ngVLA Electronics Memo # 8

Headroom, Dynamic Range, and Quantization Considerations

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Abstract

We provide a preliminary analysis of the factors that inform the system dynamic range and bit depth in sampling. System sensitivity, astronomical source variability, and robustness to RFI are considered.

1 Introduction

The ngVLA project is preparing to advance a custom digitizer chip design, and a key input parameter is the required number of bits per sample. As part of an update to the system requirements, we also require a deeper analysis of requirements related to dynamic range and headroom in a single system configuration and across observations. The associated requirements for the receivers, downconverters, and digitizers should be harmonized to deliver a balanced system considering performance, technical feasibility, and cost.

1.1 Comparison to the VLA

A number of EVLA memos explore these same topics for the EVLA [1-4]. To a large extent, this analysis remains directly relevant to ngVLA, with a few notable differences:

1) The ngVLA science requirements require a spectral resolution of 0.1 km/s, while most of the VLA analysis was performed at 1-3 km/s.

2) The difference in aperture size (25m vs 18m) requires some minor adjustment in forward gain and beamwidth assumptions.

3) The preferred ngVLA downconverter concept does not readily accommodate gain equalization across the band, so more gain variation must be accommodated, while the digitized basebands are expected to be appreciably wider.

4) The RFI environment that the ngVLA will operate in is expected to be quite different [5,6]. Broadband RFI over 100s of MHz to a few GHz is expected to be received in sky-facing sidelobes from low earth orbit (LEO) satellite constellations, at frequencies spanning from 10 to 50 GHz. Vehicular radar will also be a new source of interference above 70 GHz.

We will largely build upon the EVLA analysis, and lessons learned with the as-built EVLA electronics, while reflecting these differences in requirements, system concept, and the projected RFI environment. The equivalent EVLA requirements and design concept are summarized in the EVLA Project Book [7].

2 Definitions

We will first establish some common definitions for various specifications. While many of these are common in electrical engineering, there are nuances to their application in radio astronomy that we will attempt to clarify and standardize here.

Instantaneous Dynamic Range – This is a system-level specification for dynamic range within a single system setup or observation, representing the ratio of the maximum input power to the minimum input power to a receiver or corresponding segment of the signal chain. Typically, this is the ratio of the maximum permitted noise power in the observation, inclusive of RFI, to the noise power on cold sky. I.e., it is the RFI headroom allocation. However, for a bright source, it could also represent a measurable change in source irradiance (e.g., during observations of the active sun). This specification may vary by receiver band, informed primarily by the expected power of persistent or intermittent RFI, and solar science use cases. The specification will also vary for devices in the signal chain depending on device bandwidth and RFI occupancy.

Dynamic Range Across Setups – This is a system-level specification for dynamic range addressing the expected change in noise power, over a receiver band, which can be expected *across* all observations and system setups. It is the ratio of the maximum input power to be observed to the system noise power on cold sky. We define this as a ratio, rather than simply a maximum input power, to make the specification easily translatable to any element of the signal chain (i.e., we can ignore preceding gain).

1% Compression Point – The power input or output level where the device output deviates by 1% from a linear response. We will standardize on reporting this value relative to the *input* power level, for a *broadband* signal. Note that most components specify the compression point for a narrow-band tone, not the broadband response, which is typically lower. The 1% compression point is a convenient metric to use for defining the maximum input power (and associated dynamic range) of a device as it relates very clearly to the required performance. However, it is unfortunately very difficult to measure, which reduces its value as a specification. We will therefore determine the desired 1% compression point based on higher level requirements, and use this to specify the 1dB compression point and the 3rd order intercept (IP3), in order to have more verifiable specifications.

1dB Compression Point – The power input or output level where the system output deviates by 1dB (~20%) from a linear response. We will standardize on reporting this value relative to the *input* power level, for a *broadband* signal. Note that the 1dB compression point is typically specified for components assuming a narrowband tone for an input signal, and the equivalent point can be appreciably lower for a broadband input signal. We note that at the 1dB compression point the noise floor may be rising, with significant intermodulation products visible above the quiescent background level.

3rd Order Intercept Point Headroom – We will use this term to refer to the difference of the operating point on cold sky to the 3rd order intercept point (IP3). We will standardize on reporting this value relative to the input power (IIP3). This is most often tested in response to a narrowband tone, and is a figure of merit that indicates the non-linearity of a device.

Bit Depth – The total number of bits per sample produced by an analog to digital converter (ADC). This is a headline specification that ignores the quantization noise and added distortion of the device.

Signal to Noise Ratio (SNR) for an ADC – A measure of dynamic range that is the simple ratio of the digitized signal power to the noise level at the output. In general, both the signal and noise powers depend on the input signal, and so does the SNR. Thus, we will not assume a proportional relationship between signal power and SNR by default. In our application, the 'signal' is the output of a receiver – a combination of thermal noise, RFI, and astronomical signals. The 'noise' is the noise added by the digitizer.

The SNR of an ideal digitizer (for a tone input at full scale) is given by:

$$\mathrm{SNR} = 6.02 * \mathrm{N_{bits}} + 1.76 \qquad (1)$$

The coefficient 6.02 converts bits to dB (~20*$\log_{10}(2)$), and the coefficient 1.76 (~10*$\log_{10}(3/2)$) accounts for the SNR of a sinusoid with an amplitude of 0.5 bits embedded in a quantization noise uniformly distributed between ±0.5 bits.

