TileCal Analogue Cable Measurement Report

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Contents

1 Scope

This document reports the results of measurements made at RAL for the 75 meters TileCal analogue cable. The TileCal analogue cable is made up of 16 individually shielded twisted pairs. It has been noticed at CERN that huge performance differences exist between different pairs within the same TileCal analogue cable. The purpose of the tests at RAL is to characterize the performances of different pairs within the TileCal analogue cable. Due to the limited time, only two representative pairs are chosen for the tests at RAL, the Purple + White pair and Turquoise/Brown + White pair, representing low-skew pair and high-skew pair respectively according to the tests at CERN. As a comparison, a 21 meters LAr analogue cable is also measured at RAL using the same test setup and the results are presented in the appendix of this document.

2 Impedance measurements

2.1 Test setup

TDR (Time Domain Reflectometry) method is used to measure the impedance of the individually shielded twisted pairs of the TileCal analogue cable. Two kinds of impedance are measured, differential mode impedance and common mode impedance.

Differential mode impedance is measured using setup in Figure 1. A 1:1 wideband transformer from Mini-Circuit is used here for single-ended signal to differential signal conversion. The far end of the TileCal cable is left open.

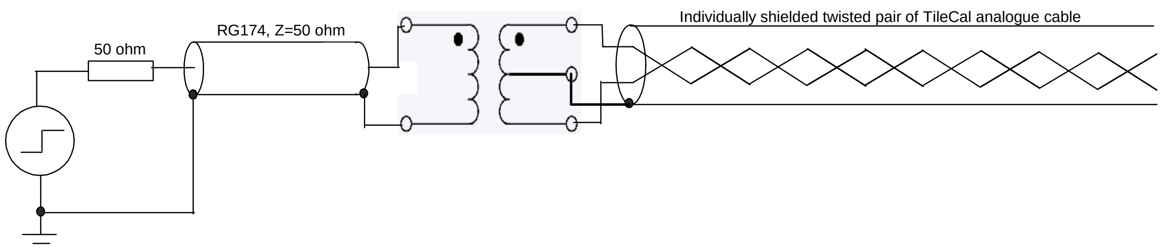

Figure 1: Test Setup for differential mode impedance measurement

Common mode impedance is measured use setup in Figure 2, where the two wires of the twisted pair are shorted together and connect to coax. The far end of the TileCal cable is left open.

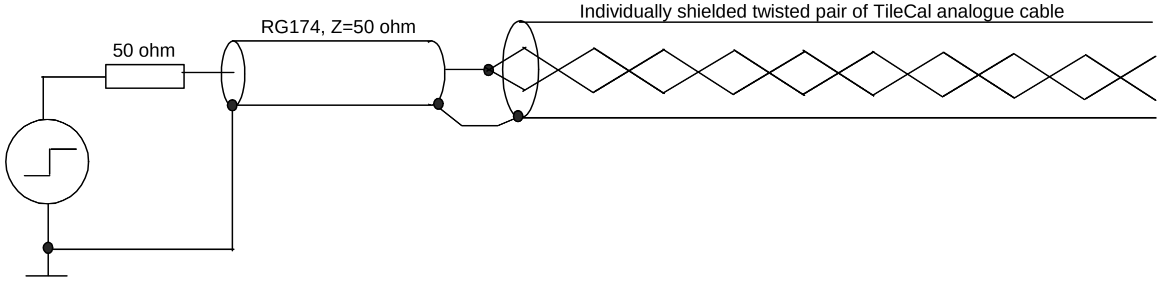

Figure 2: Test Setup for common mode impedance measurement

2.2 Differential mode impedance

The wideband transformer used in the tests has a core loss which is caused be eddy-current loss and other magnetic mechanism. This core loss can be modelled by a resistor in parallel with the primary of the transformer. In order to get the value of this transformer primary parallel resistor, a TDR measurement is done using the setup in Figure 1, where the secondary of the transformer is left open without any cable connected. The scope shot of this measurement is shown in Figure 3.

