
Deviation from linear phase vs. input frequency 4-12 GHz	<10 degree peak-peak over attenuation range 0-20 dB
Matching among all downconverters	
Amplitude vs. frequency	TBD
Phase vs. frequency	TBD
Total power detectors (TPD)	
Input path 4-12 GHz	
Number	two, one for each input channel
Response vs. input frequency at any LO2 frequency	< 2 dB peak-peak.
Output path 2 - 4 GHz	
Number	four, one for each output channel A, B, C, D
Response vs. input frequency at any LO2 frequency	< 1.5 dB peak-peak.
Linearity	<1 % deviation from square law over range -6 dB to +13 dB relative to antenna temperature = 290 K
Monotonic resolution of digitizer, minimum	16 bits for 13 dB headroom above antenna temperature = 290 K
*Readout	2 millisec integrations and dumps to MC-AMBTP card via serial or parallel interface
*Offset calibration	MC sets the input power to zero by either setting the preceding attenuator to >(20 dB + headroom) or by removing bias to the preceding amplifier
Stability of output relative to inputs from front end	<50 ppm in 1 second, <500 ppm in 60 seconds
*Interface to MC-AMBTP	dedicated total power data link to antenna bus master (ABM)
***MC control functions**	
Set levels of input total power detectors	1 byte for each of two attenuators
Set levels of output of each total power detector and input level of each output digitizer	1 byte for each of four attenuators

Set to zero all inputs to total power detectors	1 byte to remove bias to six amplifiers; or set all attenuators to maximum
Set all 3 matrix switches (select image filters for each output)	1 byte

***MC monitor functions**	
Total power detectors	3 bytes every 2 milliseconds for each of 6 detectors
Temperatures	2 bytes every 10 seconds for each of 8 locations
Supply voltages derived within module	2 bytes every 10 seconds for each of 8 voltages
***External power supply inputs**	+18 +/-0.5VDC @ <2.2A, -18 +/-0.5VDC @ <0.7A, +8 +/-0.3VDC @ <0.6A, +5 +/-0.1VDC @ <0.6A
Internal voltage regulators	
Output voltages @ amperes	+15 @ 2.2 (total of >1 regulator), -15 @ 0.6, +5 @ 0.6, -5 @ 0.1
Output regulation plus noise	0.01% peak-peak over time interval > 60 seconds
Timing generator	
*Inputs from Reference Receiver	25 MHz sine wave at 0 dBm; 20.833 Hz positive edge, 5V differential
Output for timing total power integration	500 Hz TTL pulses of >1 usec width synchronized to 20.833 Hz timing reference
Output for digitizer clock	TBD MHz to match digitizer; synchronized to 20.833 Hz timing reference
***Operational environment**	
Altitude	5000 meter (16,000feet)
Shock	Negligible
Vibration	TBD

Temperature of air flow past sides of module	Plenum temperature set 16 – 22 Celsius, variation < 2 C peak-peak
Air mass flow rate past sides of module	TBD
Specific heat of air flow	TBD
Packaging	
Module	3 to 6 width x 5U high x TBD depth standard module (ATNF) with extruded vertical heat fins on one side or both sides
*Multi-pin connector (power, MC-AMB, MC-TP)	One double density 100 pin D type [male]
*Coaxial connectors	12 OSP (M/A-COM) blind mating [male]

1. Define *headroom* as the dB ratio of *available power at 1% gain compression {P(-1%)}* to the *total system noise power {P}*. Typically, P(-1%) is 16 dB less than the available power at –1 dB gain compression and 26 dB less than the available power at third order intercept. -end-

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The Digitizers

9.2.1 Introduction, Top Level Specifications

The analog-to-digital converters, or digitizers, installed in the antennas provide the flexibility required for the fiber optic transmission of the IF. Signal digital conversion is of course indispensable to the correlator in order to derive the correlation function as a function of digital lags for spectroscopy. The digitizers are thus crucial and single-point-failure elements in the system. The ALMA system incorporates 3-bit digitizers thus improving the overall sensitivity compared to the classical 2-bit case.

