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Next Generation Analog Receiver Design: Amplifier Selection

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I. INTRODUCTION

This memo discusses design considerations for the new Analog Receivers (ARXs), focusing on the choice of amplifiers. The main concern is avoiding intermodulation from the very strong RFI that accompanies the signal received by the ARX from the antenna. The strongest RFI is outside observing band, but there is little filtering ahead of the ARX. Measurements have shown that the total RFI power is nearly 1000 times larger than the total power in the observing band [4].

II. REQUIREMENTS

A. Gain

As shown earlier [1], the minimum system noise temperature in the observing band at the LNA input (85 MHz, galaxy minimum) is expected to be about 905K, or a power spectral density of –169.0 dBm/Hz. In order for this to be 10 dB above the quantization noise at the digitizer, it must be –70.7 dB/Hz relative to the LSB [2]; for 8b quantization at 2V pp in 100 ohms, a signal whose rms voltages is 1 LSB has a power of –32.1 dBm. Therefore, a total net gain of 66.2 dB is needed. There is about 36.0 dB of gain in the front end electronics and 20.8 dB of worst-case cable loss (252.7 m of KS240 cable at 85 MHz), for a minimum net gain prior to the analog receiver (ARX) of 15.2 dB. There is about 3 dB of loss in cables and balun between the ARX output and the digitizer. The gain required in the ARX is then about 54 dB.

The ARX will have component insertion losses totaling an estimated 5 dB, and internal pads of up to 4 dB. It will also have two 0-30 dB variable attenuators which should have some margin below their minimum setting at the maximum required gain. We adopt 10 dB as that margin, leading to total losses in the ARX of 19 dB. The leads to a requirement for a total active gain in the ARX of about 73 dB.

All previous ARX versions (the current OVRO-LWA has Rev E) achieve about 75 dB active gain using three stages, each of which is a MiniCircuits Gali-74+ at 25 dB. It is difficult to find other gain-block amplifiers with this much gain (see section IV below), limiting our options unless we want to have four stages. More stages means an undesirable increase in power consumption and board space.

B. Output Power and Distortion

We expect to use ADCs with a peak-to-peak range of 2.00V into a 100-ohm load [3]. Thus a full-scale sinusoid corresponds to 5.0 mW or +7.0 dBm. From the output of the last ARX amplifier we allow 2 dB for cable losses and 1 dB for balun transformer loss, so driving the ADC with a full-scale sinusoid requires +10.0 dBm. We adopt this as the minimum required ARX output power.

Measurements of signals from an antenna with nearly the shortest coax cables (160B) gave total power at the ARX input of about –28 dBm, almost all from FM radio RFI (Figure 1). This is about 29 dB above the minimum total power in the 25-85 MHz observing band. The cable loss in this case (40m of KS240 cable) is 2.0 to 3.3 dB across the band; for fiber-coupled antennas, the link loss is expected to be at least 5 dB, so these measurements represent the strongest signal.

Figure 2 shows the planned ARX signal chain; it is the same configuration as in the current OVRO-LWA. The first amplifier stage receives the unfiltered antenna signal, so it must tolerate all the out-of-band RFI without distortion. Selectable filters are provided after the first stage. The widest filter is designed to reduce the out-of-band power by about 20 dB, and the narrower filters reduce it even more. Consequently, if the gains are equal ($G_1=G_2=G_3$), the second- and third-stage amplifiers tend to see less total power than the first, even though the in-band power increases as we proceed through the chain. When the input signal is strongest (shortest coax cables), the level into the later stages is reduced by adjustable attenuators so that the final output to the digitizer is at the desired level.

An alternative configuration is shown in Figure 3. Here the first attenuator is placed before the first amplifier. For the weakest signals (longest cables), that attenuator can be set to zero, but for the strongest signals it can reduce the power seen by the first amplifier, making it easier to avoid distortion. The filters are still placed after that amplifier so that they are isolated from the cables; otherwise the strong out-of-band signals would be reflected.

