Report of the ALMA Front-end & Digitizer Requirements Upgrade Working Group

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Change Record

Version	Date	Affected Paragraphs(s)	Reason/Initiation/Remarks
A	2019-06-27	All	First Draft
A01	2020-07-31	All	Updated with feedback from the AMT
A02	2020-10-11	All	Updated with feedback from the AMT
A03	2020-10-21	All	Minor updates to clarify text
B	2020-10-27	Several	Version released to the IXTs
B	2020-12-16	Table 12	Updated Table 12

Table of Contents

1 EXECUTIVE SUMMARY

The ALMA Development Roadmap [AD01] defines a long-term development strategy for the upgrade of hardware, software, and analysis tools to enhance the future observing capabilities of ALMA.

The ALMA Front-end & Digitizer Requirement Update Working Group (hereafter the Working Group) was established by the JAO and AMT in November 2018 to define system level technical goals that will guide ongoing and future ALMA development effort. The Working Group consists of technical and science experts from East Asia, Europe, North America, and the JAO. Its mandate is to deliver a consistent set of (revised) technical goals for front-end and digitizer products to realize the science goals defined in the ALMA 2030 Development Roadmap.

According to the board-approved Development Roadmap, the current development priorities, based on scientific merit and technical feasibility, are to:

- broaden the receiver intermediate frequency (IF) bandwidth by *at least* a factor two, and
- upgrade the associated electronics and correlator.

These improvements, when realized, will advance a wide range of scientific studies by significantly reducing the time required for blind redshift surveys, spectral scans, and deep continuum surveys.

This report summarizes the desired *technical goals* for the ALMA receiver system and digitizers, based upon the deliberations of the Working Group. In addition to the RF front-end, the portion of the ALMA system considered during the discussions includes the signal path from the output of the RF front-ends up to and including the digital samplers. However, the implementation details (i.e., component level requirements) of the front-ends, the front-end (first) local oscillator (LO) system, or the correlator have not been discussed (intentionally) by the Working Group.

The technical goals for the front-end and digitizer systems considered in this report are fairly straightforward, at least as far as operation in the interferometer mode (i.e., the cross-correlation measurements) is concerned. Some questions remain regarding the total power measurements, such as the image rejection ratio. The proposed *technical goals* that are relevant to the ALMA future front-end and digitizer system design are summarized in Table 1.

In the following paragraphs, we discuss various aspects of the receivers and make recommendations based on the current states-of-the-art technologies.

Table 1: Summary of current technical requirements and proposed technical goals.

Parameters	Req #	Existing Technical Requirement			Working Group Recommendation		Comment
Bandpass Shape: digitizer baseband	272	5.0 dB peak to peak in any 2 GHz portion of the IF band			< 5.4 dB (over TBC digitizer/IF bandwidth)		
Receiver Noise Temperatures		**Band**	**T_{RX} over 80% of the RF band**	**T_{RX} at any frequency**	**T_{RX} over 80% of the RF band**	**T_{RX} at any frequency**	
		1	28 K	32 K	N.A.	N.A.	The receiver will not be upgraded prior to the start of the 2030s.
		2	30 K	47 K	N.A.	N.A.	The receiver will not be upgraded prior to the start of the 2030s.
		3	See Comment	See Comment	35 K	40 K	The existing requirements: < 39K (averaged over all four IFs 4 GHz bandwidth at LO = 104 GHz) < 43K (averaged over all four IFs 4 GHz bandwidth for any LO setting)
		4	51 K	82 K	40 K	50 K	The existing Band 4 demonstrates performance around 40 K. Reaching 4hν/k like bands 5 – 7 is likely too ambitious, so a compromise value is suggested.
		5	55 K	75 K	41 K	51 K	The existing Band 5 demonstrates performance around 4hν/k. The proposed performance goal for 80% of the band is 4hν/k at 211 GHz and for the whole band is 5hν/k at 211 GHz.
		6	83 K	136 K	53 K	66 K	The existing Band 6 demonstrates performance around 4hν/k. The proposed performance goal for 80% of the band is 4hν/k at 275 GHz and for the whole band is 5hν/k at 275 GHz.
		7	147 K	219 K	72 K	90 K	The proposed performance goal for 80% of the band is 4hν/k at 373 GHz and for the whole band is 5hν/k at 373 GHz.
		8	196 K	292 K	100 K (390 – 420 GHz), 120 K	144 K	The proposed performance goal for 80% of the band is 5hν/k at 500 GHz and for the whole band is 6hν/k at 500 GHz. The goal is further tightened to 100 K at 390-420 GHz.
		9	175 K (DSB)	261 K (DSB)	242 K	290 K	The proposed SSB noise performance goal for 80% of the band is 7hν/k at 720 GHz and for the whole band is 1.2 × 7hν/k at 720 GHz.
		10	230 K (DSB)	344 K (DSB)	365 K	438 K	The proposed performance goal for 80% of the band is 8hν/k at 950 GHz and for the whole band is 1.2 × 8hν/k at 950 GHz.
1st Mixer Sideband Ratio	231	>10 dB suppression over 90% of the IF frequency range, SSB and 2SB >7 dB suppression over 100% of the IF frequency range, SSB and 2SB <3 dB difference across 80% of the combined IF and LO frequency ranges, DSB			>15 dB suppression over 90% of the IF frequency range >13 dB suppression over 100% of the IF frequency range		Noting that no new receivers will be DSB, we require the following performance for all 2SB and SSB receivers.
Total Instantaneous Bandwidth	250	> 8 GHz per polarization			≥ 16 GHz per polarization, with a goal of 32 GHz		IF bandwidth limitations will be set by the digitizers.
Effective Number of Bits (ENOB)	322	See Comment			≥ 5 ENOB, specified under the assumption of noise, with Gaussian distribution, as the input signal.		The existing requirement was not written in terms of ENOB, but rather on the raw number of bits: 3-bit
Digitizer Sampling Speed		4 GSps			> 40 GSps		

2 RELATED DOCUMENTS

2.1 Applicable Documents List

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

No	Document Title	Reference
AD01	ALMA Development Roadmap	Link

2.2 Reference Documents List

No	Document Title	Reference
RD01	Front-End Sub-System Technical Specifications	ALMA-40.00.00.00-001-B-SPE
RD02	Performance and Characterization of a Wide IF SIS-Mixer-Preamplifier Module Employing High-J c SIS Junctions	IEEE Trans Terahertz Sci Technol, 7(6), 694-703, 2017
RD03	Wideband 67−116 GHz receiver development for ALMA Band 2	A&A 634, A46, 2020
RD04	The ALMA Band 6 Receiver Upgrade	Presentation by J. Mangum at ESO WS 2019
RD05	ALMA Band 9 2SB Upgrade Study Progress Report July 2020	FEND-40.02.09.00-1954-B-REP
RD06	Receiver development for the IRAM telescopes	Presentation by C. Risacher at ESO WS 2019
RD07	275–500-GHz Wideband Waveguide SIS Mixers	IEEE Trans Terahertz Sci Technol, 8(6), 638-646, 2018
RD08	A Deployable 600-720 GHz ALMA-Type Sideband-Separating Receiver Cartridge	Proc. 29th Int. Symp. Space Terahertz Technol.. 2018
RD09	Sideband Separating Mixer for atmospheric window 790-950 GHz	Presentation by A. Khudchenko at ESO WS 2019
RD10	Demonstration of a Wideband Submm-wave Low-noise Receiver with 4-21 GHz IF Output Digitized by a High-speed 32 GSps ADC	A&A, 38713-20, 2020
RD11	Upgrading the ALMA Digital System, from Digitization to Correlation	Presentation by B. Quertier at ALMA 2030 Correlator WS
RD12	Band 3 Development at Herzberg	Presentation by L. Knee at ESO WS 2019
RD13	Improving Band 9 Sensitivity by Advanced Tuning Algorithms - Final Study Report	FEND-40.02.09.00-1944-C-REP
RD14	Revised ALMA System Technical Requirements - Polarization	ALMA-80.04.00.00-0038-A-SPE
RD15	Missing Specification on Receiver Alignment	Link
RD16	ALMA System Technical Requirements	ALMA-80.04.00.00-005-C-SPE
RD17	Revised ALMA System Technical Requirements - Spurious Signals	ALMA-80.04.00.00-0042-A-SPE
RD18	High-gap Nb-AlN-NbN SIS junctions for frequency band 790–950 GHz	IEEE Trans Terahertz Sci Technol, 6(1), 127-132. 2015
RD19	Superconducting Mixer Technology at NAOJ	Presentation by M. Kroug at ESO WS 2019S

