Group C Experiment 3 Analog Amplifier Frequency Response Team Report

David Mann, Daniel Mazin, Austin Long

October 13th, 2024

Introduction

The overview for the design of this lab was to give us experience in working with operational amplifiers (opamps), and how to identify various features within the generated data that may inform us about the quality of the data based on our inputs as well as the design quality of the opamps. We looked at two different types of opamps, inverting and non-inverting, of various quality. The opamps used in the experiment include the UA741 (Inverting), AD797, AD848, AD4898-1, and LMH6624 all of which are non-inverting. The difference between inverting and non-inverting has to do with the phase shift of the input signal compared to the output. The gains of each amplifier vary, ranging from magnitudes of 5 V/V, 10 V/V, 15 V/V, 20 V/V, and 100 V/V linear gains. The experiment was divided into three tasks, and data gathering was done using the network analyzer feature of the Scopy program. The data acquisition module used to interface with the software was the ADALM2000, referred to as the M2K going forward. The power supply used to power the evaluation boards containing the opamps was the Siglent SPD3303X. The common procedures through each task involved establishing a range of drive voltages based on the opamp specifications attached to the boards. For the UA741, the DC power supply voltage used was $\pm$ 10 V. For all other opamps a voltage of $\pm$ 6 V was used. With an established drive voltage range for each EB, we simply adjusted the input amplitude signal coming through the M2K via Scopy, which generated the Bode Plot for each board. Outside of everything just stated, each task had specific procedures that were carried out which are described below.

Task 1a: Estimate the GBP of the UA741 opamp

In order to perform the analysis for the lab, we would need to know some relationships between linear gain and logarithmic gain. The main difference between these gains is that the logarithmic gain is just the base-10 logarithm of the linear gain such that

$$A(dB) = 20log(A_{linear}) \tag{1}$$

Where $A_{linear} = -\frac{V_o}{V_i}$ for an inverting amplifier and $1+\frac{V_o}{V_i}$ for a non-inverting amplifier. If we consider a gain of 5 V/V then the corresponding gain in decibels evaluates out to 13.979 dB. The linear voltage gain for a 40 dB gain is 100 V/V. The power gain for the -3 dB is 0.5 V/V and the voltage gain corresponding to that -3 dB point is 0.707 V/V. This means that the DC gain will have dropped by a logarithmic gain of -3 dB or a linear gain of 0.707 V/V.

If we assume a constant GBW, we can write our gain (A) as a function of bandwidth and vice versa.

$$A = \frac{GBW}{f} \tag{2}$$

$$f = \frac{GBW}{A} \tag{3}$$

Prior to the lab, we conducted some research on the components we would be using in the experiment. The table below shows values for the M2K's maximum allowed voltage range and the maximum drive voltage for the UA741 given a maximum output voltage swing of ± 12 V from a ± 15 V power supply. The values in the table for the maximum drive voltage were calculated using the formula for linear gain of an opamp given that $V_{o,max} = 12V$ so that $V_{in,drive} = \frac{V_{o,max}}{A}$.

M2K Prelab Data	
Maximum Input Voltage	+/- 25 V

Figure 1: Maximum Input Voltage for UA741 based on provided datasheet.

UA741 Prelab Data			
Maximum Output Voltage Swing	+/- 12 V	Maximum Drive Voltage	
		5 Amp	+/- 2.4 V
		20 Amp	+/- 0.6 V
		100 Amp	+/- 0.12 V

Figure 2: Maximum Drive Voltage for UA741 based on provided $V_{in,drive} = \frac{V_{o,max}}{A}$.

For this first task, we wanted to gather data that would allow us to estimate the gain-bandwidth product (GBP) for three different configurations of the UA741 inverting amplifier. The nominal linear gains for the three configurations were -5 V/V, -20 V/V, and -100 V/V. Using the formula G = $20 \cdot \log(A)$, where A is the amplifier gain, these roughly correspond to a logarithmic gain of -13.98 dB, -26.02 dB, and -40 dB respectively.

The first thing we did for each board was to find out the exact resistor values used on the evaluation boards (EB). We wanted these values to determine the actual gain that each amplifier would be providing. These are shown in the table below along with the actual gain that was calculated using the formula $A = -\frac{R_1}{R_2}$ where R_1 corresponds to the resistor attached between the negative terminal of the amplifier and the output, while R_2 corresponds to the input resistor placed between the voltage input driver from the M2K and the negative terminal of the opamp.

UA741 Nominal Gain	UA741 Resistor	Actual Gains
5A	R1: 499 Ohm	-4.99 V/V
	R2: 100 Ohm	
20A	R1: 2000 Ohm	-20 V/V
	R2: 100 Ohm	
100A	R1: 10000 Ohm	-100 V/V
	R2: 100 Ohm	

Figure 3: Resistor values as read directly from the evaluation board. Actual gain calculated using $A = -\frac{R_1}{R_2}$.

Once we had the resistor values and gains, we placed each EB on the breadboard as instructed and connected the BNC/SMA cable from the M2K to the EB. We turned the power supply on and set it to 10 V with a 1 Amp current. Before starting the run, we checked with Martin to make sure our Scopy settings were appropriate. He suggested that we did not need such a high sample count of 1000, so we lowered it to 200 samples. We set the starting frequency to 1 kHz and the stop frequency to 2.5 MHz. The start frequency was a default value, and the stop frequency was also suggested by Martin as he mentioned this is adequate for the specific opamp we were currently using. Initially, we had the period and averages set to 1, until we were told this value influences each data point by taking measurements of the period and averaging which can help smooth out the data. At some point this has diminishing returns as it can only be so accurate, so we decided on a period of 4 with 4 averages. The rest of the settings were left at default values as we were told these do not apply to what we were doing. The wiring for the M2K, EB, and power supply are also shown below.

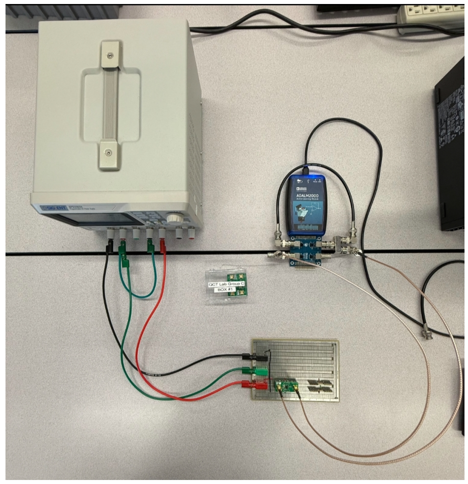

Figure 4: Overall image of the wiring setup of the M2K, EB, and power supply. Patch cables and BNC/SMA cables are used for the connections.

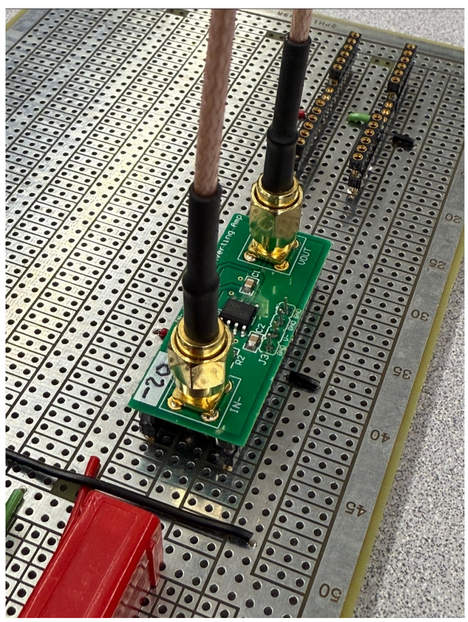

Figure 5: Close up image of the BNC/SMA cables attached from the M2K to the EB.

UA741 Scopy Settings	
Sample Count	200
Start Freq	1 kHz
Stop Freq	2.5 MHz
Period	4
Average	4

Figure 6: The settings for the network analyzer in Scopy that we used for all of the UA741 trials.

With the Scopy settings finalized, we began our runs using the input drive voltages listed in the table below.

-5A		-20A		-100A	
Vin,max	1.6 V	Vin,max	0.4 V	Vin, max	0.08 V
Vin Range		Vin range		Vin range	
20 mV		20 mV		20 mV	
50 mV		50 mV		40 mV	
100 mV		100 mV		50 mV	
1 V		200 mV		60 mV	
1.4 V					

Figure 7: Input voltage for each gain with the max input shown at the top. The range was decided based on the max input and a desired number of trials for more consistent data.

The average DC gain was taken after filtering out the input spike data that occurred in some of the trials. The -3dB point was then found based on this average. The tables below show the average DC gain in dB, the gain at the -3 dB point, the linear gain of this point, and the corresponding frequency. These last two values are what we used to calculate the GBP shown for each amplifier. Each table corresponds to a different amplifier as labeled, and the GBP was calculated for each. Runs were done for each of the three UA741s each having different gains across the listed drive voltages. Note that the GBP is calculated directly from python code and does not include any rounding. The table is formatted to show only two decimal places, so a direct calculation of the values in the table will yield a value that is slightly different than the GBP shown due to the precision of python. The -3 dB point was found using python code to calculate the average DC gain in dB across the first 50 samples after removing initial input spike data. The list of samples was then searched in order to find the point where the gain dropped by approximately 3 dB. As there was sampling involved, the exact 3 dB point could not be found, but always remains within 0.1 dB of the average value. Perhaps if more samples were taken this exact value would have been recorded by Scopy in the csv file used for calculations.

