ALMA Front-end and Digitizer Technical Requirements to Enable the ALMA 2030 Development Roadmap

Photo credit: Pablo Carillo (ALMA)

Todd Hunter

(NRAO-CV / NAASC)

Outline of Talk

1. ALMA 2030 Science goals & Development Roadmap
2. ALMA Front-End & Digitizer Working Group members and charge
3. Summary of current ALMA Front-End and Digitizer system
4. Recent advances in Front-End & Digitizer technology in the community
5. Proposed new requirements for Front-End
6. Proposed new requirements for Digitizers
7. Challenges to achieving the promise of wider bandwidth with pipeline

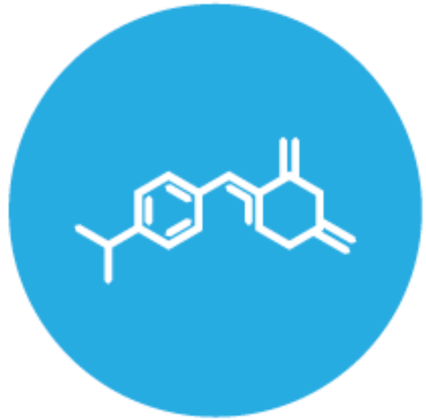
Final note: Upcoming Front-End workshop (Sep 2021)

ALMA 2030 Science Goals

Having met ALMA's original science goals, new goals have been set (ALMA Memo 612):

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.

Wider bandwidth: promotes continuum science and spectral grasp for line surveys & redshift surveys
Better Trx and digital efficiency: essential for faint spectral line imaging (protoplanet wakes, high-z lines)

ALMA Development Roadmap

- Completed in 2018 -- identifies science goals & technical development priorities for the decade of the 2020s to keep ALMA at forefront of scientific discovery
  - https://www.almaobservatory.org/en/publications/the-alma-development-roadmap/

or https://arxiv.org/abs/2001.11076

Highest priority items for next 5-10 years

- Improve receiver sensitivity [currently 4-10x quantum limit]
- Increase ALMA bandwidth by at least 2x [receivers, digital transmission system, correlator]
- Improve usability of science archive – increase science return

ALMA 2030 System Specification Recommendations (in progress)

- Report of the ALMA Front-end & Digitizer Requirements Upgrade Working Group (Draft)
- Specifications for a Second-Generation ALMA Correlator (Draft)
- Signal Chain Working Group underway to align all the subsystems

High priority for next decade (2030—2040)

- Extend baselines by factor of 2-3
- Increase collecting area (more antennas): Critical for spectral line sensitivity
- Focal-plane arrays (maybe first on 7m array and/or TP antennas?)
- 25-m class single dish

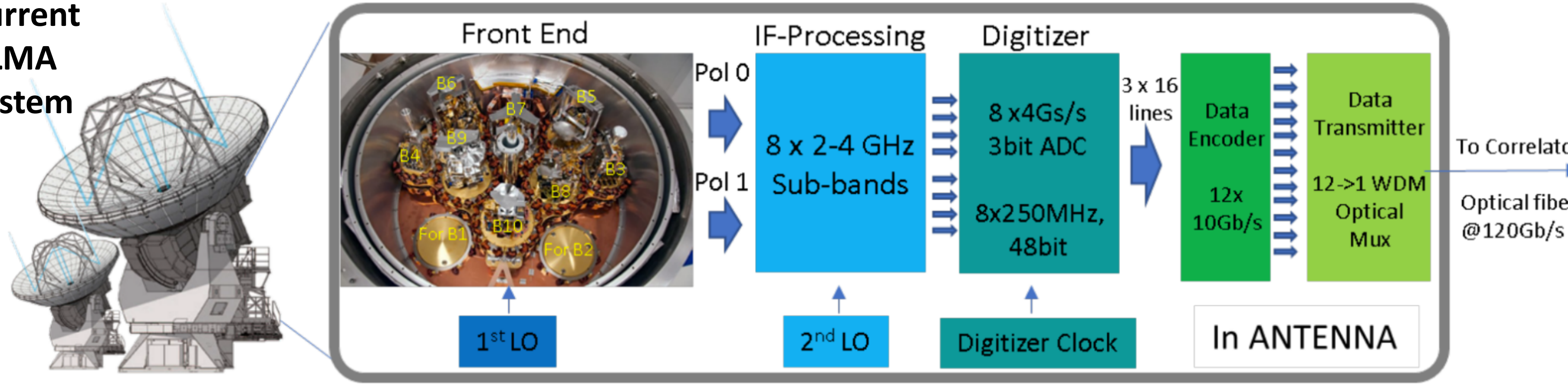
ALMA Front-End & Digitizer Requirement Update Working Group (Jan 2019-):

– Gather community input to determine the expected technical performance in next 4-6 years
– Draft an update of the Front-End & Digitizer related specifications

Working Group role	Member
Chairperson	Nick Whyborn → CTAO Shin'ichiro Asayama →SKA John Carpenter (JAO)
EU project coordinator and Front End expert	Gie Han Tan
EA project coordinator and Front End expert	Shin'ichiro Asayama
NA project coordinator and Front End expert	Kamaljeet Saini
NRAO NAASC scientist	**Todd Hunter**
ESO ALMA instrument scientist	Neil Phillips
NAOJ ALMA instrument scientist	Hiroshi Nagai
JAO ALMA observatory scientist	John Carpenter

Draft report released on 2020/12/16: https://go.nrao.edu/alma/FrontEndReport
Abridged version published in SPIE proceedings: 2020SPIE11445E..75A (Asayama et al.)