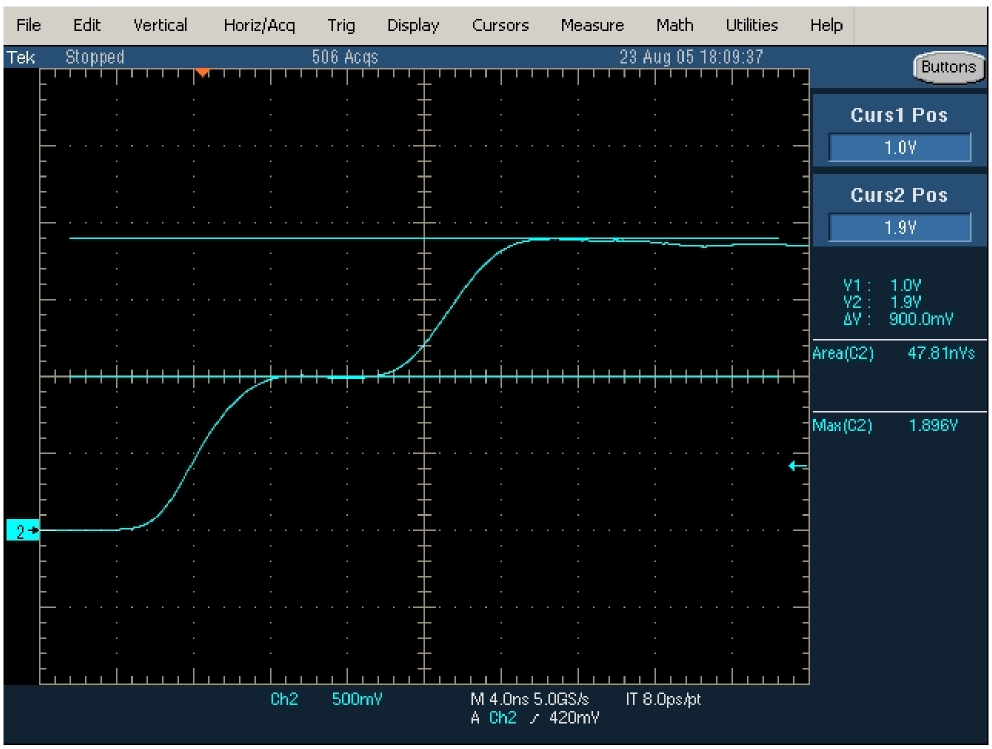

Figure 3: TDR waveform for the transformer primary parallel resistance

For a 1V input step pulse, the reflection amplitude from the transformer is 900mV. Taking into account the small attenuation of the coax RG174, the real reflection ratio is about 0.92. So the transformer primary parallel resistance is about (1+0.92)/(1–0.92) * Zcoax = 1200Ω.

Measurements of the differential mode impedance for both pairs of TileCal cable show almost the same TDR waveform as shown in Figure 4.

