LWA Analog Signal Path Planning
Version 2

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Contents

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1 Summary

This document describes some considerations in planning of the LWA analog signal path. "Analog signal path" is defined here as defined as the part of the station beginning at the antenna terminals and ending at the input to the analog-to-digital converter (ADC). With respect to the station architecture [1], the analog signal path under consideration includes the front end electronics (FEE; also known as the "active balun"), RPD (in particular, the cable between the FEE and the shelter), shelter entry panel (SEP), and analog signal processing (ASP). The ASP includes the analog receiver (ARX). The relevant aspects of the problem are taken into account by considering just 3 subsystems: FEE, the cable, and the ARX. The SEP and other portions of the RPD and ASP affect the analysis only in that they contribute a few dB loss, which in the context of this analysis can be considered part of the cable loss. Thus in this document we will consider the system of interest to consist of a "cascade" of just three "stages": the FEE, the cable, and the ARX.

The primary consideration in designing this part of the system is delivering a Galactic noise-dominated signal at a suitable level to the ADC in the presence of radio frequency interference (RFI). In this document we assume a DIG subsystem consisting of an ADC having the specifications of the Analog Devices AD9211-200 evaluation board described in LWA Memo 112 [2]. We also assume RFI conditions at the central VLA site described in LWA Memo 84 [3]. For this reason, the conclusions reached here pertain only to that site. RFI at no other site has been documented in a form suitable for the kind of analysis presented in this document, however indications from ongoing RFI measurement attempts at other sites suggest RFI characteristics which are similar in spectral distribution and occupancy but perhaps significantly worse in magnitude. Some effort to account for the possibility of sites worse than the VLA site is made and noted here.

Findings are as follows:

- At the VLA site, the system must accept a maximum expected input power of −54 dBm in the range 13-113 MHz, which is overwhelmingly dominated by RFI. This does not, however, directly translate to a linearity specification for the FEE or any other subsystem. Furthermore, there is the possibility of high-power RFI at much higher and lower frequencies (e.g., nearby two-way activity on the 2-meter amateur radio band, AM broadcast) that should be kept in mind.

- The total gain of the FEE plus the ARX (i.e., excluding cable) should nominally be variable over the range 52 dB to 97 dB, although 62–92 dB is probably sufficient. This assumes 150 m of RG-58 coaxial cable, and accounts for the frequency response of this cable. Losses (other than coaxial cable itself) in the RDP or SEP are neglected, but are small and frequency-independent, and therefore can be treated as part of the coaxial cable loss.

- ARX specifications depend on FEE choice. The possibilities with respect to four candidate FEE designs are presented in Table 9. Summarizing: The ARX input 1-dB compression point (lower bound) will be in the range −28 dBm to +10 dBm depending on FEE choice. The ARX noise figure (upper bound) will be in the range 3–10 dB depending on FEE choice. Again all this assumes 150 m of RG-58-type cable.

- The analog signal path should have a reconfigurable bandpass, probably implemented in the ARX. It will be very useful to have control of gain in the 13-23 MHz band independently of the midband gain, so as to accommodate RFI in that band. Additional configurations representing various other per-band gain settings would be desirable, but perhaps not necessary. Nirvana would be independent gain control by band, with bands as delineated in the top half of Tables 1 and 2.

- The complex nature of the RFI spectrum combined with the need for multiple bandpass configurations and variable gain make it impossible to express a simple requirement for analog path spurious generation, although this is critically important. The necessary analysis should be done as part of the design process, preferably using prototype hardware tested in field conditions.

- Cable loss has a significant impact on these findings. The primary issue is not so much the loss at any given frequency, but rather the rate at which loss increases with increasing frequency. Version 1 of this document (inadvertantly) shows the results for cable with lower loss and slower roll-off with frequency.

- There is no compelling requirement for equalization to flatten the non-uniform external noise spectrum below 54 MHz, although this could have some benefit in optimizing RF system performance. There is justification for gain boosting above 54 MHz, primarily to overcome cable loss. If lower-loss cable is used (reducing the high-end loss by, say, 10 dB) then gain boosting of the high end may become unnecessary.