Current ALMA System



Band	RF range (GHz)	IF (GHz)	Type
1	35 - 50	4 - 12	SSB
2	67 - 116	4 - 18*	2SB
3 4 5 7 8	84 - 116 125 – 163 163 – 211 275 – 373 385 - 500	4 - 8	2SB
6	211 - 275	4.5 - 10	2SB
9 10	602 - 720 787 - 950	4 - 12	DSB

1) IF Down-conversion:

* 8 GHz BW converted into 8 “basebands” of 2-4 GHz, where the 8 = 2pols * 4 spectralWindows
* DSB bands can deliver 16 GHz with 90 deg Walsh

2) Digitizers:

* Eight 4 GSps units
* 3-bits native ($\eta_{ADC} = 0.96256$), (ENOB was not spec’d)

3) Correlator:

* Only <u>2 bit correlation</u> implemented in the 64-ant correlator!
* Correlator efficiencies (Ojeda 2017): TDM: 0.908, FDM: 0.881
* <u>Total efficiencies (ADC*correlator):</u> TDM: 0.874, FDM: 0.848

Summary of current ALMA receiver noise performance

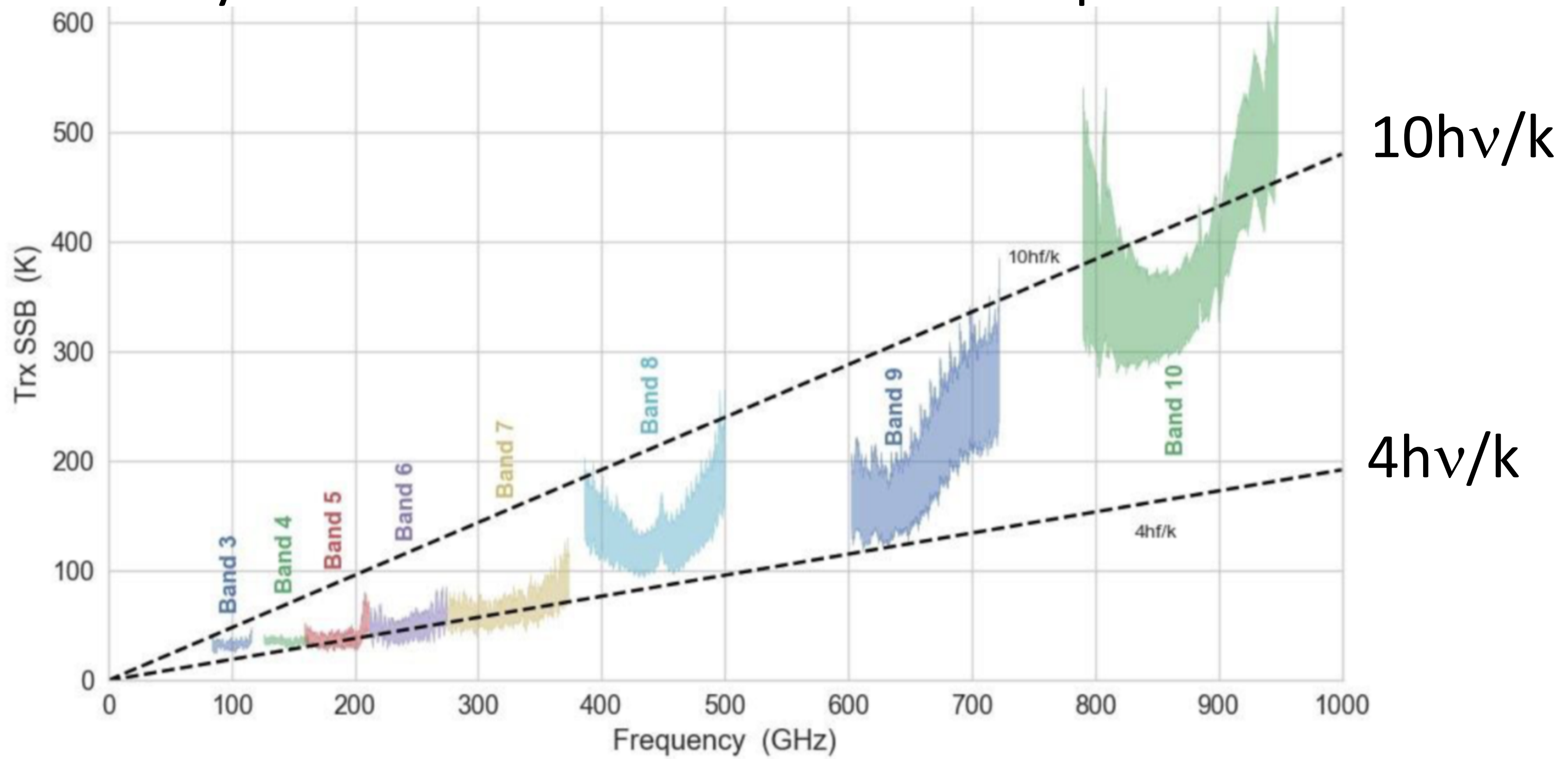


Figure 1: Achieved receiver noise temperature for the various ALMA receivers. The shaded region encompasses 75% of the receivers about the median receiver temperature from [AD01]. Bands 3-8 are 2SB receivers, and bands 9 and 10 are DSB. The noise temperature shown for the DSB receivers is twice the *measured* 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.)

Recent developments in receiver technology

- **Cryogenic LNAs**
  - Current ALMA Band 4 and 8: GaAs HEMTs with Tnoise = 7K (4-8 GHz)
  - Current ALMA Band 10: InP HEMTs with Tnoise = 5K (4-12 GHz)
  - Low Noise Factory quotes: 2.3 K (4-8GHz), 3.6 K (4-12GHz), 5.2 K (4-20 GHz)
- **Wider IF-band SIS mixers**
  - IRAM: 275-373 GHz IF=4-12 GHz (goal = 4-20 GHz) Risacher 2019 workshop talk
  - NAOJ: 385-500 GHz IF=3-18 GHz, Kojima+ 2017 ISSTT
  - SMA: 210-270 GHz IF=4-16 GHz, Tong+ 2016, Grimes+ 2016, edge mode isolator Zeng+ 2018
  - NRAO: 211-275 GHz IF=4-12 GHz (goal = 4-16 GHz w/isolator or balanced amp) Kerr+ 2019
- **Wider RF-band front-ends:** various efforts to combine bands (but wary of performance)
  - Band 2+3: HEMT, Yagoubov+ 2019 IF=4-(TBD) GHz
  - Band 2+3: IRAM 67-116 GHz mixer SOI Si membrane (Maier 2019)
  - Band 6+7: 200-400 GHz Belitsky+ (GARD at Chalmers) ESO study started December 2020
  - Band 7+8: 275-500 GHz (IF=4-21 GHz) Kojima+ 2020 A&A 640, 9
- **2SB receivers at high frequency** (Bands 9 and 10):
  - SEPIA front-end at APEX (600-720 GHz) (Hesper+ 2018 ISSTT)
  - NOVA/SRON lab tests of 800-950 GHz (Khudchenko 2019 workshop talk)