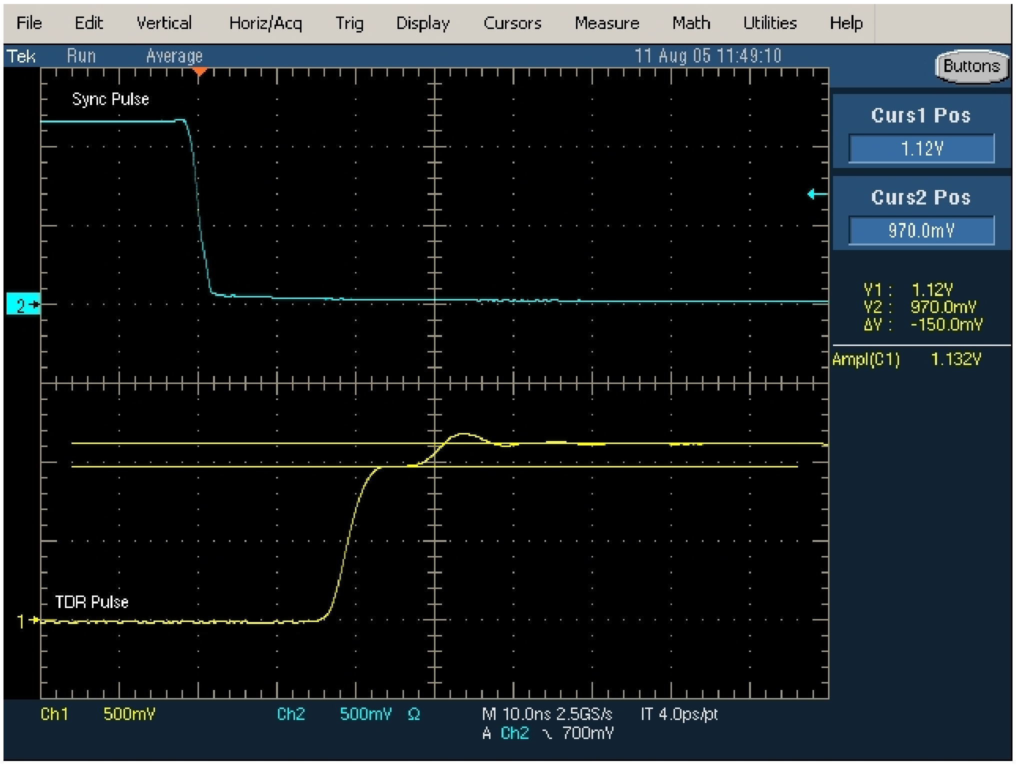

Figure 4: TDR waveform for differential mode impedance measurement.

The initial step is 970mV and the second step is 150mV. Hence, the reflection ratio ρ=150/970 = 0.155. We can calculate the impedance looking into the primary of the transformer as (1+ ρ)/(1- ρ) * Zcoax = 68**Ω**. This, in fact, is the differential impedance of the TileCal cable in parallel with the transformer primary parallel resistance (1200**Ω**). So the differential mode impedance of the TileCal cable is (1200*68)/(1200-68) = 72**Ω**. Given that the impedance tolerance of the coax RG174 used in the tests is 50 +/- 2 **Ω**, the range of the differential impedance of the TileCal cable is 72 +/- 3**Ω**.

2.3 Common mode impedance

Measurements of the common mode impedance for both pairs also show almost the same TDR waveform as shown in Figure 5.

The initial step is 1V. The second step is -350mV, which is caused by the impedance mismatch between the common mode impedance of TileCal Cable and 50**Ω** of coax RG174. Reflection ratio ρ = -350/1000 = -0.35. Thus, the common mode impedance of TileCal cable is 50*(1+ ρ)/(1- ρ) ≈ **25Ω**.

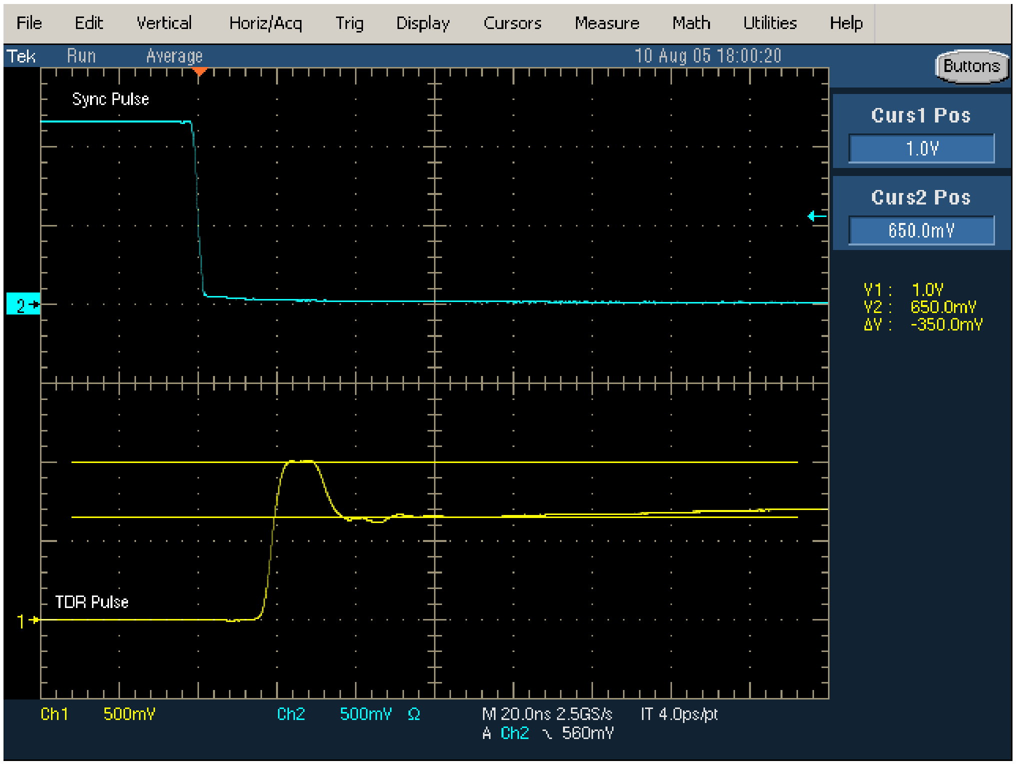

Figure 5: TDR waveform for common mode impedance measurement.