	UA741 5G 20mV	UA741 5G 50mV	UA741 5G 100mV	UA741 5G 1000mV	UA741 5G 1400mV
Average DC Gain (dB)	13.01	14.06	13.95	13.92	14.03
-3dB Log Gain	10.1	11.06	11.01	10.83	11.01
-3dB Linear Gain	3.2	3.57	3.55	3.48	3.55
-3dB Frequency (Hz)	186632	159472	153324	81735.1	62070.2
GBP	597105.55	569632.08	544709.74	284471.39	220502.31

Figure 8: GBP Values for the UA741 Inverting 5 gain amplifier across the listed drive voltages.

	UA741 20G 20mV	UA741 20G 50mV	UA741 20G 100mV	UA741 20G 200mV
Average DC Gain (dB)	24.95	26.06	25.98	25.95
-3dB Log Gain	22.01	23.03	22.94	22.86
-3dB Linear Gain	12.61	14.17	14.03	13.9
-3dB Frequency (Hz)	53037.4	47136.5	45319.2	43572
GBP	668809.18	668132.09	635868.39	605741.73

Figure 9: GBP Values for the UA741 Inverting 20 gain amplifier across the listed drive voltages.

	UA741 100G 20mV	UA741 100G 40mV	UA741 100G 50mV	UA741 100G 60mV
Average DC Gain (dB)	38.53	39.27	39.61	39.57
-3dB Log Gain	35.63	36.21	36.7	36.51
-3dB Linear Gain	60.46	64.62	68.38	66.89
-3dB Frequency (Hz)	11446	11004.7	10580.5	10580.5
GBP	692028.12	711079.58	723504.42	707695.1

Figure 10: GBP Values for the UA741 Inverting 100 gain amplifier across the listed drive voltages.

A graph of the best results for the input drive voltages is shown below. This represents the Bode plot for each amplifier at the different gains for the drive voltage listed in the legend. All graphs are presented with their data filtered to remove any inaccurate initial spike in magnitude.

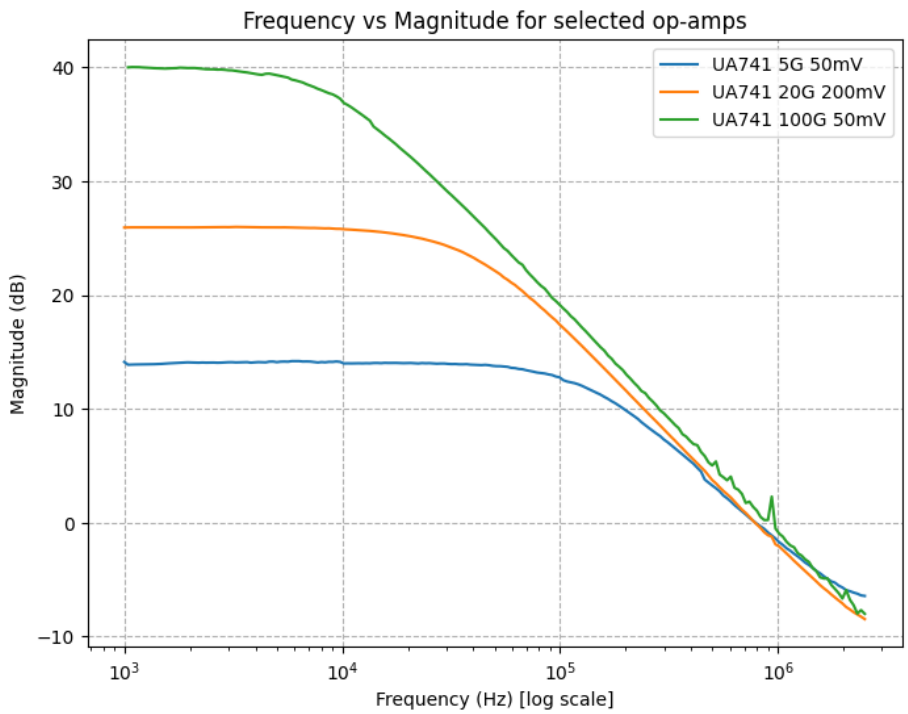

Figure 11: Comparison of "best" drive levels for UA741 configurations

Tasks 1b: Compare GBP of cascaded circuits

For the next part of this experiment, we wanted to compare the GBP from two cascaded opamps to the GBP of a single opamp. Here we cascaded the 5A UA741 with the 20A UA741 to find the GBP and compare with the 100A UA741. The table showing this cascaded configuration is shown below.

	UA741 5G 20G 20mV	UA741 5G 20G 40mV	UA741 5G 20G 50mV	UA741 5G 20G 60mV
Average DC Gain (dB)	38.68	39.85	40.12	40.22
-3dB Log Gain	35.75	36.81	37.14	37.26
-3dB Linear Gain	61.28	69.27	71.97	72.95
-3dB Frequency (Hz)	38724.2	35795.8	34415.7	33088.9
GBP	2373190	2479631	2476889	2413889

Figure 12: GBP table for the 5 gain amplifier as the first stage and the 20 gain amplifier as the second stage for the 100 total gain amplification.

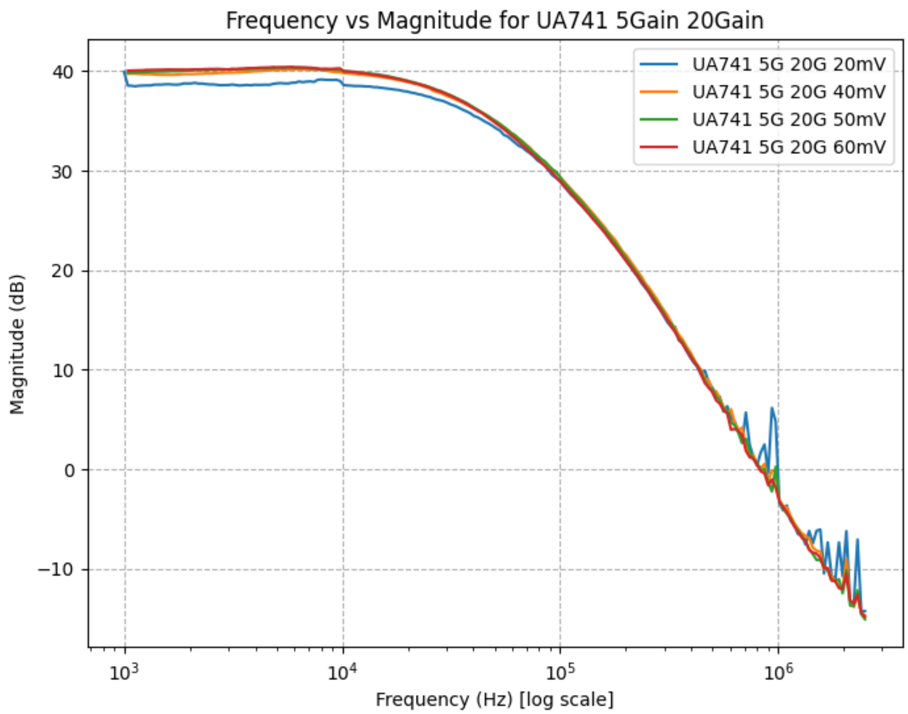

Figure 13: Cascaded configuration with the 5 gain amplifier and 20 gain amplifier as the first and second stage respectively.

We then cascaded the 20A UA741 with the 5A UA741, effectively reversing the order in which they were connected in cascade.

	UA741 20G 5G 20mV	UA741 20G 5G 40mV	UA741 20G 5G 50mV	UA741 20G 5G 60mV
Average DC Gain (dB)	38.68	39.85	40.1	40.18
-3dB Log Gain	35.74	36.88	37.03	37.24
-3dB Linear Gain	61.23	69.86	71.01	72.75
-3dB Frequency (Hz)	29407.4	27183.6	27183.6	25127.9
GBP	1800494	1898965	1930443	1828147

Figure 14: GBP table for the 20 gain amplifier as the first stage and the 5 gain amplifier as the second stage for the 100 total gain amplification.

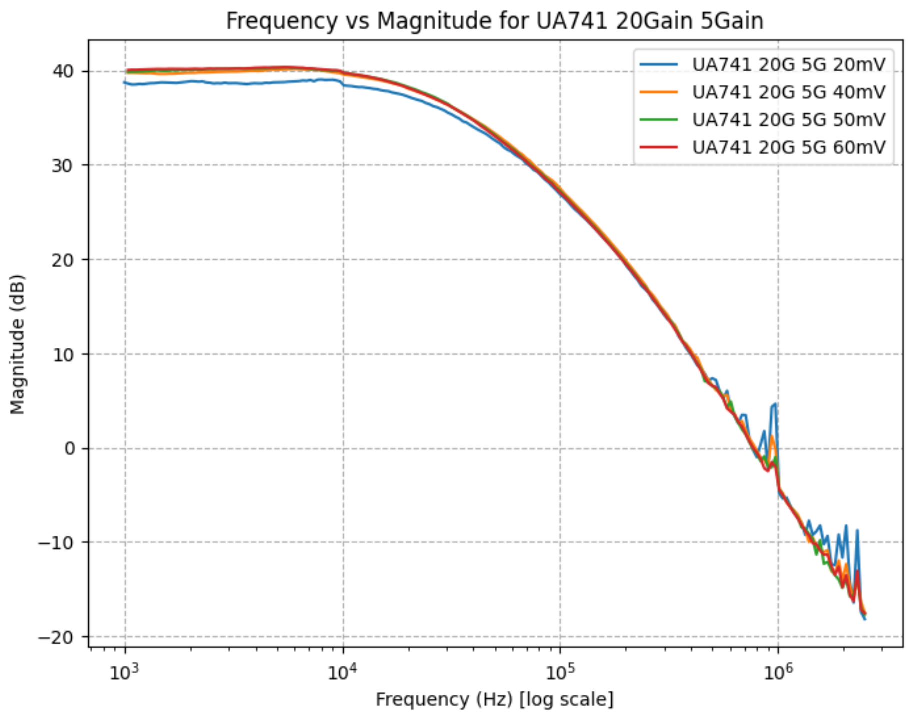

Figure 15: Cascaded configuration with the 20 gain amplifier and 5 gain amplifier as the first and second stage respectively.