Effective Number of Bits (ENOB) – This is a figure of merit for ADCs that attempts to quantify the dynamic range of the device in bits, accounting for quantization noise. The formula is derived from (1), solving for N_{bits}. A common definition of ENOB is given by:

$$ENOB = \frac{SINAD - 1.76}{6.02} \qquad (2)$$

Where the coefficients are the same as those given for SNR. SINAD substitutes for SNR, and is defined below. This is a readily testable definition, where SINAD is determined empirically.

In order to provide a top-down specification for ENOB, we will modify the definition to relate it again to the desired SNR, which is a more derivable quantity. We will use this modified ENOB for specification purposes, but the traditional measure using SINAD can still be used for verification, as the inclusion of the distortion power in the prior definition will always lead to a more conservative measure. The definition of ENOB in this memo will be given by:

$$ENOB = \frac{SNR - 1.76}{6.02} \quad (3)$$

Signal-to-Noise and Distortion Ratio (SINAD) – A measure of the quality of the signal from a device, usually expressed in dB. It is given by:

$$SINAD = \frac{P_{signal} + P_{noise} + P_{distortion}}{P_{noise} + P_{distortion}} \quad (4)$$

In our application, the 'signal' is the input to the ADC - a combination of thermal noise, RFI and astronomical signals. The 'noise' and 'distortion' is limited to the quantization noise and distortion of the digitizer. SINAD is measured by injecting a strong narrowband tone into the digitizer and isolating the noise and distortion components in the frequency domain.

Quantization Efficiency (η_Q) – We will use a simplified definition for quantization efficiency, relating the signal at the input of the digitizer to the signal at the output of the digitizer. Using this approach, achieving a given quantization efficiency requires keeping the added noise at the output to less than $1/\eta_Q - 1$. This allows us to relate the desired quantization efficiency to the required SNR and ENOB. Maximizing the efficiency of the real system requires knowledge of the signal characteristics and the correct level setting of the input to the digitizer, as is documented in a number of references [1,9,11]. This simple definition will allow us to ensure that the desired quantization efficiency is achievable, based on an allocation to the SNR budget for the digitizer, while deferring the details of input level setting.

3 Instantaneous Dynamic Range Requirements

We will consider the instantaneous dynamic range requirements within a single operational setup first. The power input to the receiver could change as a function of time for the following identified reasons:

1) A change in source/target within an observation, such as from cold sky to a bright calibrator, that changes T_{SYS}.
2) A change in source irradiance that changes T_{SYS}.
3) A change in elevation that changes the atmospheric or spillover contributions to T_{SYS}.

Of these scenarios, the most demanding is a change in source irradiance during solar observations. Changes on the scale of 3dB to 30dB are typical when the sun is active [4]. 30dB of dynamic range is a demanding specification, but since the input SNR is high, we can afford to lose efficiency in quantization. Given the irradiance of the sun, we will assume that any RFI power in the observation is significantly smaller than the power received from the sun. I.e., that the goal of 30dB of dynamic range for solar observations only has to be met in the absence of strong RFI. Practicalities of LNA design may require a reduced specification at high frequency.

Instantaneous dynamic range could also be required to provide headroom for RFI. This is a more common scenario, such as when observing faint sources in the presence of strong RFI. Observations with the VLA at L and S-bands have RFI occupying approximately 30% of the band [10]. Analysis of various scenarios suggests the EVLA 8-bit samplers have an effective RFI headroom spec of 26dB in the presence of multiple interferers [1], and this specification is rather indifferent to device bandwidth given the distribution of interferers at low frequency.

The most significant change in the RFI environment that is expected in the ngVLA's operating life is the launch of Low Earth Orbit (LEO) satellite constellations. A study of their effects suggests that limiting the losses in system availability (due to saturation) may require accommodating interference to noise ratios of 23-29dB over a span of 2GHz bandwidth. [6] Considering the noise power for the full receiver bandwidth yields the required headroom (Table 1). Given the present allocations to these satellite services and pending applications to the FCC, we will aim to accommodate the LEO satellite emissions in all bands operating between 10 and 50 GHz.

Table 1 – Approx. headroom required to accommodate RFI 29dB above the noise floor spanning 2 GHz of receiver bandwidth.

Rec. Band	F_L (GHz)	F_H (GHz)	BW (GHz)	Headroom (dB)
2	3.5	12.3	8.8	22.6
3	12.3	20.5	8.2	22.9
4	20.5	34	13.5	20.7
5	30.5	50.5	20	19.0

At higher frequencies, vehicular radar is a new concern, with spectrum allocated for this service from 76-81 GHz. A minimum of 6dB of headroom is required across the 70-116 GHz receiver band to accommodate this RFI. This source of interference, and the required headroom, is evaluated in the Appendix.

Based on the combination of these factors, we will specify the minimum instantaneous dynamic range requirements in Table 2. We provide the required dynamic range over 1 GHz of bandwidth, as well as over the full bandwidth of the receiver. Note that we have not yet defined the allowable non-linearity at the maximum input power that corresponds to the dynamic range. We consider this later in Section 4.

Table 2 - ngVLA Instantaneous dynamic range requirements for the ngVLA front ends.

Frequency Range	Inst. Dynamic Range Required over 1 GHz	Inst. Dynamic Range Required, at specified quantization efficiency, over full band	Inst. Dynamic Range Required, at lower quantization efficiency, over full band
1.2 – 3.5 (Band 1)	26dB	26dB	30dB
3.5 – 12.3 (Band 2)	29dB	23dB	30dB
12.3 – 20.5 (Band 3)	29dB	23dB	30dB
20.5 – 34.0 (Band 4)	29dB	21dB	30dB
30.5 – 50.5 (Band 5)	29dB	20dB	30dB
70 – 116 GHz (Band 6)	15dB	6dB (20dB desired)	11dB (30dB desired)

The headroom for the ADC and associated signal chain components that follow the front ends must be adjusted for the bandwidth of the device, to correctly baseline the noise power on cold sky and the power inclusive of known interferers. We will assume our interferer spans 2 GHz and is 29dB above the noise (representative of our LEO Satellite scenario for Bands 2-5), and an ADC sampling 5.8 GHz of receiver bandwidth (after the anti-aliasing filters). The ADC then requires an instantaneous dynamic range allocation of approx. 24dB for RFI headroom.

