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**Analog Signal Path Analysis
for Fiber-Connected Antennas of LWA352**

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2020 April 7

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I. INTRODUCTION

The OVRO LWA is subject to strong RFI at frequencies outside the nominal observing band, 20-85 MHz. This includes FM radio (88-108 MHz) and HF communication (<20 MHz). Intermodulation among these RFI signals can produce undesired signals in the observing band.

The current design of the signal path includes strong filtering of the out-of-band signals, but that filtering occurs after the front end electronics (FEE, 36 dB gain) and after the first amplifier stage of the analog receiver (ARX, 23 dB). For the fiber-coupled antennas, it is also after the optical link. These amplifiers and the optical link are not perfectly linear, so they can produce intermodulation. They are designed to tolerate the known RFI, but some intermodulation still occurs. To minimize this residual intermodulation, signal levels at these components should be small. On the other hand, the signal path must have sufficient gain, properly distributed, to avoid having downstream components add significantly to the system noise temperature.

This memo provides a quantitative analysis of the trade-off between intermodulation and noise temperature. It concentrates on the fiber-connected antennas. The coax-connected antennas have a similar issue, but whereas the coax cable can be considered completely linear there is less intermodulation and the ARX has sufficient gain to keep the noise impact small, even for the longest cables.

II. METHODS

Figure 1 is a block diagram of the signal path for a fiber-connected antenna in the current design. There are two attenuators, AT0 and AT1, whose values can be chosen to control the distribution of gain. If they are both at their minimum values (0 dB and 1.3 dB respectively), the total net gain available is 101.7 dB. The total net gain needed to amplify the minimum system noise (905K) to 10 times the digitizer's quantization noise (49.6 MK for 8b digitization)¹ is 57.4 dB. Therefore, up to 44.3 dB of attenuation could be used in AT0 and AT1 if the components between the FEE and the digitizer contribute no additional noise or distortion. (Internal details

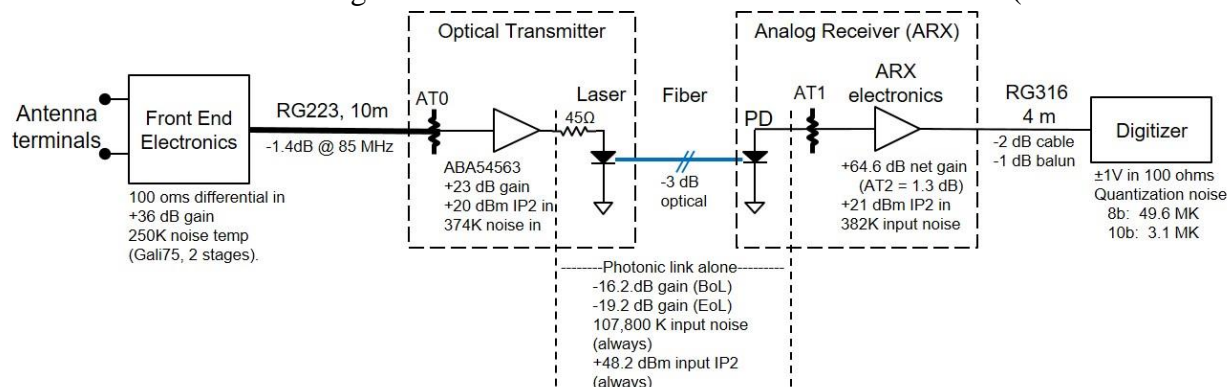


Figure 1. Block diagram of the signal path for a fiber-coupled antenna.

¹ The minimum available power spectral density in the observing band (due to sky noise) is 655K at 85 MHz, and the FEE noise temperature is 250K [1]. The digitizer's quantization noise (49.6 MK) is for a full-scale range of 2V p-p in 100 ohms, 196 MHz sampling, and 7.8 ENOB. For 10b quantization (9.8 ENOB), the noise is 3.1 MK.

of the ARX electronics are not shown in Fig. 1 but are discussed below.)

Given the gain, noise, and distortion characteristics of each element of the signal path, along with the available power from the antenna in the observing band and the RFI bands, the performance of the cascaded elements can be analyzed. Such an analysis is shown in the spreadsheet of Table 1 for one set of attenuations AT0 and AT1 [2]. Results over a range of attenuation values and for several different cases are presented in Section IV. There are 14 elements in the cascade, numbered from output (digitizer) to input (FEE). Elements 2-8 correspond to the "ARX electronics" of Fig. 1. For each element, the basis of its parameters and any assumptions in its modeling are discussed separately in Section III.

Power levels at the antenna terminals are calculated in the spreadsheet of Table 2 from the measurements described in [3] and plotted in Figure 2. Here P_{low} is the total power in 0-20 MHz (low RFI band); P_{obs} is the total power in 20-85 MHz (observing band), and P_{high} is the total power in 88-165 MHz. Measurements of the spectrum of signal 160B were made at the end of the coax cable delivering the FEE output to the LWA signal processing shelter. A spectrum was recorded every 15 min for 12.5 hours. Antenna 160 is one of the closest to the shelter, with a cable length of 37.5 m. The spreadsheet adjusts for the cable attenuation and FEE gain in order to estimate the power in each band at the FEE input.