2 Noise and RFI Environment

This section summarizes the noise and RFI environment described in LWA Memo 84. The measurements were made with a "big blade" antenna fitted with a 250 K active balun, and thus should be a reasonable indication of the RFI and noise that the goal LWA system should see.

Table 1 summarizes the RFI observations and shows some additional computations that will be useful in the subsequent analysis. First, note that results have been computed in two different ways: (1) as the integral of the power spectral density from a time-averaged result and (2) as the peak value observed in a frequency range. Note that (1) typically gives the most pessimistic values. Thus these are used in the subsequent analysis and we can have some confidence that the results will be ergodic in the sense that the presence of intermittent strong signals is not likely to affect the findings here. Also, not that these results have been computed with respect to the antenna terminals, but including in some cases cable loss. The assumed cable loss is that expected from 150 m of RG-58, including frequency dependence. The specific formula for cable loss assumed here is:

$$L = \left(0.0014 f_{\mathrm{MHz}} + 0.05\right) l_{\mathrm{m}} \text{ [dB]} \tag{1}$$

where f_{MHz} is frequency in MHz, l_{m} is length in meters, and the result is in dB.

Table 1 shows that the total RFI power expected at the antenna terminals is about −54 dBm. Assuming that Galactic noise is significantly less (it is, as we will soon find) then this is approximately the total power successfully transferred to the FEE. *However, this should not be used as the basis for determining necessary linearity specifications for the FEE*, as it is the *system* linearity specifications – difficult to anticipate without doing a complete analysis as is done later in this document – which are relevant.

Table 2 summarizes the Memo 84 results for the noise P_a, defined as the combination of Galactic and FEE-generated noise referenced to the antenna terminals, in some cases with the (frequency-variable) cable loss added in order to capture the effect of the non-spectrally-white noise delivered to the ADC. For the purpose of this analysis it is assumed that the noise is Galactic-noise dominated over the entire frequency range considered. More likely, the ratio of Galactic noise to FEE noise is large only towards the center of the passband and probably drops to a factor of 4 or so at 20 MHz and 80 MHz. However, the analysis in this document depends primarily on the observed total noise power (P_a) and is not sensitive to the ratio of Galactic to FEE noise in this result, although clearly the latter should be as large as possible for sensitivity reasons.

Next, note that the total noise power referenced to the antenna terminals is $P_a = -86$ dBm. The ratio of total RFI power to total noise referenced to the antenna terminals is therefore about 32 dB at this site, confirming our previous assertion that the FEE sees a strongly RFI-dominated input. Results from RFI measurement attempts at other sites suggest that this ratio could potentially be larger at other sites.

Also shown in Figure 2 is the column "P_a Equal.", which indicates the gain that would be applied to the indicated frequency bands if it were desired to equalize (i.e., make spectrally flat) the noise power. In a receiver with limited dynamic range, this would be useful in that it would tend to make the ratio of P_a to digitizer quantization noise (which is nominally spectrally flat) uniform over the passband. However, note that the relative gain required is +3 dB in 13–23 MHz, +6 dB in 42–54 MHz, and relatively small in between. Given that even the extreme values in this range are small compared to the overall dynamic range required for the receiver to deal effectively with the RFI (i.e., 10's of dB), there is probably not much value in implementing this equalization over the range 13–54 MHz. The relative gain requirement jumps to +16 dB in 54-88 MHz, so there may be benefit to boosting gain over this portion of the passband.

Frequency Range [MHz]	Sum [dBm]	Peak [dBm]	Max [dBm]	Remarks
13-23	−69	−82	−69	At antenna terminals, cable loss added
23-28	−94	−88	−88	
28-38	−123	−110	−110	
38-42	−99	−98	−98	
42-54		−114	−114	
54-88	−105	−107	−105	
88-108	−102	−111	−102	
108-113	−131	−139	−131	
13-113	−54		−54	At antenna terminals
13-113	−69		−69	At antenna terminals, cable loss added
13-108	−69			
13-23 down 6 dB	−75			
13-23 down 10 dB	−79			
13-23 down 25 dB	−90			
13-23 down 31 dB, 23-28 down 6 dB	−94			
Tight filter on 28-54	−99			

Table 1: Summary of RFI from Memo 84. “Sum” is the integral of RFI power spectral density, from Memo 84 Table 7, over the indicated frequency range/response. “Peak” is peak value in indicated range from Memo 84 Figure 6. “Max” is the maximum value from the “Sum” and “Peak” columns. Where cable loss is indicated, 150 m of RG-58, including non-constant (monotonically decreasing) frequency response, is assumed (see text). The lower portion of the table indicates results for various candidate ARX bandpass shapes.