3.1 Desired SNR and ENOB for the ngVLA Digitizers

3.1.1 3.5 – 50.5 GHz Band (ngVLA Bands 2-5) Requirements

We will develop a simple budget for the signal to noise ratio required of the ngVLA digitizers. We start with the Band 2-5 samplers, as these presently share a common architecture in the design.

The system requirements call for a minimum quantization efficiency, η_Q, of 0.96. Using the definition from Section 2, we can determine that the noise power added by the digitizer must be less than 0.0417 the noise power at its input (1/0.96-1). This means that the signal of interest (i.e., input noise to the digitizer) must be at least 13.8dB above the digitizer noise (10*log(0.0417)) to achieve η_Q=0.96.

The present downconverter-digitizer design aims to eliminate any gain-slope equalization (for most bands it would have to be implemented after the mixer, which could negatively impact the sideband separation). Initial discussions suggest the FE can accommodate an allocation of 3dB peak-to-peak for passband slope and ripple over a digitized band. The IRD, which includes most of the system gain, can accommodate a limit of 5dB over the center 80% of a digitized band. The combined system level budget is 8dB of passband slope and ripple combined, peak to peak. This is a variation in Power Spectral Density (PSD), not integrated power, but since the shape is unconstrained, we will assume a worst case of 8dB for passband shape in our SNR budget, as exemplified in Figure 1. This could be reduced to 5.6dB if it proves problematic, which corresponds to the change in power for an 8dB linear gain slope across the band.

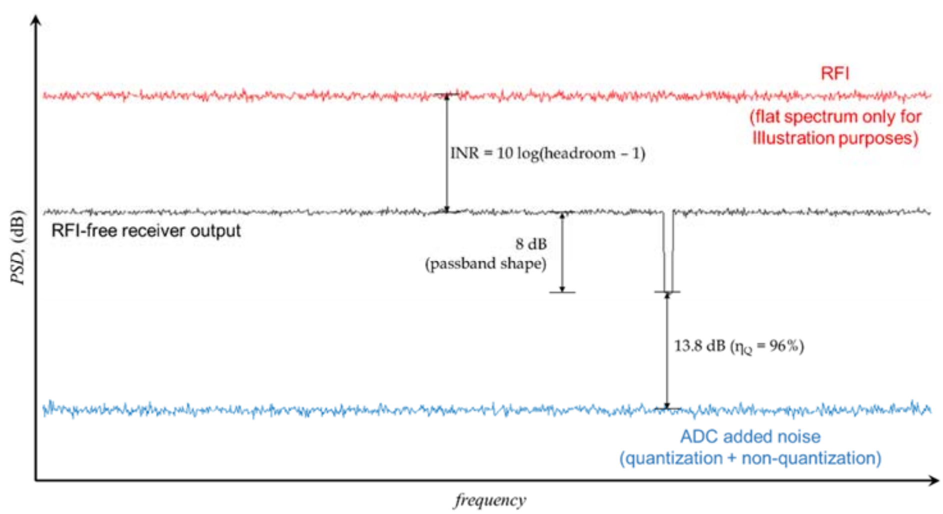

Figure 1 – Illustration of the SNR budget used in the development of ENOB requirements. A receiver passband gain that is flat except for a narrow notch represents a worst case scenario for a given peak-to-peak gain specification. The quantization efficiency specification must be satisfied across the band, including frequency channels within the notch.

Consistent with the previously derived instantaneous dynamic range requirements for the ADCs, we will allocate 24dB to RFI headroom in our SNR budget.[1]

Table 3 - Digitizer SNR Budget for 3.5 GHz to 50 GHz systems (Bands 2-5).

Parameter	Power Allocation	Notes
Receiver Noise	14dB	For η_Q=0.96.
Passband Shape	8dB	Allowed slope and ripple variation integrated over full bandwidth. Includes IRD and FE allocations.
RFI Headroom / Inst. Dynamic Range	24dB	Based on LEO satellite studies.
Required SNR	46dB	

The resulting ENOB required to support this SNR would be:

$$ENOB = \frac{SNR - 1.76}{6.02} = \frac{(46) - 1.76}{6.02} = 7.35\ bits$$

Accepting this ENOB specification of 7.35 bits, we can consider the available trade-offs in individual system configurations between SNR allocations to dynamic range vs the receiver noise baseline, and the associated impact on quantization efficiency.

Figure 2 plots the quantization efficiency obtained for three different ADC models. The first model, '8B IDEAL', corresponds to an ideal 8-bit ADC. The second model, 'ENOB 7.35', includes the extra noise at the ADC output such that the ENOB for a full scale tone becomes 7.35. Because they are difficult to model, we do not include any distortion effects, but instead we assume an extra noise contribution independent of the ADC input, as when it is due to the ADC's thermal noise. The third model considered, 'ENOB 7.35 w SLOPE', includes the effect of the receiver gain in the quantization efficiency, measured at the frequency channels with minimum gain (minimum value). However, instead of using the worst-case shape represented in Figure 1, here we take a less pessimistic approach and assume a linear gain (in natural power units) across the receiver passband, with 8dB excursion. This results in a signal loss of 5.6dB at the frequency channels with minimum gain, which negatively impacts the quantization efficiency as shown in the figure.