The intermodulation analysis here assumes that the dominant distortion is second-order. We can get intermodulation products in the observing band as the second harmonic or frequency sum of signals in the low RFI band (0-20 MHz), and as the frequency difference between high band (>88 MHz) and low band signals or between widely-separated high-band signals. We use the second-order intercept power (IP2, I_2) of each element separately to estimate its contribution to the intermodulation via

$$M_2 = P_1 P_2 / I_2$$

where P_1 and P_2 are the powers of the two RFI signals (possibly the same signal) and M_2 is the intermodulation product power; all values apply at the output of the element. This formula is accurate for sinusoidal signals provided that $P_1 \ll I_2$ and $P_2 \ll I_2$. In practice, the RFI is more complicated than one or two sinusoids, but if we take P_1 and P_2 to be the total RFI power in each of two sub-bands, then M_2 is the total intermodulation power in the sum or difference sub-band. To estimate the worst case, we base P_1 on the maximum observed power in the low band (-66.71 dBm, Table 2), since power in that band is highly time variable (Fig. 2); and P_2 on the typical power in the high band (-60.79 dBm, Table 2). Since only the product $P_1 P_2$ is important, the antenna RFI power is represented by their geometric mean (-63.75 dBm) in the last line of Table 1. The resulting intermodulation power at the signal path output (digitizer) can then be compared against the total observing band power (sky signal plus receiver noise) there, obtained by multiplying the observing band power at the antenna (-91.08 dBm, Table 2) by the total gain. The intermodulation-to-desired power ratio (IM ratio) at the input of each element is calculated in the last column of Table 1.

Note that this approach does not allow estimating the intermodulation power in any narrow channel, and the spectrum of the desired sky signal is far from flat. For both reasons, the IM ratio in some channels can be much larger than the estimate, and in others much lower.

III. SIGNAL PATH ELEMENT MODELS AND PARAMETERS

Front End Electronics (FEE), element #14. This consists of two stages of gain using 3 Mini Circuits Gali-75 amplifiers, where the first stage is differential [1]. The total gain is 36 dB and the noise temperature is 250K. The Gali-75 data sheet does not specify I_2 ; it gives only I_3 (third-order intercept power). A survey of small RF amplifier devices shows that when I_2 and I_3

are both specified, I_2 is 8 dB to 9 dB larger than I_3 , so we adopt $I_2 = 10^{0.8} I_3$ (8 dB larger) as our estimate. This gives $I_2 = 46$ dBm at the output of the FEE.

FEE to Optical Transmitter Coax (#13) and all other passive elements (#12, 9, 7, 6, 4, 2). Passive elements are taken to be perfectly linear ($I_2 = \infty$) and to be at a physical temperature of $T_a = 300$ K, so their noise temperatures are $(g - 1)T_a$ for gain $g < 1$. The FEE output coax is assumed to be 10m of RG223. Since it is short and its loss is small, the loss at 85 MHz (1.4 dB) is assumed to be sufficiently accurate at all frequencies.

Optical link (#10). The current design uses a YiGuDian laser diode (PN GLD-PSA2-D3160B-2GR) and photodiode (PN GPD-PSA1-55BR or similar). A pair of these devices was tested recently [4], and we rely on those results for the distortion parameters at the link output, $I_2 = +32$ dBm and $I_3 = -4.5$ dBm (where only I_2 is used in this analysis) and for the output noise temperature (2600K, corresponding to 108 kK at its input with the calculated gain). However, the individual devices tested were purchased in 2018 and they seemed to have responsivities lower than specified on their data sheets. For estimating the gain, we assume that new devices will conform to the data sheets and that the gain is given by

$$G = [2 \alpha \beta G_{opt} R_0 / (R_0 + R_m + R_L)]^2$$

where α is the laser responsivity (0.2 W/A minimum, per data sheet [5]²), β is the photodiode responsivity (0.90 A/W typical, per data sheet [6]), G_{opt} is the optical power gain (loss in fiber, assumed to be -3 dB in the field, including splice and connector losses), $R_0 = 50$ ohms is the source and load resistance, R_L is the laser's RF resistance (5 ohms, from [4]), and R_m (45 ohms) is the value of the matching resistor in series with the laser diode (see Fig. 1). It would be possible to operate with $R_m = 0$, but that would require the driver amplifier to deliver higher output current at the same input power than it would deliver to 50 ohms, in which case we could not rely on the gain and distortion parameters on the amplifier's data sheet.

We assume that the laser will be operated at constant bias current, set to produce 3 mW optical power at installation. Laser diodes are known to degrade over time, with optical power at a given current decreasing, and responsivity decreasing nearly in proportion. Performance near laser end-of-life is discussed in Section IV.

ARX electronics (#8 through #3). An ARX channel includes three stages of amplification (each using an ABA54563 device with 23 dB gain and 374K input noise, see below), filtering to select the observing band, and two digitally-controlled attenuators (AT1 and AT2, 0-31.5 dB in 0.5 dB steps, but AT1 is considered separately, see Fig. 1). There are switches for filter selection (insertion loss 1.6 dB). The attenuators have insertion loss of 1.3 dB [7] when set to "0.0 dB".

The filters have an insertion loss of approximately 1.5 dB in the observing band (here modeled as independent of which filter is selected, but actually 1 to 2 dB depending on the selection) and 30 dB at the frequencies of out-of-band RFI.

Although the ARX has a second digitally-controlled attenuator just before the final amplifier (AT2), the analysis here concentrates on AT0 (before the optical link) and AT1 (at the ARX input. As will be shown in Section IV, setting AT2 at greater than its minimum attenuation

² Actually, the laser responsivity α is not directly specified on the data sheet. It gives the minimum optical power as 2 mW at bias current 20 mA above threshold, but that is for the lowest-power version of the family covered by the data sheet. For PN GLD-PSA2-D3140B-2GR, the minimum optical power is 4.0 mW for the same bias current, and this gives the 0.2 W/A responsivity used here. We actually intend to use PN GLD-PSA2-D3160B-2GR, for which the minimum optical power is 6.0 mW, but this is not covered by the data sheet. We already have 220 of these, purchased for DSA110, and the factory test data shows that 6 mW is achieved at 30 mA above threshold, giving the same responsivity as 4 mW devices. We have not yet tested these ourselves.

increases the system noise temperature without reducing intermodulation. Its main use in LWA operation will be to prevent ADC saturation when the power in the observing band (not the RFI bands) is much higher than normal, such as during an intense solar flare or with strong in-band RFI. In such cases, an increase in noise temperature is acceptable.