2.3 Abbreviations and Acronyms

A complete set of acronyms and abbreviations can be found on the ALMA Acronym Finder web page.

3 SCIENCE

The ALMA Development Roadmap identified the following three science goals to drive future technical developments over the next decade.

Origins of Galaxies
Trace the cosmic evolution of key elements from the first galaxies (z>10) through the peak of star formation (z=2–4) by detecting their cooling lines, both atomic ([CII], [OIII]) and molecular (CO), and dust continuum, at a rate of 1-2 galaxies per hour.

Origins of Chemical Complexity
Trace the evolution from simple to complex organic molecules through the process of star and planet formation down to solar system scales (~10-100 au) by performing full-band frequency scans at a rate of 2-4 protostars per day.

Origins of Planets
Image protoplanetary disks in nearby (150 pc) star formation regions to resolve the Earth forming zone (~ 1 au) in the dust continuum at wavelengths shorter than 1mm, enabling detection of the tidal gaps and inner holes created by planets undergoing formation.

The primary driver needed to achieve the science goals for the *Origins of Galaxies* and the *Origins of Chemical Complexity* is increased observing speed of spectral lines. This calls for technical improvements to process larger IF bandwidths at fine spectral resolution to increase the spectral breadth for redshift surveys and chemical surveys, lower receiver temperatures for improved instantaneous sensitivity, and improved efficiency of the digital processing. These same developments will also improve the continuum sensitivity needed to probe the *Origins of Planets.*

4 OVERVIEW OF CURRENT ALMA SYSTEM AND POTENTIAL UPGRADES

4.1 Overview of current ALMA system

Before discussing the new technical goals, it is necessary to review some basic information on the current ALMA front-end and digitizer systems. The ALMA front-end is the first element in a complex chain of signal processing and contains the analog-RF portion of the receivers. The ALMA front-end covers all the available atmospheric frequency windows between 35 GHz and 950 GHz in 10 bands with the use of High Electron Mobility Transistors (HEMT, bands 1 and 2) or Superconductor-Insulator-Superconductor mixers (SIS, bands 3 to 10) as RF detectors. Band 1 employs a single sideband scheme (SSB) with an IF bandwidth of 8 GHz per polarization. The most recent design proposed for Band 2 employs a sideband separating scheme (2SB) with an IF of (at least) 14 GHz per polarization. Bands 3 to 8 employ sideband separating mixers and have 4 GHz of IF bandwidth per polarization sideband (5.5 GHz IF bandwidth for Band 6 only). The higher frequency bands (bands 9 and 10) are double sideband systems (DSB) with an IF bandwidth of 8 GHz per polarization. These two receivers may be upgraded with a sideband separation scheme [RD05][RD08][RD09][RD19]. Currently, the ALMA digitizer system employs a 3-bit quantization, with the correlator subsequently truncating the least significant bit to reduce quantization levels from 3- to 2-bit per sample.

Table 2: Tabulation of the existing IF configurations for the ALMA bands.

Band	IF (GHz)	Type
1 (under construction)	4-12	SSB
2 (under development)	4-18 (maybe wider)	2SB
3, 4, 5, 7, 8	4-8	2SB
6	4.5-10*	2SB
9, 10	4-12	DSB

* The Band 6 IF bandwidth has been increased by 0.5 GHz to extend from 4.5 to 10 GHz for simultaneous observations of the J=2-1 transitions of ^{12}CO, ^{13}CO, and $C^{18}O$ from ALMA Cycle 6.

Apart from the collecting area, array sensitivity depends primarily on the system noise temperature and bandwidth (for continuum). The RF front-ends have a major role in defining these quantities. Figure 1 shows the receiver temperature for the current ALMA receivers. At low frequencies (bands 3 to 7), the receiver noise temperatures are only a few times the quantum limit and approach practical physical limits. However, there is room for improvement in the noise performance of some bands, particularly at higher frequencies.

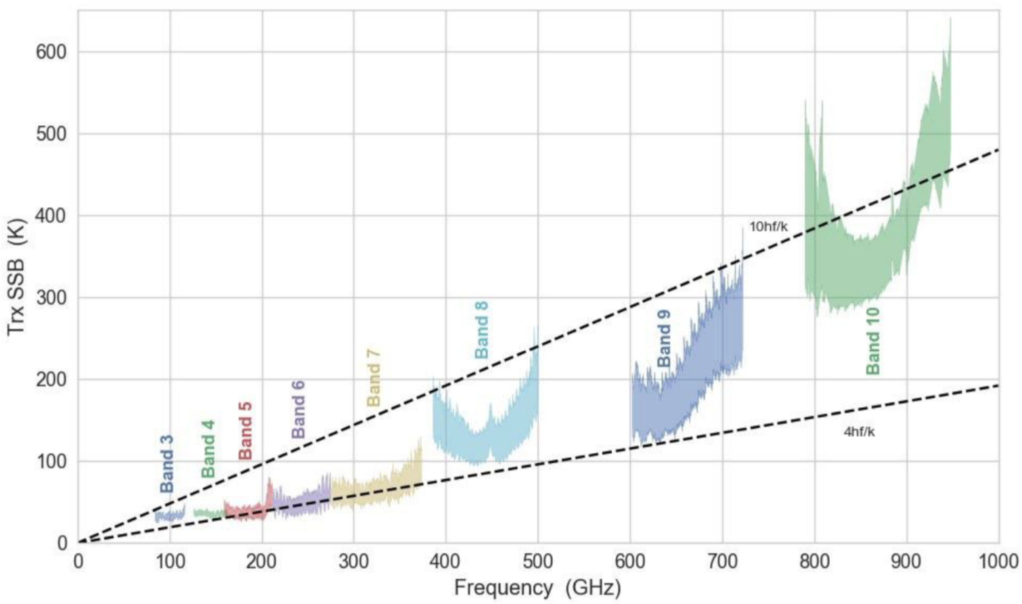

Figure 1: Achieved receiver noise temperature for the various ALMA receivers. The shaded region encompasses 75% of the receivers about the median receiver temperature from [AD01]. Bands 3-8 are 2SB receivers, and bands 9 and 10 are DSB. The noise temperature shown for the DSB receivers is twice the *measured* DSB temperature, to enable a fair comparison to the 2SB values indicated for other bands. (Note: The on-sky measured T_{RX} for Band 4 (see Figure 3) is slightly higher than the laboratory measured values plotted here; the reason for this is under investigation.)