We can note some differences between these setups. The first cascaded setup with the 5A feeding into the 20A we have the highest bandwidth and highest GBP. The second setup where the 20A feeds into the 5A has a BW and GBP in the middle of the first setup and the 100A opamp. The single stage x100A EB has the lowest BW and GBP. All of this is due to how the BW changes as a result of the amplification step. A graph comparing the cascaded amplifiers to the 100A UA741 is shown below along with the table from above as reference for the 100A GBP.

	UA741 100G 20mV	UA741 100G 40mV	UA741 100G 50mV	UA741 100G 60mV
Average DC Gain (dB)	38.53	39.27	39.61	39.57
-3dB Log Gain	35.63	36.21	36.7	36.51
-3dB Linear Gain	60.46	64.62	68.38	66.89
-3dB Frequency (Hz)	11446	11004.7	10580.5	10580.5
GBP	692028.12	711079.58	723504.42	707695.1

Figure 16: GBP Values for the UA741 Inverting 100 gain amplifier across the listed drive voltages.

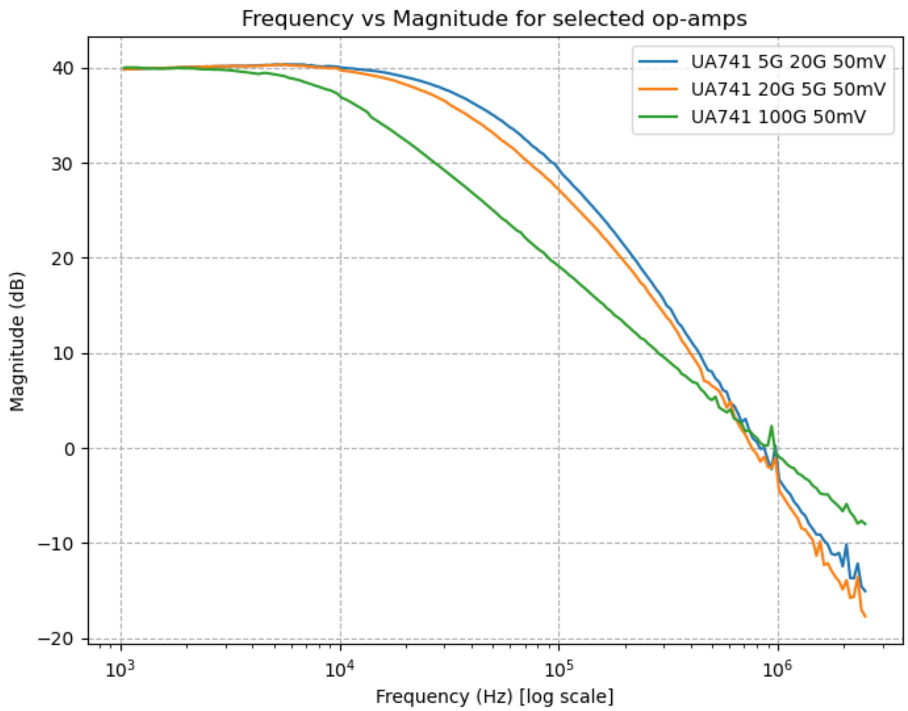

Figure 17: Comparison of frequency response for cascaded opamps vs single opamp

Task 1c: Characterize high-performance opamp circuits

In order to make sure we operate the equipment properly, we wanted to know the minimum signal for the network analyzer of Scopy that it could source and read. This turns out to be 1 mV p-p.

For the final task of the experiment, we wanted to compare some high-performance opamps. Prior to this, we were given some data sheets for each opamp in order to determine some of their specifications and appropriate values to use for our input drive voltages.

Once we had the appropriate information for each opamp, we established a range of drive input voltages to use based on the gain of each amplifier. The values for the nominal gain as well as the actual gain based on the resistor values of the EB are shown below along with a table of drive voltages for each amplifier. The output voltage swing is the typical value as stated in the data sheet for each amplifier. The maximum input voltage is calculated based on this output voltage swing and the actual gain.

The equation used for the actual gain is based on an ideal non-inverting amplifier gain equation. The maximum input voltage is calculated using this actual gain along with the output voltage swings from each of the amplifiers data sheet.

$$A = 1 + \frac{R_1}{R_2} \tag{4}$$

$$V_{in,max} = \frac{V_{o,swing}}{A} \tag{5}$$

AD797	
Nominal Gain	15
Resistor 1 (Ohms)	681
Resistor 2 (Ohms)	49.9
Actual Gain	14.647
Output Voltage Swing	3
Maximum Input Voltage	0.205

Figure 18: Values for the AD797 Non-Inverting amplifier

AD848	
Nominal Gain	10
Resistor 1 (Ohms)	475
Resistor 2 (Ohms)	49.9
Actual Gain	10.519
Output Voltage Swing	4.6
Maximum Input Voltage	0.437

Figure 19: Values for the AD848 Non-Inverting amplifier

ADA4898-1	
Nominal Gain	10
Resistor 1 (Ohms)	475
Resistor 2 (Ohms)	49.9
Actual Gain	10.519
Output Voltage Swing	4.4
Maximum Input Voltage	0.418

Figure 20: Values for the AD4898-1 Non-Inverting amplifier

LMH6624	
Nominal Gain	100
Resistor 1 (Ohms)	4990
Resistor 2 (Ohms)	49.9
Actual Gain	101
Output Voltage Swing	4.9
Maximum Input Voltage	0.0485

Figure 21: Values for the LMH6624 Non-Inverting amplifier

Drive Voltages			
AD797	AD848	ADA4898-1	LMH6624
20 mV	20 mV	20 mV	20 mV
40 mV	40 mV	40 mV	60 mV
50 mV	50 mV	50 mV	
100 mV	100 mV	100 mV	
200 mV	200 mV	200 mV	

Figure 22: Input drive voltage settings for each amplifier.

The Scopy settings are shown in the table below and were used for each of the high-performance amplifiers.

Task 1c Scopy Setting	
Sample	200
Start	50 kHz
Stop	25 MHz
Period	10
Average	10

Figure 23: Scopy settings used for all high performance amplifiers

The GBP was calculated using the same method applied to the UA741. The tables for each of the amplifiers is shown below along with a Bode plot using the data determined to be the "best" input voltage of 50 mV.

	AD797 20mV	AD797 40mV	AD797 50mV	AD797 100mV	AD797 200mV
Average DC Gain (dB)	23.11	23.55	23.34	23.37	23.36
-3dB Log Gain	20.03	20.51	20.44	20.47	20.35
-3dB Linear Gain	10.03	10.6	10.52	10.56	10.41
-3dB Frequency (Hz)	7395990	6948180	6734540	4776600	2809010
GBP (Hz)	74205538	73667522	70819513	50445087	29238379

Figure 24: Table for AD797 data showing measured gains and calculated GBP based on the displayed cutoff frequency.

	AD848 20mV	AD848 40mV	AD848 50mV	AD848 100mV	AD848 200mV
Average DC Gain (dB)	20.21	20.66	20.45	20.49	20.48
-3dB Log Gain	17.23	17.69	17.27	17.49	17.35
-3dB Linear Gain	7.27	7.67	7.3	7.49	7.37
-3dB Frequency (Hz)	16658100	16658100	17186500	16658100	16658100
GBP (Hz)	1.21E+08	1.28E+08	1.26E+08	1.25E+08	1.23E+08

Figure 25: Table for AD848 data showing measured gains and calculated GBP based on the displayed cutoff frequency.

	ADA4898-1 20mV	ADA4898-1 40mV	ADA4898-1 50mV	ADA4898-1 100mV	ADA4898-1 200mV
Average DC Gain (dB)	20.2	20.66	20.45	20.49	20.48
-3dB Log Gain	17.04	17.77	17.36	17.35	17.46
-3dB Linear Gain	7.11	7.73	7.38	7.37	7.47
-3dB Frequency (Hz)	9495050	9203110	9495050	9203110	7630600
GBP (Hz)	67499764	71173711	70038568	67832780	56974259

Figure 26: Table for AD4898-1 data showing measured gains and calculated GBP based on the displayed cutoff frequency.

	LMH6624 20mV	LMH6624 40mV
Average DC Gain (dB)	39.59	40
-3dB Log Gain	36.57	36.92
-3dB Linear Gain	67.41	70.13
-3dB Frequency (Hz)	4629740	4629740
GBP (Hz)	3.12E+08	3.25E+08

Figure 27: Table for LMH6624 data showing measured gains and calculated GBP based on the displayed cutoff frequency.