Recent developments in digitizer technology

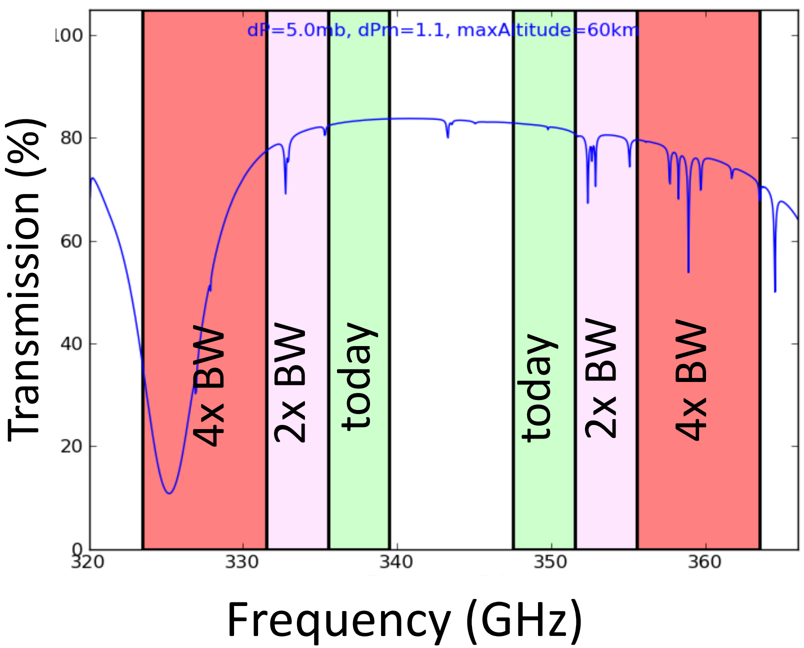
Table from **Benjamin Quertier's** presentation at ESO workshop (June 2019)
Micram ADC2 loaned and tested at LAB at 40 GSps (beyond the data sheet)
Challenges: calibrating interleaving cores, spurious tones; specs still a niche market

	HMCAD5831	ASNT7123	ADC2	AD6B40G	PMCC_56SAR
Company	Analog Device	Adsantec	Micram	Alphacore	Pacific µchip
Bandwidth	20GHz	16GHz	25GHz	20GHz	28GHz
Sampling Freq.	26GSps	16GSps	34GSps	40GSps	56GSps
Resolution	3 bits	4 bits	6 bits	6 bits	8 bits
Power	4.2W	4.3W	12W	TBD	0.5W
Architecture	single core	single core	2 cores	2 cores	64 cores
Output interface	6 lanes	4 lanes	24 lanes	24 lanes	64 lanes
Package	QFN	CQFP	Module	Chip-On-Board	BGA
Availability	Discontinued	Yes	Yes	2020	Q2 2020
Tested at LAB	Yes	Yes	Yes	Not yet	Not yet

Proposed new requirement on Instantaneous Bandwidth

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

Band 7 ALMA Default Continuum Tuning



This additional recommendation would deliver four times larger bandwidth than today.

Associated Front-End requirements changes:

- Trx (better match to current ALMA performance, slides 11-15)
- Sideband rejection (slightly tighter, see slide 16)
- IF power variation (slightly tighter, see slide 18)
- Beam squint (better match to current ALMA performance in OMT bands, see slide 19)

Tightening of Trx spec (mostly to match current ALMA performance)

Table 2. Existing requirements and proposed receiver noise temperature goals for ALMA Band 3 - 10

Band	Existing Requirement		Proposed Goal		
	80% of the RF band	Any RF frequency	80% of the RF band		Any RF frequency
3	See Note	See Note	35 K	6.3	40 K
4	51 K	82 K	40 K	5.1	50 K
5	55 K	75 K	41 K	4	51 K
6	83 K	136 K	53 K	4	66 K
7	147 K	219 K	72 K	4	90 K
8	196 K	292 K	100 K (390 – 420 GHz), 120 K	5	144 K
9	175 K (DSB)	261 K(DSB)	242 K (2SB)	7	290 K (2SB)
10	230 K (DSB)	344 K (DSB)	365 K (2SB)	8	438 K (2SB)

$h\nu/k$

Note:
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)