3 S-parameters measurements

S-parameters method works in frequency domain. I have measured four parameters: differential-to-differential attenuation, differential-to-common conversion, common-to-common attenuation, and common-to-differential conversion. The frequency scan range is from 100 KHz to 50MHz, which is believed to cover the spectral of real TileCal signal.

3.1 Test setup

Two test setups are used to measure 4 S-parameters, as shown in Figure 6 and Figure 7.

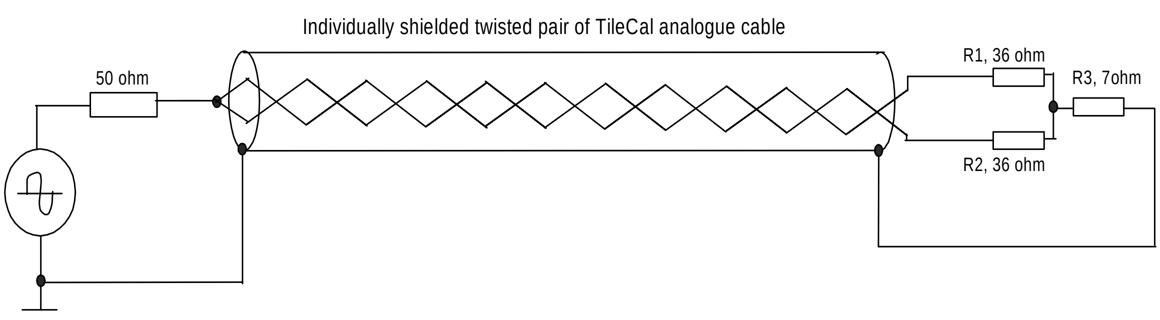

Figure 6: Test setup for Common-to-Common and Common-to-Differential measurement.

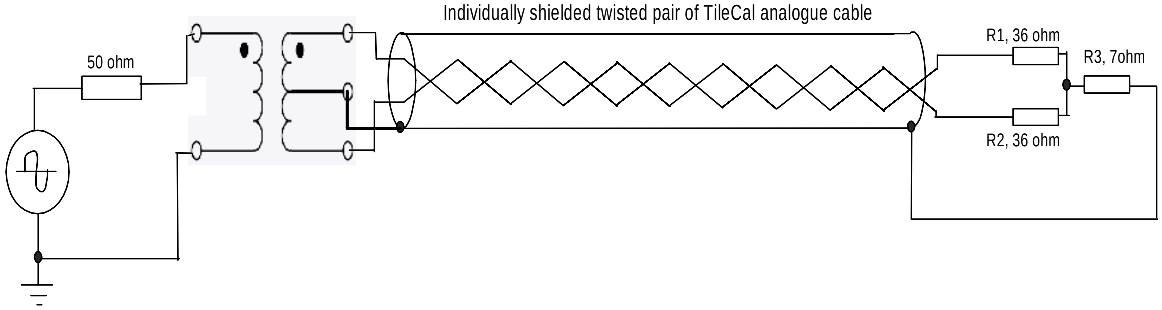

Figure 7: Test setup for Differential-to-Differential and Differential-to-common measurement.

In order to measure the genuine S-parameters of the cable itself, good termination is essential. Otherwise, signal reflections at the end of the TileCal cable would induce errors. Having known the differential mode impedance (72Ω) and common mode impedance (25Ω) of the TileCal cable, a "Y" termination is used as shown in Figure 6 and Figure 7. This "Y" termination exactly matches both the differential and common impedance of the TileCal cable, resulting in no reflection at all at the end of the cable.