In Figure 2, we assume a Gaussian distribution model for the voltages of both the noise and RFI, assuming multiple RFI sources of unrelated frequencies. [1] In addition, we arbitrarily define the operating headroom of the ADC such that it is 0dB when the rms value of the input matches the ADC full-scale voltage.[2] In other words, the operating headroom is the ratio of the ADC's full-scale voltage and the input rms value. Note that the quantization efficiency only accounts for the SNR loss due to quantization. For example, for an RFI-free input and the ADC operating at 30dB headroom, the minimum quantization efficiency is 95.6%

[1] As a reminder, we define the required RFI headroom as the ratio of the ADC input power with and without RFI. This is the interference-to-noise ratio (INR) plus 1. As a result, the headroom and the INR are approx. equal when INR $\gg$ 1.

[2] We note that [1] defined the ADC saturation point for a Gaussian-like RFI input when its full-scale voltage matches 3 times the RFI rms value (plus the RFI-free noise contribution, which can be neglected at high INR). This value corresponds to a headroom of approx. 10 dB according to our definition.

when considering the gain slope effect. Then, if an RFI decreases the headroom to 10dB, paradoxically the quantization efficiency increases to 99.9%, because the model does not include the SNR loss due to the RFI itself.

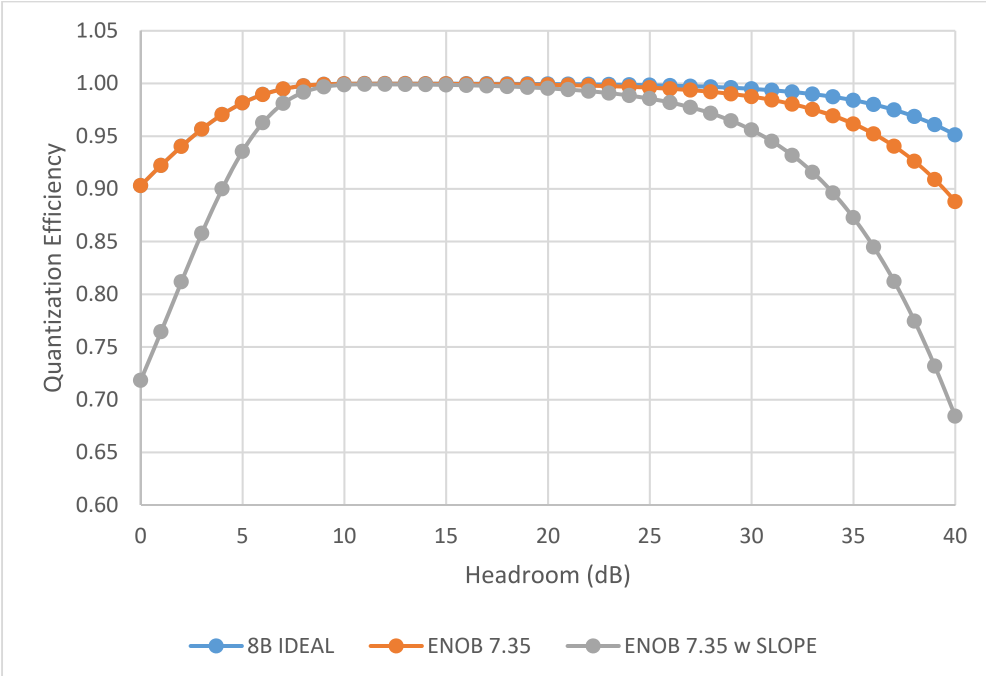

Figure 2 – Quantization efficiency of an 8-bit ADC for a Gaussian input as a function of its operating headroom, which is defined as the ADC's full-scale voltage relative to the input rms voltage. '8B IDEAL' stands for an ideal digitizer. 'ENOB 7.35' includes the additional noise such that the ADC's ENOB for a full-scale input tone results 7.35 bits. 'ENOB 7.35 w SLOPE' represents the minimum efficiency when the noise PSD is linear with an 8dB peak-to-peak variation.

Using the values from Figure 2, we determine that an 8-bit ADC with an ENOB≥7.35 offers a best-value solution satisfying the minimum dynamic range requirements. When operated at a headroom around 30dB, it meets the quantization efficiency requirements while still permitting a few dB of headroom in the worst case RFI scenarios. Because those are transitory events, such as LEO satellite transits through on-sky sidelobes (for which the antenna gain is assumed greater than 0dBi), [6] it would also be possible to factor their loss into the array availability, providing a degree of contingency should our analysis not be sufficiently conservative. There is also an additional gain not considered in the curves from the reduced receiver bandwidth as compared to the sampling frequency, which should improve overall efficiency. Finally, the initial estimates of the antialiasing filter response suggest that the maximum in-band loss could be as low as 2-dB, instead of the more than 5 dB assumed for the 'ENOB 7.35 w SLOPE' curve. These considerations improve our confidence that the specified ADC should suffice in practice.

As regards the dynamic range requirements for bright sources, if we want to level the digitizers to permit input power to rise 30dB (supporting the reduced efficiency spec in Table 2), we would accept a quantization efficiency of approx. 90%, and set the operating headroom at 34dB. This guarantees that a similar quantization efficiency is obtained at the initial operating point and for a 30dB increase in power. Alternatively, the desired quantization efficiency could be increased at lower input power, if a higher loss is accepted when the input power increases, e.g., from 95.6% at 30dB headroom to 71.8% at 0dB. In conclusion, an ADC of ENOB=7.35 appears to accommodate a range of setups that support both the requirements in Table 2.