Frequency Range [MHz]	P_a [dBm]	P_a [dBm/Hz]	P_a Equal. [dB]	Remarks
13-23	−109	−179	+2	At antenna terminals, cable loss added
23-28	−110	−177	0	
28-38	−108	−178	+1	
38-42	−114	−180	+3	
42-54	−112	−183	+6	
54-88	−118	−193	+16	
88-108	−126	−199		
108-113	−135	−202		
13-113	−86			At antenna terminals
13-113	−103			At antenna terminals, cable loss added
13-108	−103			
13-23 down 6 dB	−104			
13-23 down 25 dB	−105			
13-23 down 31 dB, 23-28 down 6 dB	−105			
Tight filter on 28-54	−106			

Table 2: Summary of noise P_a delivered by the active antenna from Memo 84. Results expressed in terms of total power in band [dBm], and mean power spectral density over the band [dB(mW/Hz), abbreviated “dBm/Hz”]. Where cable loss is indicated, 150 m of RG-58, including non-constant (monotonically decreasing) frequency response, is assumed (see text). “P_a Equal.” indicates the gain that would be applied if it were intended to equalize the P_a across the span 13–88 MHz. The lower portion of the table indicates results for various candidate ARX bandpass shapes.

3 Analog Signal Path Requirements

In this section, some analog signal path (i.e., FEE + cable + ARX, as described previously) requirements are developed following the general strategy described in [4]. An important consideration in this analysis is the DIG specifications. In this document we assume an DIG with an ADC having the specifications of the Analog Devices AD9211-200 evaluation board described in LWA Memo 112 [2]. The relevant parameters and design constraints are shown in Table 3. Given this information, we can compute the required number of bits:

$$N_b \geq 1.67 \log_{10} \frac{P_t \ \gamma_r}{P_a \ \delta_r} \tag{2}$$

where P_t is the sum of the total RFI power plus P_a, which (as pointed out above) is approximately equal to the total RFI power. Also, the minimum required gain in the analog signal path G_{min}, and the maximum allowed gain G_r, is:

$$G_{min} = \frac{P_Q \ \gamma_q}{P_a} \text{ , and} \tag{3}$$

$$G_r = \frac{P_{clip} \ \delta_r}{P_t} \text{ , respectively.} \tag{4}$$

Note that G_r is in some sense the optimal gain, as this results in the greatest ratio of external noise to quantization noise, referenced to the ADC input. G_{min} is the minimum gain for which this ratio is acceptable, and may be desired if RFI for whatever reason turns out to be higher than expected. Reasonable analog signal path designs have $G_r \geq G_{min}$. If G_r/G_{min} is greater than a few dB, then a flexible trade-off can be implemented through gain control.

A summary of the analysis is provided in Table 4 and discussed in the following sections.

3.1 Configuration 1: Maximum Bandwidth, Flat Response

As shown in Table 4, an analog signal path that is "wide open" – i.e., one with no significant filtering other than that required for anti-aliasing – results in $N_b = 9$ bits, $G_{min} = +62$ dB, and $G_r = +62$ dB (gain in both cases being expressed as the sum of the FEE and ARX gains, excluding cable loss, as indicated in Table 4). The AD9211 ADC has 10 bits, which appears to meet this requirement although it is risky since the effective number of bits (ENOB) of any ADC is typically 1–2 dB less than it's actual number of bits. The complete analog signal path (including cable loss) requires an overall gain of about +47 dB at 38 MHz (as always, assuming 150 m of RG-58-type cable), and variable gain would probably be pointless.

