Delay Board Electrical Measurements

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1. Introduction

This document describes electrical measurements made on a sample DOM delay board in February and March 2004. The delay board used was number 1/60, revision 9/22/03, with target operating characteristics of 70ns delay and 95Ω impedance.

I would like to acknowledge Nobuyoshi Kitamura and Chris Wendt for their invaluable advice on these measurements.

2. Delay

The delay through the delay board was measured using an oscilloscope to record the total time between input and output waveforms, and subtracting an offset delay measured without the delay board to account for cable delays. The measurements were repeated at three temperatures: room temperature (21ºC), 0ºC, and –40ºC.

The complete circuit also included impedance-matching resistors, as shown below:

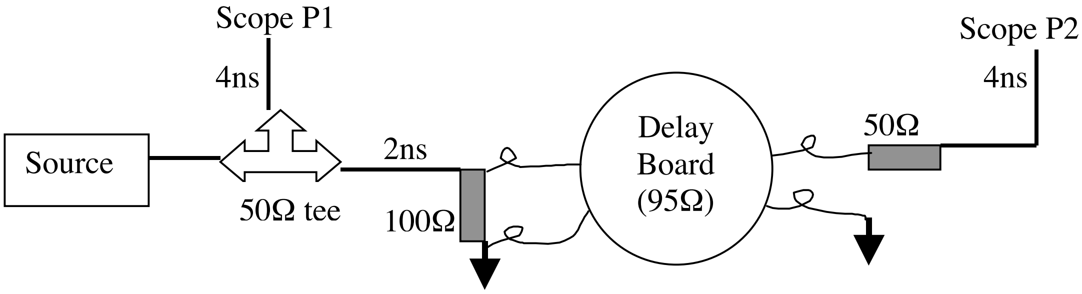

Figure 1: Delay board measurement circuit

The input source used was an HP 8004A pulse generator, set to generate a square pulse with amplitude 2.5V and width 0.1μs. The input rise time as measured at P1 was 1.5ns. Both cables connecting the measurement circuit to the scope inputs were equal in delay (4ns). The delay board was connected to the measurement circuit with two short twisted lengths of wire, hooked to the I/O and ground pins on the delay board.

The delay measurements were taken with a LeCroy digital oscilloscope, using measurement cursors to find the half-max crossing. The pulse amplitudes as measured at scope points P1 and P2 were 1.35V and 0.63V respectively. Each scope waveform measured was an average of 1000 sweeps, and five delay measurements were taken at each temperature. For the low-temperature measurements, the delay board was placed inside the freezer and allowed to equilibrate overnight. A table of the results is given below:

Temp.	**Delay (ns)**					**Average (ns)**
21ºC	94.9	94.7	94.8	94.7	94.7	**94.76**
0º C	94.6	94.5	94.6	94.6	94.6	**94.58**
-40ºC	94.3	94.2	94.2	94.2	94.3	**94.24**

Table 1: Total circuit delay at various temperatures

The offset was assumed to be constant over all temperatures, since only the delay board and a small portion of the connector leads were placed in the freezer. The connector leads were shorted with a very short piece of wire, and delay measurements shown below were taken at room temperature:

Temp.	**Delay (ns)**					**Average (ns)**
21ºC	18.7	18.75	18.73	18.65	18.65	**18.70**

Table 2: Offset delay

A summary of the delay board results, with offset subtracted, is given in the following table:

Temperature	**Average Delay (ns)**
21ºC	76.1
0º C	75.9
-40ºC	75.0

Table 3: Delay board delay at various temperatures

2. Resistance

The resistance of the delay board was measured, with connector leads attached, with a handheld Fluke multimeter. Five resistance measurements were recorded at three temperatures: room temperature (21ºC), 0ºC, and –40ºC. A table of the results is shown below:

Temp.	**Resist. (Ω)**					**Average (Ω)**
21ºC	13,6	13.5	13.5	13.4	13.5	**13.50**
0º C	12.6	12.3	12.3	12.3	12.2	**12.34**
-40ºC	10.5	10.7	10.7	10.5	10.5	**10.58**

Table 4: Total resistance at various temperatures

The resistance of the connector leads was measured separately, at room temperature only. The results are shown in the following table:

Temp.	Resist. (Ω)					Average (Ω)
21ºC	0.3	0.4	0.3	0.4	0.4	**0.36**

Table 5: Connector lead resistance

A summary of the resistance of the delay board, with the lead resistance subtracted, is given in the following table:

Temperature	Resistance (Ω)
21ºC	13.14
0º C	11.98
-40ºC	10.22

Table 6: Delay board resistance at various temperatures

3. Impedance

The impedance of the delay board was measured at room temperature by minimizing the amplitude of a reflected pulse by varying the termination resistance of the delay board. A square pulse with a rise time of 2.5ns and amplitude 708mV at point P2 (see Figure 2), was used as the test waveform. Two input pulse widths were used for the measurement: 15ns and 50ns. A resistor network, calculated to have input resistance of 50Ω from the source side and 95Ω from the delay board side, was used to limit unwanted reflections. A 20-turn, 200Ω potentiometer was used as the variable terminating resistor. The input and reflected pulses were measured at point P2 with a LeCroy digital oscilloscope using a 1MΩ probe.

The circuit used for the impedance measurement is shown in the following figure:

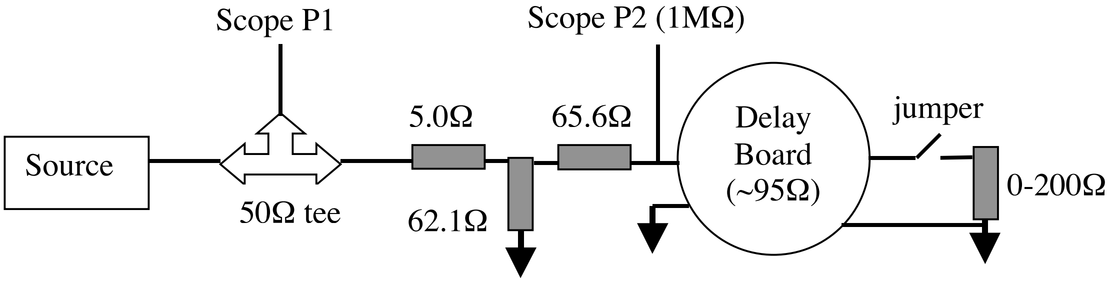

Figure 2: Impedance Measurement Circuit

The circuit elements were assembled on a small breadboard placed directly next to the delay board pins, replacing the long twisted-pair leads used in the previous measurements with very short wires to the delay board. A jumper allowed measurement of the potentiometer resistance isolated from the rest of the circuit.

The time location of the reflected pulse peak was first located by removing the termination. Then, with the termination in place, the resistance was varied slowly, and the reflected amplitude of the pulse (an average of 1000 sweeps) was taken at each value for the termination resistance. Also, at each point the jumper was removed and the termination resistance measured with a multimeter.

Because minimizing the reflected pulse requires knowledge of the baseline voltage (which was not precisely 0.0V), and because the uncertainty in this baseline is the primary source of error in the impedance result, the baseline voltage range (at several points just before the reflected pulse) was measured at various termination resistances. The following tables show the variation in this baseline for the two pulse widths:

Termination Resistance(Ω)	Minimum Baseline (mV)	Maximum Baseline (mV)
73.6	-6.8	12.7
89	-7.4	10.7
100.3	-8.3	10.1
109.1	-5.7	13.1

Table 7.1: Baseline voltage variation, 15ns pulse

Termination Resistance(Ω)	Minimum Baseline (mV)	Maximum Baseline (mV)
77.4	0.5	9.9
92.2	1.4	9.2
101.9	0.6	10.2
108.4	-0.1	10.2

Table 7.2: Baseline voltage variation, 50ns pulse

The average baseline, taken as the average midpoint between the minimum and maximum variation, is calculated to be **2.3 mV** and **5.2 mV** for the15ns and 50ns pulses, respectively, and is subtracted from each measured reflected pulse amplitude. The maximum deviations from this average are ±9.8mV and ±5.3mV for the two pulse widths. Slightly more high-frequency ringing contributed to the larger uncertainty in the measurement using the short pulse width.