Amplifiers (#11, 8, 5, 3). In the current design, the laser driver amplifier and all ARX amplifiers use the ABA56463 device³. We use the gain (23 dB) and noise figure (3.6 dB, 374K) from its data sheet [8]. The data sheet does not give I_2 but rather only I_3 , so we estimate $I_2 = 10^{0.8} I_3$ (8 dB larger), as we did for the Gali-75 in the FEE. This gives $I_2 = 44$ dBm with respect to the output.

ARX to Digitizer (#13). The ARX output will be connected to the digitizer via two 2m lengths of RG316 coax with a bulkhead connector, with estimated loss of 2 dB at 85 MHz. The digitizer includes a transformer balun with about 1 dB loss before the signal reaches the ADC chip. We model all of this as a 3 dB loss.

Digitizer (#14). Two ADC chips are under consideration for use in the digitizer, providing 8b and 10b quantization (7.8 and 9.8 effective bits or ENOB), respectively. An ADC adds quantization noise to the signal, and we use the theoretical value calculated from the ENOB. This agrees well with the SNR specification on the data sheets. This noise is spread uniformly over the Nyquist bandwidth, 98 MHz for 196 MHz sampling rate. This gives the noise spectral density, which we express as temperature: 49.6 MK for 8b and 3.1 MK for 10b. Table 1 uses the 8b digitizer noise. Non-ideal ADCs can also have spurious responses to strong narrow-band signals; those are neglected here.

IV. OPTIMIZATION AND TRADEOFFS

In Table 1, the columns whose headings are in red font are results calculated in the spreadsheet, and most other data are inputs. For the gain and noise cascade, the calculation starts at the output (digitizer) and works toward the input. For the intermodulation cascade, it starts at the input; the intermodulation power generated at each stage is added to that from previous stages and propagated to later stages.

Table 1 shows that when $AT_0 = -22$ dB and $AT_1 = -9.3$ dB the ratio of intermodulation power to desired power in the observing band (IM ratio) is about -40 dB at the digitizer (last column). At the same time, the receiver temperature at the antenna terminals is 341K, which is 91K more than the FEE contributes, or an increase of 10% in the 85 MHz system temperature. This is a good choice of settings. Other choices can be explored in the underlying spreadsheet [2].

To examine this in more detail, a Matlab function was written to perform the same calculations over a range of attenuator settings. The code is listed in Appendix A [8]. Results from this code have been checked against the spreadsheet and found to agree.

Using the same parameters as Table 1 except for varying AT_0 and AT_1 produces the results plotted in Figure 3. AT_2 is fixed at its minimum value, 1.3 dB. Total input noise temperature T_n (receiver temperature) is plotted in red and the total output intermodulation ratio is plotted in blue. This shows the tradeoff between low intermodulation and low noise temperature. If T_n is limited to ≤ 341 K (10% system temperature increase at 85 MHz), the smallest available intermodulation ratio is -40.4 dB, and this occurs at $AT_0=22.2$ dB and $AT_1=9.3$ dB. This is the case shown in Table 1.

³ ABA54563 was originally made by Avago, which was purchased by Broadcom. It is no longer manufactured, but a large inventory is available from distributors.

To see the effect of varying AT2, we consider trying to keep the total gain constant by setting $AT2 \cdot AT1 \cdot AT0 = 44.28$ dB, expect that AT2 is kept below 11.3 dB. The result is plotted in Figure 4. There is no discernable change in the IM ratio, but T_n is slightly larger at most settings. The smallest IM ratio available with $T_n \leq 341$ K is now -39.9 dBm, 0.5 dB worse.

Examining the last column of Table 1 from bottom to top shows that most of the increase in IM ratio occurs in the laser driver amplifier, although additional IM occurs in the optical link and in the ARX stage 1 amplifier. Among all the active components, the laser driver has the highest RFI power at its output (see column "RFI in" in Table 1). Furthermore, attenuator AT0, which is just ahead of that 23-dB-gain amplifier, has an optimum value of 22 dB; thus there is a net gain of only 1 dB ahead of the laser.

We therefore consider a design change in which the laser driver amplifier is eliminated, so it cannot produce any intermodulation. (This can easily be done in the model by setting the gain of that amplifier to unity and its IP2 to infinity.) The result is plotted in Figure 5. For $T_n \leq 341$ K, the lowest available IM ratio is now -43.2 dB, 2.8 dB better. This occurs at $AT0 = 0$ dB and $AT1 = 9.3$ dB. It looks like we could do slightly better with a few dB of gain ahead of the laser, provided that it adds no intermodulation. A low-gain, high power amplifier would be best. However, with no amplifier, the entire $T_n \leq 341$ K region is in the lower left corner of Fig. 5, where both attenuators have small values, so that we have little gain margin. If some active gains are less than usual (including laser wear-out) or losses are more than usual (including excess optical loss), there is not much room to compensate by reducing attenuation. Figure 6 shows the result when AT2 is used to keep the total gain constant when possible; the optimum result is again worse, so it remains true that AT2 should be kept at its minimum value.

Now consider what happens as the laser degrades over time. We assume that only the responsivity, and hence the link gain, degrades. If the DC bias current and RF drive current are kept constant, the distortion measure I_2 (at the output) should remain constant. The output noise temperature is also assumed constant, although actually it should decrease as optical power declines because it is dominated by shot noise. The noise temperature at the input then increases because of the decreased gain. When the laser degrades sufficiently it will have to be replaced; this is its "end of life" (EoL). We want adequate performance until then, so we need to define EoL. Somewhat arbitrarily, we consider the laser at EoL when optical power is 0.707 of its initial value for the same DC bias current. We assume that the responsivity has declined by the same factor⁴, which means that the link gain has declined by 0.50 (-3.0 dB) to -19.2 dB and its input noise temperature becomes 215 kK.. Figures 7 and 8 show the situation at EoL for the cases where the driver amplifier is included and omitted, respectively. For both plots, AT2 is at its minimum attenuation. From Fig. 7, the lowest available IM ratio for $T_n \leq 341$ K is -39.8 dBm, vs. -40.5 dBm with a new laser (Fig. 3). From Fig. 8, $T_n \leq 341$ K is not achievable at all, even when both attenuators are at minimum; there is not enough total gain. We can achieve about 360K with the IM ratio at about -40.5 dBm, but there is no gain margin; cf. Fig. 5.