The goal specifications are given in Table 9.2.1

Input BW 2-4 GHz

Sample clock 4 GHz (250 ps)

Bit resolution 3 bits

Quantization levels 8

Aperture time ~ 50 ps

Jitter a few ps

Threshold indecision region a few mV

Output demultiplexing factor 1/32 (125 MHz system clock)

PLL Clock distribution 4 GHz, 125 MHz (system)

Fine delay command

Low power consumption

ALMA Correlator

This section describes the ALMA correlator. The design described here is for a lag correlator with a system clock rate of 125 MHz. The goals of Phase 1 are to produce paper designs and some simulations of all major correlator elements, including the correlator chip, and to fabricate and test prototype hardware. The goals of Phase 2 are to produce a prototype minimally populated correlator, deliver such a prototype for use in the test interferometer, and deliver the complete correlator to the ALMA site.

Table 10.1 ALMA Correlator Specifications

Item	Specification
Number of antennas	64
Number of baseband inputs per antenna	8
Maximum sampling rate per baseband input	4 GHz
Digitizing format	3 bit, 8 level or 4 bit, 16 level
Correlation format	2 bit, 4 level
Maximum baseline delay range	30 km
Hardware cross-correlators per baseline	1024 lags + 1024 leads
Autocorrelators per antenna	1024
Product pairs possible for polarization	HH, VV, HV, VH (for orthogonal H and V)

Table 10.3 Selected correlator modes

# of Digitizers	Bandwidth/ Digitizer	Cross-pol Products?	Channels/ Product	At 230 GHz, in velocity space: Range	Resolution km/s
8	2 GHz	Yes	64	9391	40.8
8	2 GHz	No	128	18783	20.4
8	1 GHz	No	256	9391	5.1
8	500 MHz	Yes	256	2348	2.5
8	250 MHz	No	1024	2348	0.32
4	2 GHz	Yes	128	4696	20.4
4	1 GHz	No	512	4696	2.5

4	500 MHz	Yes	512	1174	1.3
4	250 MHz	No	2048	1174	0.16
2	2 GHz	Yes	256	2348	10.2
2	1 GHz	No	1024	2348	1.3
2	500 MHz	Yes	1024	587	0.64
2	250 MHz	No	4096	587	0.08

ALMA Computing, principal requirements

Sustained data rate, science data	6 MB/s (Average) 60 MB/s (Peak sustained)
Image pipeline	First-look images produced automatically for standard observing.
Dynamic scheduling	Nearly automatic scheduling of the array, accounting for current weather and other conditions, to optimize the scientific throughput of the array.
Archiving	Networked archive of all ALMA raw science data and associated calibration data and derived data products.

Antenna configuration on the Chajnantor site

Table 15.1 Guidelines for Configuration Design

Main D&D Task	Design a set of configurations which allow for a range of angular resolution and sensitivity
Flexible design philosophy	Configurations must allow for graceful expansion through possible collaboration
Costing	Optimize for shared stations to minimize cost
Site placement	Choose specific locations for antenna placement on Chajnantor site

The table below outlines different designs up to 3 km maximum baseline. A larger, 12 km baseline will now be included as well; the beam size at 345 GHz will be approximately 0.013 arc seconds. The choice between a donut or a spiral configuration is being discussed.

Table 15.3 Specifications for the ALMA strawperson configurations.

Array	Minimum	Maximum	Array	Time for	Natural
	Baseline	Baseline	Style	FOC = 0.5	Beam at 345 GHz
	[m]	[m]		[hours]	[arcs]
A	30	3000	donut	10	0.050
B	24	1430	donut	2	0.101
C	18	680	donut	0.1	0.22
D	16	325	donut	0.1	0.47
E	16	150	filled	0	0.97

Table 15.4 Specifications for the compact configuration N-S elongations.

Array	Min. N-S	Elev. of first	Min. observing	Max. observing	N-S
	Distance	Shadowing	Elevation	Elevation	Elongation
E1	1.3 D	50 deg	40-45	90	1.2
E2	1.9 D	31 deg	30	50+	1.6
E3	3.0 D	19 deg	14	33+	2.9