Additional implications are shown in Table 5. Note that the resulting ratio of P_a/P_Q is greater than or equal to γ_q in all bands, except for 54-88 MHz, for which the level drops to 0 dB – not acceptable. Also shown in Table 5 is a rough estimate of the ratio of ADC-generated spurious to P_Q on a power spectral density basis, in this case assuming 10 kHz channels. Assuming spurious levels peaking at −62 dBFS (the extreme worst case noted in [2]), we see that ADC spurious will be plainly visible assuming the expected levels of RFI are available to stimulate it. It should also be pointed out that this is independent of intermodulation generated in the analog signal path, which might

Parameter	Value	Definition
P_{clip}	+3 dBm	ADC full scale
P_Q	−51 dBm	ADC quantization noise power (50Ω SE), referenced to ADC input
γ_q	+10 dB	Desired ratio of P_a (referenced to ADC input) to P_Q
δ_r	−10 dB	Maximum acceptable input power relative to P_{clip}

Table 3: Assumed analog-to-digital converter (ADC) specifications and associated design constraints.

Freq Range / Resp.	P_t	P_{ext}	N_b	G_{min}	G_r
13–113 MHz	−69 dBm	−103 dBm	9.0	+62 dB	+62 dB
13–108 MHz, 13–23 MHz down by 6 dB	−75 dBm	−104 dBm	8.2	+63 dB	+68 dB
13–108 MHz, 13–23 MHz down by 25 dB	−90 dBm	−105 dBm	5.9	+64 dB	+83 dB
23–54 MHz	−99 dBm	−106 dBm	4.5	+65 dB	+92 dB

Table 4: Design implications (N_b,G_{min},G_r) corresponding to various choices of frequency range and response. Gain here defined is defined from antenna terminals to ADC input, excluding cable.

also be prominent. However, the analog intermodulation performance is an issue which is extremely difficult to assess in a reasonable way without a site-specific simulation analysis of the type described in [4]. Once the spurious frequencies and levels are obtained, however, the assessment is pretty much the same; i.e., a determination of spurious-to-P_a ratio given a specified channel bandwidth.

Configuration 1 is not recommended. The primary reasons are (1) this system would have so little headroom that a temporary increase in RFI (or, stronger RFI as the result of being located at a different site) would significantly degrade the system performance (spurious levels in particular), and (2) unacceptable P_a/P_Q in the 54–88 MHz range. However, it is clear from Table 1 that the total RFI is dominated by contributions from the low end of the passband, 13–23 MHz, and to a lesser extent, 23–28 MHz. Thus, we now consider some options that attempt to exploit this finding to achieve improved performance and flexibility.

3.2 Configuration 2: 13–88 MHz, 13–23 MHz Down by 6 dB

In this configuration we simply attenuate the 13–23 MHz band by 6 dB. The details of how this is done are not relevant to the analysis; essentially we are discussing here any bandpass shape that reduces the total RFI power in the 13-23 MHz band by 6 dB. The implications of this approach are shown in Table 4 and Table 6. Note that N_b decreases from 9 to 8.2 bits, G_r/G_{min} increases from 0 dB to 5 dB, and that a useful level of P_a/P_Q is maintained even in the attenuated 13–23 MHz band. P_a/P_Q in the 54–88 MHz band is now perhaps just barely usable, but still much less than the 10 dB or so desired. Unfortunately, the additional gain is not sufficient to significantly improve the ADC spurious situation. This configuration, while superior to Configuration 1, is still a bit risky.

3.3 Configuration 3: 13–88 MHz, 13-23 MHz Down by 25 dB

In this approach we continue to attenuate the 13-23 MHz band until its contribution is roughly equal to that of the remaining bands. The results are shown in Table 4 and Table 7. Note that N_b decreases to 5.9 bits, G_r/G_{min} increases to 19 dB, and that P_a/P_Q is at least +10 dB (reasonable) even in the heavily-attenuated 13–23 MHz band. The ADC spurious is reduced, although still onerous especially in the lowest (13–23 MHz) and highest (54–88 MHz) bands.