Finally, consider the situation for 10b ADCs. This makes the quantization noise smaller by a factor of 16 (3.1 MK vs. 49.6 MK), so in principle the gain can be lower for the same input noise temperature, allowing IM to be lower. Results are shown in Figures 9 and 10 for the cases where the driver amplifier is included and omitted, respectively. Both plots are for beginning of laser life and with AT2 at minimum. Comparing Figs. 9 and 3 (with driver) and 10 and 5

⁴ This should be true if the injection current, or bias current minus threshold current, is kept constant. But threshold current also increases over time, so keeping total bias current constant means that the decrease in responsivity will be larger a EoL.

(without), we see that very little improvement is obtained relative to the 8b ADC. That is because the total gain is more than 80 dB (Table 1), so that the 8b ADC noise contributes less than 0.5 K to the receiver temperature.

The results from this section are summarized in Table 3.

Table 3: Summary

Driver	Laser	ADC	Figure	Optimum Settings [a]			
				AT0, dB	AT1, dB	Tn, K	IM/Obs, dB
Included	BoL	8b	3	22	9.3	341	-40.5
Included	EoL	8b	7	20.8	7.3	341	-39.8
Included	BoL	10b	9	20.3	9.8	341	-40.5
Omitted	BoL	8b	5	0	9.3	341	-43.3
Omitted	EoL	8b	8	0	1.3	360	-41.4
Omitted	BoL	10b	10	0	9.8	341	-43.4

[a] For all these cases, AT2 is at minimum attenuation (1.3 dB).

V. DISCUSSION

This analysis must be considered approximate because it involves multiple assumptions that might be inaccurate. First, we do not actually have IP2 data or specifications for the amplifiers; those values are extrapolated from the specified IP3 values. Second, the noise and distortion performance of the optical link are based on measurements of only one LD-PD pair, and those measurements contain some inconsistencies [4].

Also, the analysis here is based on what I'm calling the "current design," depicted in Fig. 1. At this time, changes to the design are not precluded. One such change, eliminating the laser driver amplifier, was explored in Section IV. Other changes can be considered, including more filtering of RFI prior to the optical link.

In our model and at the expected RFI levels, the IM ratio due to the FEE alone (Gali-75 amplifier) is -46 dB (Table 1). We cannot do better than this no matter what we do with the rest of the signal path; it would be necessary to modify the FEEs. Changes to the FEEs are now considered impractical since all of those needed for LWA352 are already on hand and most are installed in the field.

We would like to know how long a new laser will last before reaching its end of life, as we have defined it. We have no such data for our lasers, but we know that lifetime declines exponentially with operating temperature. Data on other lasers [10] suggests that ours should have lifetimes of at least 4 years at 60C. Our average operating temperature is likely to be much lower.

In spite of these limitations, some conclusions can be stated with high confidence:

- An intermodulation ratio of about -40 dB at the digitizer should be achievable without increasing the system noise temperature by more than 91K (10% increase at 85 MHz vs. everything after the FEE being perfect).
- There is no advantage to 10b over 8b quantization in the digitizer.
- In the current design, the laser driver amplifier is problematic. Even with optimum attenuations at AT0 and AT1, it has larger RFI power at its output than any other active element in the signal chain and it contributes the most intermodulation. On the other hand, if it is omitted then there is little margin available in total gain, especially at the laser's end of life. A different amplifier, with less gain and higher IP2, would be desirable.

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Table 1: Gain, Noise, and Intermodulation Analysis

Element		Gain & Noise: Out to In (read down)				Intermodulation: In to Out (read up)						
		G	Gtot	T	Ttot	Obs in	RFI in	IP2out	IM2out	IM2out	IM2/Obs	
		dB	dB	K	K	dBm	dBm	dBm	dBm	mW	dB	
1	Digitizer	0		49,602,276	49602276	-9.41	-10.58					-40.36
2	Cable and balun	-3.0	-3.0	300	98969702	-6.41	-7.58		-49.77	1.054E-05		-40.36
3	Stage 3 amplifier	23.0	20.0	374	496398	-29.41	-30.58	44	-46.77	2.102E-05		-40.62
4	AT2	-1.3	18.7	300	669699	-28.11	-29.28		-70.03	9.927E-08		-40.62
5	Stage 2 amplifier	33.0	51.7	374	709.64	-61.11	-62.28	44	-68.73	1.339E-07		-40.62
6	Switches (4x)	-1.6	50.1	300	1118	-59.51	-60.68		-101.73	6.709E-11		-40.62
7	Filters (2x)	-1.5	48.6	300	1667	-58.01	-30.68		-100.13	9.697E-11		-40.62
8	Stage 1 amplifier	23.0	71.6	374	382	-81.01	-53.68	44	-98.63	1.370E-10		-41.66
9	AT1	-9.3	62.3	300	3519	-71.71	-44.38		-122.67	5.406E-13		-41.66
10	Optical link -- BoL	-16.2	46.1	107,823	255535	-55.48	-28.15	32	-113.37	4.601E-12		-42.54
11	Laser driver amplifier	23.0	69.1	374	1655	-78.48	-51.15	44	-98.02	1.579E-10		-46.42
12	AT0	-22.0	47.1	300	262551	-56.48	-29.15		-124.90	3.236E-13		-46.42
13	FE to Opt Xmtr coax	-1.4	45.7	300	362505	-55.08	-27.75		-102.90	5.129E-11		-46.42
14	Front end	36.0	81.7	250	341.06	-91.08	-63.75	46	-101.50	7.079E-11		