To set requirements for amplifier distortion, consider that the out-of-band RFI is mostly in the 88-108 MHz FM radio band with worst-case stable power of about –28 dBm at the ARX input, and that there is also RFI in the 5-20 MHz range whose level is highly variable. The peak of –32 dBm in <20 MHz power seen in Fig. 1 is the largest observed in about a week of measurements of 4 signals, so we take that as the worst case. We consider 2nd-order and 3rd-order distortion products (ignoring higher-order products that should be much weaker), and adopt the requirement that those in the observing band be at least 20 dB below the weakest observing-band power of –57 dBm (Fig. 1). For two sinusoids with powers P_1 and P_2, the power in each distortion product is given by

$$P_{\mathrm{IM2}} = P_1\, P_2/I_2$$

$$P_{\mathrm{IM3}} = P_1^2\, P_2\,/I_3^2$$

where I_2 and I_3 are the 2nd- and 3rd-order intercept points of the processing device, respectively. This assumes that the gain of the processing device is the same at all relevant frequencies. For our case, 2nd-order products from the low-frequency RFI band and 2nd-order combinations of low- and high-band signals can fall in the 25-85 MHz observing band. So can 3rd-order products of high-band signals, but 2nd-order products of FM radio signals cannot. (Second-order products between FM radio signals and RFI above 88 MHz can be in the observing band, but these are much weaker.) Our RFI does not consist of two sinusoids, so the above two-tone formulas do not depict it accurately; the total power in both the low- and high-frequency RFI bands is normally spread among multiple signals. We nevertheless model the situation as if all the RFI power were concentrated in two sinusoids. An actual distortion product at any one frequency will always be much less than the model predicts, but the total power in observing-band distortion products is expected to be comparable to the prediction. Using the above formulas and taking P_1 = –28 dBm and P_2 = –32 dBm for the 2nd order case and $P_1 = P_2$ = –31 dBm (half of –28 dBm in each tone) for the 3rd-order case gives

$$P_{\mathrm{IM2}} = -60\ \mathrm{dB(mW^2)}/I_2 \;< -77\ \mathrm{dBm} \;\rightarrow\; \underline{I_2 > +17\ \mathrm{dBm}}$$

$$P_{\mathrm{IM3}} = -93\ \mathrm{dB(mW^3)}\,/I_3^2 < -77\ \mathrm{dBm} \;\rightarrow\; \underline{I_3 > -8\ \mathrm{dBm}}.$$

These results are referred to the ARX input and they apply to the cascade of all devices in the signal chain. Here we consider only the amplifiers, since other devices are expected to produce negligible intermodulation. On amplifier data sheets, I_2 and I_3 are usually referred to the output, so for each amplifier our criteria should be multiplied by the total gain ahead of its output.

Table 1 is a spreadsheet in which the required minimum output I_2 and I_3 are computed for each amplifier assuming that that amplifier dominates the total. The table includes both of the configurations (Fig. 2 and Fig. 3), and it includes the signal and RFI levels for both minimum cable length and maximum cable length. Column 'Phigh' is the total power above 88 MHz; 'Plow' is the total power below 20 MHz; and 'Pobs' is the total power in the 25-85 MHz observing band. All amplifier gains are set to 23 dB. For maximum input levels (minimum cable length), the first attenuator (AT1) is set to 10 dB and for minimum levels it is set to its minimum, but it has an insertion loss of about 1 dB. (Amplifier gains and first attenuator setting are easily changed in the spreadsheet.) The second attenuator setting (AT2) is calculated to make the observing-band output level[1] –22.8 dBm. The filter is assumed to reduce the RFI power at >88 MHz by 15 dB and the RFI at <20 MHz by 10 dB; this is conservative, since simulations show that the actual filters will do better. Line IL includes the insertion loss of the switches (1 dB each) and of the filter (about 5 dB). As expected, the most stringent requirements on amplifier intermodulation are for the first amplifier, prior to filtering. The requirements are reduced in the second configuration by setting the first attenuator to 10 dB at maximum level; at minimum level, the requirements remain less stringent even though the attenuator is set to 0 dB.[2]