3.4 Configuration 4: 28–54 MHz

Finally, we consider an configuration in which we tightly limit the bandpass to the central region of 28–54 MHz, and completely exclude the troublesome bands below 23 MHz and above 54 MHz where most of the RFI power lies.[1] The results are shown in Table 4 and Table 8. Note that N_b decreases now to just 4.5 bits, G_r/G_{min} increases to 27 dB, and P_a/P_Q is pleasantly large across the entire band. Furthermore, ADC spurious is now well below external noise, which is not achieved in any other configuration. If for whatever reason strong RFI were to appear in this band, the gain

[1]It is no coincidence that this corresponds pretty closely to the ETA frequency range.

Band [MHz]	Gain [dB]	P_a/P_Q [dB]	Spurious/P_a [dB(mW/10kHz)]
13–23	62	14	18
23–28	62	16	16
28–38	62	14	17
38–42	62	13	19
42–54	62	10	22
54–88	62	0	32

Table 5: Noise and ADC spurious ratios for **13–108 MHz bandpass, 62 dB (max) gain, flat response**. Assuming an ADC spurious level of −62 dBFS in the indicated bandwidth.

Band [MHz]	Gain [dB]	P_a/P_Q [dB]	Spurious/P_a [dB(mW/10kHz)]
13–23	62	14	18
23–28	68	22	10
28–38	68	20	11
38–42	68	19	13
42–54	68	16	16
54–88	68	6	26

Table 6: Noise and ADC spurious ratios for **13–108 MHz bandpass, 68 dB (max) gain, 13-23 MHz down by 6 dB**. Assuming an ADC spurious level of −62 dBFS in the indicated bandwidth.

could be decreased by at least 8 dB to accommodate it with the only impact being to bring the spurious-to-external noise ratio to about zero. Should strong RFI emerge in-band, the gain could be reduced another 19 dB or so without significantly affecting any other parameter, including sensitivity – demonstrating the value of gain control. This configuration is worth having for the simple reason that it provides the ultimate "fallback position" in the sense that this configuration is the last hope for observing if every other configuration is, for whatever reason, impossible due to strong RFI.

3.5 Conclusions

It is clear from the preceding analysis in this section that no one configuration is optimal, and conclude that the analog signal path should have a *reconfigurable bandpass* – probably implemented in the ARX – capable of producing Configurations 2 through 4 above, preferably with intermediate versions of these configurations. Analog signal path gain should be variable over a range of about 30 dB (that is, mid-frequency gain minus cable loss should be between 62 dB and 92 dB) in order

Band [MHz]	Gain [dB]	P_a/P_Q [dB]	Spurious/P_a [dB(mW/10kHz)]
13–23	58	10	22
23–28	83	37	−5
28–38	83	35	−4
38–42	83	34	−2
42–54	83	31	1
54–88	83	21	11

Table 7: Noise and ADC spurious ratios for **13–108 MHz bandpass, 83 dB (max) gain, 13-23 MHz down by 25 dB**. Assuming an ADC spurious level of −62 dBFS in the indicated bandwidth.

Band [MHz]	Gain [dB]	P_a/P_Q [dB]	Spurious/P_a [dB(mW/10kHz)]
28–38	92	44	-13
38–42	92	43	-11
42–54	92	40	-8

Table 8: Noise and ADC spurious ratios for **28–54 MHz bandpass, 92 dB (max) gain**. Assuming an ADC spurious level of -62 dBFS in the indicated bandwidth.

to accommodate the anticipated range of observing requirements and constraints. Keeping in mind the likelihood of encountering sites that are worse than or better than the VLA site, it may be worthwhile to consider increasing the range of gain another 5 dB upward and another 10 dB or so downward in order to accommodate the broadest possible range of situations, including situations where the RFI must be suppressed even at the expense of Galactic noise-limited sensitivity. This broader range corresponds to gain in the range 52–97 dB; i.e., a 45 dB span.

4 Derived ARX Requirements

We are now in a position to determine linearity and noise figure requirements for the analog signal path. In the preceding section it was determined that the overall gain (including FEE and ARX, but excluding cable loss) should be in the range 52–97 dB. It was also determined that the maximum total power expected at the antenna terminals was −54 dBm. Setting the system input 1-dB compression point (P1dB) be 15 dB higher than this we obtain −39 dBm. Using the rule of thumb that third-order intercept point (IP3) is 10-15 dB above the 1-dB compression point, we obtain a conservative system input IP3 (IIP3) requirement of −24 dBm. Note that this applies to the "full bandwidth" configuration ("Configuration 1" from the previous section), and one might consider reducing this for other configurations. However, since most of the bandpass limiting is likely to occur late in the signal path (i.e., in the ARX), it is reasonably conservative and probably wise to assume that the system will need to meet the "Configuration 1" system linearity requirements regardless of what configuration(s) are actually implemented.

