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Signal Integrity Over Long Cables

Sandia National Laboratories

Thursday, July 30, 2015 – Mark Olsen – Dept. 5358

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Abstract

The purpose of this project is to research and mitigate signal integrity issues in long cables. Laboratory tests were performed using various cables and prototype boards to simulate different signal communication methods. The most valuable knowledge obtained thus far has been: The best two cables (PE-C200, and RG58-C/U), the lack of effect that substrate material plays in signal integrity at the frequencies of interest, and the need for 50 Ω termination schemes regardless of input impedance.

Introduction

The motivation for this project comes from the loss of signal integrity that occurs in hardware testing where signals are carried over long distances at high frequencies. In engineering, cables are often used to transmit data from products to testing equipment. Problems can occurs when the cables become so long, that the signals are distorted in transmission between hardware. This effect often begins to have a noticeable effects when the cable length is a quarter of the signal wavelength, but can be noticed at much smaller cable lengths. For example, in radiation testing of hardware in the Annular Core Research Reactor (ACRR) long cables must be used due to the length of the reactor. Because this testing is performed in radiation environments, it is not possible to place additional integrated circuits in the reactor as a way to amplify the signal. Therefore this project looks to determine what cable, and termination configuration will yield the lowest amount of distortion in transmitting signals.

Methods

In order to understand the best electrical configuration for signal integrity, a series of tests were performed during signal transmission that varied: signal frequency, source impedance, load impedance, cabling type, and substrate material used. A depiction of this test setup is shown in Figure 1.

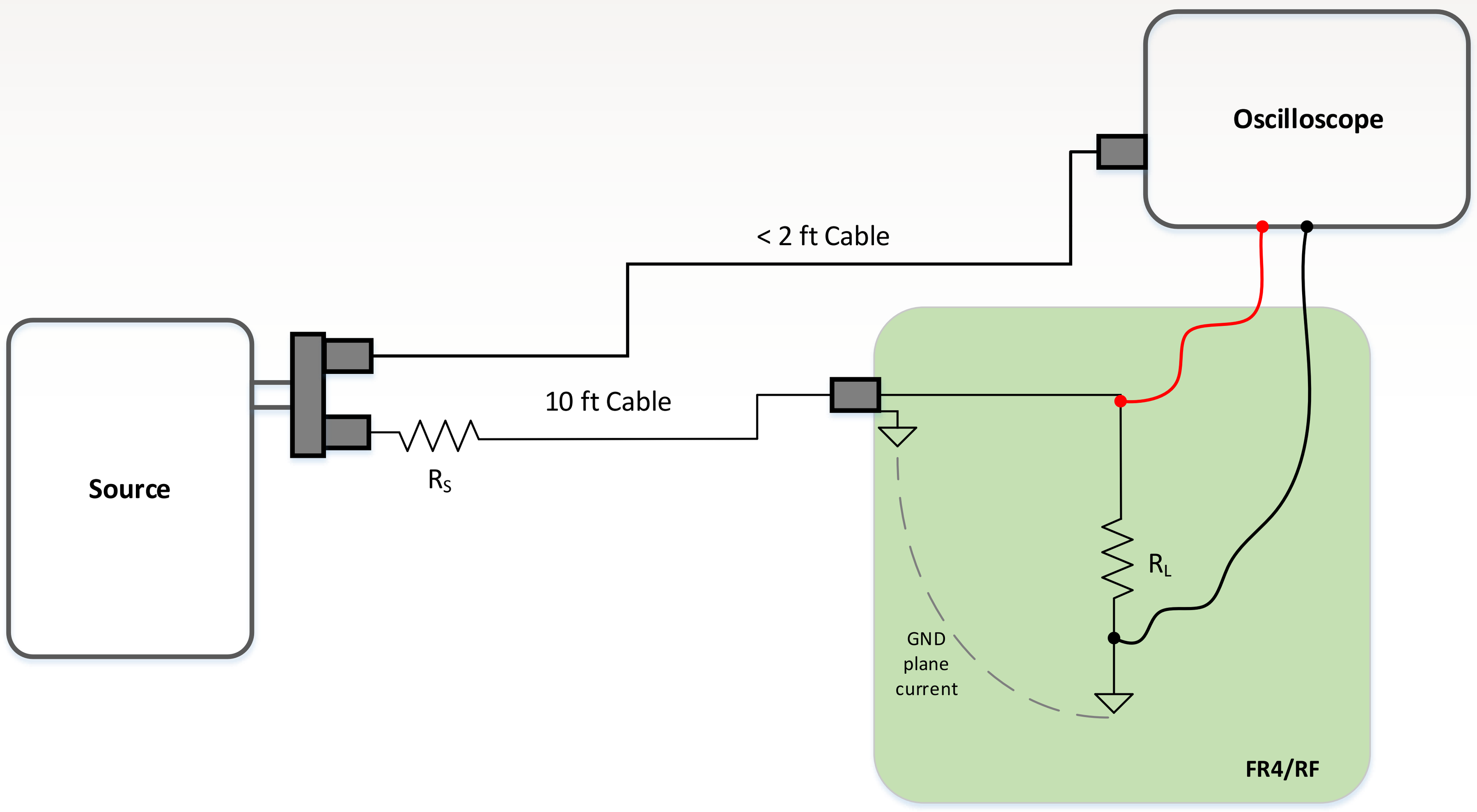

Figure 1: Illustration of setup where R_L denotes the various load configurations that are tested. The ten foot cable represents all ten different types of cable to be tested.