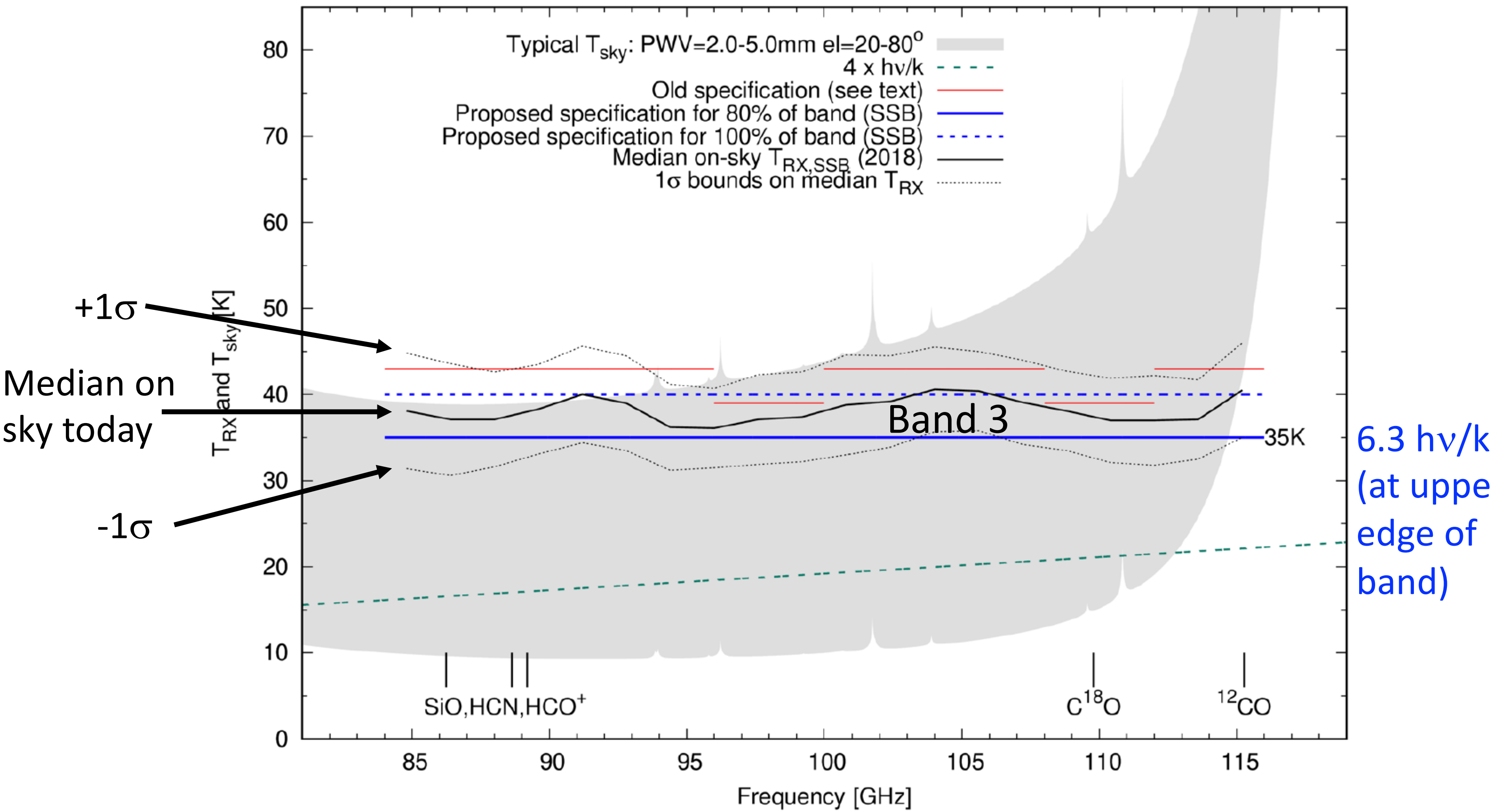


Figure 2: Existing requirements and proposed receiver noise temperature goals for Band 3. Where available, the existing median on-sky receiver noise temperature values are indicated along with 1σ bounds.

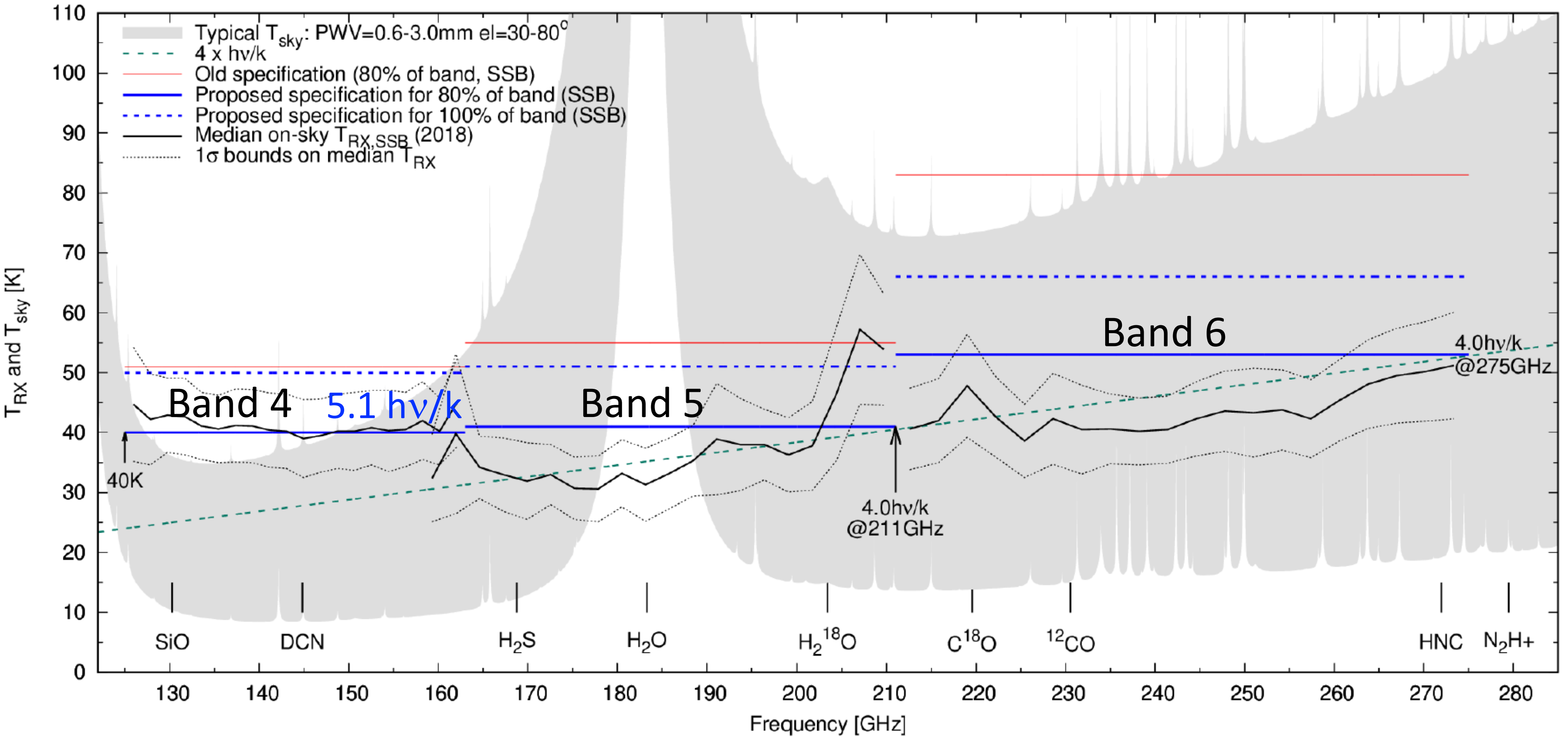


Figure 3: Existing requirements and proposed receiver noise temperature goals for Band 4, Band 5, and Band 6. The existing median on-sky receiver noise temperature values are indicated along with 1σ bounds.