Table 1: Calculation of Required Intermodulation Intercept Points for Amplifiers

		Minium Cable Length (measured input levels)									Maximum Cable Length (extrapolated)									
		Input, dBm			Max IM	Gain	Output, dBm		I2	I3	Input, dBm			Max IM	Gain	Output, dBm		I2	I3
	Stage	Phigh	Plow	Obs.	dBm	dB	Total	Obs.	dBm	dBm	Phigh	Plow	Obs.	dBm	dB	Total	Obs.	dBm	dBm
Figure 2	G1	**-28**	**-32**	**-57**	-77	**23**	-5.0	-34	40	15	-45.5	-49.5	-74.5	-94.5	**23**	-22.5	-51.5	22.5	-2.5
	AT1					**-10**									**-1**				
	IL					-7									-7				
	G2	-37	-36	-51	-71	**23**	-13.0	-28	21	-1.5	-45.5	-44.5	-59.5	-79.5	**23**	-21.5	-36.5	12.5	-10
	AT2	-14	-13	-28		-20.8					-22.5	-21.5	-36.5		-12.3				
	G3	-34.8	-33.8	-48.8	-68.8	**23**	-10.8	-25.8	23.2	0.7	-34.8	-33.8	-48.8	-68.8	**23**	-10.8	-25.8	23.2	0.7
						31.2									48.7				
Figure 3	AT1	**-28**	**-32**	**-57**	-77	**-10**	-38.0	-67			-45.5	-49.5	-74.5	-94.5	**-1**	-46.5	-75.5		
	G1	-38	-42	-67	-87	**23**	-15.0	-44	30	5	-46.5	-50.5	-75.5	-95.5	**23**	-23.5	-52.5	21.5	-3.5
	IL					-7									-7				
	G2	-37	-36	-51	-71	**23**	-13.0	-28	21	-1.5	-45.5	-44.5	-59.5	-79.5	**23**	-21.5	-36.5	12.5	-10
	AT2	-14	-13	-28		-20.8					-22.5		-36.5		-12.3				
	G3	-34.8	-33.8	-48.8	-68.8	**23**	-10.8	-25.8	23.2	0.7	-34.8	-33.8	-48.8	-68.8	**23**	-10.8	-25.8	23.2	0.7
						31.2									48.7				

C. Power consumption

The Gali-74+ (and many other similar gain-block amplifiers that consist of two Darlington-connected bipolar transistors) is biased with approximately 5 VDC at the output pin, but is unstable if connected to a constant-voltage source [5]. Such amplifiers require biasing through a series resistor of a specified minimum value and a higher-voltage supply. This leads to wasted power. A few gain block amplifiers are available for constant-voltage biasing (e.g., Mini-Circuits PHA-13LN+ and Broadcom ABA-54563), so these are preferred.

It is also preferred to minimize the number of supply voltages needed for devices in the signal path, so as to minimize the number of wires into each independent signal chain and

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[1] This produces –25.8 dBm at the digitizer, which is 6.26 dB above 1 LSB rms for 8b, 2V p-p, 100 ohms. It was shown in [2] that the signal PSD is then 10 dB above the quantization noise at its weakest frequency (85 MHz).

[2] The cable attenuation has a range of about 17 dB, so it would be possible to set the attenuator to make the cable plus attenuator gain constant, in which case the amplifier requirement would be independent of cable length. In reality it is a bit more complicated because the cable attenuation increases with frequency. The calculations here are based on the cable attenuation at 85 MHz.

potential cross-talk paths.

IV. Available Components

Selected commercial gain-block amplifiers are listed in Table 2. These were selected to have a frequency range of at least 1-100 MHz and a gain at 100 MHz of at least 19 dB. Other manufacturers were considered (including Fairview Microwave, RF Lambda, Texas Instruments, Macom, and Skyworks), but none had any products suitable for our purposes. The two Broadcom (formerly Avago) devices are no longer manufactured, but there are distributers who have many thousands in stock, so it would be possible to use them.

Table 2: Selected COTS Gain-Block Amplifiers

Manufacturer	*Model*	*Gain*	*NF*	*P1dB*	*I2*	*I3*	*Minimum*		*Power*	*IP3/Pdc*	*Unit Price, $*	
		dB	dB	dBm	dBm	dBm	*I, mA*	*V*	mW	W/W	1 ea	2400 ea
Mini Circuits	**Gali-74+**	25	2.7	19.2		38	80	7	560	11.27	2.65	
Mini Circuits	**PHA-13LN+**	24	1.1	23		40	138.9	5	695	14.40	9.45	6.75
Mini Circuits	**PHA-13LN+**	23.2	1.0	16.9		33	71.2	3	214	9.34	9.45	6.75
Mini Circuits	LEE-59+	20.6	4.5	17.3		33	65	7	455	4.39	2.05	
Mini Circuits	ERA-50SM+	20.7	3.5	20.7		32.5	60	7	420	4.23	3.00	
Analog Dev	AD8353	19.8	8.0	8.5	31.6	23	43	5	215	0.93	1.61	0.69
Analog Dev	AD8354	19	6.4	4.8	28.7	19.3	26	5	130	0.65	1.55	0.68
Qorvo	AG303-86G	21.4	2.9	14.2	34	26.5	35	5	175	2.55	3.11	1.21
Qorvo	AG303-63G	20.5	3.0	14	34	26	35	5	175	2.27	2.14	0.83
Broadcom	ABA52563	21.5	3.3	9.8		19.9	35	5	175	0.56		
Broadcom	**ABA54563**	23	3.6	18		35	90	5	450	7.03		4.30