4.2 Potential Upgrades

Each of the ALMA Executives hosted a regional development workshop after the Working Group was established. The workshops provided an overview of the ongoing Studies and Projects in each region and the prospects of long-term developments. The list of workshops and links are provided in Table 2. The Working Group presented a summary of the activity at the European Development Workshop on 3 - 5 June 2019. There were open discussion sessions on the ALMA Development Roadmap, receiver development, and a system-wide bandwidth increase. The Working Group used the community feedback to update the technical feasibility and readiness of various developments from the regional communities and development teams.

The ALMA 2030 Correlator Workshop was held at Charlottesville, 11-13 February 2020. There was a discussion on limitations of the IF bandwidth and maximum IF frequency.

Due to the COVID-19 pandemic, the ALMA Development Workshop "The ALMA 2030 Vision: Design considerations for Digitizers, Backend and Data Transmission System" originally scheduled for 11-13 March 2020, was postponed to 14-16 October 2020. Further information may become available in the coming months and that would need to be considered for trade off analysis and overall system requirements (e.g., state of the art industrial digitizer performance).

Table 3: Working Group participation in the regional ALMA Development workshops.

Workshop / Conference	Dates	Webpage
East Asia Development Workshop 2018	14-15 Dec. 2018	URL
NRAO ALMA Development Cycle 7 Studies Call for Proposals meeting	16 Jan. 2019	URL
European Development Workshop	3-5 Jun. 2019	URL
East Asia Development Workshop 2019	10-11 Dec. 2019	URL
The ALMA2030 Vision: Design Considerations for the Next ALMA Correlator Workshop	11-13 Feb. 2020	URL
The ALMA 2030 Vision: Design considerations for Digitizers, Backend and Data Transmission System	14-16 Oct. 2020	URL

4.3 Survey of the technical feasibility and readiness

Receiver Sensitivity:

Results from recent studies carried out by the various ALMA partners as well as at other observatories have indicated a potential for receiver noise temperature improvement for Band 3 of the order of 10 K or more with improved SIS mixers [RD12].

The current ALMA receivers are equipped with cryogenic low noise amplifiers (CLNA) based on the technology from 10 years ago. For example, the noise temperature for the 4 – 8 GHz CLNAs used in Band 4 and 8 receivers is 7 K (GaAs HEMTs), whereas that for the 4 – 12 GHz

CLNA (Band 10) is 5 K (InP HEMTs). The current state-of-the-art CLNAs have noise temperature values of 2.3 K for 4 – 8 GHz, 3.6 K for 4 – 12 GHz, and 5.2 K for 4 – 20 GHz, as reported by the Low Noise Factory[1]. The noise temperature in Band 4/8/10, therefore, could be improved just by replacing their CLNAs.

Additionally, for the higher bands, several groups have investigated high-Jc superconducting junction technology and preliminary results indicate the possibility of wider IF and RF bandwidths, as well as flat noise temperature performance across the full bands [RD18][RD19].

Wideband IF/RF:

A survey of various receiver development efforts revealed impressive progress by the receiver community with regard to broader IF bandwidths. Current technology indicates promise for much increased IF bandwidth. The community has either started work on, or has achieved, 12 GHz (4 – 16 GHz) and 16 GHz (4 – 20 GHz) IF bandwidths (reports from NAOJ [RD02], ESO (B2) [RD03], NRAO [RD04], SRON [RD05], IRAM [RD06]); consequently 4 – 16 GHz (i.e., 3 times larger bandwidth than most current ALMA receivers) certainly appears to be feasible with existing technology. However, a careful evaluation of several kelvins worth of trade-off on receiver noise temperature between wideband and narrowband designs is necessary. IF gain variation requirement on the wider designs will depend on sampler bandwidth and precise architecture.

The community has already demonstrated the feasibility of wider RF bandwidth by combining two ALMA bands (e.g. NAOJ Band 7+8 (SIS) [RD07], IRAM 100 GHz mixer (SIS: 67 – 116 GHz) [RD06], Band 2 (CLNA: goal 67-116 GHz) [RD03]). Therefore, increasing the RF bandwidth is within the reach of existing technology.

An increase in RF bandwidth of the ALMA receivers can lead to the reduction in the total number of receivers that need to be operated and maintained in the ALMA front-end, which could, in principle, make operations more effective and increase the time devoted to science observations.

The ALMA cryostat can house 10 cartridge receivers. Due to its thermal performance, only three receivers can be operated at the same time. Changing to a new band that is not among those thermally ‘ready’ requires more than 10 minutes. Rapidly changing sources, such as solar flares, comets and AGN, may also benefit from simultaneous or near simultaneous observations. Extension of the boundaries of an existing band or combining bands into a single cartridge will benefit simultaneous or near simultaneous observations.

However, given the existing agility of ALMA receiver band switching, there is not a strong science-community justification/support for doing so. It is also important that one should compare the performance of new wider bandwidth designs against the achieved receiver noise temperature on ALMA, and not just with the original ALMA requirements since the existing ALMA receivers surpass the requirement by quite some margin in many cases. For example,

[1] https://www.lownoisefactory.com/

current ALMA bands 5 to 9 have achieved receiver noise temperatures well below the original requirements across most of the band.

Sideband Separating SIS receivers at high frequency bands:

SRON/NOVA have developed a high-performance sideband-separating (2SB) receiver for 600 – 720 GHz (Band 9) [RD05]. The receiver has been commissioned in the SEPIA front-end at APEX [RD08]. A new Band 790 – 950 GHz 2SB mixer has been tested in the laboratory recently and shows comparable performance characteristics [RD09].

Digitizer:

The Working Group carried out a review of current existing and future promising ADCs. From a receiver system architectural point of view, digitization of broad bandwidths early in the signal processing chain is favored. In this way, system complexity can be reduced; e.g., there is no need for a second heterodyne stage, which can also introduce issues like additional signal spurs due to local oscillators, and calibration is easier. Evolution of high-speed digitizer technology makes it feasible in the near future to cover the instantaneous bandwidth as required for ALMA2030 with one integrated digitizer chip.

NAOJ has carried out a demonstration of an ADC module from Keysight technologies[2], capable of high-speed sampling at 32 GSps with 12.5 GHz bandwidth per channel and an effective number of bits of 6.5 [RD10].

Laboratoire d'Astrophysique de Bordeaux (LAB), part of Bordeaux University, made a survey of current and future commercial products with bandwidth and sampling frequencies commensurate with the ALMA2030 objectives [RD11]. Devices from Analog Devices, Adsantec, Micram, Alphacore, Pacific Microchip, Intel, and Fujitsu were considered. At least one device with very promising performance was identified, and it has a demonstrated sampling speeds of up to 40 GSps in the laboratory, and is considered suitable for further development. New devices may become available in the coming months and be considered for another trade off analysis of overall system requirements (e.g., state of the art industrial digitizer performance).

However, it is emphasized that a final decision for a digitizer device is urgently needed since delaying this decision will begin to impact the ALMA2030 development schedule.

[2] M8131A–16/32 GSa/s Digitizer, Preliminary Data Sheet, version 0.8

5 DEFINITIONS

This document presents the key technical goals for future ALMA front-end and digitizer products that are consistent with the science goals in the ALMA2030 Development Roadmap. These technical goals are defined as those requirements directly flowing down from the science goals as derived from the ALMA Development Roadmap [AD01]. There are secondary, non-key, requirements applicable to the ALMA front-end and digitizer products; these are currently in development and not presented in this document.

Any proposed technical performance parameter presented in this document should be considered a *technical goal* to be achieved for future upgrades. In some cases, the required technology is still in development and consequently, design/development teams are not able to guarantee the required performance. Furthermore, it is recognized that various design/development teams might have to make informed trade-offs between receiver noise temperatures, IF/RF bandwidths, IF passband ripple, and other specifications when optimizing a design. Given the impact of these trade-offs on the ALMA system architecture and performance, these decisions must be made in consultation and agreement with the JAO.