With this in mind, Table 9 shows some options assuming four possible choices for the FEE subsystem. The resulting minimum and maximum gain are shown, as well as the noise figure required to maintain the system noise temperature at a level reasonably close to that provided by the FEE. Also shown is the stage IIP3 required to achieve system IIP3 of −22 dBm (2 dB greater than the requirement derived in the previous paragraph) and −12 dBm (approximately equal to the maximum IIP3 that can be obtained by all four FEEs considered). The results obtained using the higher value also convey some idea of what is required to significantly increase linearity – for example, note that the required stage IIP3 does not necessarily increase linearly (in dB) with increasing system IIP3.

Table 9 indicates that the required IIP3 of the ARX is in the range −13 to +25 dBm, depending on which FEE is selected and the desired system IIP3. It should be emphasized that here IIP3 is really being used as a surrogate for 1 dB compression point, which as noted above is typically 10–15 dB lower.[2] Thus, the required input 1-dB compression point is in the range −28 to +10 dBm; once again depending on FEE selection and desired system linearity. ARX noise figure and gain requirements are similarly variable. However the values shown in Table 9 can be used in combination with the variable bandlimiting capability recommended in the previous section can be used as design guidance in developing the FEE and ARX.

[2]A caveat here is that certain classes of operational amplifier ("opamp") based designs which might be considered for use in the ARX can in some cases achieve IP3-to-compression point ratios much greater than this, albeit with noise figures which are typically very high.

	FEE Options				Stage Characteristics					
	G	T	IIP3	IP1dB	G_lo	G_hi	F	IIP3_lo	IIP3_hi	T_sys
Device	[dB]	[K]	[dBm]	[dBm]	[dB]	[dB]	[dB]	[dBm]	[dBm]	[K]
Hicks (1)	24	250	7.5	-5.0	28	73	3	-13	-3	322
RTA (2)	35	250	-2.3	-18.8	17	62	7	-2	8.5	267
RTA+ (3)	47	250	-10.3	no data	5	50	10	5	25	253
120K (4)	32	120	-6.0	-14.0	20	65	7	-5	6	148

All calculations performed at 38 MHz
"G_lo" is gain required between cable and digitizer input in order to achieve an overall gain (antenna terminals to digitzer input) of 37 dB
"G_hi" is gain required between cable and digitizer input in order to achieve an overall gain (antenna terminals to digitzer input) of 82 dB
(With respect to the text: The above numbers correspond to gain *excluding cable loss* of 52 and 97 dB respectively)
(**Assumed cable loss is 15 dB**, which corresponds roughly to 150 m of RG-58 at 38 MHz)
"F" is noise figure required for the stage between cable and digitizer input in order to achieve "T_sys" (see below)
"IIP3_lo" is the IIP3 required from the stage between cable and digitizer input in order to achieve **system IIP3 = -22 dBm**
"IIP3_hi" is the IIP3 required from the stage between cable and digitizer input in order to achieve **system IIP3 = -12 dBm**
"T_sys" is the overall system temperature, not including external / galactic noise

(1) LWA Memo 19
(2) LWA Memo 120, modified to insert BPF between gain stages. Memo 120 specs were G=36 dB, T=250K, IIP3=-1.8 dBm, IP1dB=-18.3 dBm
(3) LWA Memo 120, modified to insert BPF between gain stages and changing final gain stage to a GALI-74 to increase gain
(4) LWA Memo 81

Table 9: RF Options. Note the columns labeled "Stage Characteristics" are referring to the ARX.

5 Document History

- This is Version 2, which is the second version released. Corrected errors resulting from incorrect cable loss model; thanks to Aaron Kerkhoff for pointing out the error. The correct RG-58 model has considerably more loss assumed previously. Version 1 of this document is still relevant as an example of the results for cable with significantly lower loss.

References

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