To achieve the +10 dBm minimum output power needed to drive the ADC to full scale, we require that the final amplifier have a 1 dB compression point of >15 dBm. That excludes some devices from Table 2, but they could be used in the earlier stages.

For most devices, the 2nd-order intercept power I_2 is not specified. When specified, it is 8 to 9 dB above I_3, so we assume that the other devices have the same I_2/I_3 ratio.

Comparing Table 2 with Table 1, we see that any of the listed devices could be used for the stage 2 amplifier in either configuration. For stage 3, any of the MiniCircuits devices or the Broadcom ABA54563 could be used. For stage 1, which requires the highest I_2 and I_3, it seems likely that the same subset would work, but since I_2 is not specified it is uncertain. However, in the second configuration (Fig. 3), the most stringent requirement for stage 1 is $I_2 > 30$ dBm, so most devices in Table 2 could be used.[3]

As noted earlier, amplifiers with low power consumption and requiring a 5V or lower d.c. power supply are preferred. From this point of view, the PHA-13LN+ operating at 3V seems like the best choice for all stages. It also has the lowest noise figure. Other reasonable choices are the ABA54563 and the PHA-13LN+ at 5V. If 7V devices are accepted, the Gali-74+ remains a good choice. The others might be usable for some stages, especially if the Fig. 3 configuration is used.

Table 3 shows the calculated performance of the second configuration (Fig. 3) with specific choices for the amplifiers. The PHA-13LN+ at 3V is used for all amplifier stages. It is

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[3] These conclusions do not follow only from inspection of Tables 1 and 2 because Table 1 as shown has all amplifier gains at 23 dB and the devices in Table 2 range from 19 to 25 dB. Nevertheless, the conclusions hold if the appropriate gains are used in the spreadsheet used to create Table 1.

assumed that its 2nd order intercept is given by $I_2 = I_3 + 8$ dB.[4] In the 'Cascade' columns, the net gain from the input of each stage to the ADC is calculated, along with the total 2nd- and 3rd-order intermodulation powers at the output of that stage, including any intermodulation from earlier stages multiplied by the subsequent gain. The observing band total power is given for comparison. Finally, the noise temperature at the input of that stage is calculated, including the noise from all subsequent stages.

For the purpose of the noise calculation, the ADC's quantization noise and the effect of the input cable from the antenna are included. All passive devices are taken to be at a physical temperature of 300K.

V. DISCUSSION

The red-font numbers in Table 3 show the performance of the ARX signal chain. We see that the worst intermodulation is at least 29 dB below the observing band power, so our requirement of >20 dB is met. The noise temperature at the antenna (front end output) is adequate, considering that the front end has about 36 dB of gain. For minimum cable length, the intermodulation performance could be somewhat improved by increasing the attenuation of AT1 and decreasing that of AT2, at a sacrifice in noise performance.

The Mini Circuits PHA-13LN+ amplifier is relatively expensive. If selected, it would consume about 25% of the cost of the Analog Signal Processing subsystem. It has unusually high dynamic range, but there may be difficulties in using it because of other properties, like a tendency to oscillate (it appears not to be unconditionally stable). Laboratory tests are needed before its choice is final. Fortunately, alternatives with adequate performance are available.

REFERENCES

[1] L. D'Addario " Spectra of OVRO-LWA signals at correlator: predicted vs. observed." OVRO-LWA engineering memo, 26 April 2019.

[2] L. D'Addario, " Effective Dynamic Range of Digitizers in the OVRO-LWA Telescope." OVRO-LWA engineering memo, 27 April 2019.

[3] Analog Devices Inc,, HMDAC1511 data sheet; and Texas Instruments Inc., ADS5296A data sheet.