3.1.2 1.2-3.5 GHz (ngVLA Band 1) Requirements

The 26dB of desired RFI headroom in ngVLA Band 1 results in a very similar SNR budget to bands 2-5, with the key difference being an additional 2dB of headroom compared to Bands 2-5. The Band 2-5 SNR (and ENOB) is achievable with a real 8-bit ADC (ENOB ≥ 7.35 bits), but requiring an additional 2dB of SNR in Band 1 could push us outside the feasible specs of an 8-bit device. Fortunately, we know that our passband shape budget allocation is conservative[3], so we will instead trade 2dB between the headroom and passband slope allocations to yield the same total SNR and ENOB specifications (Table 4) as the Band 2-5 devices.

Table 4 - Digitizer SNR Budget for 1.2 GHz to 3.5 GHz system (Band 1).

Parameter	Power Allocation	Notes
Receiver Noise	14dB	For η_Q=0.96.
Passband Shape	6dB	Allowed slope and ripple variation integrated over the full bandwidth. Includes IRD and FE allocations.
RFI Headroom / Inst. Dynamic Range	26dB	Based on VLA experience.
Required SNR	46dB	

3.1.3 70-116 GHz Band (ngVLA Band 6) Requirements

Using the same methodology described in the preceding section for bands 1-5, but with a smaller allocation to dynamic range, results in the SNR budget for band 6 given in Table 5.

Table 5 - Digitizer SNR Budget for 70 GHz to 116 GHz systems (Band 6).

Parameter	Power Allocation	Notes
Receiver Noise	14dB	For η_Q=0.96.
Passband Shape	8dB	Allowed slope and ripple variation integrated over full bandwidth. Includes IRD and FE allocations.
Headroom/ Inst. Dynamic Range	11dB	Automotive radar RFI (See Appendix). For 11.6 GHz digitizer input bandwidth (4-bit design).
Required SNR	33dB	

The receiver noise and passband shape allocations remain the same as for the lower frequency bands. We retain the full 8dB of passband shape since the digitized bandwidths are wider (i.e., this is not as

[3] Not only due to the derivation given in Section 3.1.1, but also due to the narrower bandwidth sampled at this band. The additional gain in quantization efficiency after fine frequency channelization, as compared to a truly flat input spectrum across the whole band, could be as high as 1.8 dB (10 $\log_{10}$[3.5GHz/2.3GHz]).

conservative as it was for the lower bands). The headroom requirement is driven primarily by new automotive radar systems operating in the 76-81 GHz range, and assumes an input bandwidth of 11.6 GHz (representative of our present 4-bit ADC design). The derivation of the headroom spec is provided in the Appendix, and corresponds to a single vehicle 1km from the antenna. For an SNR of 33dB, the resulting ENOB is 5.2 bits.

Clearly an ENOB of 5.2 is well in excess of what is achievable with a 4-bit digitizer, as specified in the Reference Design. Using a 4-bit digitizer, given our passband shape allocation, would limit the headroom to ~3dB at the specified quantization efficiency. This would present an unreasonable risk of saturation at the lower end of band 6.

If an ADC of narrower input bandwidth were used, we would need to adjust the headroom requirement to match the device bandwidth. Assuming the device with a larger ENOB than specified were employed (e.g., an 8-bit digitizer of ENOB 7.35, same as Bands 1-5) the passband slope and ripple budget could also be increased to reduce the difficulty in meeting the present allocation in Band 6 (this is in addition to the benefit afforded by reduced bandwidth). Accepting that a 4-bit device is not practical, we provide the updated SNR budget in Table 6, and propose adopting the same ADC as bands 1-5 as the preferred technical solution.

Table 6 - Updated SNR budget for Band 6, assuming narrower digitizer bandwidth.

Parameter	Power Allocation	Notes
Receiver Noise	14dB	For η_Q=0.96.
Passband Shape	10dB	Allowed slope and ripple integrated over full bandwidth (ratio of average gain to in-band minimum gain).
Headroom/ Inst. Dynamic Range	20dB	Automotive radar RFI, 2 vehicle scenario (See Appendix). For 5.8 GHz digitizer input bandwidth.
Contingency/ Extra Headroom	2dB	Additional headroom available while matching total SNR budget of 7.35 ENOB ADC. Could also be used to raise η_Q to 0.97.
Total SNR	46dB	Equivalent to 7.35 ENOB ADC.

4 Dynamic Range Across System Setups

The instantaneous dynamic range would be a floor on the system dynamic range across setups. The instantaneous dynamic range requirements provide ample dynamic range for observation of faint sources, where the source irradiance is less than the system noise power. A few sources are appreciably brighter, with the active Sun presenting a limiting case. To observe these sources will imply a larger range of input power, but we can adjust the system setup (e.g., adjusting variable attenuators in the signal path.)

The requirements for solar observations were studied for the EVLA and are documented in EVLA Memo 70. [4] The associated findings remain relevant, with minor adjustments for the smaller aperture size and differences in T_{SYS}.

The brightness temperature of the quiet sun spans from 100,000 K at the bottom of Band 1, where emission is dominated by the corona, to 6,000 K at high frequency. Compared to the system temperature on cold sky, the quiet sun can raise the system temperature 34dB to 19dB across the ngVLA frequency bands (Table 7). We will aim to accommodate this range in source brightness temperatures while keeping the system in the linear operating range.

Table 7 - Quiet sun dynamic range requirements.