3.2 Purple + White pair S-parameters

Figure 8 shows the S-parameters plot for the Purple + White pair, and the corresponding data is listed in Table 1 and Table 2. We can see from this plot that the common-to-differential conversions stay at least 23dB below the primary differential-to-differential response at all frequencies up to 20MHz, and the differential-to-common conversions stay at least 32.3dB below the primary differential-to-differential response at all frequencies up to 20MHz.

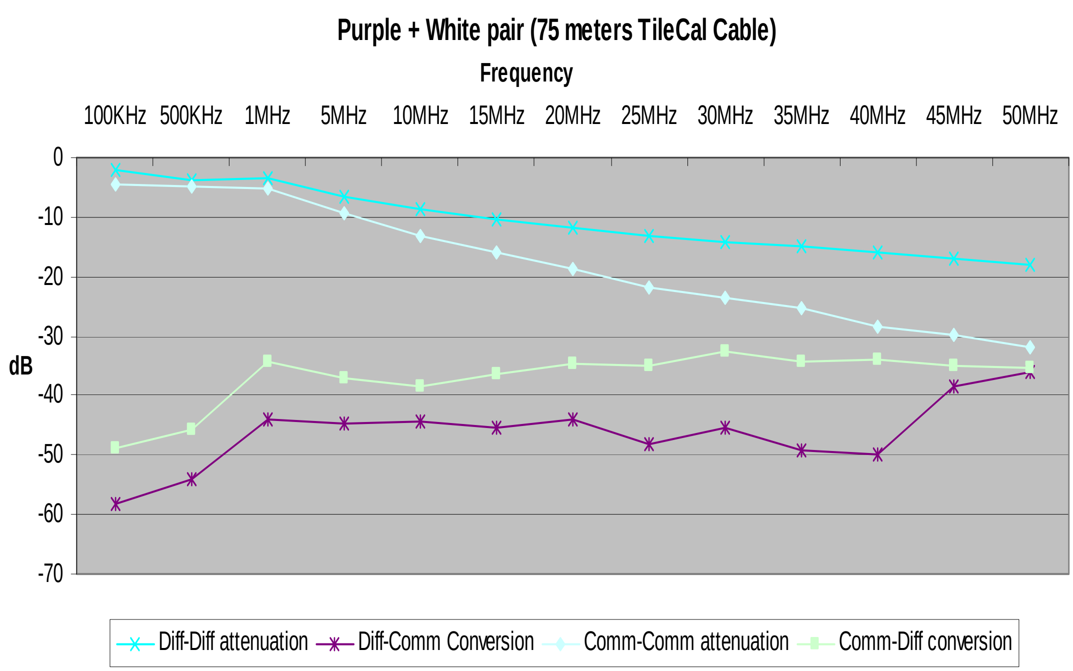

Figure 8: S-parameters plot for Purple + White pair

Frequency	Differential input (mV)	Differential output (mV)	Common output (mV)	Diff-to-Diff (dB)	Diff-to-Comm (dB)
100KHz	662	516	0.8	-2.2	-58.4
500KHz	664	424	1.3	-3.9	-54.2
1MHz	664	448	4.2	-3.4	-44.0
5MHz	662	310	3.9	-6.6	-44.6
10MHz	656	242	4.0	-8.7	-44.3
15MHz	660	201	3.6	-10.3	-45.3
20MHz	658	169	4.1	-11.8	-44.1
25MHz	660	147	2.6	-13.0	-48.1
30MHz	660	131	3.5	-14.0	-45.5
35MHz	658	118	2.3	-14.9	-49.1
40MHz	660	106	2.1	-15.9	-49.9
45MHz	664	95	8.0	-16.9	-38.4
50MHz	658	84	10.2	-17.9	-36.2

Table 1: Differential to Differential and Common mode data for Purple + White pair

Frequency	Common input (mV)	Differential output (mV)	Common output (mV)	Comm-to-Comm (dB)	Comm-to-Diff (dB)
100KHz	660	2.4	387.8	-4.6	-48.8
500KHz	658	3.4	373.2	-4.9	-45.7
1MHz	658	12.6	367.4	-5.1	-34.4
5MHz	662	9.2	226.0	-9.3	-37.1
10MHz	662	8.0	144.7	-13.2	-38.4
15MHz	662	10.0	103.8	-16.1	-36.4
20MHz	660	12.0	75.4	-18.8	-34.8
25MHz	664	11.8	52.8	-22.0	-35.0
30MHz	664	15.4	44.8	-23.4	-32.7
35MHz	658	12.5	36.4	-25.1	-34.4
40MHz	666	13.5	25.5	-28.3	-33.9
45MHz	658	11.5	21.5	-29.7	-35.2
50MHz	662	11.4	17.1	-31.7	-35.3