Figure 1 represents all of these parameter changes: First, the source impedance represented by R_S, and controlled by the function generator was either 50 Ω or set to high impedance. Second, the cable type, represented in Figure 1 by the ten foot cable, was changed to test each cable type described in Table 1. Third, the load impedance, as represented by R_L in Figure 1, was changed between three different configurations A, B and C respectively: two 1 MΩ resistors with a 50 Ω resistor in parallel, 1 MΩ and 50 Ω resistor in parallel, and a 1 MΩ resistor. These different configurations can be seen in schematic form in Figure 2. Lastly, the type of board material, either RF or FR4, was changed by having two identically laid out boards with their only difference being the substrate material.

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Methods Continued

Equipment Used

- Agilent 33500B Series True Waveform Generator
- Tektronix Oscilloscope
- Miscellaneous measurement and cabling equipment

Cables used

All cables listed are ten feet in length.
LMR-195, PE-C195, PE-C200, RG6A-U, RG58C-U, RG58-P, RG59B-U, RG213-U, RG216-U, RG223-U

Table 1: Cable Legend

Cable #	P/N
1	LMR-195
2	PE-C195
3	PE-C200
4	RG6A-U
5	RG58C-U
6	RG58-P
7	RG59B-U
8	RG213-U
9	RG216-U
10	RG223-U

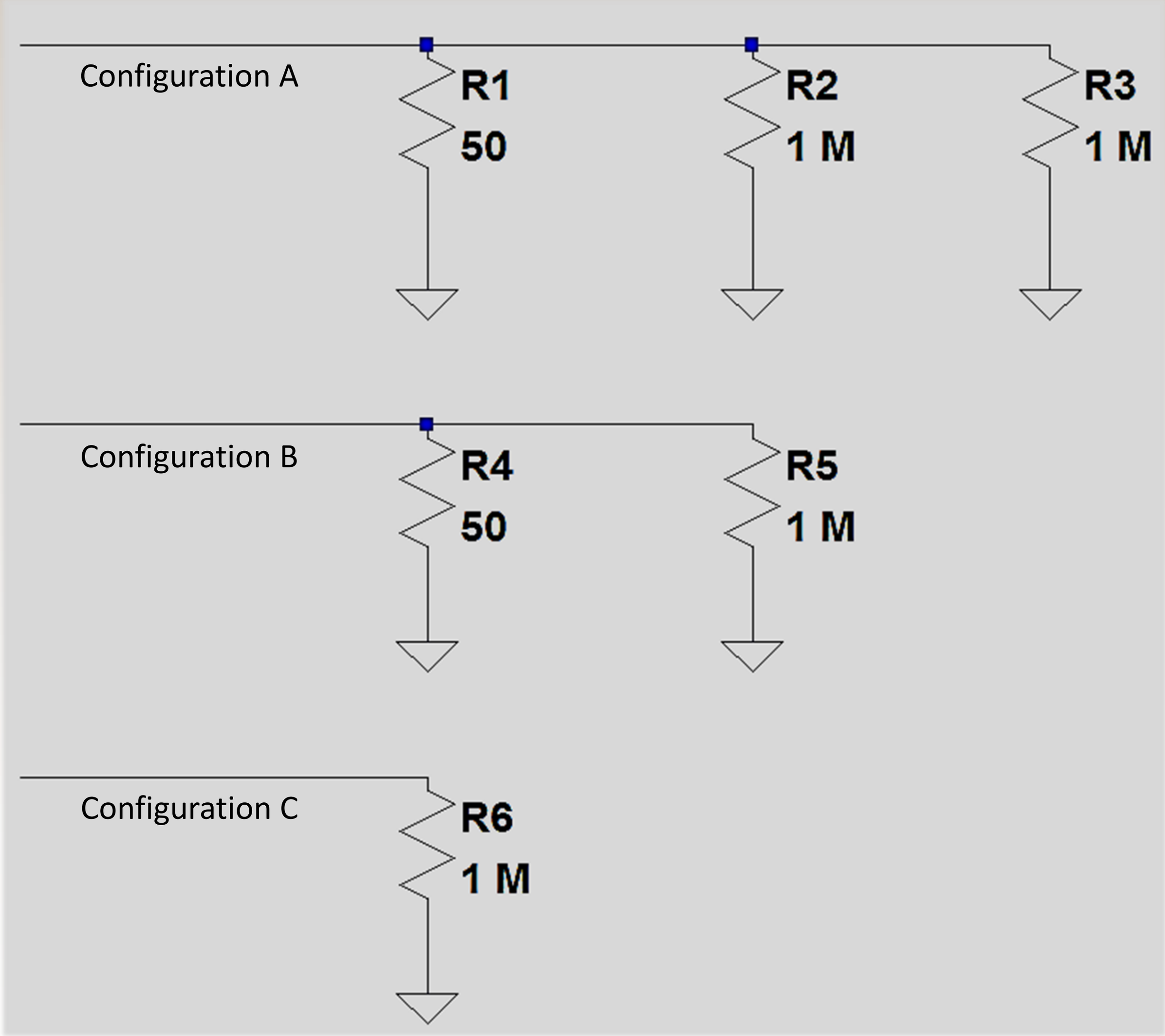

Figure 2: Schematic of different load configurations A, B, and C.

The integrity of a signal was analyzed by comparing the voltage value of the input wave to the waveform voltage value across the load resistor using values taken from the oscilloscope. An example waveform for the testing of RG6A-U cable with a 500 kHz, high input impedance, $5V_{p-p}$ waveform and terminated by a 1 MΩ resistor on FR4 material is shown in Figure 3.

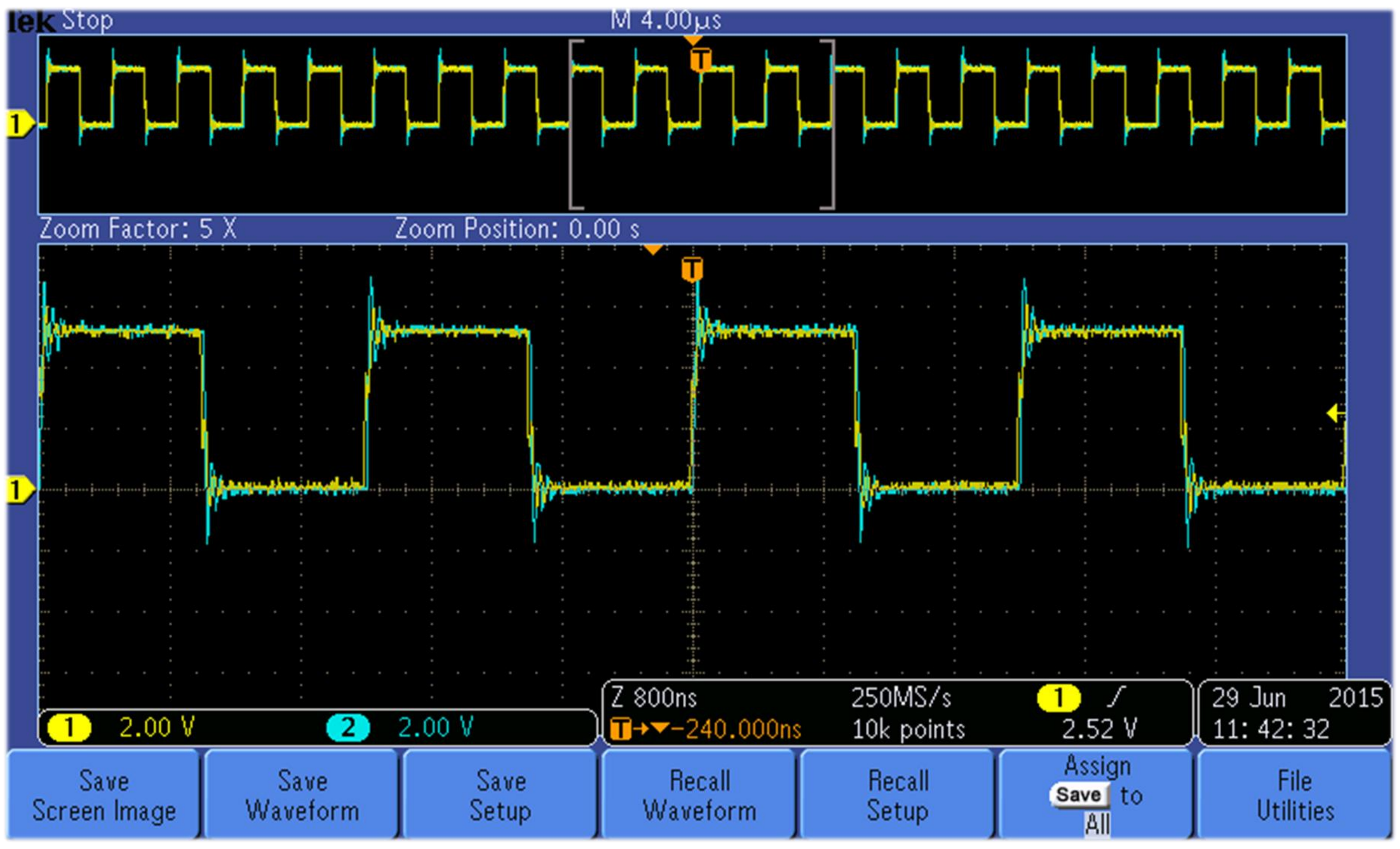

Figure 3: Screen image of oscilloscope for signal test with RG6A-U cable, and a 500 kHz, 5Vp-p waveform applied to it.