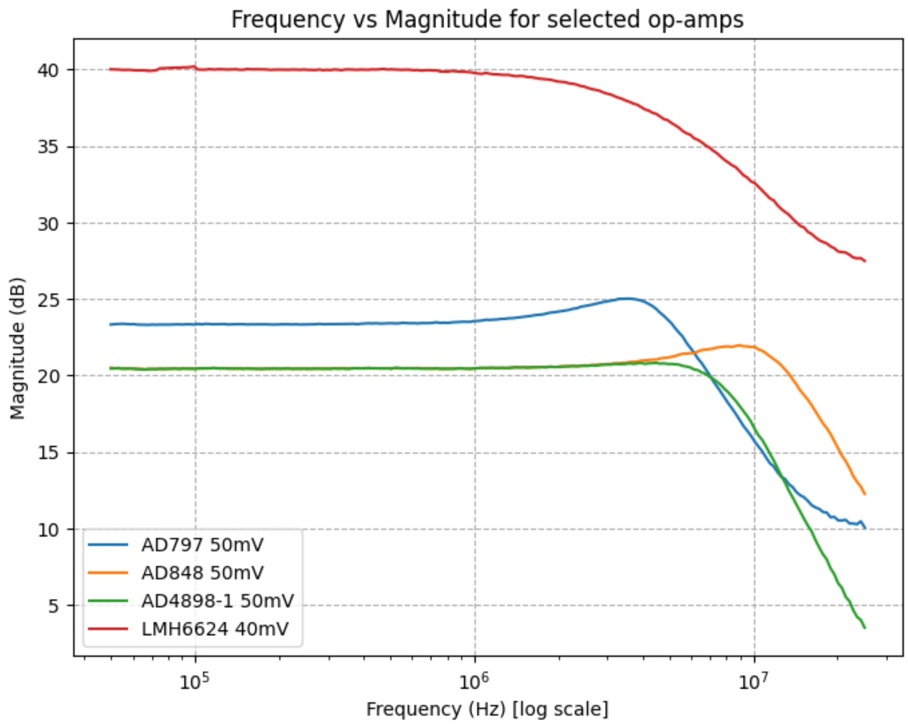

Figure 28: Comparison of frequency response for high quality opamps

Appendix

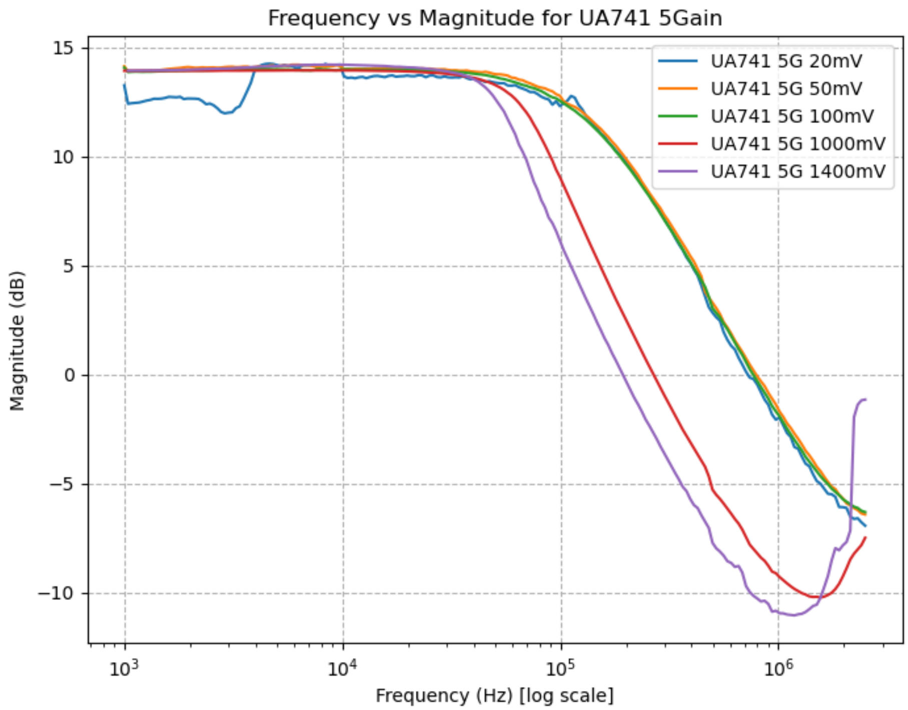

Figure 29: Comparison of frequency response for the UA741 5 gain inverting opamp

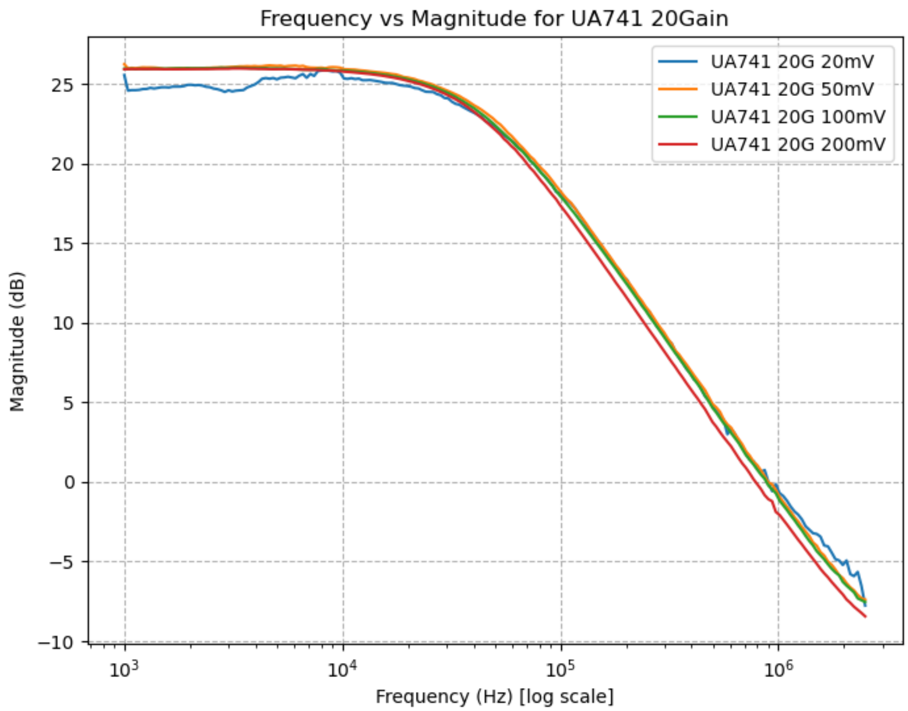

Figure 30: Comparison of frequency response for the UA741 20 gain inverting opamp

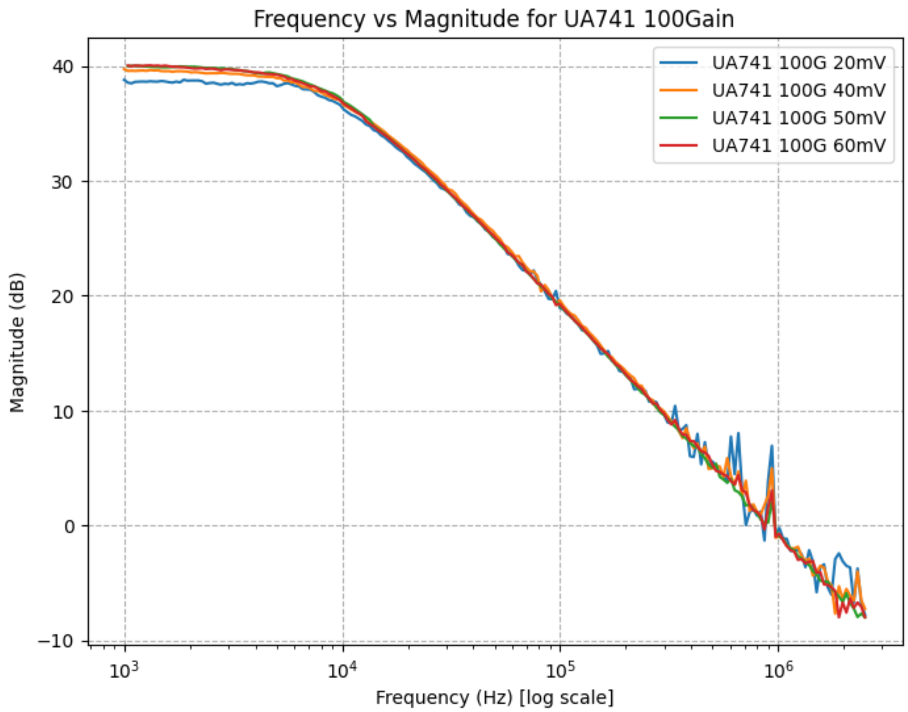

Figure 31: Comparison of frequency response for the UA741 100 gain inverting opamp