[4] L. D'Addario, " RFI Environment at the OVRO LWA: Quantitative Measurements." OVRO-LWA engineering memo, 20 April 2019.

[5] Mini-Circuits, "Biasing of constant current MMIC amplifiers." Application Note AN60-010, undated. https://www.minicircuits.com/appdoc/AN60-010.html

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[4] It is easy to substitute the specifications of different amplifiers in the spreadsheet that underlies Table 3. The spreadsheet file is available from the author.

Table 3a: Performance With Specific Devices, minimum cable length

	Inputs			Specifications					Cascade				
	Phigh	Plow	Pobs	Device	Gain	I2	I3	NF	Gain	IM2	IM3	Pobs	Tn
stage	dBm	dBm	dBm		dB	dBm	dBm	dB	dB	mW	mW	mW	K
cables				KSR240, 85MHz	-3.3				24.9				12,545
AT1	**-28.0**	**-32.0**	**-57.0**		-10.0				**28.2**				**5,793**
G1	-38.0	-42.0	-67.0	PHA-13LN+	23.2	41.0	33.0	1.0	38.2	3.47E-08	1.15E-12	4.17E-05	552
Filter					-7.0				15.0				99,701
G2	-36.8	-35.8	-50.8	PHA-13LN+	23.2	41.0	33.0	1.0	22.0	1.64E-06	2.63E-12	1.74E-03	19,845
AT2	-13.6	-12.6	-27.6		-21.4				-1.2				4,130,535
G3	-35.0	-34.0	-49.0	PHA-13LN+	23.2	41.0	33.0	1.0	20.2	**2.91E-06**	**9.12E-12**	2.63E-03	29,921
cables+balun					-3				-3.0				6,235,679
ADC				8b 2V 100Ω									3,125,168

Table 3b: Performance With Specific Devices, maximum cable length

	Inputs			Specifications					Cascade				
	Phigh	Plow	Pobs	Device	Gain	I2	I3	NF	Gain	IM2	IM3	Pobs	Tn
stage	dBm	dBm	dBm		dB	dBm	dBm	dB	dB	mW	mW	mW	K
cables				KSR240, 85MHz	-20.8				24.5				30,260
AT1	**-45.0**	**-49.0**	**-74.0**		-1.0				**45.2**				**255**
G1	-46.0	-50.0	-75.0	PHA-13LN+	23.2	41.0	33.0	1.0	46.2	8.71E-10	4.57E-15	6.61E-06	153
Filter					-7.0				23.0				16,326
G2	-44.8	-43.8	-58.8	PHA-13LN+	23.2	41.0	33.0	1.0	30.0	4.11E-08	1.05E-14	2.75E-04	3,210
AT2	-21.6	-20.6	-35.6		-13.4				6.8				654,885
G3	-35.0	-34.0	-49.0	PHA-13LN+	23.2	41.0	33.0	1.0	20.2	**8.29E-07**	**9.12E-12**	2.63E-03	29,921
cables+balun					-3				-3.0				6,235,679
ADC				8b 2V 100Ω									3,125,168