The yellow signal in Figure 3 represents the input waveform, and the blue signal represents the load waveform seen across the 1 MΩ resistor. An excel file was then extracted from the oscilloscope having the amplitude values for each waveform corresponding to ten-thousand data points in time. Matlab was then used to compute the average absolute difference between the two signals at each data point.

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Results

The measured effects of varying each parameter, with the exception of frequency, were small, but for certain parameters the results followed general trends. A series of different tests were performed to determine the best cable. Each cable type was measured under the single 1 MΩ termination at frequencies of 2 kHz, 32 kHz, 500 kHz, and 30 MHz. Both 50 Ω and High Z input impedances were used. Figure 4 shows a graphical representation of the average voltage error versus the logarithm of the frequency.

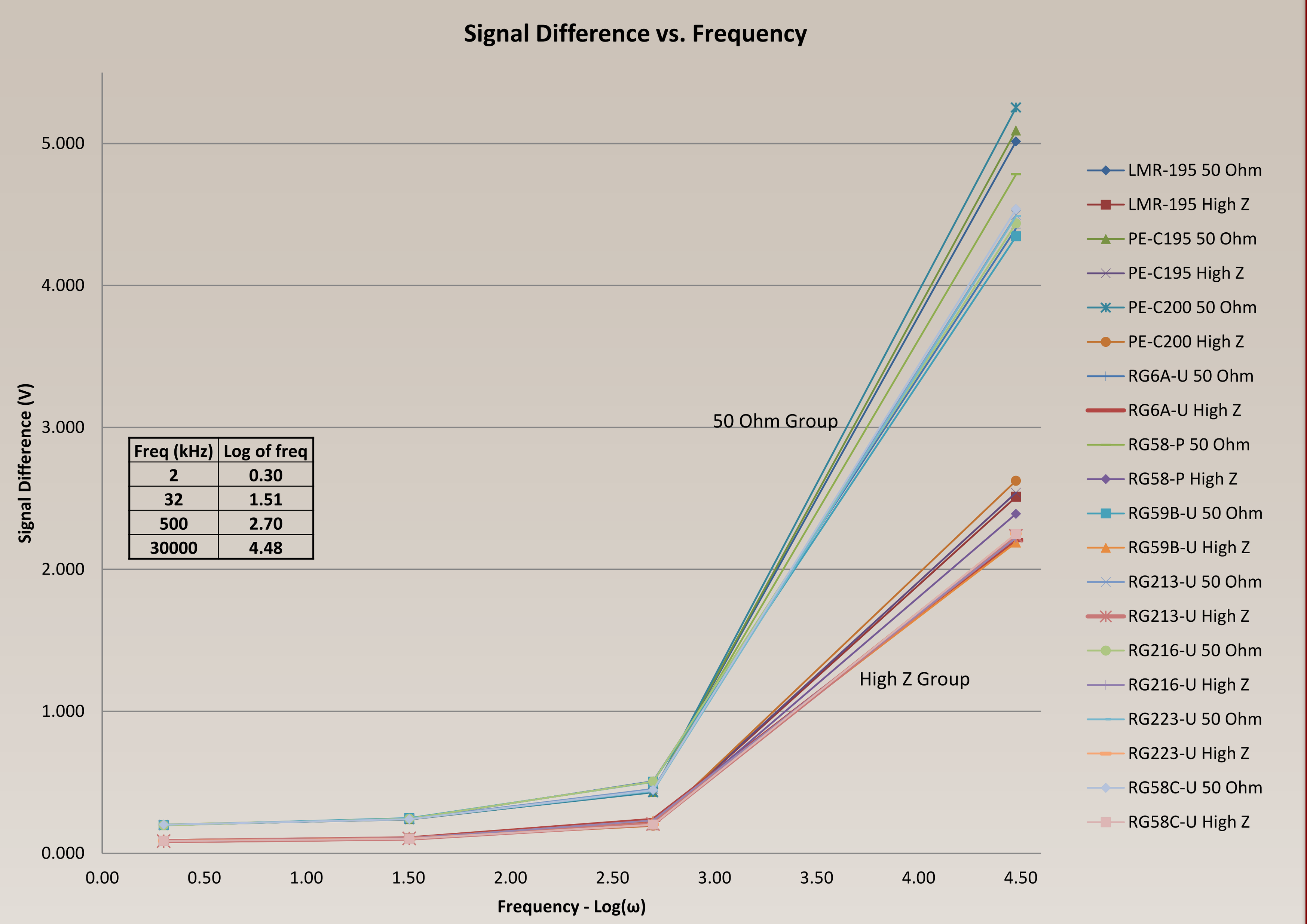

Figure 4: Figure # Signal difference for each cable across all four frequencies on a log scale.