The following tables show the measured reflection amplitude, with the average baseline subtracted, as a function of the termination resistance:

Termination Resistance(Ω)	Reflection Amplitude (mV)
66.7	-126.0
73.6	-90.9
81.4	-54.2
89.0	-22.3
94.8	-0.7
100.3	17.8
105.1	35.4
109.1	47.3
116.7	72.5
124.3	93.3
135.3	122.4

Table 8.1: Reflected pulse amplitude, 15ns input pulse

Termination Resistance(Ω)	Reflection Amplitude (mV)
65.1	-101.1
72.2	-73.6
77.9	-51.4
81.8	-36.6
87.5	-16.6
91.5	-3.4
96.0	10.6
100.4	23.5
104.5	34.1
112.3	54.6
120.6	73.7

Table 8.2: Reflected pulse amplitude, 50ns input pulse

The following figure shows a plot of the same data, with a quadratic fit:

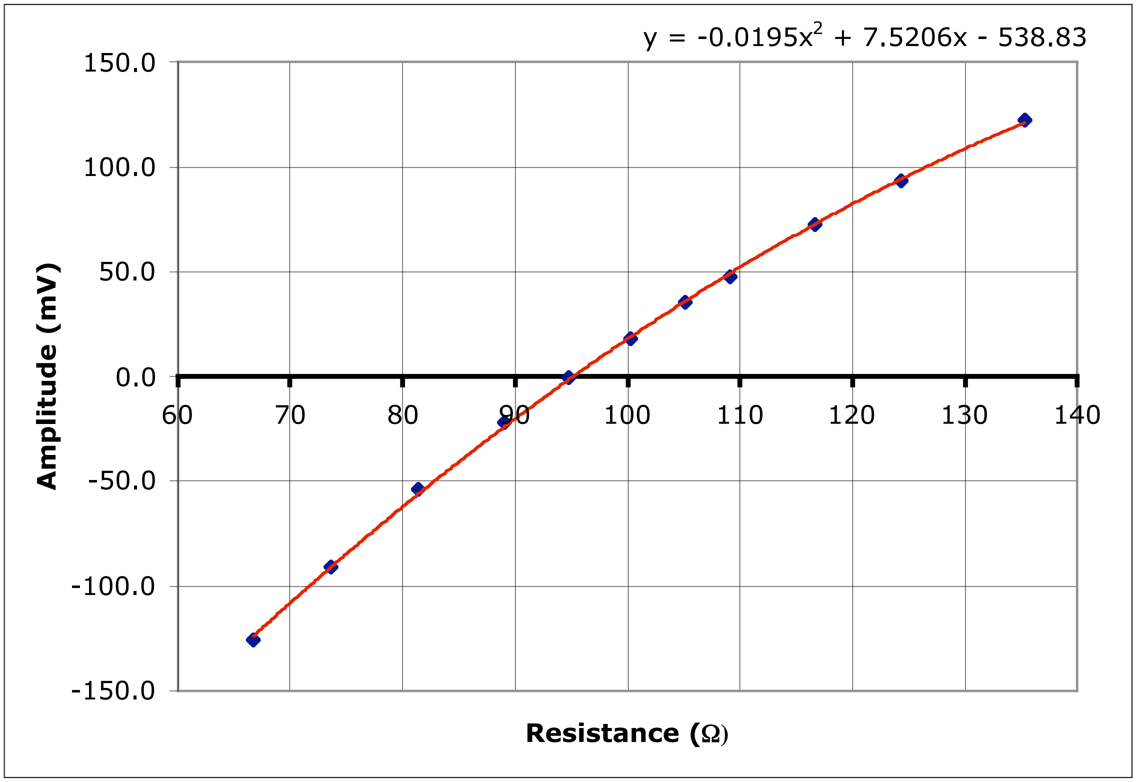

Figure 3.2: Plot of reflected pulse amplitude (15ns input pulse) with quadratic fit