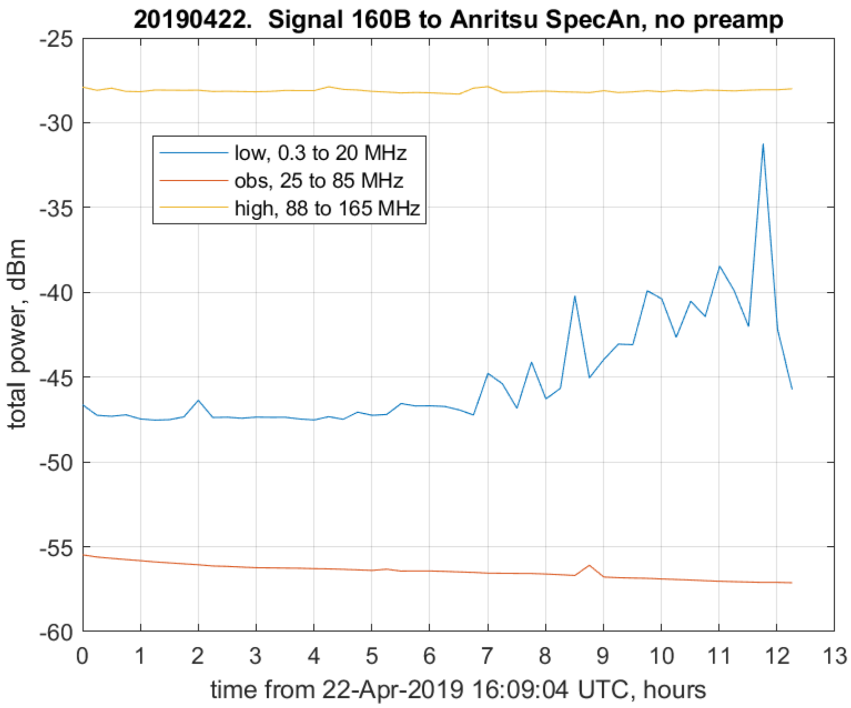

Figure 1. Time series of measured power at the processing shelter for a signal from an antenna with near-minimum cable length, integrated over three frequency ranges using a spectrum analyzer. See [4] for a description of the setup.

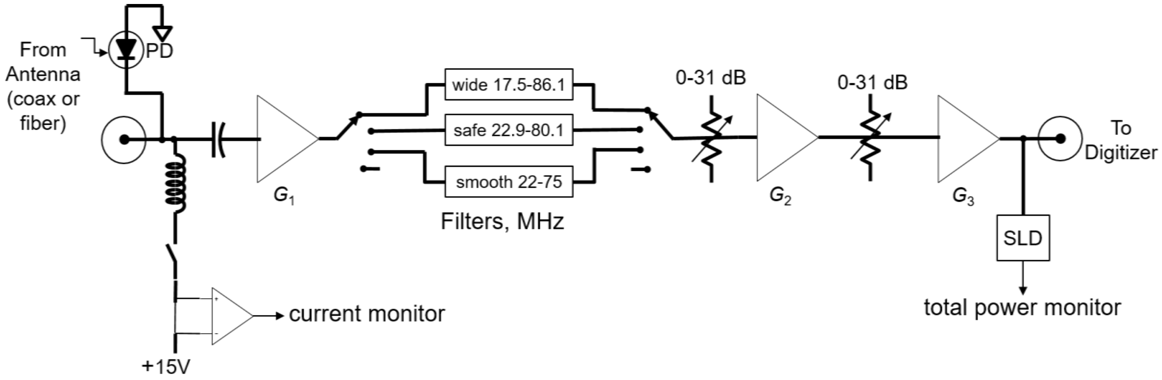

Figure 2. Block diagram of one ARX signal path, using the configuration of the existing ARXs. The first amplifier sees the entire signal, including all out-of-band RFI.

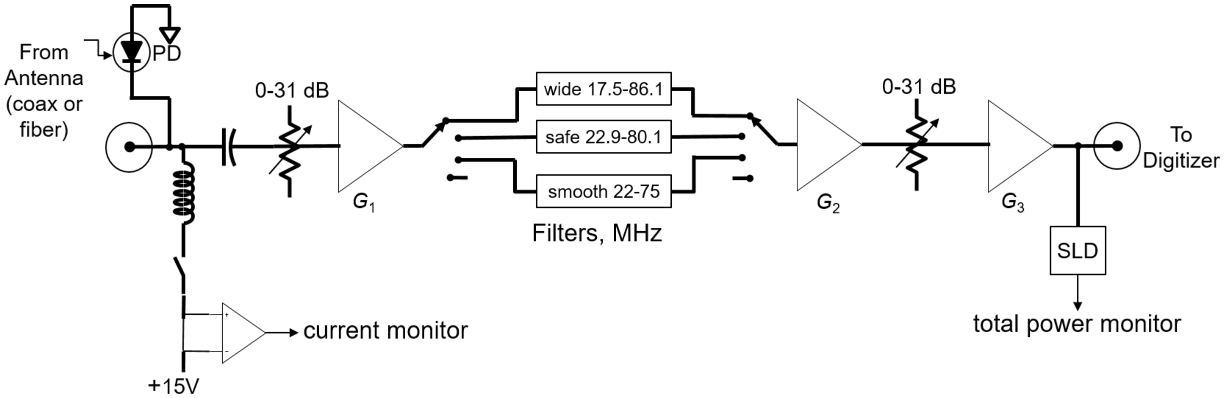

Figure 3. Alternative configuration, with first variable attenuator moved to the input.