Table 2: Signal and RFI Power at Antenna Terminals

	Cable length	Plow	Plow	Pobs	Phigh
	m	Typ	Max	Min	
Observed for signal 160B Apr 2019, dBm		-44	-32	-57	-28
Representative frequency, MHz		15	15	33	92.5
Cable loss, dB (KSR240DB coax)	37.5	1.29	1.29	1.92	3.21
Estimated power at FE output, dBm		-42.71	-30.71	-55.08	-24.79
FEE gain, dB		36	36	36	36
Estimated power at FE input, dBm		-78.71	-66.71	-91.08	-60.79

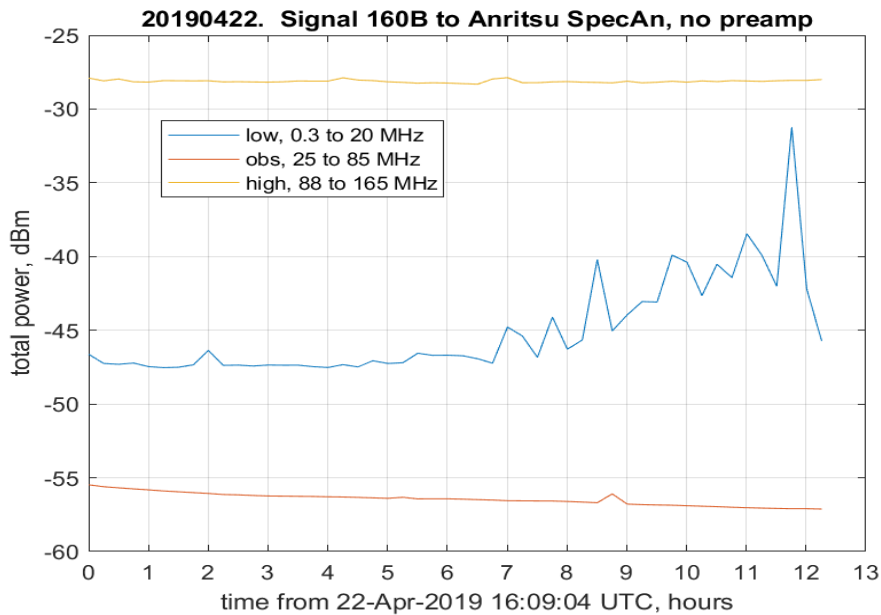


Figure 2. Measured RFI and observing band power for antenna 160, polarization B, on 2019 Apr 22. See [3] for details of the measurements. These results are similar to those presented in [3] except that no preamp was used ahead of the spectrum analyzer.

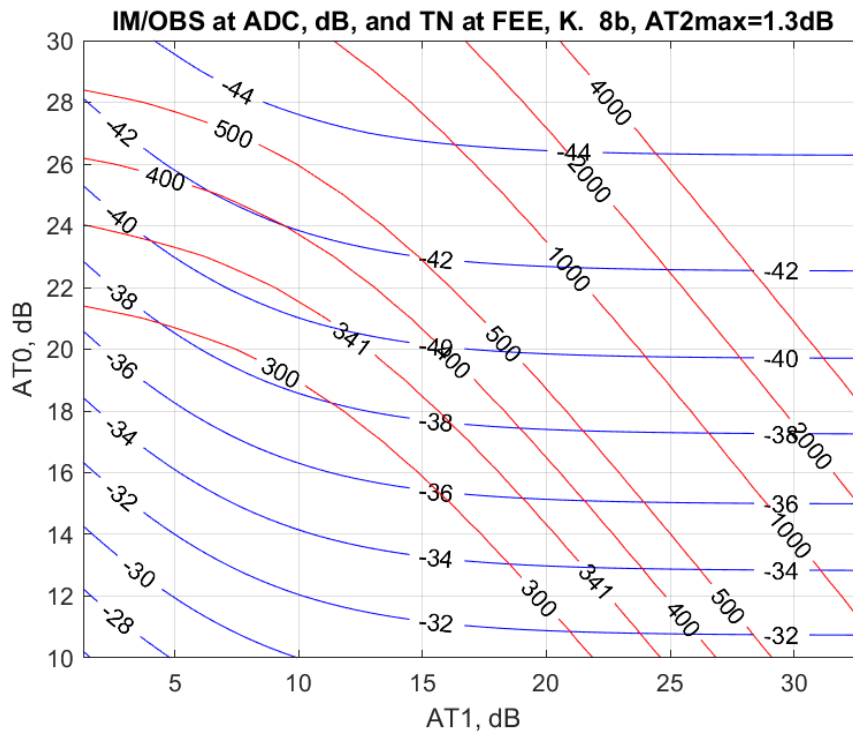


Figure 3. Noise (red) and intermodulation ratio (blue) vs. AT0 and AT1. AT2 is fixed at 1.3 dB (insertions loss only).