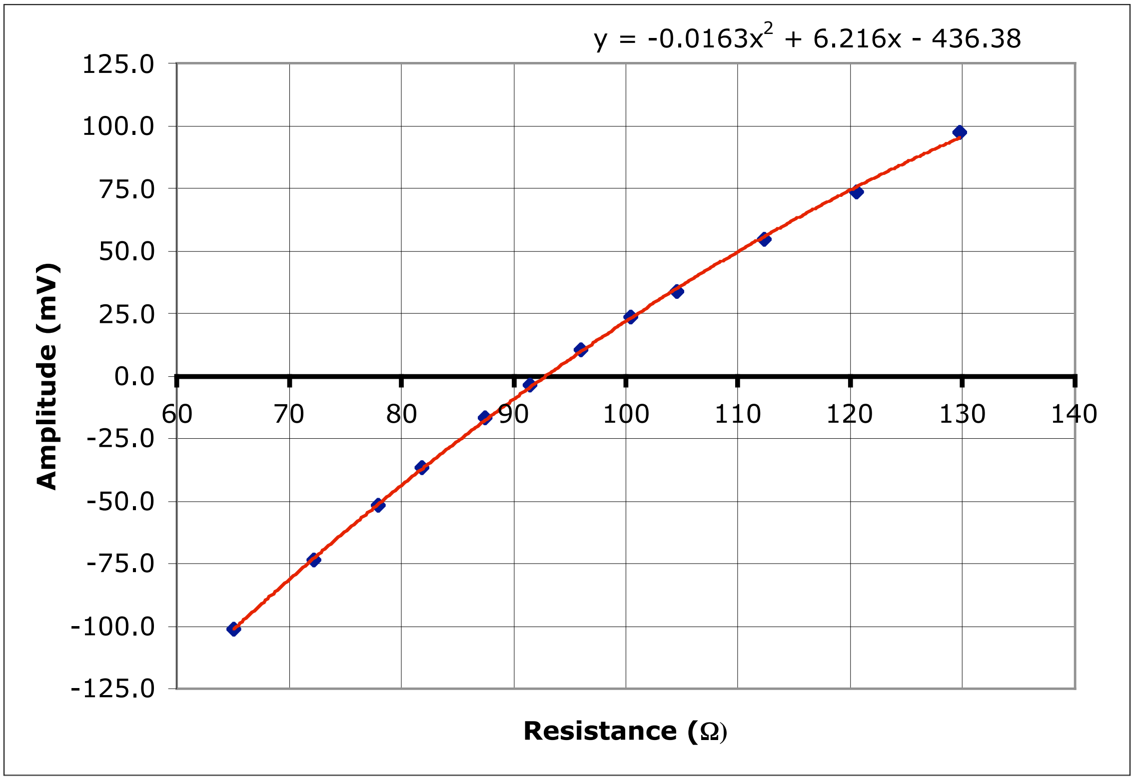

Figure 3.2: Plot of reflected pulse amplitude (50ns input pulse) with quadratic fit

Extracting the zero-amplitude point by solving the fit given in the plots results in an impedance for the delay board of **95.1Ω** and **92.8Ω** for input pulses of 15 and 50 ns, respectively. Combining the baseline uncertainty of with the curves above gives a bound on the impedance uncertainty of **±2.5Ω** and **±1.7Ω**.

The final results of this measurement are given in the table below:

Input Pulse Width (ns)	**Impedance (Ω)**
15	95.1±2.5
50	92.8±1.7

Table 9: Delay Board Impedance (Room Temperature)

The following screen shots from the oscilloscope show sample waveforms taken at maximum reflection amplitude (infinite impedance) and minimum amplitude:

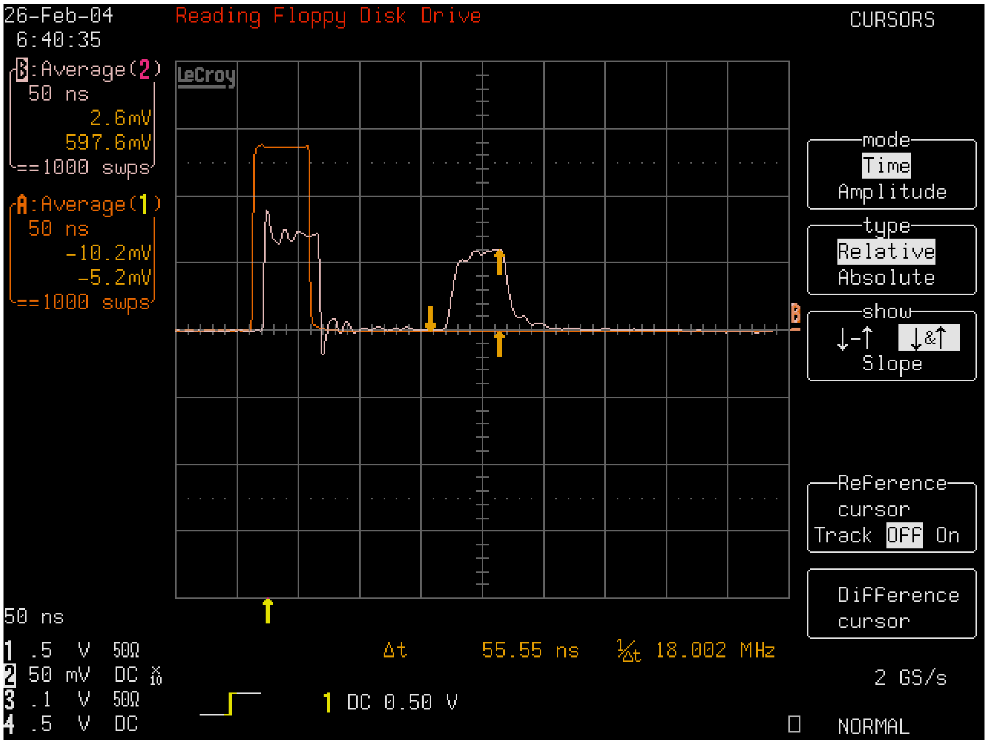

Figure 4: Screenshot of Maximum Reflection (50ns Input Pulse)