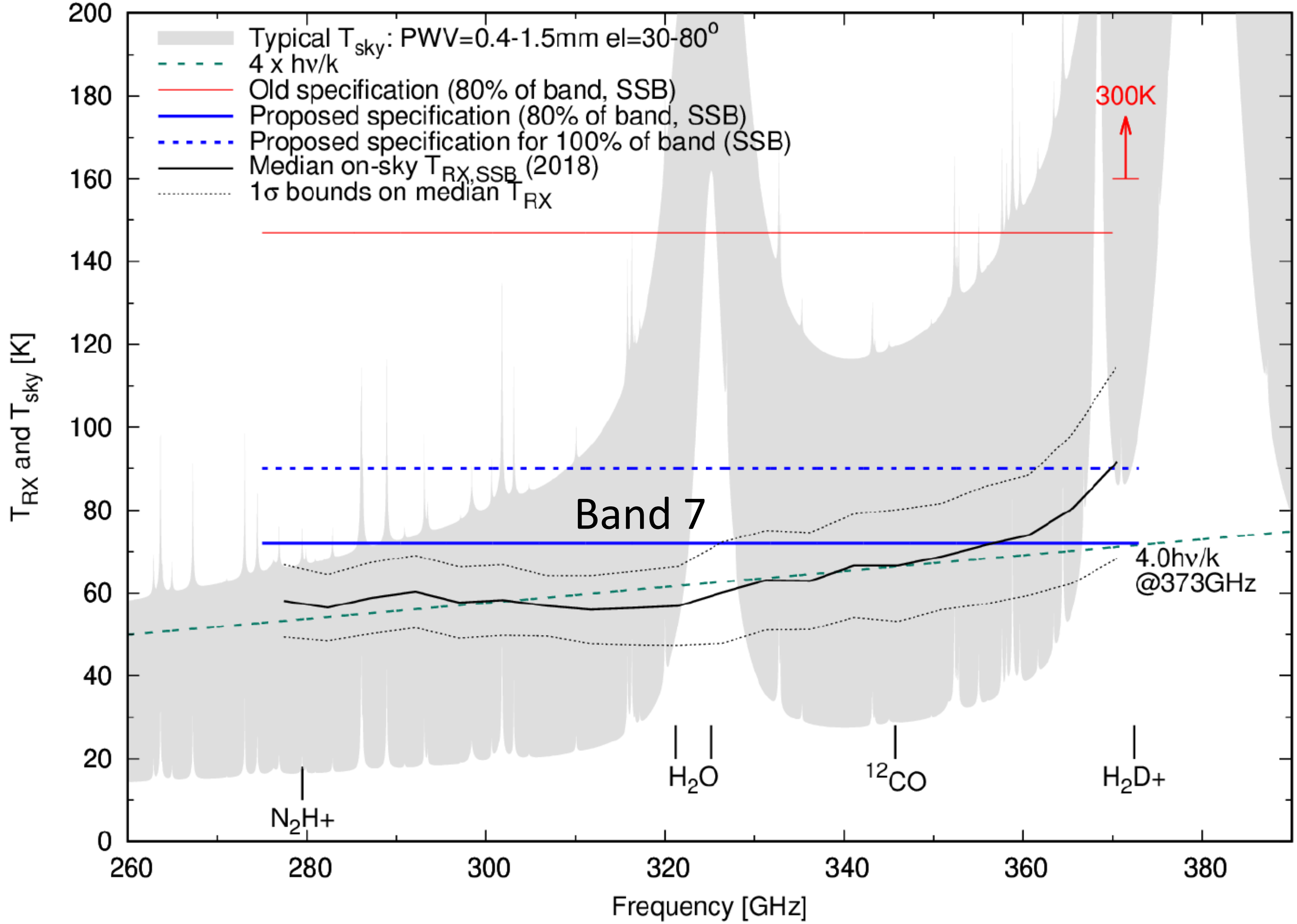


Figure 4: Existing requirements and proposed receiver noise temperature goals for Band 7. The existing median on-sky receiver noise temperature values are indicated along with 1σ bounds.