Table 2: Common to Differential and Common mode data for Purple + White pair

3.3 Turquoise/Brown + White pair S-parameters

Figure 9 shows the S-parameters plot for the Turquoise/Brown + White pair, and the corresponding data is listed in Table 3 andTable 4. We can see from this plot that the performance of the Turquoise/Brown + White pair is really very bad as compared to the Purple + White pair above. Over 15MHz, the common-to-differential conversion exceeds the differential-to-differential attenuation, rendering this pair useless over this frequency.

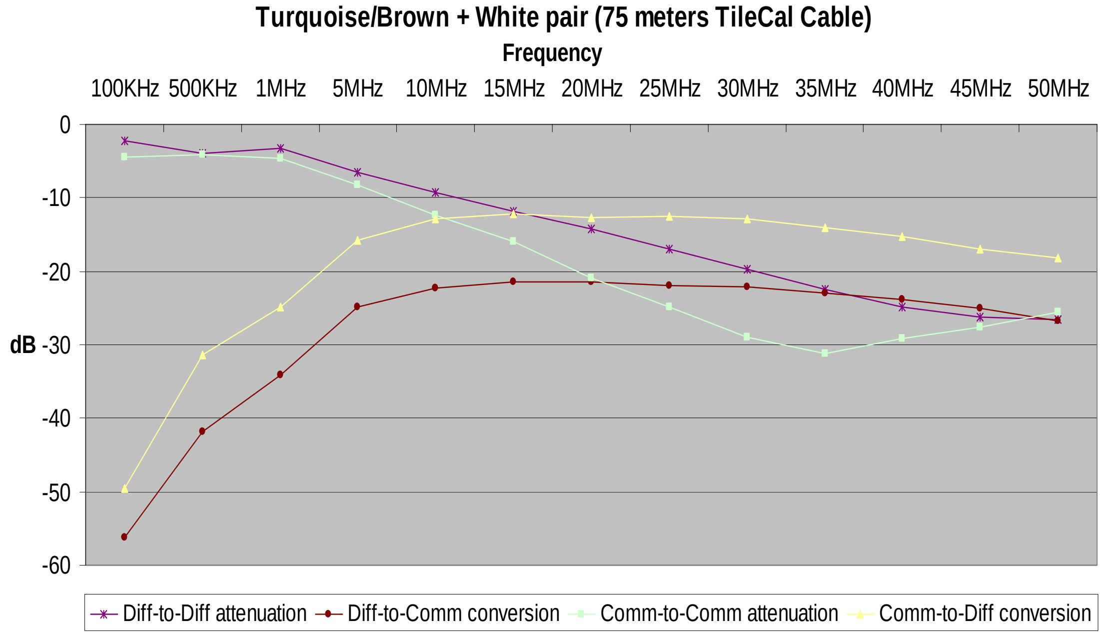

Figure 9: S-parameters plot for Purple + White pair

Frequency	Differential input (mV)	Differential output (mV)	Common output (mV)	Diff-to-Diff (dB)	Diff-to-Comm (dB)
100KHz	660	512	1.0	-2.2	-56.2
500KHz	660	422	5.3	-3.9	-41.9
1MHz	660	451	13.0	-3.3	-34.1
5MHz	660	312	37.6	-6.5	-24.9
10MHz	660	226	50.7	-9.3	-22.3
15MHz	660	168	55.8	-11.9	-21.5
20MHz	660	128	56.1	-14.2	-21.4
25MHz	660	93	53.2	-17.0	-21.9
30MHz	662	69	52.1	-19.6	-22.1
35MHz	660	50	46.7	-22.4	-23.0
40MHz	660	38	42.3	-24.8	-23.9
45MHz	660	32	36.8	-26.3	-25.1
50MHz	660	31	30.6	-26.6	-26.7