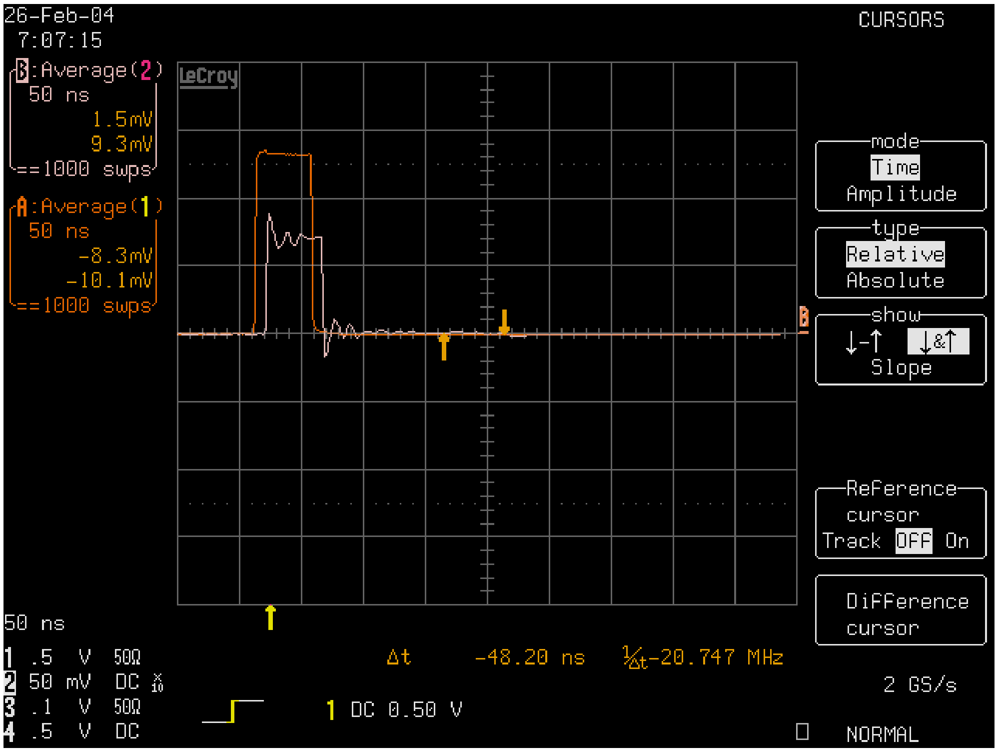

Figure 5: Screenshot of Minimum Reflection (50ns Input Pulse)

3.1 Impedance at –40C

Because of limitations of the experimental setup used, the impedance could not be directly measured at –40C using the above method. However, an estimate of the change in impedance from room temperature could be determined by optimizing the termination resistor for minimum reflection at room temperature, and then measuring any reflection when the circuit was cooled to –40C.

At room temperature, the terminating resistor was set to the measured optimal value for a pulse width of 50ns, 92.8Ω, and the reflected pulse was measured to be negligible. After placing in the freezer and allowing the circuit to equilibrate overnight, the measured reflected pulse amplitude at –42C was 0.11mV on an average baseline of 0.53mV, for an effective pulse amplitude of –0.42mV (with an input pulse width of 50ns).

Assuming the previously measured reflected amplitude curve does not drastically change with temperature, this results in a maximum shift in impedance from room temperature to –42C of **–0.13Ω**. This, however, is well below the error in the impedance measurement and is consistent with zero impedance shift.

Note that this result also assumes that the temperature dependence of the potentiometer used in the test circuit and the temperature dependence of the actual terminating resistor on the mainboard are roughly the same.

4. Bandwidth

The bandwidth of the delay board has not been measured. Katherine Rawlins and Nobuyoshi Kitamura have taken attenuation data on a previous revision of the delay board, available at:

http://www.amanda.wisc.edu/kath/private/delayboard/