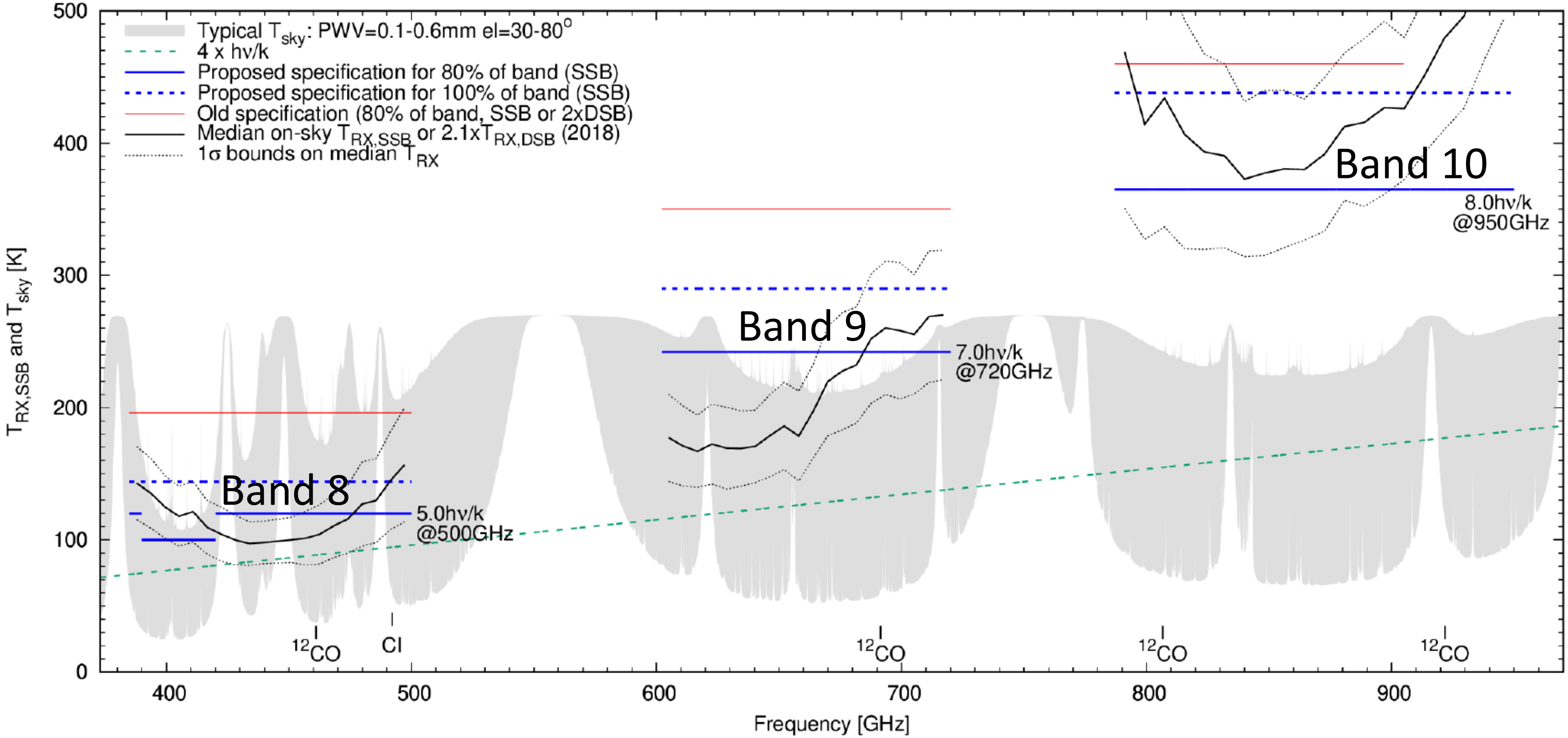


Figure 5: Existing requirements and proposed SSB receiver noise temperature goals for Band 8, Band 9, and Band 10. The existing median on-sky receiver noise temperature values are indicated along with 1σ bounds. For bands 9 and 10, the measured DSB noise has been multiplied by 2.1 to indicate an approximate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

Proposed new requirement on image sideband rejection

ALMA uses LO offsetting to strongly reject image sideband (in cross-correlation), so digital SB rejection scheme not warranted. But still some room to improve FE atmospheric noise rejection and hence Tsys.

Current ALMA specs

SSB and 2SB receivers:

- >10 dB suppression over 90% of IF range
- >7 dB suppression over 100% of IF range

DSB receivers:

- <3 dB difference across 80% of combined IF range

Proposed upgraded specs

All receivers are 2SB:

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

Some units already meet this level. But in a full production run, mean values will need to be better.

Table 3. Estimated observing time improvements (%) by improving the image rejection to 15 dB and 20 dB.

Band	Frequency (GHz)	T_{RX} (SSB) [K]	Octile (PWV [mm])	DSB → SSB (10 dB)	10 → 15 dB	10 → 20dB
				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

Proposed new requirements for Digitizers

1) Strong desire for "direct sampling", i.e. to avoid a second down-conversion, including the inevitable spurs from LO2. For Nyquist frequency to be equal to upper end of a 16GHz wide IF, e.g. 4-20 GHz, we require

Digitizer sampling speed > 40 Gs/sec

2) ENOB (effective number of bits) establishes upper limit on digital efficiency. Goal for efficiency is 99% (prior to the correlator).
Smallest ENOB that can meet this goal is 5-bits, which provides $\eta_{ADC} = 0.9965$ (only at optimal input power)

ENOB >= 5 (for a noise signal with Gaussian amplitude statistics)

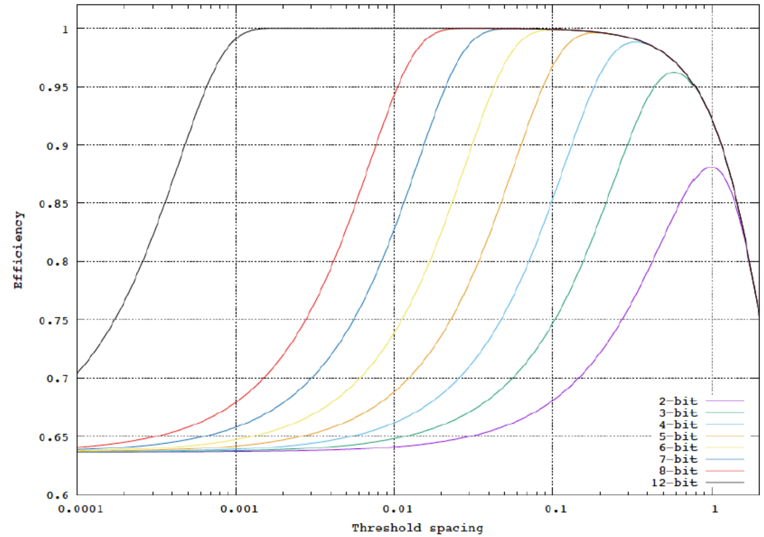
This implies that at least 6 physical bits will be needed.

Proposed requirement on Passband Gain Variations

- Maintaining high efficiency (99%) requires limiting the signal power level variations vs. IF frequency slightly better than the original ALMA spec.