Rec. Band	F_L (GHz)	F_H (GHz)	T_B (1000 K)	T_A (1000 K)	T_{COLD}	T_A/T_{COLD}
1	1.2	3.5	80	57	26	33.4
2	3.5	12.3	30	24	28	29.3
3	12.3	20.5	10	8.0	28	24.6
4	20.5	34	8	6.4	33	22.9
5	30.5	50.5	6	4.8	42	20.6
6	70	116	6	4.8	69	18.4

The active sun can lead to further increases in system temperature, up to 55dB above cold sky. This is well above the dynamic range of realizable low noise amplifiers (LNAs). Accommodating such signals while directly pointed at the sun would require that we bypass the first LNA. The associated bypass circuitry in front of the LNA would increase the system temperature for all observations, harming the overall sensitivity of the instrument for a majority of use cases. We will therefore pursue other solutions for active sun and solar flare observations. An example would be to employ offset pointing, observing the sun through the 1st or 2nd sidelobe of the antenna, to reduce the forward gain and power at the input to the 1st LNA by 20dB to 30dB. This solution, or other alternatives, should be considered in more detail in the preliminary design phase.

Given these choices, the resulting input power dynamic range required across system setups is defined in Table 8.

Table 8 - Dynamic range and linearity requirements.

Frequency Range (Band)	Dynamic Range Across Setups, dB (1% Compression)	Dynamic Range Across Setups, dB (1dB Compression)	System Headroom to IIP3, dB (on cold sky)
1.2 – 3.5 (Band 1)	34	46	56
3.5 – 12.3 (Band 2)	30	42	52
12.3 – 20.5 (Band 3)	25 (30 Desired)	37 (42 Desired)	47
20.5 – 34.0 (Band 4)	23 (30 Desired)	35 (42 Desired)	45
30.5 – 50.5 (Band 5)	21 (30 Desired)	33 (42 Desired)	43
70-116 GHz (Band 6)	19 (30 Desired)	31 (42 Desired)	41

As explained in Section 2, measuring the 1% compression point of a system is difficult in practice. We therefore also provide a 1dB compression point and IIP3 specification. A suitable amplifier will have the

3rd order intercept point appear to be 10dB above the 1dB compression point, and the 1dB compression point will be 12dB above the 1% compression point. These are typical relationships that also, fortunately, support the higher level requirements.

The headroom to the IP3 point, when observing cold sky, must ensure that intermodulation products from RFI are sufficiently low power to not be confused for spectral lines. As described in EVLA Memo 82 [1], we can compute the required headroom to the IP3 for continuum observations with an 8-bit digitizer, in the presence of multiple high-power interferers, to be approximately 34dB.[4]

Extending the analysis to spectral line observations requires a correction for resolution bandwidth, raising the IP3 point by the square root of the number of channels across the band. [1] The required velocity resolution of 0.1 km/sec corresponds to channel widths of 3.3E-7*f_c, raising the IP3 point an additional 32dB above continuum levels to avoid the appearance of false spectral lines. Fortunately, we can count on a minimum of 17-26dB of interferometric attenuation of these intermodulation products [8], reducing the required specification. An IP3 point 22dB above the 1% compression point should suffice for interferometric modes in practice, and should be an achievable specification.

Total power observations would require an IP3 point 66dB above the operating point on cold sky to mitigate the appearance of false spectral features at the specified spectral resolution, when operating in a high-RFI environment. Such a specification may not be achievable in practice, and should be considered more carefully as part of the total power mode requirements.

5 References

[1] Perley, R. “Headroom Requirements for the EVLA” EVLA Memo 82, Aug 2004.

[2] Carlson, B. and Perley, R. “Quantization Loss for a Sloped Passband” EVLA Memo 83, Aug 2004.

[3] Perley, R. and Hayward, B. “The Effect of Amplifier Compression by Narrowband RFI on Radio Interferometer Imaging” EVLA Memo 110, Aug 2007

[4] Perley, R. and Bastian, T. “Desiderata for Solar Observing with the EVLA” EVLA Memo 70, Jan 2004.

[5] Erickson, A. “ngVLA Radio Frequency Interference Forecast” ngVLA Memo 48, July 2018.

[6] Selina, R. “Requirements for Mitigation of LEO Constellations” ngVLA Electronics Memo (In prep.)

[7] Kutz, C. et al. “EVLA Project Book, Chapter 5: Receivers” March, 2009. http://www.aoc.nrao.edu/evla/admin/projbook/chap5.pdf

[8] Selina, R. “System L1 EMC Compatibility and RFI Mitigation Requirements” ngVLA Doc 020.10.15.10.00-0002-REQ, Rev B, Nov 2020.

[4] This analysis ignores the effect of passband shape. Adding in the passband gain variation reduces the IP3 headroom required, but makes the analysis more fragile should the system have a flatter passband than specified. In an effort to be conservative, we therefore assume a flat passband when computing the headroom to IP3 requirement.

[9] Thompson A., Moran J., Swenson G. "Interferometry and Synthesis in Radio Astronomy" Chapter 8, Second Edition. 2004.

[10] Various "Guide to Observing with the VLA: Radio Frequency Interference" Sept. 2020 https://science.nrao.edu/facilities/vla/docs/manuals/obsguide/rfi

[11] Thompson A., Emerson D., Schwab F., "Convenient Formulas for Quantization Efficiency" Radio Science Vol 42, RS3022, doi:10.1029/2006RS003585, 2007.

6 Appendix: Considerations for Vehicular Radar

Vehicular radar is a new source of radio frequency interference that we can expect in the 76-81 GHz frequency allocation (the lower end of ngVLA Band 6). Mitigating this new source of RFI must be considered in the ngVLA Band 6 front end, downconverter, and digitizer design. We estimate the impact this RFI will have on dynamic range and quantization requirements.