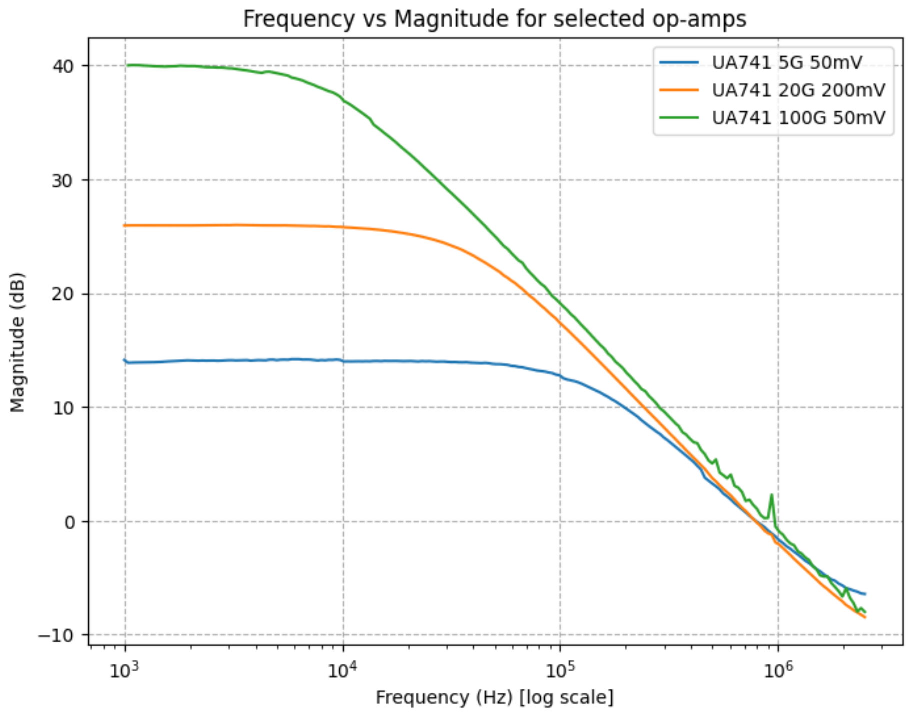

Figure 32: Comparison of “best” drive levels for UA741 configurations

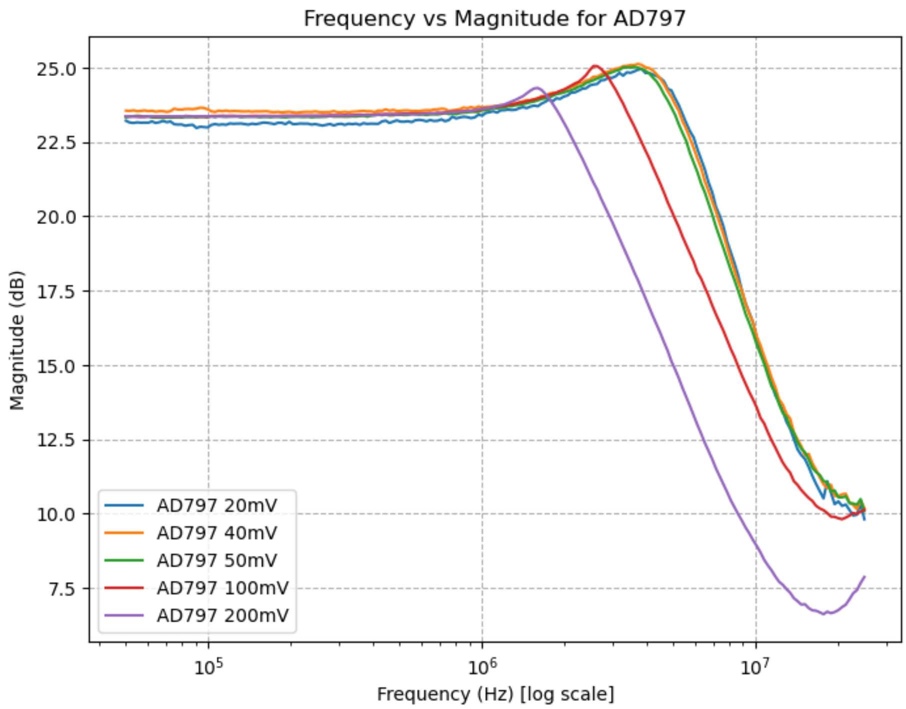

Figure 33: Comparison of frequency response for the AD797 non-inverting opamp

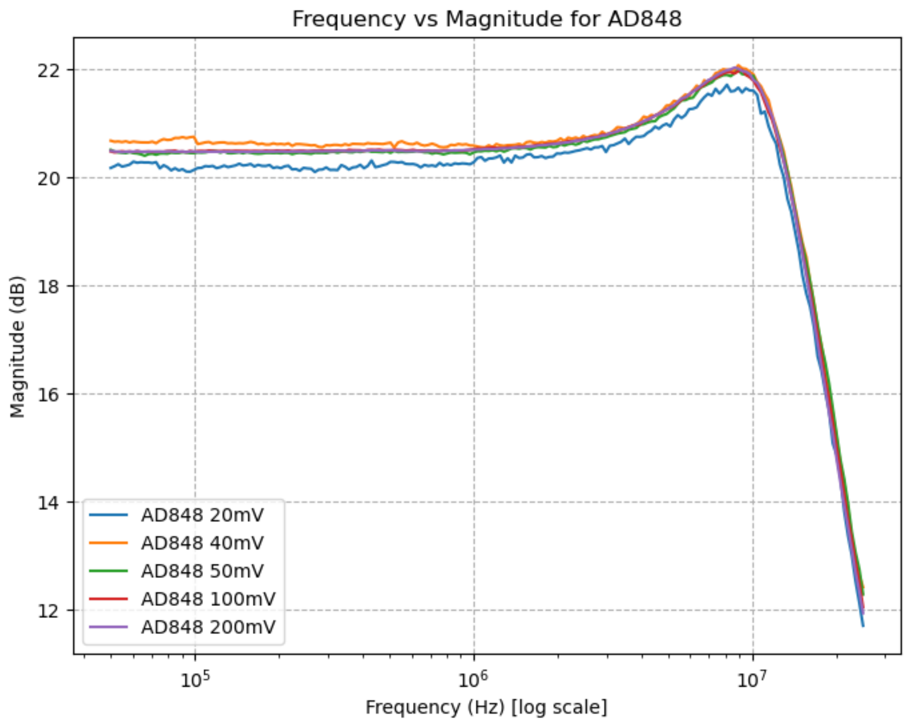

Figure 34: Comparison of frequency response for the AD848 non-inverting opamp

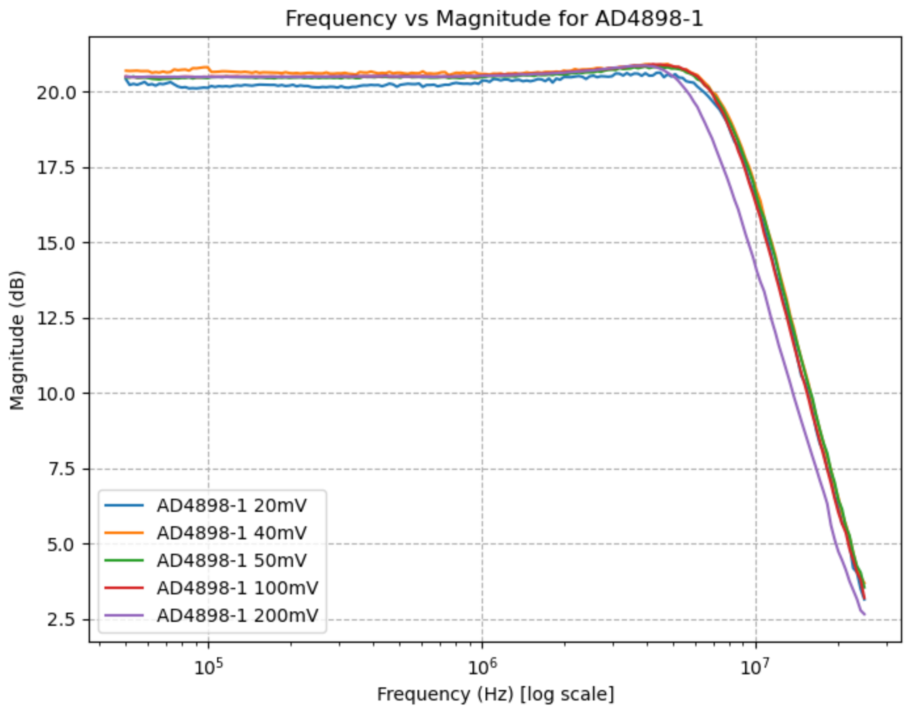

Figure 35: Comparison of frequency response for the AD4898-1 non-inverting opamp