- Current spec: <7 dB over whole IF
  (and <5 dB over any 2 GHz baseband)

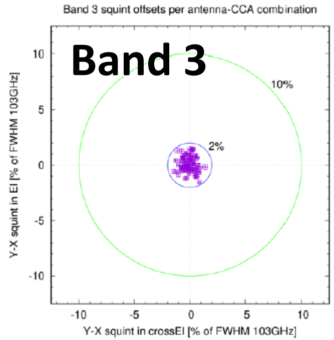
- Proposed spec: < 5.4 dB over whole IF
  which allows for 3dB for temporal sky variations during an SB execution, for a total variation < 8.4 dB

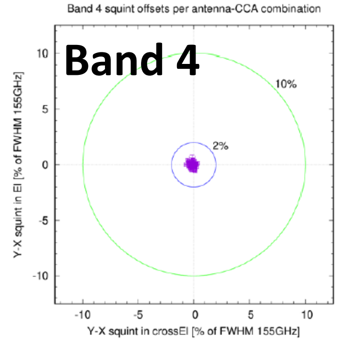


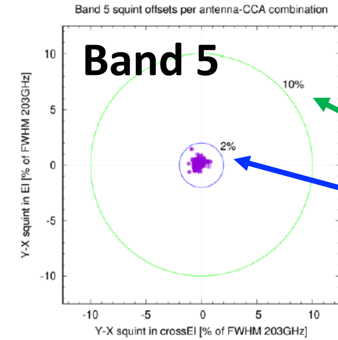
Plot and table from Bordeaux group report

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

ENOB ηmin	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





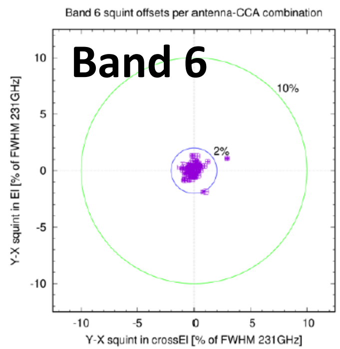


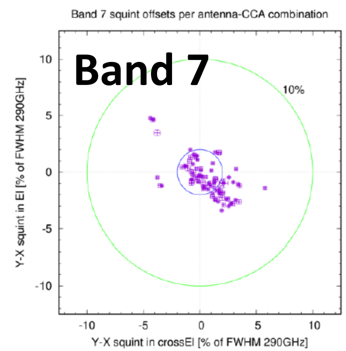
Beam squint

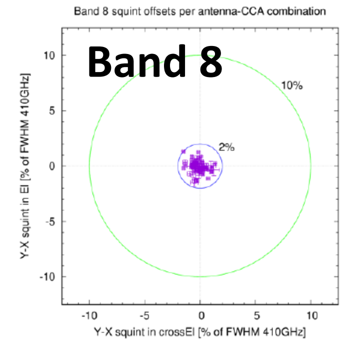
Current spec = **10%**

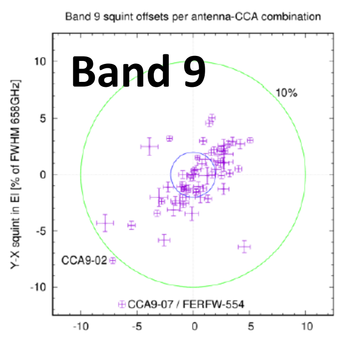
Proposed spec = **2%**

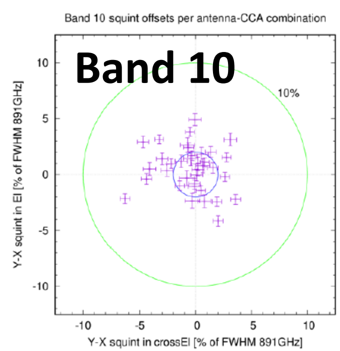
(OMT bands already meet this, but wire grid bands would need tighter alignment spec)











Random variations in squint between antennas needs to be avoided!

With linear feeds, squint mixes Stokes Q and U and this rotates with parallactic angle.

Keeping rms squint below 0.6%/0.4% allows high dynamic range imaging to 0.5/0.25-power point of primary beam (Sramek 2010, ALMA-80.04.00.00-0038-A-SPE).

If spec = 2%, then hopefully rms will be < 1%.

Challenges of achieving desired improvement from wider bandwidth

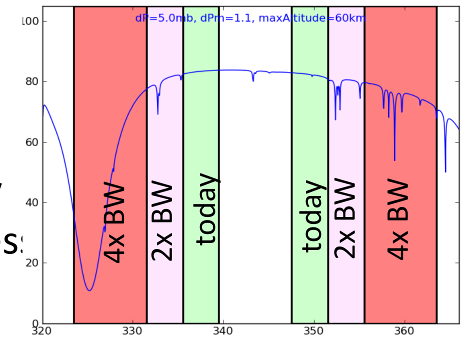
1. Effect of spectral index becomes more important

- Fractional bandwidth at Bands 1 & 3: $(f_{max}-f_{min})/f_{mean}$ is currently 18% & 15%
- Doubling IF bandwidth will make it 37% (SSB) & 25% (2SB)
- Any errors in flux calibrator spectral index propagate to science target
- Precision of spectral index from calibrator database needs improvement
- Will need 2 or more Taylor terms for continuum subtraction & imaging

2. Greater variation in atmospheric transmission across each tuning, hence variable Tsys and sensitivity both within and between spws:

- Use of per-channel weights is more important to achieve optimal sensitivity
- Will increase size of measurement set by 50%, and it will increase the processing time (first ALMA dataset tested took 30% longer: CAS-8868)

Band 7 Tuning



Frequency (GHz)

Potential Benefits

1. Might be able to fit for calibrator spectral index (in low-freq bands)
2. Greater opportunity for self-calibration

- Self-calibration is not yet in ALMA Pipeline, but is coming eventually (Cycle 10?)
  - Even a single solution per EB will remove residual antenna position errors
  - Especially important at long baselines where surface brightness sensitivity is low and antenna positions are uncertain and problematic (CSV-3579)