However, from this graph it was difficult to determine which cable performed best because of the shear number of data points. One of the results that is apparent though was that at low frequencies, such as 2 and 32 kHz, the voltage differences were so small that it would be impossible to decipher which cable was best. Therefore a column graph was created as shown in Figure 5 displaying only 500 kHz and 30 MHz results.

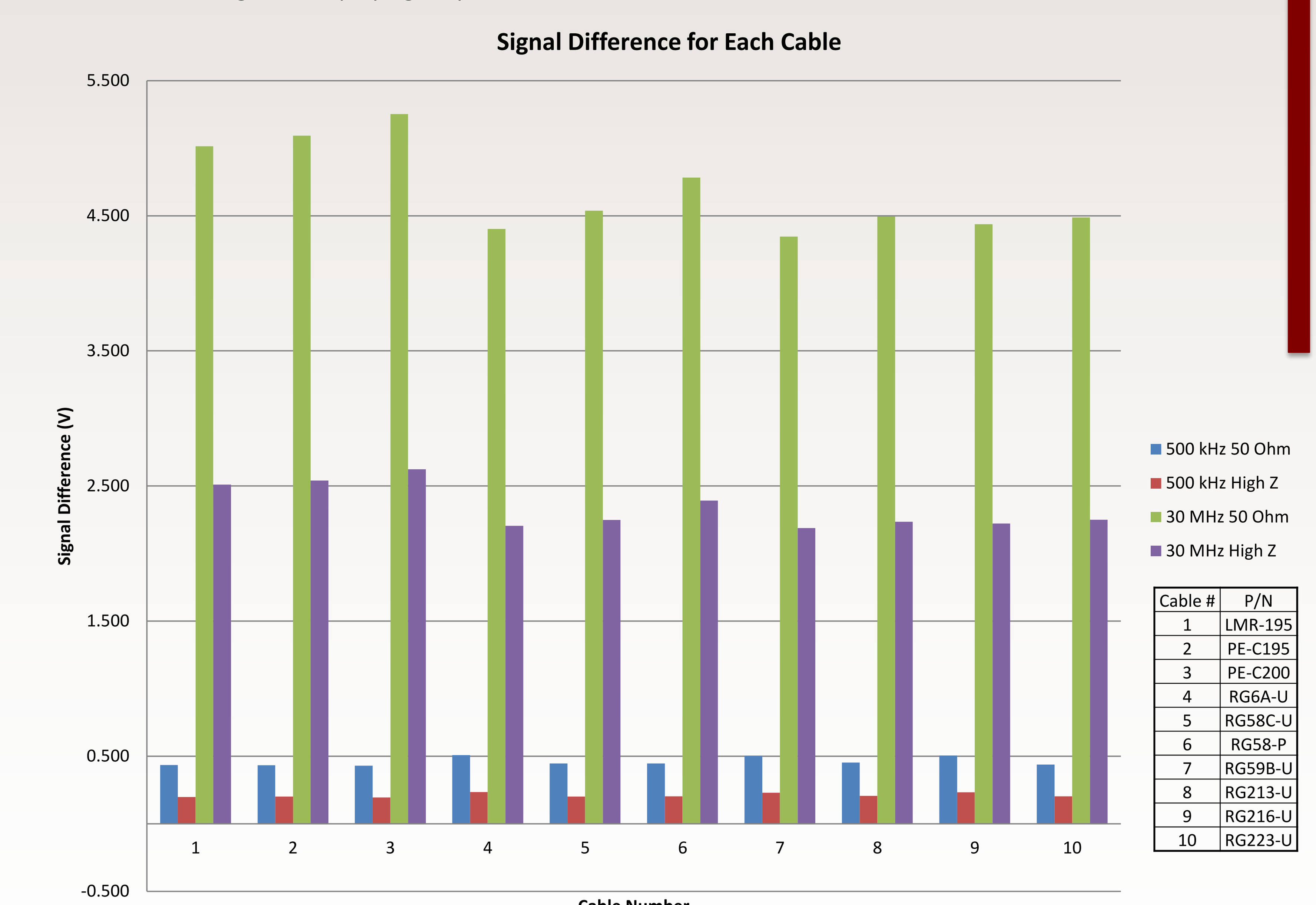

Figure 5: Column plot of error for all combinations of 500 kHz, 30 MHz, 50Ω input, and High Z input.

From Figure 5, it can be seen that the best two cables are Cable #3, and Cable #7; which correspond to cable type PE-C200, and RG59B-U. Cable #3 has the lowest error for the 500 kHz frequency, and cable #7 has the lowest error for the 30 MHz frequency.