It is expected that in the next few years, once the necessary technology development has sufficiently matured, these technical goals (perhaps modified if deemed necessary) will be formalized as technical requirements, which would be binding requirements for deliveries to the JAO.

6 RECEIVERS

Apart from the collecting area, array sensitivity depends primarily on the system noise temperature and bandwidth (for continuum), and the RF front-ends have a major role in defining these quantities.

6.1 Receiver Noise Temperature

Updated receiver noise temperature goals have been determined based on the on-array performance of existing ALMA receivers, typical sky temperatures, technical limitations (e.g., need for warm optics), and the status of ongoing developments in the field. The technical goals are intended to be ambitious but attainable on the 2030 timescale.

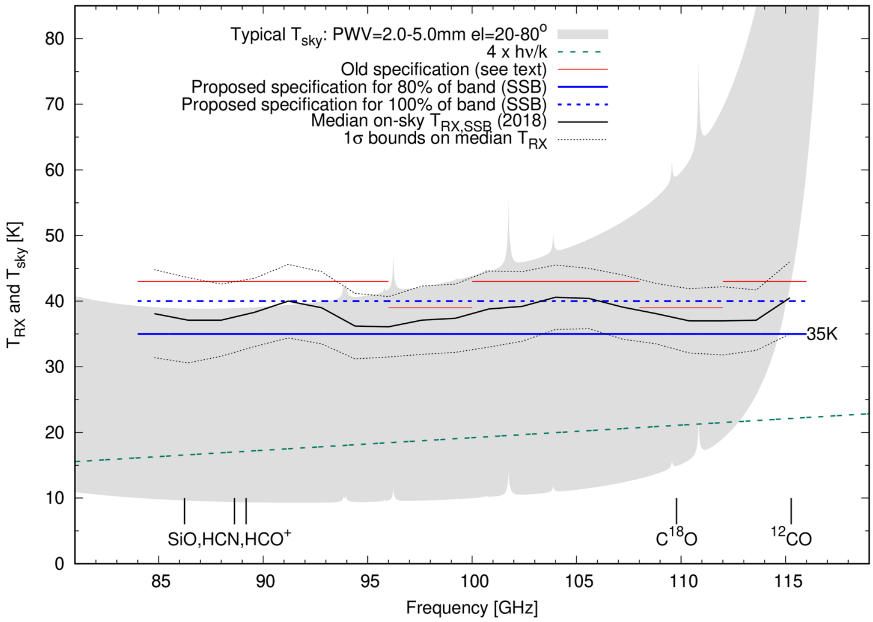

Figure 2: Existing requirements and proposed receiver noise temperature goals for Band 3. Where available, the existing median on-sky receiver noise temperature values are indicated along with 1σ bounds.

6.1.1 Band 1 and 2

Band 1 and 2 are under construction. These receivers will not be upgraded after their initial implementation prior to the start of the 2030s.

6.1.2 Band 3

Recent receiver developments demonstrate that a noise reduction in Band 3 is possible [RD12]. Due to the ^{12}CO(*J*=1-0) line at the top of the band, and the very low T_{sky} at the bottom end of the band, receiver temperature at the band edges must be well controlled.

Table 4: Existing requirements and proposed receiver noise temperature goals for Band 3

Band	Existing requirement		Proposed goal	
	T_{SSB} over 80% of the RF band	T_{SSB} at any RF frequency	T_{SSB} over 80% of the RF band	T_{SSB} at any RF frequency
3	See Note	See Note	35 K	40 K

<u>Note:</u>
For Band 3, the existing noise temperature requirements are as follows:
< 39K (averaged over all four IFs 4 GHz bandwidth at LO = 104 GHz)
< 43K (averaged over all four IFs 4 GHz bandwidth for any LO setting)

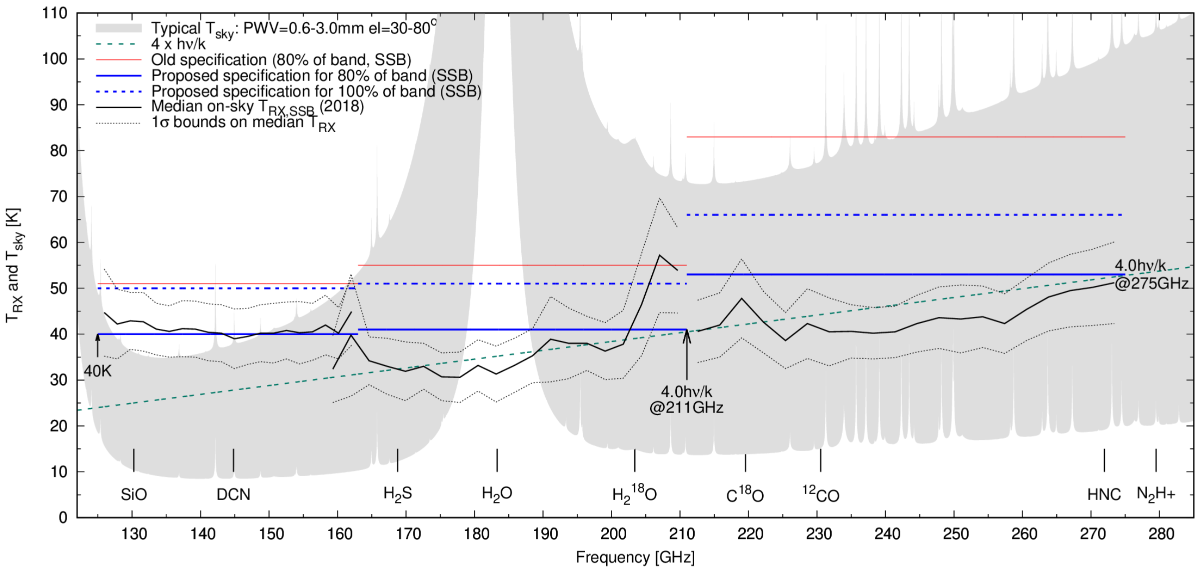

Figure 3: Existing requirements and proposed receiver noise temperature goals for Band 4, Band 5, and Band 6. The existing median on-sky receiver noise temperature values are indicated along with 1σ bounds.

6.1.3 Band 4, 5, and 6

Given the low T_{sky} and the relatively large on-sky measured receiver noise temperatures for Band 4 (compared to the 4hν/k photon limit), a significant noise improvement for Band 4 is desirable. As mentioned in Section 4.3, there is room for noise temperature improvements for Band 4 by just replacing its CLNA. However, due to the noise contribution from the RF input optics and ohmic losses of the waveguide circuit, reaching 4hν/k like bands 5 – 7 is likely too ambitious, so a compromise value is suggested.

Table 5: Existing requirements and proposed receiver noise temperature goals for Band 4

Band	Existing requirement		Proposed goal	
	T_{SSB} over 80% of the RF band	T_{SSB} at any RF frequency	T_{SSB} over 80% of the RF band	T_{SSB} at any RF frequency
4	51 K	82 K	40 K	50 K

The existing Band 5 demonstrates the median performance around 4hν/k except for the high band edge. The proposed performance goals for 80% of the band is 4hν/k at 211 GHz and for the whole band is 5hν/k at 211GHz. Improved flatness of noise across the band is desired.