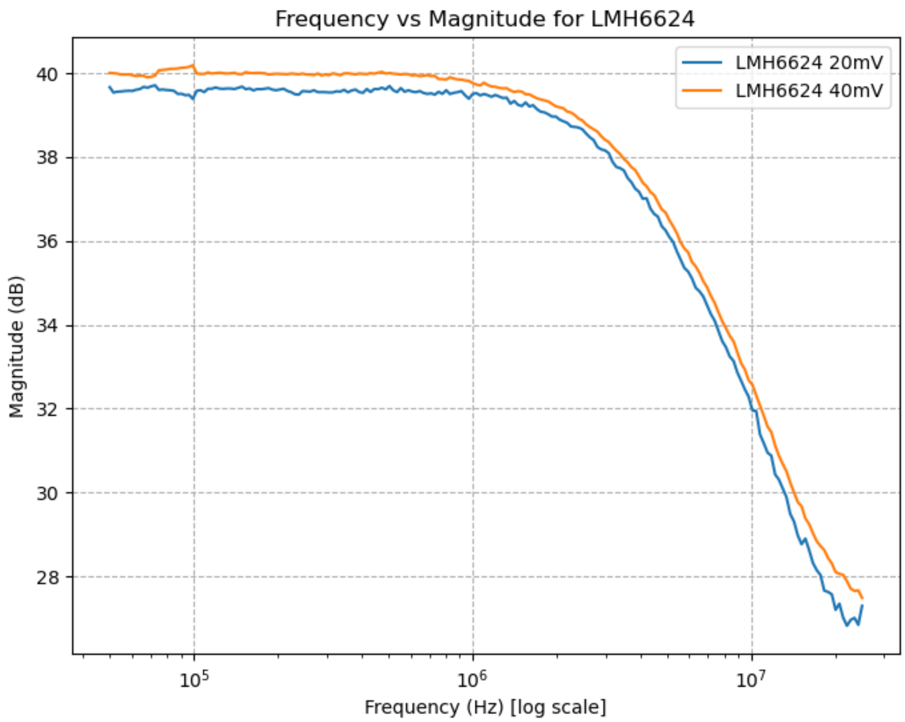

Figure 36: Comparison of frequency response for the LMH6624 non-inverting opamp

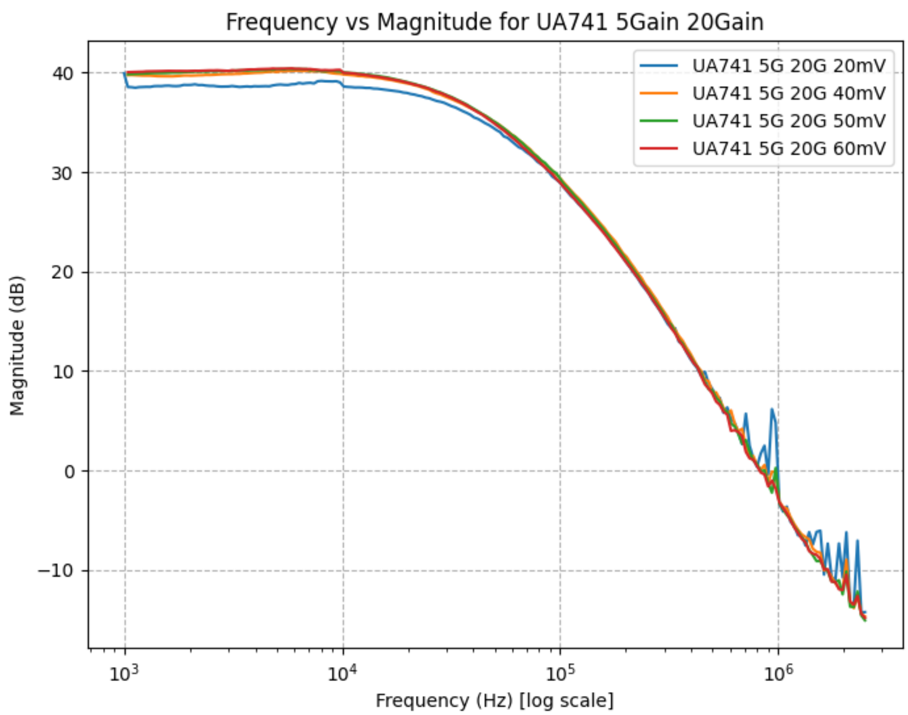

Figure 37: Comparison of frequency response for the UA741 5 gain cascaded with 20 gain inverting opamp

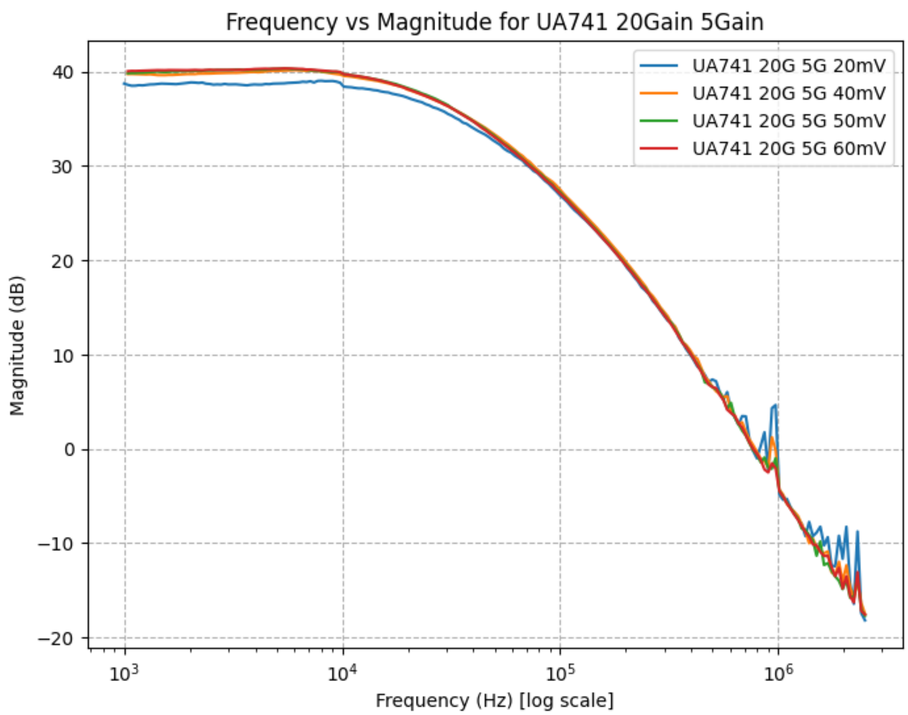

Figure 38: Comparison of frequency response for the UA741 20 gain cascaded with 5 gain inverting opamp