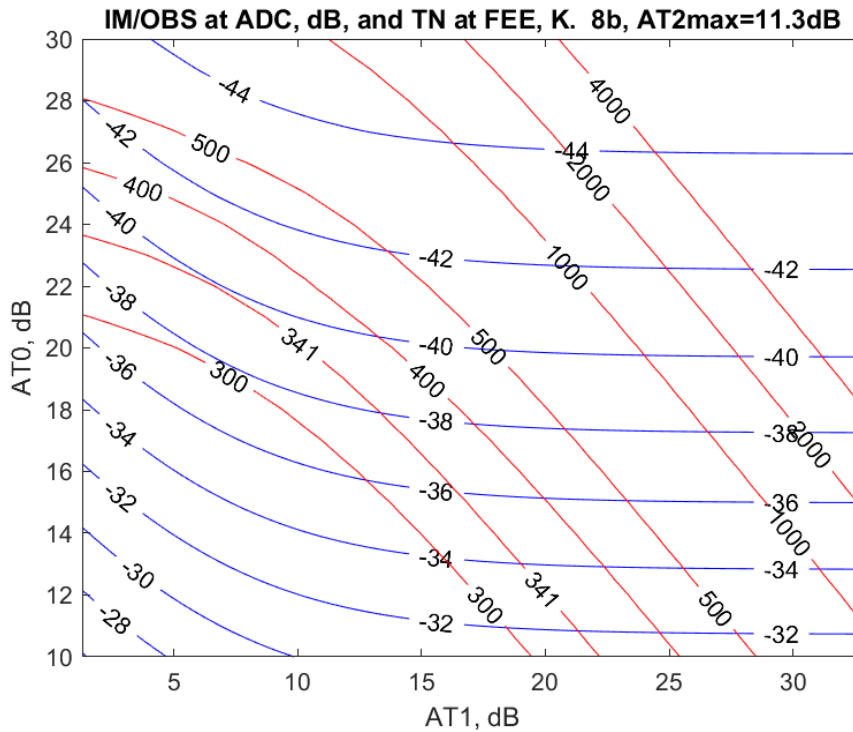


Figure 4. Like Fig. 3 but with $AT2 = 44.28\text{dB}/(AT0 \cdot AT1)$, constrained to $1.3\text{dB} \leq AT2 \leq 11.3\text{dB}$. That is, the total of the three attenuators is 44.28 dB when possible, but AT2's setting is at most 10dB.

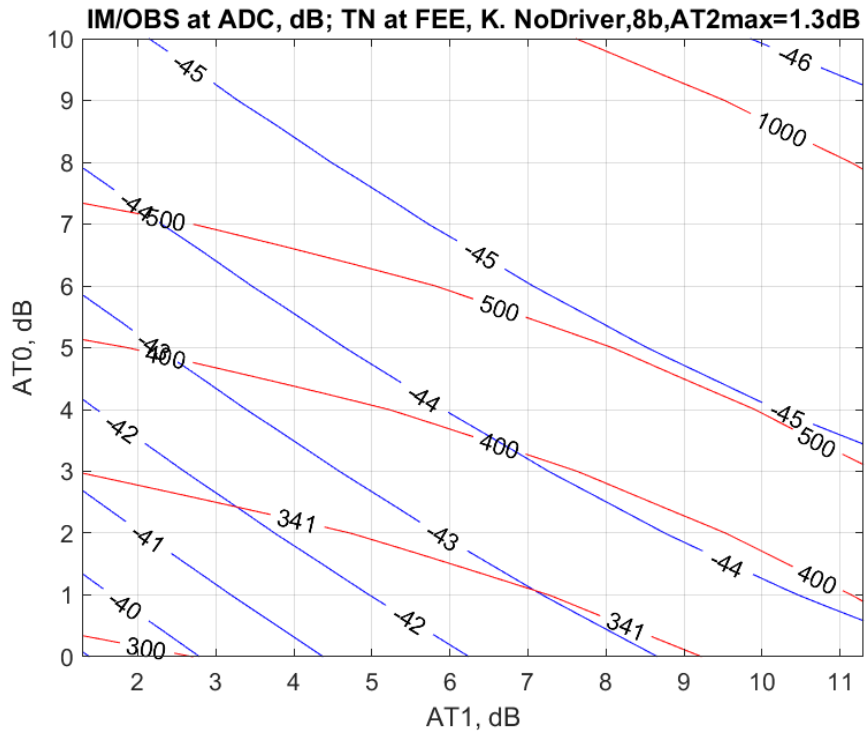


Figure 5. Noise (red) and intermodulation ratio (blue) with the laser driver amplifier (element 11 i Table 1) removed. AT2 is fixed at 1.3 dB.

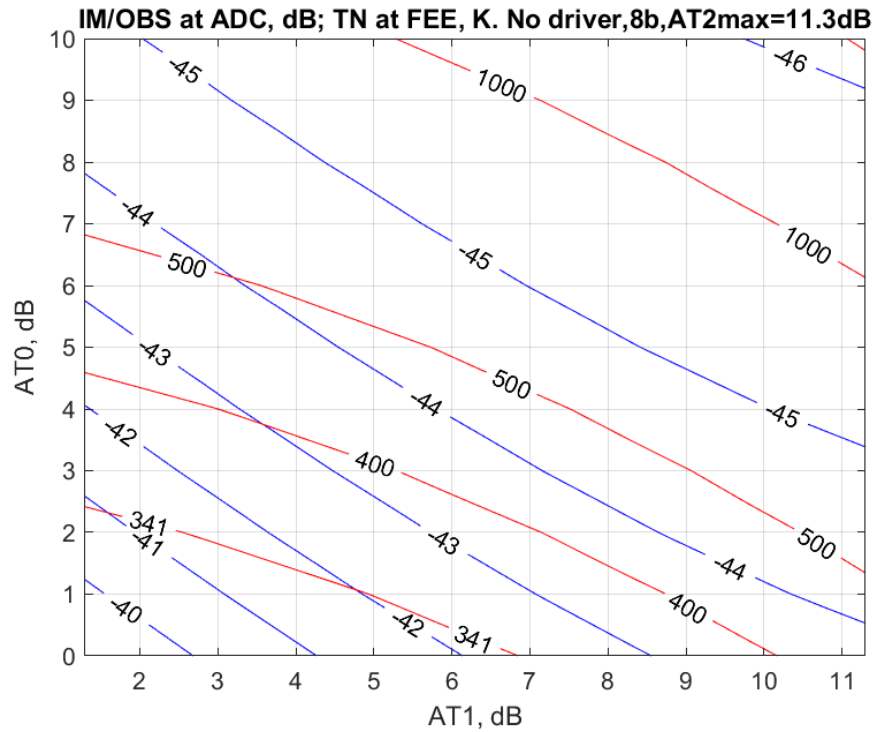


Figure 6. Like Fig. 5, but with $AT2 = 44.28\text{dB}/(AT0 - AT1)$, constrained to $1.3\text{dB} \leq AT2 \leq 11.3\text{dB}$. That is, the total of the three attenuators is 44.28 dB when possible, but AT2's setting is at most 10dB.