Table 6: Existing requirements and proposed receiver noise temperature goals for Band 5

Band	Existing requirement		Proposed goal	
	T_{SSB} over 80% of the RF band	T_{SSB} at any RF frequency	T_{SSB} over 80% of the RF band	T_{SSB} at any RF frequency
5	55 K	75 K	41 K	51 K

The existing Band 6 demonstrates median performance around 4hν/k within its RF band. Further improvement is likely too ambitious due to the noise contribution from the ohmic losses of the waveguide circuit. Therefore, a compromise value is suggested. The proposed performance goals for 80% of the band is 4hν/k at 275 GHz and for the whole band is 5hν/k at 275 GHz.

Table 7: Existing requirements and proposed receiver noise temperature goals for Band 6

Band	Existing requirement		Proposed goal	
	T_{SSB} over 80% of the RF band	T_{SSB} at any RF frequency	T_{SSB} over 80% of the RF band	T_{SSB} at any RF frequency
6	83 K	136 K	53 K	66 K

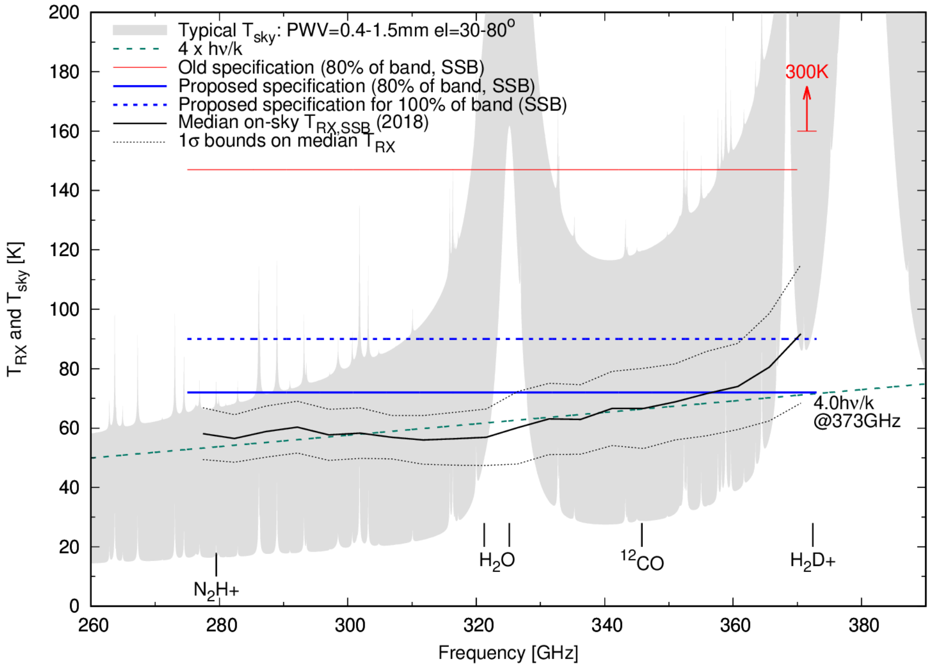

Figure 4: Existing requirements and proposed receiver noise temperature goals for Band 7. The existing median on-sky receiver noise temperature values are indicated along with 1σ bounds.

6.1.4 Band 7

The existing Band 7 receiver demonstrates median performance around 4hν/k at the center of the band. The proposed performance goals for 80% of the band is 4hν/k at 373 GHz and for the whole band is 5hν/k at 373 GHz. Improved flatness of noise across the RF band is desired, and the recent receiver development in the Band 7 frequency range suggest this should be feasible.

Table 8: Existing requirements and proposed receiver noise temperature goals for Band 7

Band	Existing requirement		Proposed goal	
	T_{SSB} over 80% of the RF band	T_{SSB} at any RF frequency	T_{SSB} over 80% of the RF band	T_{SSB} at any RF frequency
7	147 K	219 K	72 K	90 K

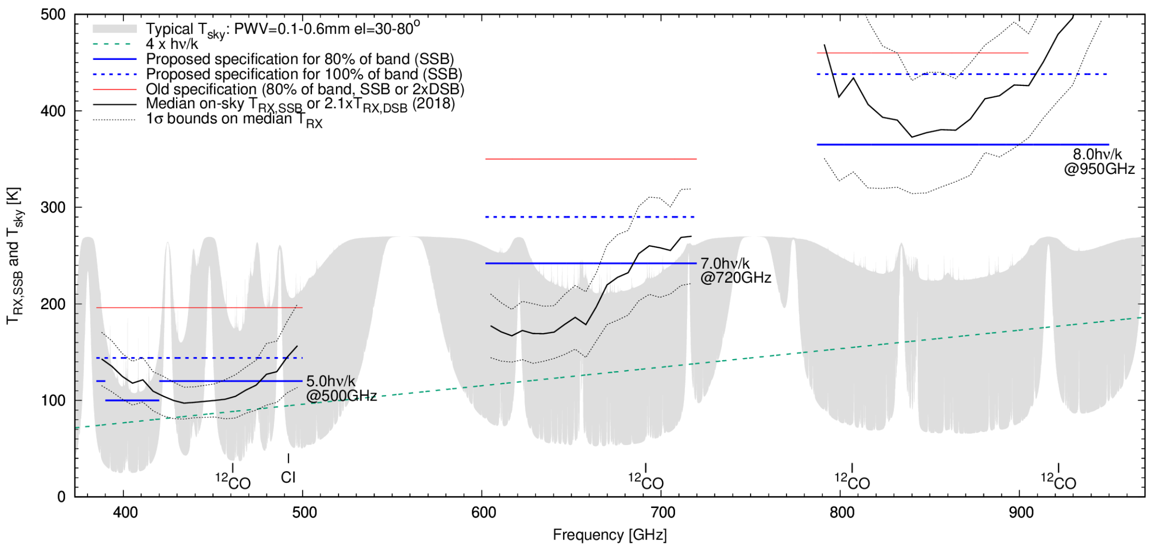

Figure 5: Existing requirements and proposed SSB receiver noise temperature goals for Band 8, Band 9, and Band 10. The existing median on-sky receiver noise temperature values are indicated along with 1σ bounds. For bands 9 and 10, the measured DSB noise has been multiplied by 2.1 to indicate an approximate SSB value.

6.1.5 Band 8

The current Band 8 receiver noise temperature is considerably far from the 4hν/k photon limit demonstrated by bands 5 – 7, but recent developments suggest that improved performance in this regard is feasible. Improved flatness across the band is also desirable due to the important CI (neutral carbon) line at the top of the band and the 410 GHz window at the bottom of the band. Due to the low T_{sky} available in the 410 GHz window, a tighter noise requirement is recommended in the corresponding frequency span. The proposed performance goals outside the 410 GHz window are 5hν/k at 500 GHz over 80% and 6hν/k over the whole band.

Table 9: Existing requirements and proposed receiver noise temperature goals for Band 8

Band	Existing requirement		Proposed goal	
	T_{SSB} over 80% of the RF band	T_{SSB} at any RF frequency	T_{SSB} over 80% of the RF band	T_{SSB} at any RF frequency
8	196 K	292 K	100 K (390 – 420 GHz), 120 K	144 K

6.1.6 Band 9

The Working Group assumed that Band 9 will be upgraded to 2SB. Improvement in the noise temperatures of the mixers might be possible by using higher Jc junctions, and some optimization of noise temperature at the top of the band also seems plausible even with the existing AlN mixers [RD13]. A 2SB Band 9 is expected to be receiver noise limited rather than sky noise limited, so lower receiver noise is highly desirable. The proposed performance goals for 80% of the band is 7hν/k at 720 GHz and for the whole band is 1.2 × 7hν/k at 720 GHz.