Based off of this, a series of tests, specifically Test 1-48, were then performed using Cable #4 that varied the type of board material, the frequency, and the input impedance. Table 2 describes Tests 1-48 that were performed. Tests 25-48 are an exact copy of tests 1-24 with the only difference being the type of board material used; Tests 1-24 used RF, and Tests 25-48 used FR4. By comparing these to sets of data, the difference between the material types can be compared across a broad range of configurations. Figure 6 then shows a bar graph of the difference between the signal differences of Tests 1-24 and Tests 25-48. For example data point "1" in Figure 6 corresponds to the signal difference of Test 1 subtracted from Test 25. A positive difference indicates the RF substrate being better, and a negative difference indicates the FR4 substrate being better.

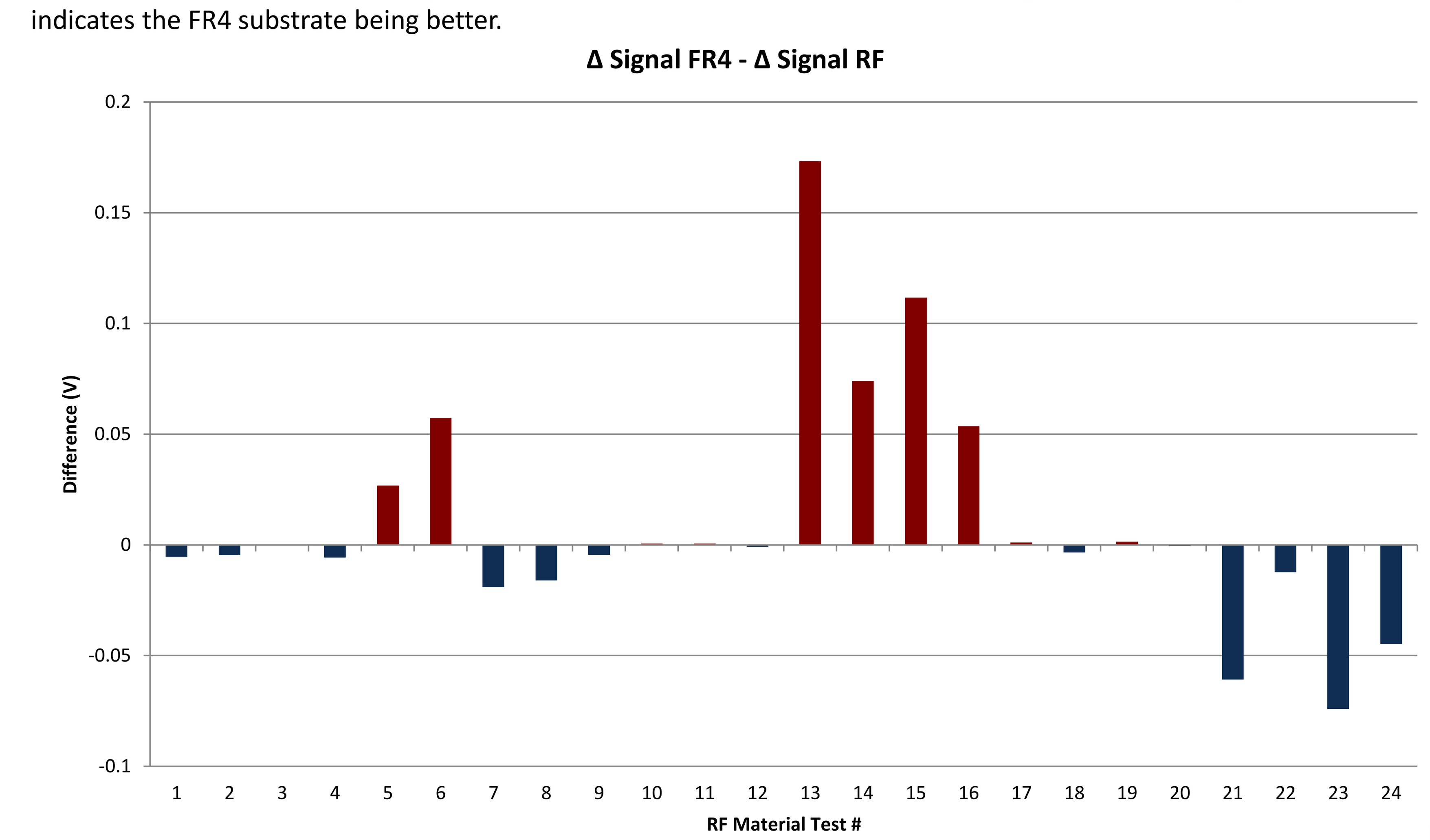

Figure 6: Column plot of the difference between the signal difference of Tests 25-48 and Tests 1-24.

From Figure 6, it is apparent that the effect of the board material at the tested frequencies does not play a significant role in the signal integrity. Thus, the data collected in Table 2 for the FR4 and RF material can be taken to be equivalent.