Two frequency spans are presently allocated for long-range and short-range automotive radar. The band allocations and power limits established by the FCC are given in Table 9.

Table 9 - FCC Allocations to Vehicular Radar Service.

Radar Band	Lower Band Edge	Upper Band Edge	Peak EIRP	Mean EIRP	Bandwidth
Automotive Long Range (LR)	76 GHz	77 GHz	55 dBm	50 dBm	1 GHz
Automotive Short Range (SR)	77 GHz	81 GHz	55 dBm	50 dBm	4 GHz

These automotive radar systems are both broadband, typically sweeping most of their frequency allocation. The beams are low gain with a wide azimuth, and both systems may be operational concurrently.

We will assume that the antennas are located a minimum of 1km from any busy roadway. We will then compute the ratio of the PSD received from a vehicle with a radar beams pointed at the antenna, and received through an isotropic (0dBi) sidelobe. This could be considered a worst case scenario, as the gain is typically -5dBi to -20dBi in the far sidelobes of the ngVLA antenna pattern, but it accounts for the fact that we do not know in which orientation the antenna is pointed. The key ngVLA input parameters assumed are given in Table 10, with the radar system parameters in Table 11.

Table 10 - ngVLA antenna, key parameters.

Parameter	Qty	Units	Notes
Nu (GHz)	76.5	GHz	Point frequency for Tsys
Tsys (K)	70	K	From reference design estimates, ngVLA Band 6.
Sys Noise PSD, Input (W/Hz)	9.66E-22	W/Hz	R-J approximation, Pin = kTsys, spectral noise power.
Sys Noise PSD, Input: (dBW/Hz)	-210.2	dBW/Hz	
Sidelobe Effective Area: A_e (m^2)	0.000001	m^2	Isotropic sidelobe.

Table 11 – Radar system, key parameters.

Parameter	LR Radar	SR Radar	Notes
Distance (km)	1	1	Assumption. Impacts site selection.
EIRP, Peak (dBm)	55	55	Worst Case.
EIRP, Average (dBm)	50	50	Average over time.
BW (MHz)	1000	4000	Some short range systems operate over 2GHz BW - may be a 'de facto' standard. Add 3dB to SPFD for that scenario.
EIRP, Peak (dBW/BW))	25	25	
EIRP, Peak (dBW/Hz)	-65.0	-71.0	
Path Attenuation (dB)	71.0	71.0	Over 1km.
PFD, Radar Main Beam (dBW/m^2/BW)	-46.0	-46.0	Using peak EIRP, but average may be representative given integration times. Using Peak ensures we do not saturate in the presence of pulsed radar systems.
PFD, Radar Main Beam (W/m^2/BW)	2.5E-05	2.5E-05	
SPFD, Radar Main Beam (W/m^2/Hz)	2.5E-14	6.3E-15	
SPFD, Radar Main Beam (dBW/m^2/Hz)	-136.0	-142.0	

We can then calculate the received PSD from the radar system, and compare it to the system noise to determine the interference to noise ratio (INR) over the impacted bandwidth. These values are given in Table 12. We then integrate the PSDs over their respective bandwidths to determine the total power and associated headroom required for various devices in the signal chain. These values are given in Table 13.

Table 12 - Received Radar Signal-to-Noise Ratio

Parameter	LR Radar	SR Radar	Notes
Received PSD from Radar (dBW/Hz)	-195	-201	Through an isotropic sidelobe.
System Noise PSD (dBW/Hz)	-210	-210	At given Tsys
Radar Signal INR (dB)	15.0	9.0	Instantaneous INR. Increases with time and BW.

Table 13 - Headroom Requirements by device. The LNAs and 8-bit and 4-bit ADC options are presented, with their corresponding bandwidths.

Parameter	LNA	ADC-8B	ADC-4B	Units	Notes
System BW	46.0	5.8	11.6	GHz	BW after anti-aliasing filters.
Thermal Noise Power	4.4E-11	5.6E-12	1.1E-11	W	
Radar Power, LR	3.1E-11	3.1E-11	3.1E-11	W	
Radar Power, SR	3.1E-11	3.1E-11	3.1E-11	W	
Total Noise (1 vehicle, LR+SR)	1.7E-10	1.3E-10	1.3E-10	W	Coherently summed.
Headroom Required (1 vehicle, LR+SR)	**5.8**	**13.6**	**10.8**	**dB**	
Total Noise (2 vehicles, LR+SR)	5.4E-10	5.0E-10	5.0E-10	W	Coherently summed.
Headroom Required (2 vehicles)	**10.8**	**19.5**	**16.5**	**dB**	

The headroom requirements in Table 13 assume both the LR and SR radar systems are operating simultaneously and are applicable for one or two vehicles. If many vehicles are present, the required headroom depends on the degree of constructive or destructive interference between radar systems. Given the swept nature of the radar systems (and the associated frequency occupancy or duty cycle), coherent summation of the radar powers may not be uncommon for small numbers of vehicles. A second vehicle, coherently summed, increases the headroom required by 5.0, 5.9, and 5.7dB for the LNA, ADC-8B and ADC-4B respectively.

Unfortunately, inclusion of even a single vehicle's allocation in the digitizer SNR budget pushes us beyond the capabilities of a 4-bit digitizer while maintaining the required quantization efficiency (See Figure 3, Figure 4), while accounting for the known passband slope and ripple. Figure 3 shows the headroom available when we assume incoherent summation of many RFI sources and a Gaussian distribution of the voltage sum. Figure 4 shows the headroom available when we assume coherent summation of two RFI sources, consistent with this scenario.