Table 10: Existing requirements and proposed receiver noise temperature goals for Band 9

Band	Existing requirement		Proposed goal	
	T_{DSB} over 80% of the RF band	T_{DSB} at any RF frequency	T_{SSB} over 80% of the RF band	T_{SSB} at any RF frequency
9	175 K	261 K	242 K	290 K

6.1.7 Band 10

The Working Group assumed that Band 10 will be upgraded to 2SB. Noise reduction is highly desirable considering how much the receiver noise dominates over the sky in a 2SB receiver for Band 10. High current density junctions are demonstrating much improved noise flatness across the band, indicating that improvement is feasible. The proposed performance goal for 80% of the band is 8hν/k at 950 GHz and for the whole band is 1.2 × 8hν/k at 950 GHz.

Table 11: Existing requirements and proposed receiver noise temperature goals for Band 10

Band	Existing requirement		Proposed goal	
	T_{DSB} over 80% of the RF band	T_{DSB} at any RF frequency	T_{SSB} over 80% of the RF band	T_{SSB} at any RF frequency
10	230 K	344 K	365 K	438 K

6.2 RF Bandwidth

The current ALMA requirements specify the RF ranges for 10 receiver bands. The Working Group considered three reasons to modify the RF ranges of the bands. First, the frequency range may be extended to cover additional important spectral lines. This could improve the efficiency of some programs that would otherwise require two tunings in different receivers, or it could enable users to expand their science by adding additional lines simultaneously to the main science goal. A second use case is that by having the RF ranges of bands overlap by one IF bandwidth, the efficiency of spectral surveys that span more than one band could be increased. Finally, if two or more bands could be covered by one receiver, there could be operational benefits since there would be fewer receivers to maintain. Also, this would open up a spot in the front-end that could be used, for example, for a multi-beam receiver (although that would not be without its own technical challenges, and it is not clear that this would be useful for the interferometric array).

After considering these aspects, the Working Group determined that optimizing the receiver performance was more important than increasing the RF range. Considerations for broader RF ranges are not precluded in any receiver, but no changes in the band definitions are proposed as a goal. Should there be proposed changes in the RF definition of the bands by receiver development groups (to cover, for instance, additional spectral lines at the band edges due to scientific merit), there should be no loss in RF coverage from the ensemble of ALMA receivers.

6.3 Instantaneous Bandwidth

The Working Group has investigated the most recent research of several groups within and external to the ALMA partnership before reaching a conclusion on a realistic goal for the instantaneous bandwidth of the signal chain. We deliberately use the term instantaneous bandwidth, instead of IF bandwidth, in this context to emphasize that the entire signal chain should be capable of meeting this technical goal. All of this instantaneous bandwidth should be usable for science, and should be in one contiguous IF frequency range such that there need be no RF frequency gaps and no significant sensitivity loss due to filter roll-offs in the correlated bandwidth other than that between the two receiver sidebands.

Instantaneous Bandwidth: *At least ≥ 8 GHz per IF polarization sideband (for 2SB receiver configurations), following the ALMA 2030 Development Roadmap.* ***The Working Group strongly recommends to achieve 16 GHz per IF polarization/sideband (for 2SB receiver configurations)****.*

Over this bandwidth, other key technical goals as specified in this document should also be met, especially receiver temperature (T_{RX}), image rejection ratio and passband gain variations.

The proposed goal of an instantaneous bandwidth ≥ 16 GHz per IF polarization/sideband is at least four times larger than the current system requirement of slightly less than 4 GHz. How this 16 GHz instantaneous bandwidth is positioned in the IF range (e.g., 2 to 18 GHz or 4 to 20 GHz) is still to be determined and will depend on the architecture that provides the best performance. For some receivers, it is conceivable that a bandwidth smaller than 16 GHz per polarization/sideband may be determined to be scientifically optimum given performance (or cost) trade-offs against a 16 GHz bandwidth design. The Working Group states an absolute minimum requirement of 8 GHz per IF polarization/sideband so that all new receivers are at least compliant with the ALMA 2030 Development Roadmap. However, the Working Group strongly recommends that receiver designs strive to achieve the goal of 16 GHz per IF polarization/sideband. The Working Group also recommends that the signal chain downstream of the receivers be redesigned so as to meet this 16 GHz per polarization/sideband goal.

6.4 Image Rejection Ratio

6.4.1 Current Requirement

The current ALMA requirement on sideband suppression in terms of sideband ratio (SBR) of the first mixer is:

- >10dB suppression over 90% of the IF frequency range, SSB and 2SB,
- >7dB suppression over 100% of the IF frequency range, SSB and 2SB, and
- <3dB difference across 80% of the combined IF and LO frequency ranges, DSB.

Although this level of SBR performance does limit the effect of atmospheric noise entering the signal sideband from the image sideband, it does not eliminate it entirely. Further improvements to the SBR would yield better sensitivity at many tunings in several ALMA bands. Better SBR performance would also help to reduce further the possibility of contamination of single-dish spectra by the presence of strong celestial lines in the image sideband, which is a non-trivial problem to solve in data analysis.

6.4.2 Effect of improvements on sensitivity

As a simple illustration, we have computed the effect in each band of improving the SBR in terms of the reduction in observing time required to reach the same sensitivity. For bands containing a CO line that can be observed in either sideband (bands 6, 7, 8 and 9), we use that line frequency, otherwise we use a frequency near the middle of the band. Using the atmospheric model in CASA, the appropriate PWV octile for observing each frequency, and the T_{RX} performance in the ALMA Cycle 7 Observing Tool, we compute the improvement when observing at an elevation of 60 degrees at this frequency in USB, and again in LSB, and take the mean value. Table 12 shows the results for an SBR improvement to 15 dB from 10 dB. The reduction in observing time is quite significant (12% – 18%) in bands 5 and 8. These numbers would improve to (16% – 25%) for an SBR of 20 dB. In the rest of the bands, the improvement is 4%-7%, which is equivalent to 2 – 4 antennas in raw collecting area. These numbers improve to 5% – 10% (i.e., 3 – 5 antennas) for an SBR of 20 dB. We see that most of the benefit is already obtained by using a SBR of 15 dB.

6.4.3 New Technical Goal

Noting that no new receivers will be DSB, we require the following performance for all 2SB and SSB receivers:

- >15dB suppression over 90% of the IF frequency range
- >13dB suppression over 100% of the IF frequency range.

Table 12: Estimated observing speed improvements by improving the image rejection to 15 dB and 20 dB.

Band	Frequency (GHz)	T_{RX} (K)	Octile (PWV [mm])	DSB → SSB (10 dB)	10 → 15 dB	10 → 20 dB
				Observing time reduction (%)		
3	100	40	7 (5.186)	N. A.	3	4
4	140	42	6 (2.748)		3	4
5	195.3	50	5 (1.796)		15	20
6	230.538	50	5 (1.796)		4	5
7	345.796	72	3 (0.913)		6	8
8	461.08	135	2 (0.658)		10	13
9	691.47	210 (105 @ DSB)	1 (0.472)	45	5	7
10	806.65	460 (230 @ DSB)	1 (0.472)	34	4	5

6.5 Passband Gain Variations

The passband gain variations are defined as the frequency dependent gain variations related to the analog signal chain. This includes the optical path, the RF and IF path in the front-end sub-system, and all the way through to the input of the digitizer within the back-end. The frequency range to be considered for the gain variations is the IF range equal to the digitized frequency band (see Section 7) and includes all of the optical/RF/IF analog signal path upstream in the receiver. These passband gain variations are directly coupled with the requirements for quantization efficiency of the digitizer and the Effective Number of Bits (ENOB) as specified in Section 7.