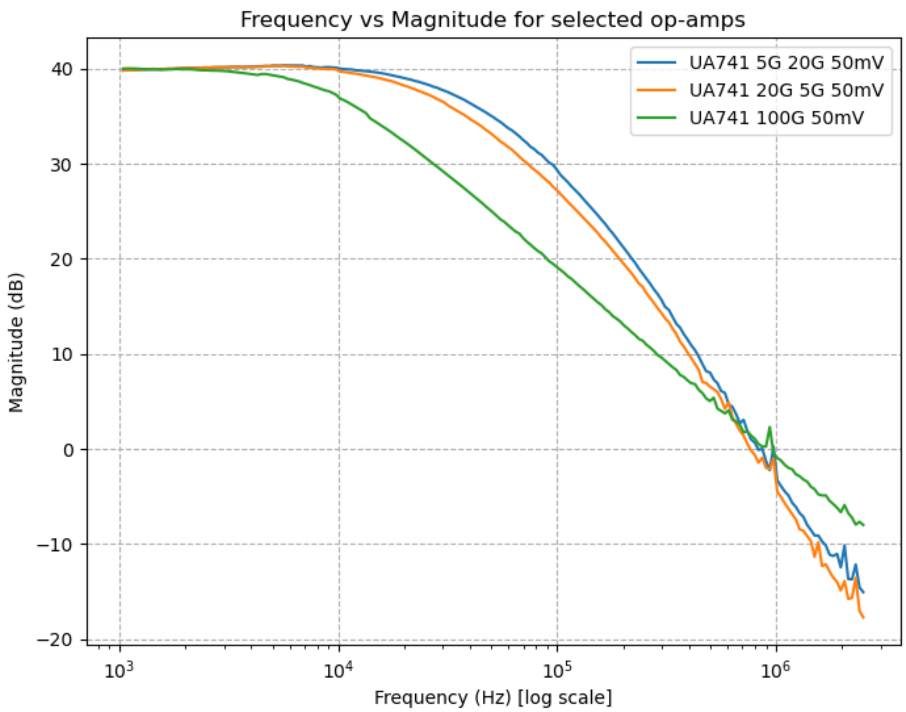

Figure 39: Comparison of frequency response for cascaded opamps vs single opamp

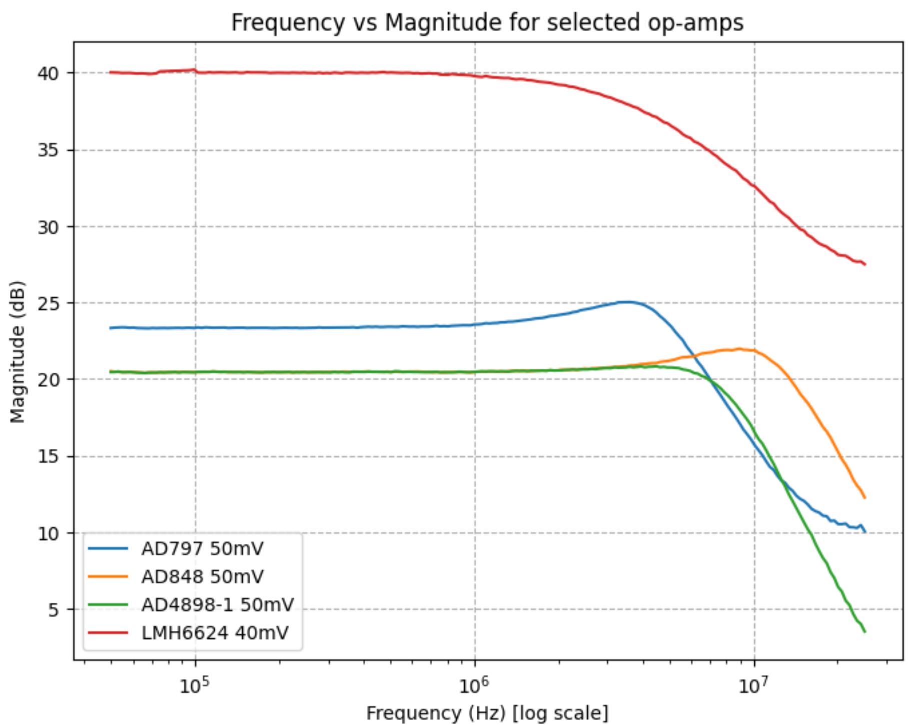

Figure 40: Comparison of frequency response for high quality opamps

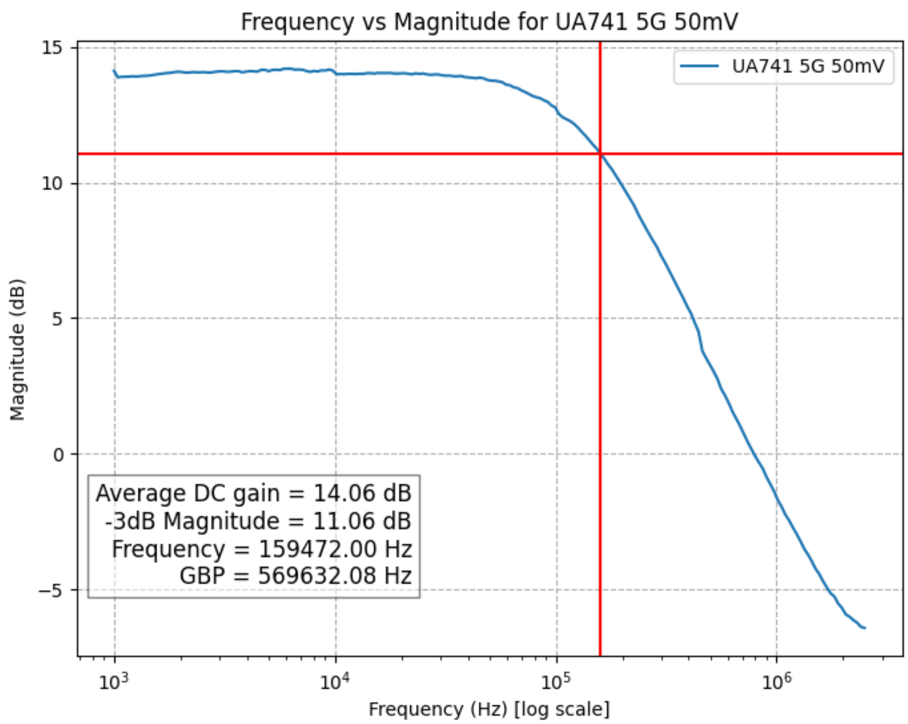

Figure 41: UA741 5G showing -3dB point

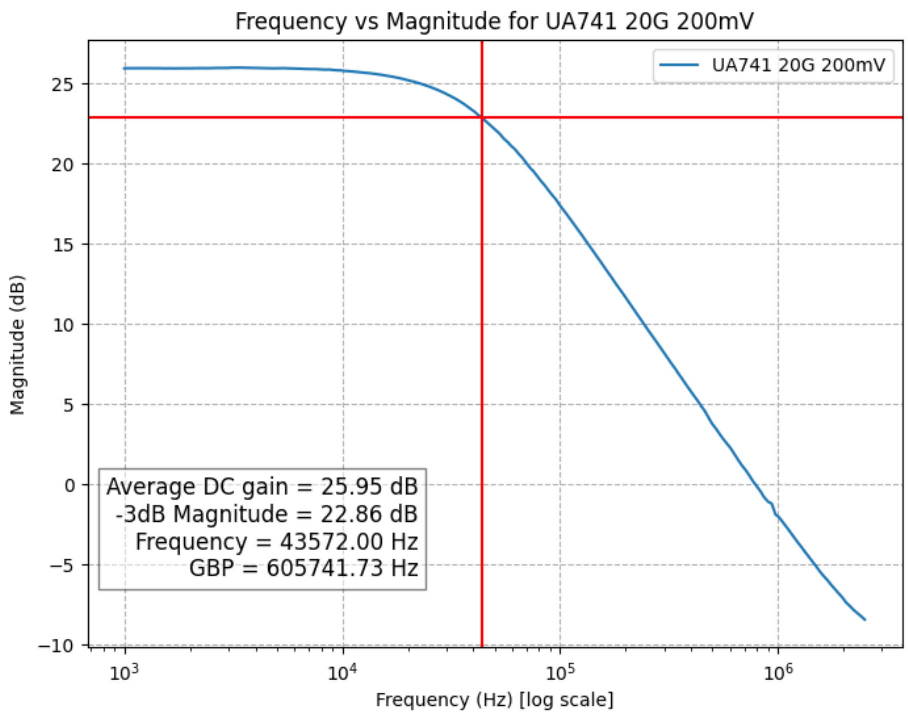

Figure 42: UA741 20G showing -3dB point

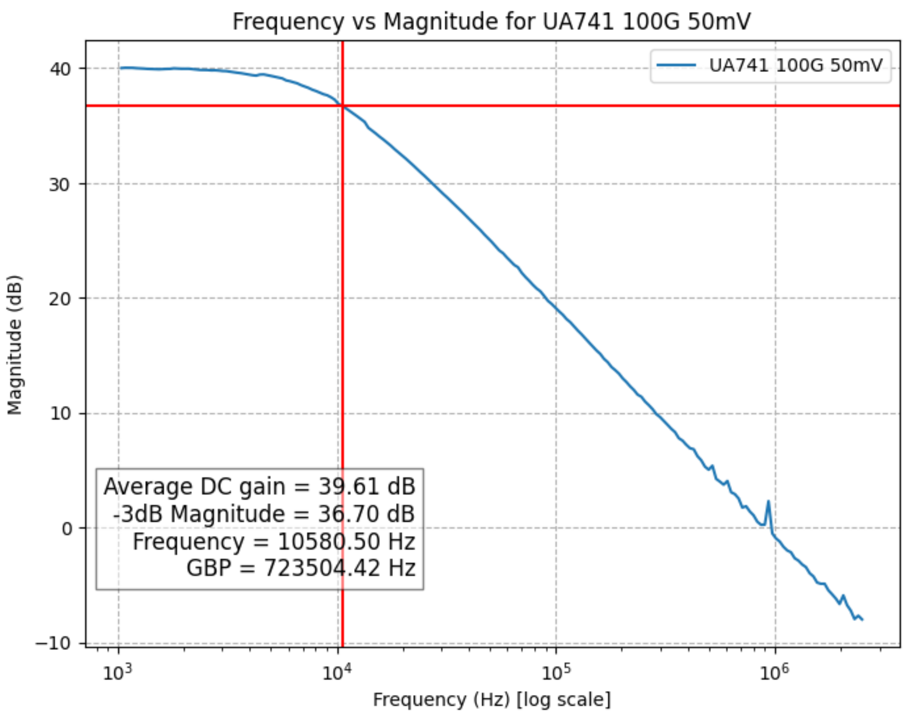

Figure 43: UA741 100G showing -3dB point