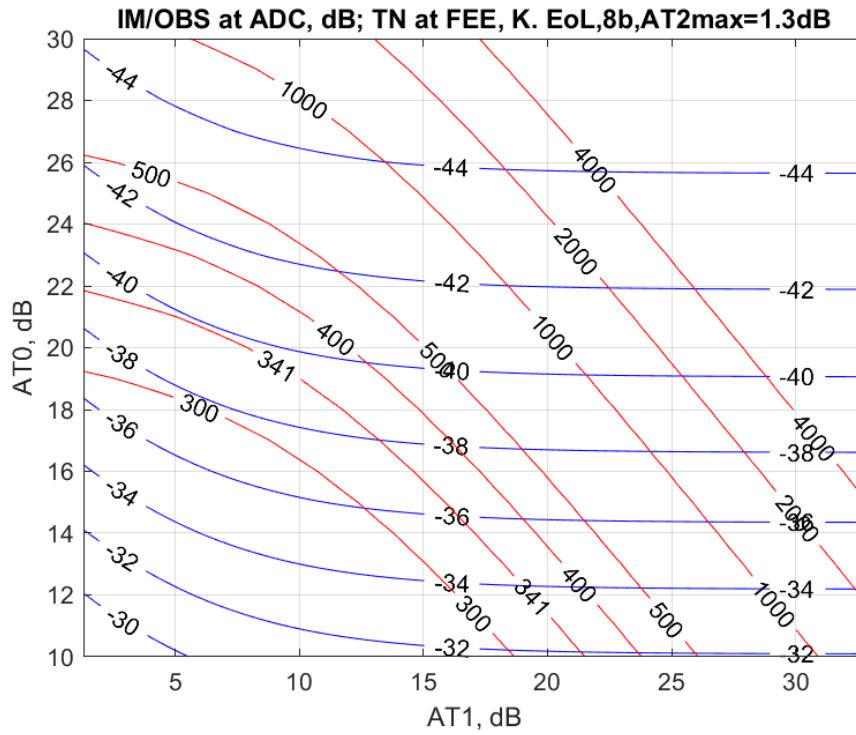


Figure 7. Noise (red) and intermodulation ratio (blue) at laser end-of-life, including laser driver amplifier. See text for definition of end-of-life.

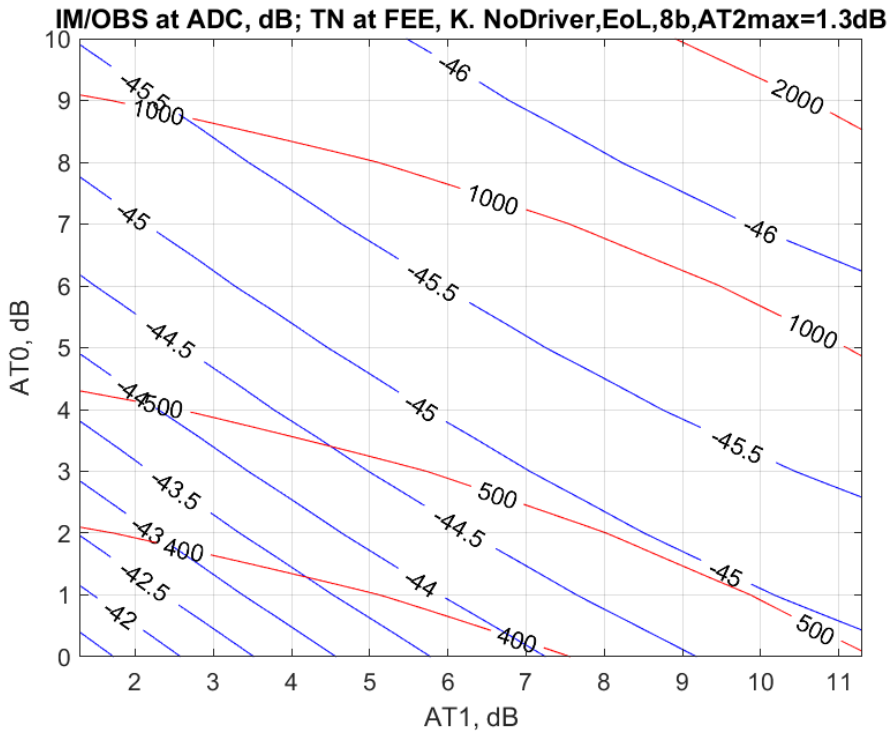


Figure 8. Like Fig. 7, but with laser driver amplifier removed.

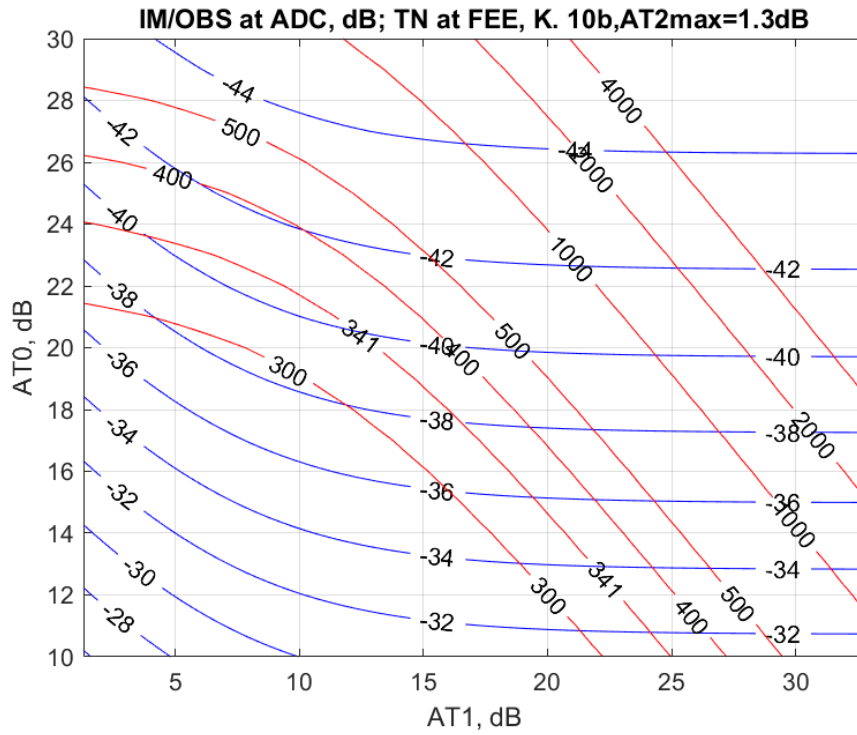


Figure 9. Noise (red) and intermodulation ratio (blue) for 10b ADC, including laser driver amplifier. New laser, AT2 at minimum attenuation.