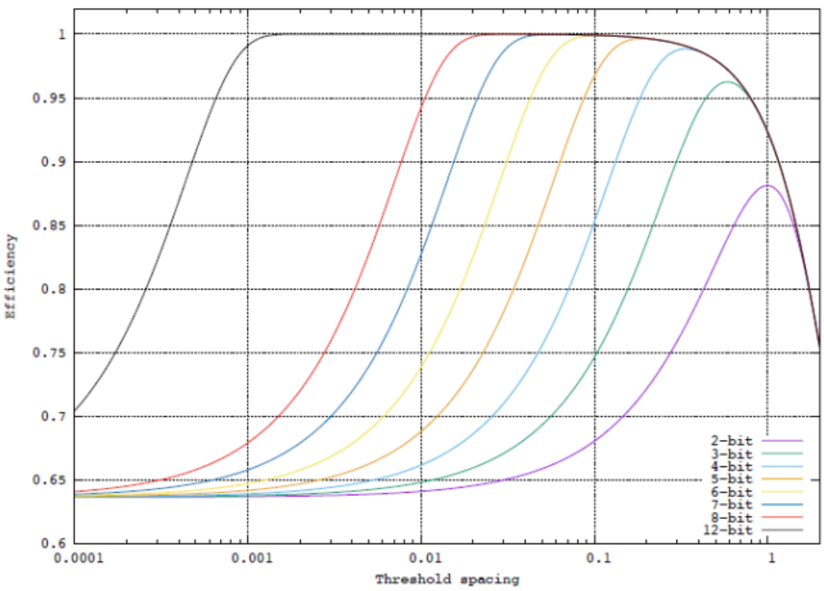

Figure 6: Quantization efficiency versus the threshold spacing (in units of the RMS noise prior to quantization) in the range 0.0001 to 2 for n = 2, 3, 4, 5, 6, 7, 8 and 12 bits[3].

[3] From Internal Memo "Quantization efficiency and Impact of gain variations within the passband", Alain Baudry / Laboratoire d'astrophysique de Bordeaux (LAB)

High priority is given to improving the quantization efficiency to at least 99% (see Figure 6). The ENOB is essentially set by what is commercially available, currently at least 5 ENOB, to provide 8.4 dB of sample dynamic range (see Table 13). Assuming that the sky-brightness variations during an observation are 3 dB, the goal for the passband gain variations is:

Passband Gain Variations: *< 5.4 dB*

Table 13: Sampler dynamic range for a minimum quantization efficiency[4]

ENOB η_{min}	2-bit	3-bit	4-bit	5-bit	6-bit	7-bit	8-bit	12-bit
99%	-	-	-	8.4 dB	14.7 dB	20.9 dB	26.8 dB	51.0 dB
96%	-	2.2 dB	11.0 dB	17.6 dB	23.7 dB	29.8 dB	35.9 dB	60.0 dB
92%	-	9.5 dB	16.7 dB	23.1 dB	29.3 dB	35.4 dB	41.4 dB	65.6 dB
85%	6.9 dB	16.5 dB	23.4 dB	29.8 dB	35.9 dB	42.0 dB	48.0 dB	72.2 dB

7 DIGITIZER

The signals from the front-end at each antenna will pass through an IF selector switch with amplitude gain settings. Analog, continuous gain setting should be feasible, assuming that it is stable. The gain setting accuracy and settling time of gain changes should be defined. The requirement for S/N, efficiency, ENOB need to be specified according to characteristics of input signal (white noise).

7.1 Digitizer Sampling Speed

Considering the strong desire to avoid a second down-conversion stage, as is implemented in the current ALMA system, the instantaneous bandwidth as defined in Section 6.3 of this document should lie within the first (or, in theory but practically speaking unlikely, second) Nyquist band of the digitizer. Assuming that the Nyquist frequency is equal to an upper instantaneous bandwidth goal of 20 GHz (e.g., for an IF Band of 4 to 20 GHz), the sampling frequency should be 40 GHz.

Digitizer Sampling Speed: *> 40 GSps*

It might be that a single digitizer core cannot achieve the required performance in terms of ENOB at the specified digitizer sampling speed (see Section 7.2). As an alternative to a single core digitizer, interleaved or dual-rate digitizer architectures can be considered as long as they achieve the applicable goals as provided in this document.

A second down-conversion stage is not favored due to the increased complexity, costs and practical issue with internally generated spurious signals due to an second local oscillator.

[4] From Internal Memo "Quantization efficiency and Impact of gain variations within the passband", Alain Baudry / Laboratoire d'astrophysique de Bordeaux (LAB)

7.2 Effective Number of Bits (ENOB)

The ENOB to be achieved for the digitizer is a major technological challenge, recognizing the strong desire to increase the quantization efficiency to at least 99% for standard astronomical observations (excluding solar and calibration) from the current 96%.

The digitizer performance matching our astronomical requirements, including continuous sampling at the rate specified in Section 7.1 with very low spurious levels, is a niche market for commercial devices. Considering the ongoing evaluation of COTS devices and market forecasts, we have come to the following, conservative *technical goal*:

> *Effective Number of Bits[5]: ≥ 5 (ENOB specified under the assumption of noise, with Gaussian distribution, as the input signal)*

This performance should be achieved at the Digitizer Sampling Speed specified in Section 7.1. The Working Group believes that a conservative approach is justified on the basis of how the commercial market for these very fast digitizers has developed over the last 3 – 4 years and what has been announced for the future. An ASIC development for a suitable digitizer, even based on an already developed IP core, is most likely out of reach of ALMA unless substantial funding (> 10 MEUR) is made available for its development.

7.3 Interface between Digitizer and Back-end / Correlator

It is urgent to specify at least bit width and data rate transferred to the correlator. To allow for maximum flexibility, a simplistic approach is considered as a first proposal to the Correlator Requirements Working Group. The simplistic approach means that all ENOB available from the digitizer, without any digital processing at the antennas, will be sent to the back-end/correlator. Technically this is feasible using 400 Gbit/s ethernet channels (e.g., the 400ZR/ IEEE 802.3cw standard supports Dense Wavelength Division Multiplexing of 400Gb/s channels on a single mode fiber up to 80km in length), but might have additional costs. The Working Group will converge on this goal in consultation with Correlator Requirements Working Group and the AMT at a later time.

At the ALMA 2030 Correlator Workshop, there was a near consensus that a first “F” will be necessary (i.e., FFX architecture). There was a concern expressed about adding complexity to the antennas. Performing the initial Fourier transform at the antenna may result in an efficiency loss (depending on the number of bits preserved), however most felt that the savings in

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[5] A limitation of using ENOB is that it depends on the properties of the input signal. Digitizer data sheets commonly specify ENOB for a sinusoidal (continuous wave) input signal while the input signal for ALMA’s applications has a Gaussian-like amplitude distribution. This dependence on the input signal properties applies as well to quantization efficiency, at least for practical situations where the number of quantization levels (i.e. ENOB) is limited. A more practical, compelling reason for using ENOB is that it directly provides the minimum number of bits that comes out of the digitizer and that needs to be processed by the digital transmission system and the correlator. Therefore, ENOB provides a clear requirement for the other systems, while specifying quantization efficiency would require a cumbersome translation.

electronics complexity for the overall new design would still yield a net improvement. Final data transport requirements should drive the final answer in this regard.