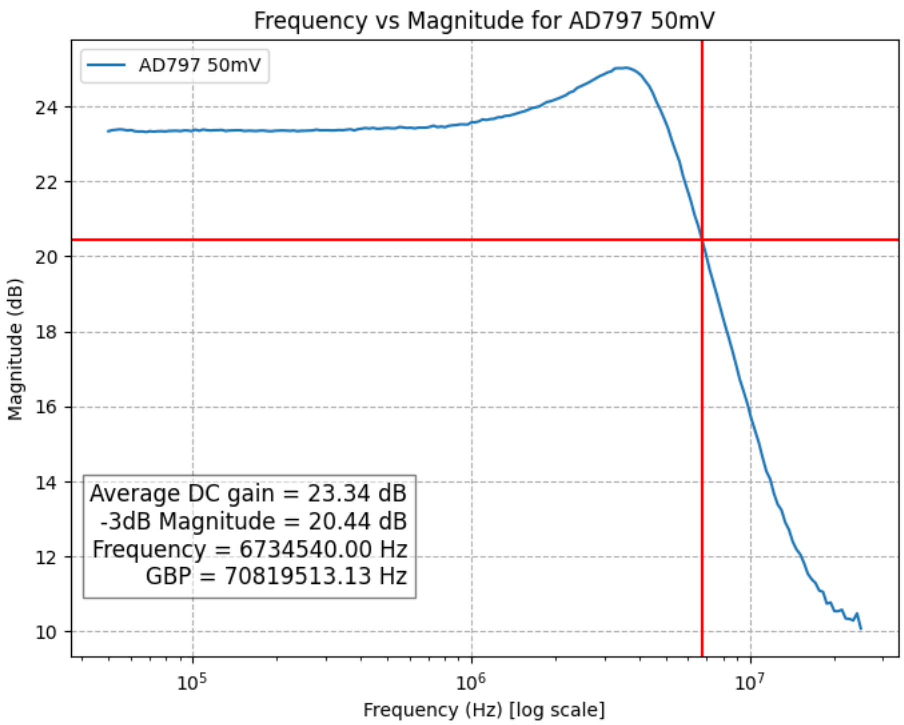

Figure 44: AD797 showing -3dB point

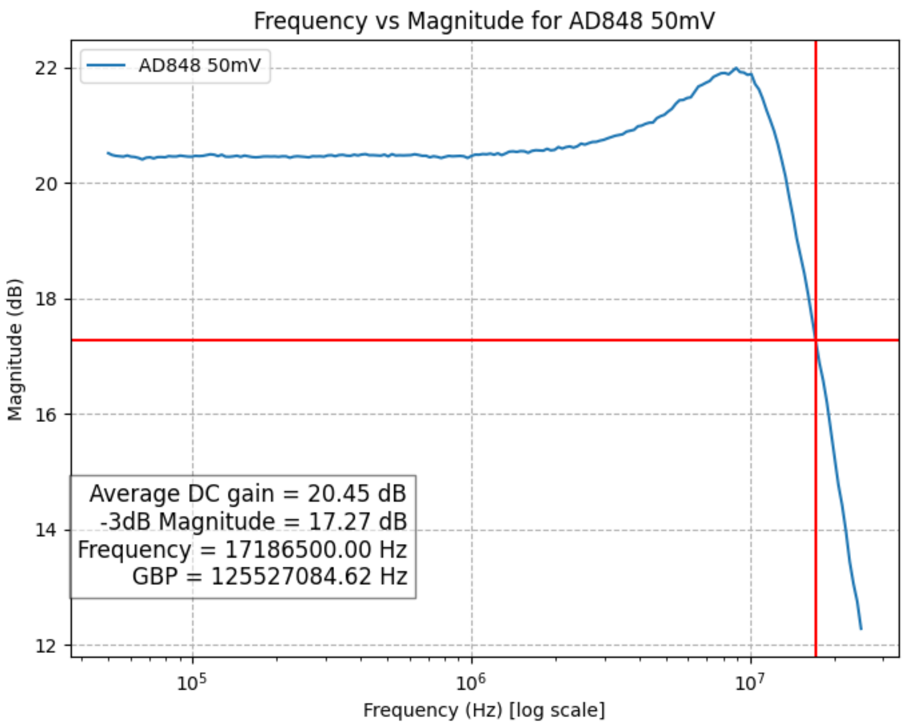

Figure 45: AD848 showing -3dB point

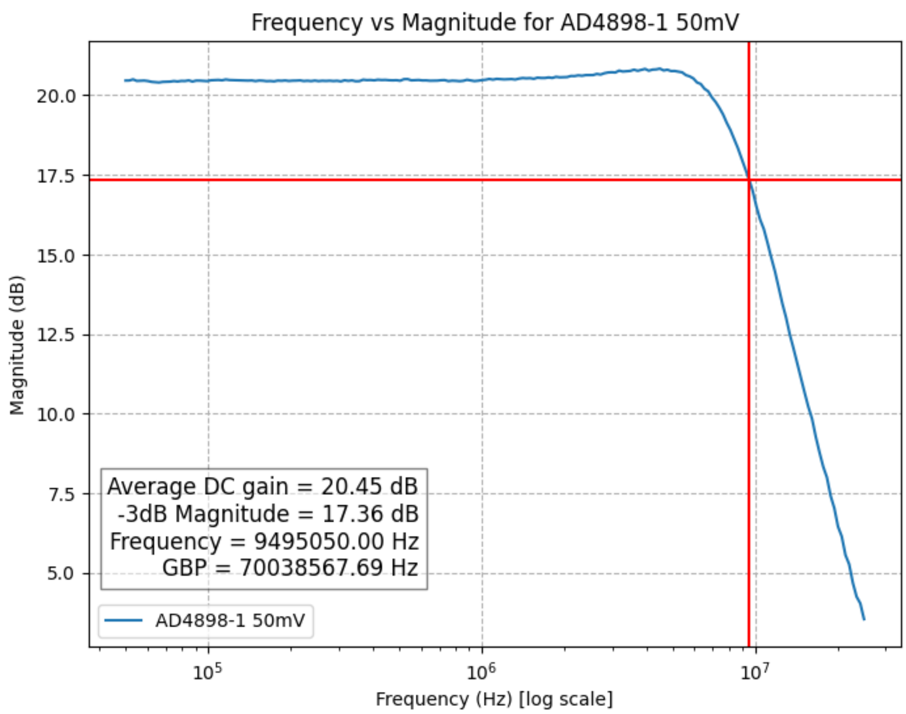

Figure 46: AD4898-1 showing -3dB point

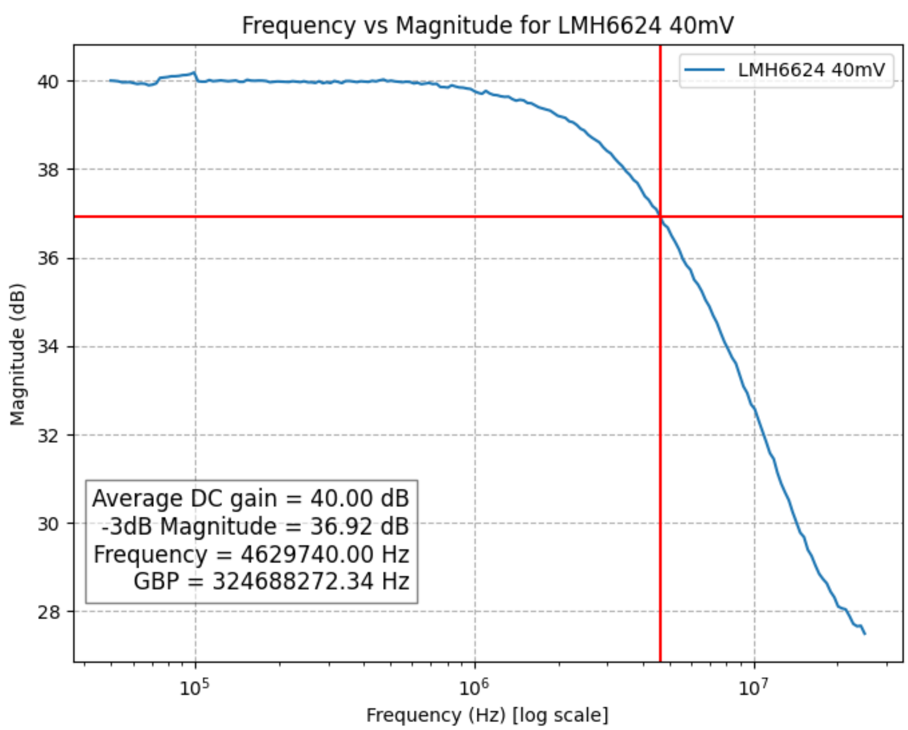

Figure 47: LMH6624 showing -3dB point

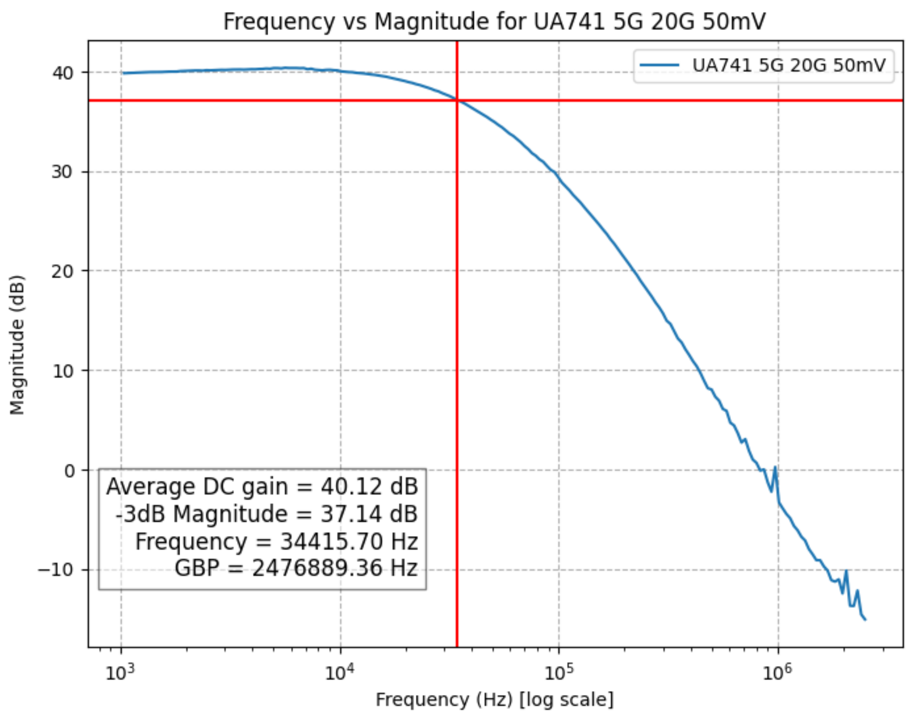

Figure 48: UA741 5G cascaded to 20G showing -3dB point

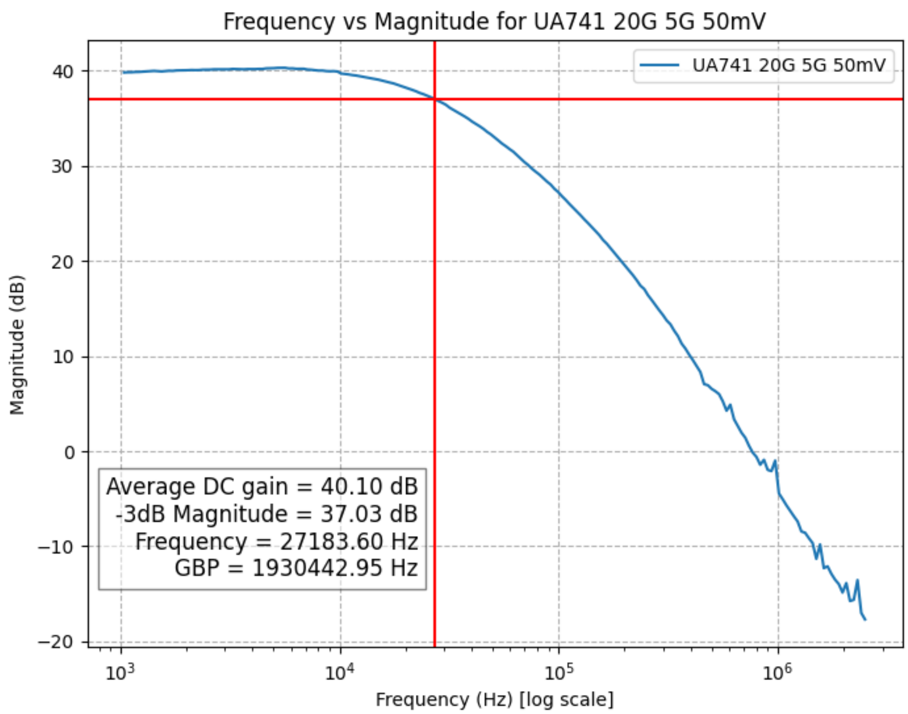

Figure 49: UA741 20G cascaded to 5G showing -3dB point