From the measurements taken in Tests 1-48 as described in Table 2, the following Table of input to output signal difference values was generated. The Table included all four frequencies, both input impedances, both substrate materials, and all three termination configurations as depicted in Figure 2.

Table 3: Input to output signal difference values for Tests 1 - 48

		RF Board			FR4 Board		
Freq (kHz)	Input	50 Ω, 2 High Z	High Z	50 Ω, High Z	50 Ω, 2 High Z	High Z	50 Ω, High Z
2	High Z	0.079656	0.085384	0.076176	0.07504	0.085992	0.072724
32	High Z	0.083624	0.108984	0.080804	0.077884	0.108248	0.08028
500	High Z	0.160472	0.21164	0.220984	0.217748	0.285592	0.208584
30000	High Z	1.740836	2.137384	1.79676	1.724936	2.190944	1.75208
2	50 Ω	0.101032	0.19678	0.095928	0.095768	0.19234	0.097016
32	50 Ω	0.108168	0.24384	0.108176	0.107912	0.2443	0.109736
500	50 Ω	0.360488	0.46114	0.388408	0.387264	0.6344	0.327568
30000	50 Ω	3.484952	4.26628	3.591768	3.466	4.37798	3.51768

Since the RF and FR4 section values can be treated as equivalent, as demonstrated by Figure 6, the board material sections can be averaged together to give a more simple set of data. This average difference is shown in Table 4.

Table 4: Average input to output signal difference values for Tests 1 - 48

	Average Difference (mV)					
	50 Ω Input			High Z Input		
Freq (kHz)	50 Ω, 2 High Z	High Z	50 Ω, High Z	50 Ω, 2 High Z	High Z	50 Ω, High Z
2	98.4	194.56	96.472	77.348	85.688	74.45
32	108.04	244.07	108.956	80.754	108.616	80.542
500	373.876	547.77	357.988	189.11	248.616	214.784
30000	3475.476	4322.13	3554.724	1732.886	2164.164	1774.42

All six cases of input impedance, and load configuration can then be plotted across the range of frequencies. The frequencies as displayed previously, are on a logarithmic scale of base ten. This plot is shown in Figure 7.

Table 2: Test plan for Tests 1 - 48

Test #	Name	Brd Material	Connector	Freq	Z_{input}	Configuration
T1	50RF	Matched RF	J14	2 kHz	50 Ω	A
T2					High	
T3				32 kHz	50 Ω	
T4					High	
T5				500 kHz	50 Ω	
T6					High	
T7				30 MHz	50 Ω	
T8					High	
Test #	Name	Brd Material	Connector	Freq	Z_{input}	Configuration
T9	50RF	Matched RF	J16	2 kHz	50 Ω	C
T10					High	
T11				32 kHz	50 Ω	
T12					High	
T13				500 kHz	50 Ω	
T14					High	
T15				30 MHz	50 Ω	
T16					High	
Test #	Name	Brd Material	Connector	Freq	Z_{input}	Configuration
T17	50RF	Matched RF	J15	2 kHz	50 Ω	B
T18					High	
T19				32 kHz	50 Ω	
T20					High	
T21				500 kHz	50 Ω	
T22					High	
T23				30 MHz	50 Ω	
T24					High	
Test #	Name	Brd Material	Connector	Freq	Z_{input}	Configuration
T25	50FR4	FR4	J10	2 kHz	50 Ω	A
T26					High	
T27				32 kHz	50 Ω	
T28					High	
T29				500 kHz	50 Ω	
T30					High	
T31				30 MHz	50 Ω	
T32					High	
Test #	Name	Brd Material	Connector	Freq	Z_{input}	Configuration
T33	50FR4	FR4	J12	2 kHz	50 Ω	C
T34					High	
T35				32 kHz	50 Ω	
T36					High	
T37				500 kHz	50 Ω	
T38					High	
T39				30 MHz	50 Ω	
T40					High	
Test #	Name	Brd Material	Connector	Freq	Z_{input}	Configuration
T41	50FR4	FR4	J11	2 kHz	50 Ω	B
T42					High	
T43				32 kHz	50 Ω	
T44					High	
T45				500 kHz	50 Ω	
T46					High	
T47				30 MHz	50 Ω	
T48					High	