8 OTHER PERFORMANCES

8.1 ALMA Polarization Performance

8.1.1 On-axis and off-axis instrumental polarization

Current requirements for the on-axis and off-axis instrumental polarization come from the polarization science requirement of 0.1%. This requirement has been achieved for small-field linear polarization, but the current achieved systematic uncertainty for circular polarization is 0.6%. ALMA is unlikely to detect Zeeman splitting in most sources at this level of accuracy. If future testing can demonstrate that an uncertainty of 0.1% can be achieved in circular polarization, it would be valuable to specify for future receivers a more ambitious goal of 0.03% (1 sigma error) to improve the robustness of circular polarization observations. This will tighten the on-axis instrumental polarization to D~3% while the current requirement is D=10% (in voltage; see Revised ALMA System Technical Requirements – Polarization [RD14]).

ALMA recent polarization mosaicking tests indicate the actual error on the polarization image outside of 1/3 FWHM is as good as 0.3%. If the new receivers can achieve D~3% at on-axis, we can probably achieve 0.1% accuracy at off-axis as well after the on-axis cross polarization is removed. Tightening beam squint performance will also help to achieve this goal. An analysis of the effect of beam squint on wide field polarization is presented in [RD14]. The linear feed beam squint leads to a spurious Stokes Q gradient across the beam of each array element. While a systematic squint that is common to all array elements is feasible to calibrate during imaging, variations from receiver to receiver would be much more difficult to reliably measure and compensate, and without doing so there is increased calibration errors over the field of view and spurious Stokes Q signal. In [RD14], it is recommended to keep RMS repeatability of beam squint to no more than 0.4% FWHM to keep the impact negligible when imaging to the –6dB field of view, or correspondingly about 0.6% FWHM for imaging to the half power point. Such small values are potentially difficult to achieve, and a requirement on repeatability would not be practical to test as it requires all receivers to be present to determine the systematic squint.

Figure 7 shows scatter plots of the 2D on-sky Y-X polarization squint for the existing receivers. As expected, OMT (single feedhorn) bands are considerably better; e.g., compare Band 8 (OMT) with bands 7, 9, and 10 (wire grid). Based on these statistics, a technical goal of 2% FWHM squint instead of the current 10% FWHM would be quite straightforward to achieve if OMTs are to be assumed for all bands (implying a change for bands 7, 9, and 10). This would also imply an RMS repeatability that is considerably better than the peak 2% FWHM limit, close to the desired goal from [RD14], while being testable for individual receivers and array elements. It may also be possible to meet the 2% FWHM requirement with tightened alignment tolerances of wire grid (2 feedhorn) designs, which may still be the best choice for bands 9 and 10 due to the receiver noise impact of waveguide losses in an OMT.

At least for the receivers with OMTs, there seems to be little room to improve the performance. The random component in the beam squint will be hard to quantify and control too much beyond existing values.

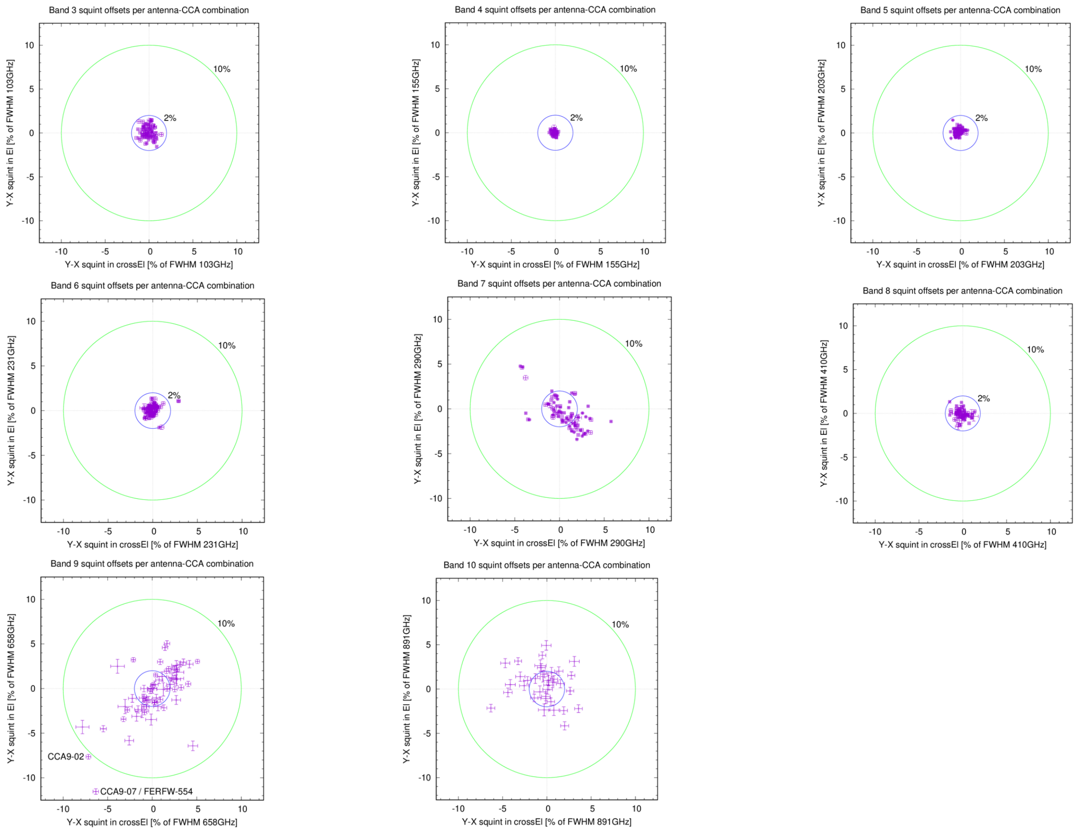

Figure 7: Scatter plots of the 2D on-sky Y-X polarization squint in units of percent of the beam FWHM at the measurement frequency indicated in the axis labels.

8.1.2 Optics: Pointing offset

In addition to tightening the squint requirement, another front-end requirement that we highlight is the receiver alignment with respect to the center of the aperture (i.e., the "illumination offset" or "pointing offset"), which Richard Hills noted was missing from the requirements on the early bands (bands 3, 4, 6, 7, 8, 9, and 10) in his document [RD15]. This requirement was added to the Band 5 requirements (and Band 1 and Band 2+3[6] requirements) as "5.9.1.1.3. Pointing offset".

8.2 System Internal Spurious Signals

[6] http://edm.alma.cl/forums/alma/dispatch.cgi/iptfedocs/docProfile/142743/d20171025114453

An update of the requirements limiting the level of internally generated spurious signals based on science requirements is appropriate. But it is emphasized that at this moment no complete flow-down from science requirements is feasible. The System Requirements document, version C [RD16] tries to address this issue, but for a science justification of spurious levels, it refers to another document (Revised ALMA System Technical Requirements - Spurious Signals, [RD17]) which has not been formally reviewed and released.

The need for an update of these spurious signals requirements is illustrated by current issues like the spurs generated by local oscillators of the WVR and the second down-conversion stage. The issue is likely to become critical for future receiver systems that have a wider IF bandwidth with upper frequencies of ~20 GHz, which overlap with the first LO fundamental frequency.
For defining limits on internally generated spurious signals, one option is to adopt the values as defined by ITU Recommendation ITU-R RA.769-2. In this way the same RFI limits as advocated for external spurious signals would also apply for system internal spurious signals. Following this approach would also put the JAO in a stronger position towards other services generating interference in defending the frequency bands in which ALMA is operating.

However, it is noted that the ITU recommended RFI limits are challenging to meet and a more relaxed set of requirements for ALMA system generated interference is preferred on practical grounds. In the latter case, technical requirements must flow down from widely accepted science requirements.