With an 11dB RFI headroom allocation (single vehicle), the 4-bit ADC quantization efficiency could drop from 92% to 76% across the band, depending on the variation in gain across the passband. A 17dB RFI headroom allocation (two vehicles) could drop quantization efficiency to 47%. Given the expected proliferation of these radar systems in modern vehicles, adjusting our assumptions (e.g., assuming a lower sidelobe gain, single radar system operation, or incoherent summation) to reduce the required headroom seems risky.

We won't dwell on the number of possible vehicles present or other distance scenarios, as the single vehicle scenario analyzed pushes us towards a higher bit-depth digitizer. Considering the ADC development costs and IRD architecture, adopting an 8-bit system which is capable of much higher headroom seems the most logical approach. We will adopt the two vehicle headroom requirements for our SNR budget in Band 6.

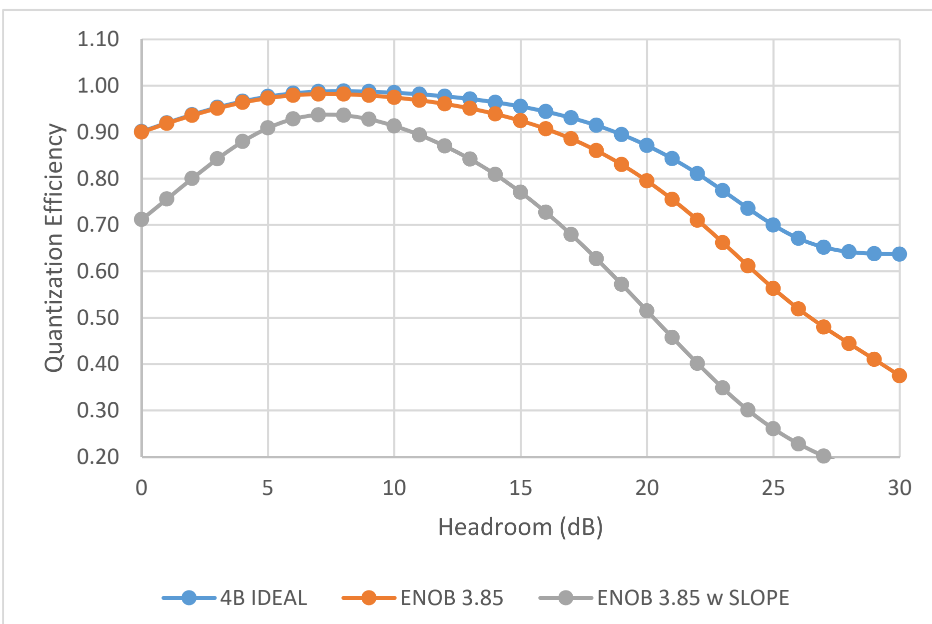

Figure 3 – Gaussian Model: Quantization efficiency that can be achieved with a 4-bit ADC or ADC of ENOB=3.85 (SNR=25dB) for various levels of dynamic range (or headroom) relative to the front end noise floor. The grey curve shows the efficiency in the worst channel given the allowable gain slope across the digitized subband. Headroom in this plot is based on a gaussian distribution of input amplitude, apropriate for many RFI sources that sum incoherently and for bright astronomical sources such as the Sun.

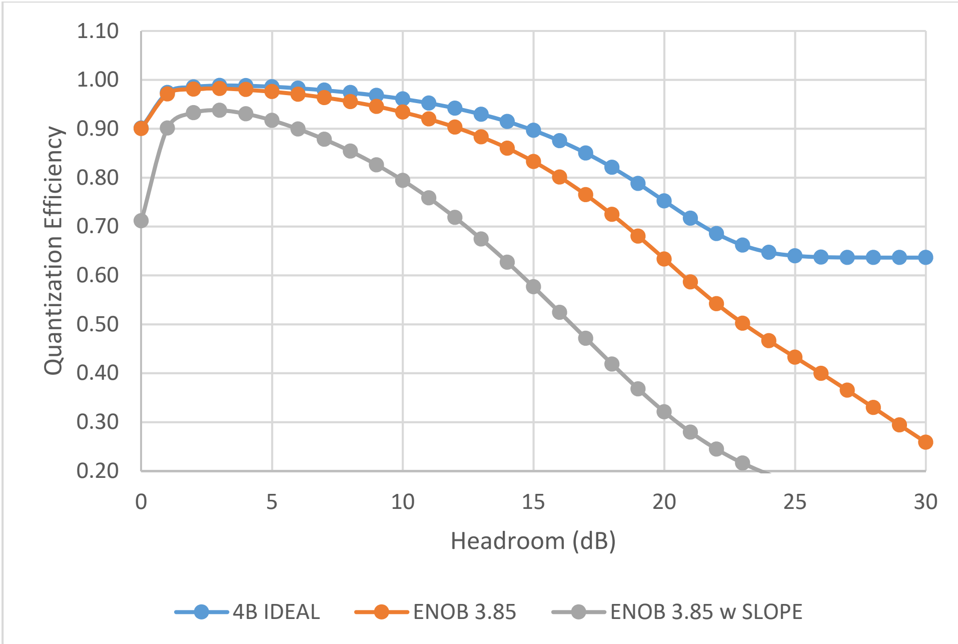

Figure 4 – Non-Gaussian Model: Quantization efficiency that can be achieved with a 4-bit ADC or ADC of ENOB=3.85 (SNR=25dB) for various levels of dynamic range (or headroom) relative to the front end noise floor. The grey curve shows the efficiency in the worst channel given the allowable gain slope across the digitized subband. Headroom in this plot is based on coherent summation of RFI amplitudes, apropriate for scenarios with a limited number of sources that may sum coherently.