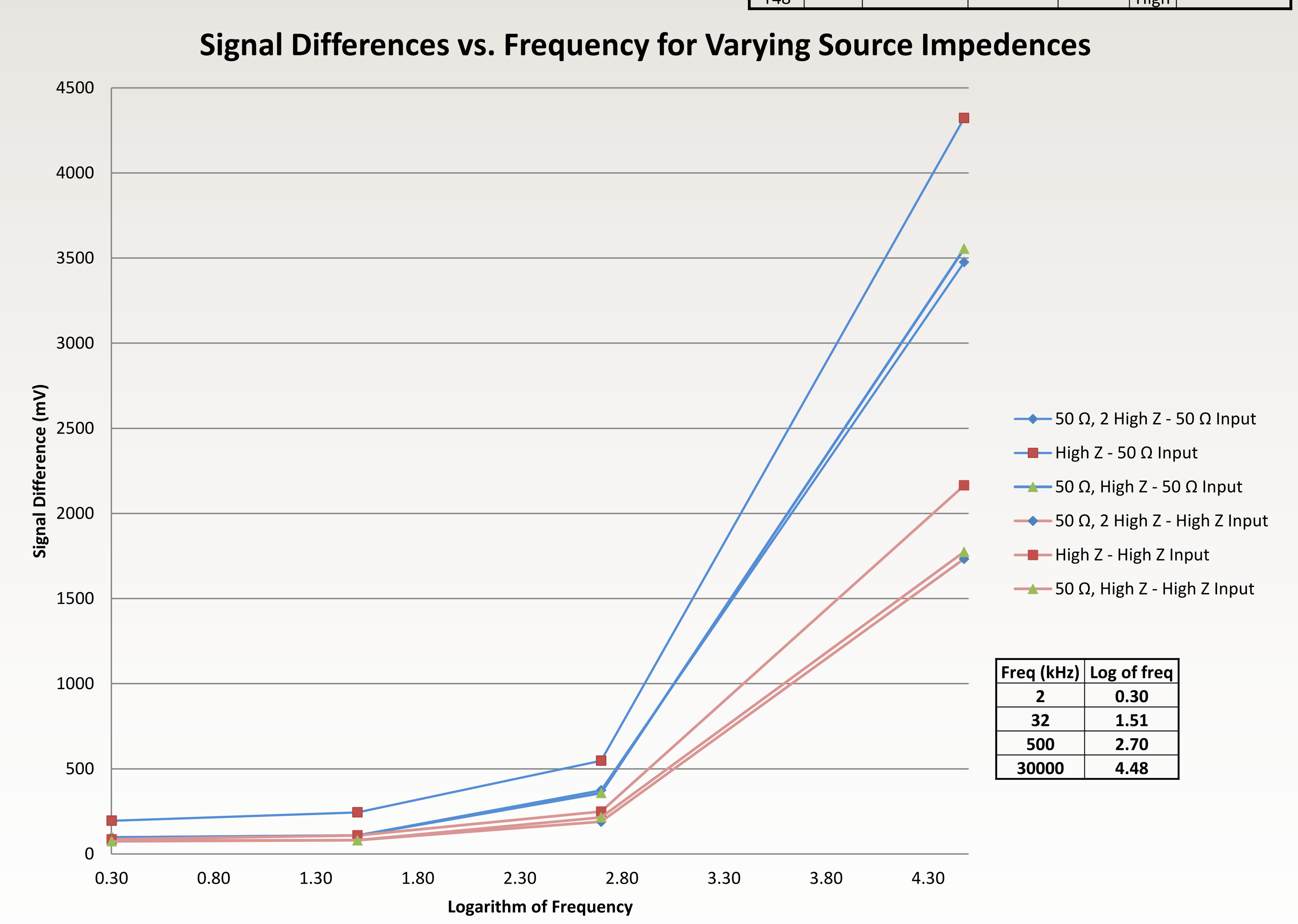

Figure 7: Plot of voltage differences with respect to frequency from the six different configurations as shown in Table 4.

By looking at Figure 7, it is apparent that regardless of the input impedance the termination configurations with a 50 Ω resistor had significantly less error than the terminations with only a high impedance load. Further, the 50 Ω resistors with two 1 MΩ resistors in parallel had slightly lower error than the 50 Ω resistors with one 1 MΩ resistor in parallel. Also, the high input impedance signals had a much lower error than the 50 Ω input impedances.

Discussion

In looking at the results from each parameter test, the following statements can be made about each parameter:

- The least significant parameter was the substrate material. Regardless of the frequency, the RF substrate material did not seem to behave significantly different than the FR4 substrate material.
- The next parameter which did show a trend (though small), was the cable type. The PE-C200 was the best cable at 500 kHz. Although at that frequency, the overall signal difference between the best, and worst cable was 80 mV. The RG59B-U was the best cable at 30 MHz. At that frequency, the overall signal difference between the best, and worst cable was 500 mV to 900 mV.
- The best termination configuration was configuration A (50 Ω resistor with two 1 MΩ resistors in parallel). Although because there was such little difference between configuration A and configuration B (50 Ω resistor with one 1 MΩ resistor in parallel), either configuration can be used.
- A high input impedance will yield lower signal error than a 50 Ω input impedance. However there is a tradeoff to this since high input impedances are hard to drive.
- Finally, the most obvious trend is that the higher the signal frequency, the more prevalent these small effects will have.

For future testing, different grounding configurations will be taken into account. In all of the tests described thus far the ground return path has been though the shielding of the cable. The next step in testing will be to see how having a dedicated return cable will affect the signal integrity.

Acknowledgements and Contacts

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