Related presentations and upcoming workshop

- 2019 ALMA ESO development workshop: https://zenodo.org/communities/almadevel2019
- 2020 ALMA North America workshop on “Design Considerations for the Next Generation ALMA Correlator”, https://osf.io/meetings/NextALMACorrelator/
- 2020 ALMA East Asia workshop on “Design considerations for Digitizers, Backend, and Data Transmission System” held online on Oct 14-16, 2020
- 2021 upcoming workshop on “A Next Generation of Front-End Receivers” sponsored by ESO: to be held online September 27-30, 2021 https://www.eso.org/sci/meetings/2021/ALMAFED2021.html

  invited speakers are not yet chosen

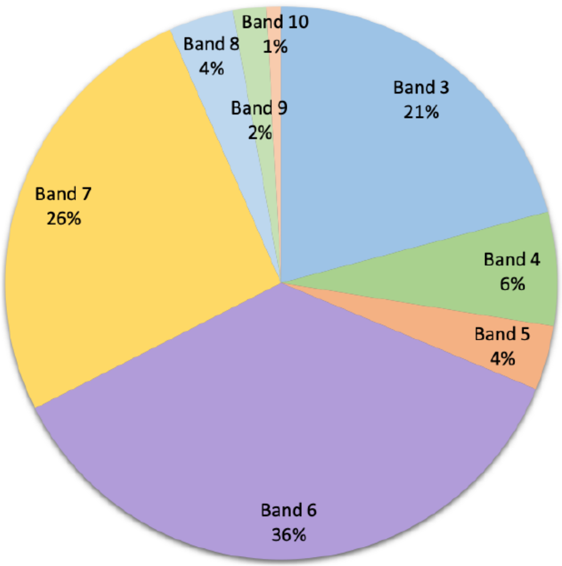
  abstracts due June 15, 2021

Extra slides

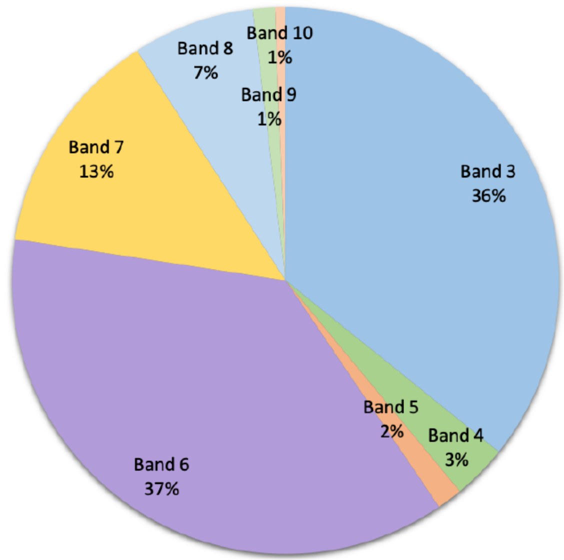
For any questions related to the Cycle 9 North America ALMA development project call, send an email to: almadevelopment@nrao.edu

Cycle 7 submitted proposal statistics vs. Band number

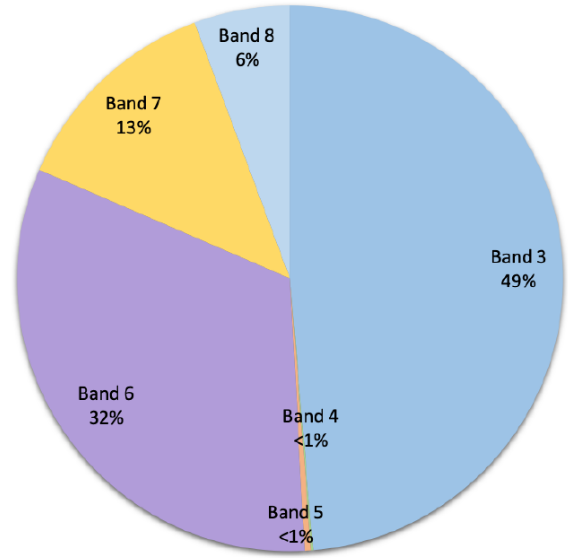
12m array



7m array



Total power array



https://almascience.nrao.edu/news/documents-and-tools/cycle7/cycle-7-proposal-submission-statistics

Cycle 7 accepted proposal statistics vs. Band number

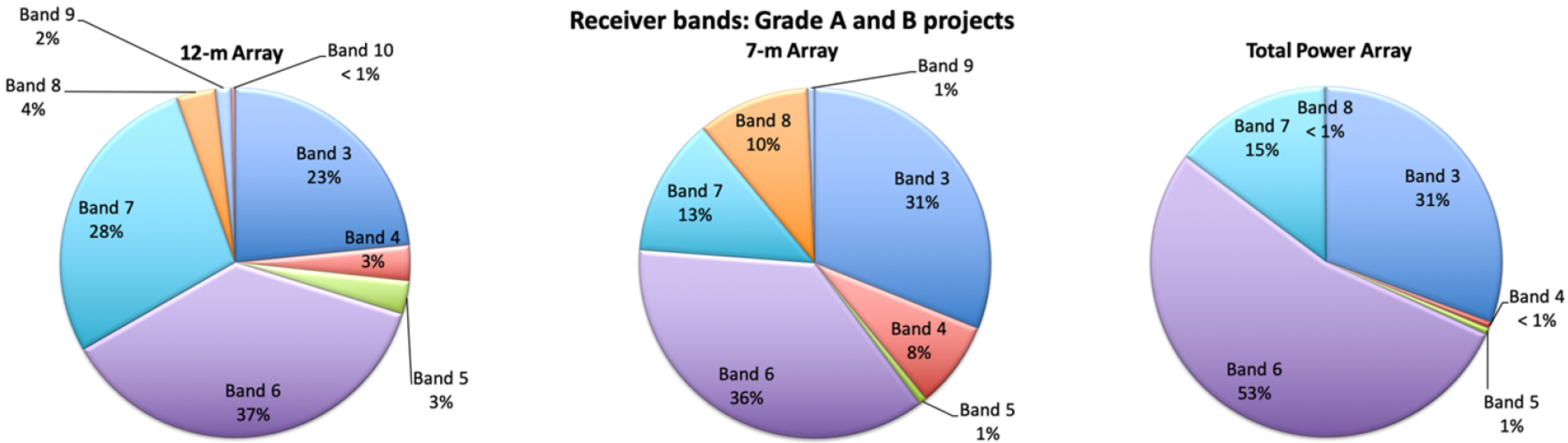


Figure 3. Distribution of the scheduled execution time for Grade A and B projects by receiver band for the 12-m (left), 7-m Array (center), and Total Power (right) arrays. The results for the 7-m and Total Power arrays include both ACA standalone proposals and proposals requesting the 12-m Array + ACA.

https://almascience.nrao.edu/news/documents-and-tools/cycle7/alma-cycle7-stats