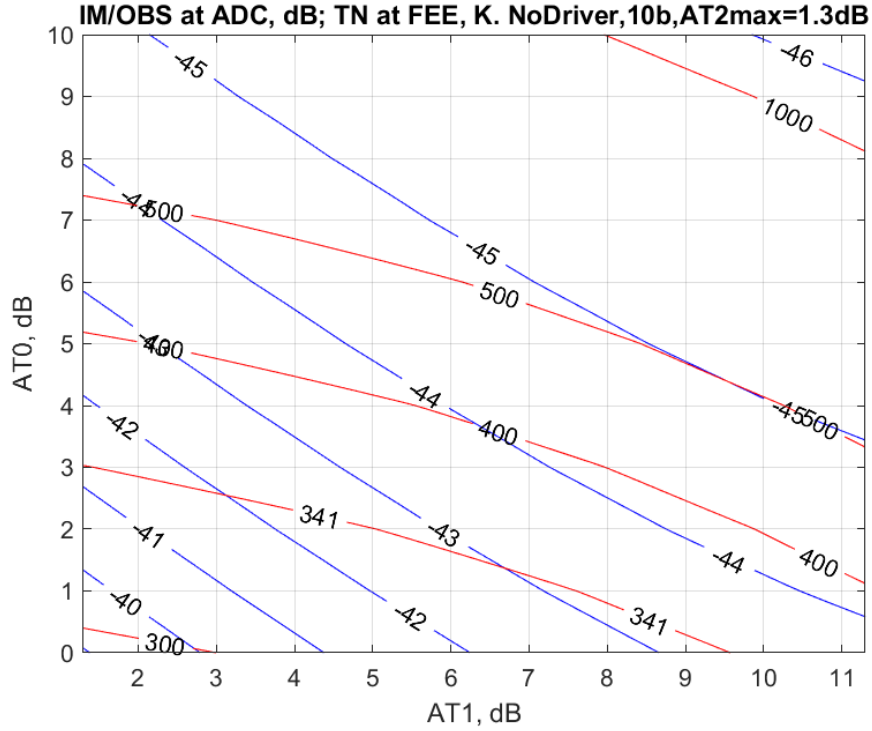


Figure 10. Like Fig. 9, but with laser driver amplifier removed.

Appendix A: Listing of Matlab Function

```

function [IM,TN,G,SIG]=lwaAnalogPathAnalysis(g,t,ip,pobs,prfi,at0,at1,at2max)
%USAGE: [IM,TN,G,SIG]=lwaAnalogPathAnalysis(g,t,ip,pobs,prfi,at0,at1,at2max);
% Analyze analog signal path over a range of attenuator settings
% Input: g(1:14) element gains, output to input g(1)=1 is ADC;
%         t(1:14) element noise temp or physical temp, K;
%         ip(1:14) element IP2s, mW;
%         pobs observing band total power at FEE input, mW;
%         prfi RFI total power at FEE input, mW;
%         at0 vector of values of attenuator 0 (before laser driver), dB;
%         at1 vector of values of attenuator 1 (after 1st ARX amp), dB;
%         at2max maximum setting of attenuator 2 (after 2nd amp), dB.
% Element 4 is AT2
% Element 7 is RFI filter, grfi=.001 (-30 dB)
% Element 9 is AT1
% Element 12 is AT0
% Element 14 is FEE.
% Output: IM1 2nd order intermod power to ADC, mW
%          TN1 noise temperature at FEE input (100ohms)
%          G1 total gain, from FEE input to ADC.
%          SIG observing band total power to ADC, mW

% 20200403 LRD, Initial version.

grfi = g; grfi(7)=.001; %set RFI band gain

IM=zeros(length(at0),length(at1));
TN=zeros(length(at0),length(at1));
G=zeros(length(at0),length(at1));
i=0;
for AT0=at0 %dB
    i=i+1;
    j=0;
    for AT1=at1 %dB
        j=j+1;
        AT2 = min(at2max,44.28-AT0-AT1); %Total attn <=44.28dB
        AT2 = max(AT2,1.3); % 1.3dB <= AT2 <= at2max
        g(4) = 10^(-0.1*AT2);
        g(9) = 10^(-0.1*AT1);
        g(12) = 10^(-0.1*AT0);
        grfi([4 9 12]) = g([4 9 12]);
        %disp([i j AT0 AT1 AT2])

        %intermod cascade
        pim=0; %no intermod power into FEE.
        pi=prfi; %RFI power into FEE, -60.79 dBm.
        for k=length(g):-1:1,
            [pim,pi] = intermodCascade(pim,pi,g(k),grfi(k),ip(k),2);
            %disp(10*log10([pim,prfi])),
        end
        IM(i,j)=pim;

        %gain and noise cascade
        tt=t(1);gg=g(1);

```

```
    for k=2:length(g),  
        if g(k)<1, [tt,gg]=noiseCascadePassive(t(k),g(k),tt,gg);  
        else, [tt,gg]=noiseCascadeActive(t(k),g(k),tt,gg); end  
    end  
    TN(i,j)=tt;    %FEE input noise temperature (Tr)  
    G(i,j)=gg;    %Total gain  
end  
end  
SIG=G*pobs;    %observing band power into FEE * total gain.
```