Table 3: Differential to Differential and Common mode data for Turquoise/Brown + White pair

Frequency	Common input (mV)	Differential output (mV)	Common output (mV)	Comm-to-Comm (dB)	Comm-to-Diff (dB)
100KHz	660	2.18	397.3	-4.4	-49.6
500KHz	664	17.9	415.5	-4.1	-31.4
1MHz	658	37.5	386.4	-4.6	-24.9
5MHz	660	108.2	255.2	-8.3	-15.7
10MHz	662	151	160.4	-12.3	-12.8
15MHz	664	163	105.7	-16.0	-12.2
20MHz	660	154	59.4	-21.0	-12.6
25MHz	664	157	37.9	-24.9	-12.5
30MHz	660	149	23.7	-28.9	-12.9
35MHz	664	132	18.2	-31.2	-14.0
40MHz	660	114	23.0	-29.2	-15.3
45MHz	660	93.5	27.3	-27.7	-17.0
50MHz	660	81	35.0	-25.5	-18.2

Table 4: Common to Differential and Common mode data for Turquoise/Brown + White pair

4 Skew measurements

Step-delay methods can be used to measure the intra-pair skew of shielded twisted pairs. However, due to the common-to-differential and differential-to-common conversions and the different propagation velocities and losses between the modes, it is hard to get accurate delay results. The skew measurements presented here are only meant to be a qualitative indication of the performances for the pairs.

4.1 Test setup

The test setup is the same as shown in Figure 6 and Figure 7. The only difference is that, instead of sending a sine wave down the cable, a step pulse is sent down the cable. Figure 6 is used to measure the common mode intra-pair skew, and Figure 7 is used to measure the differential mode pulse intra-pair skew.

4.2 Purple + White intra-pair skew

The common mode skew for Purple + White pair is shown in Figure 10. The differential mode skew for Purple + White pair is shown in Figure 11. It can bee seen from both figures that both common mode skew and differential skew are less than 1ns.

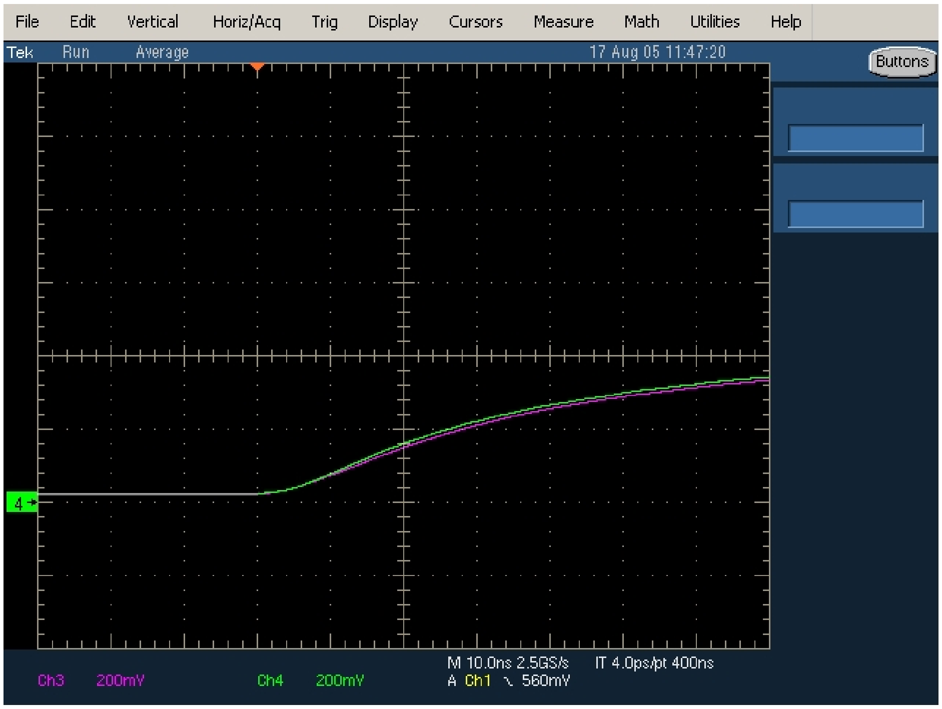

Figure 10: Common mode intra-pair skew for Purple + White Pair

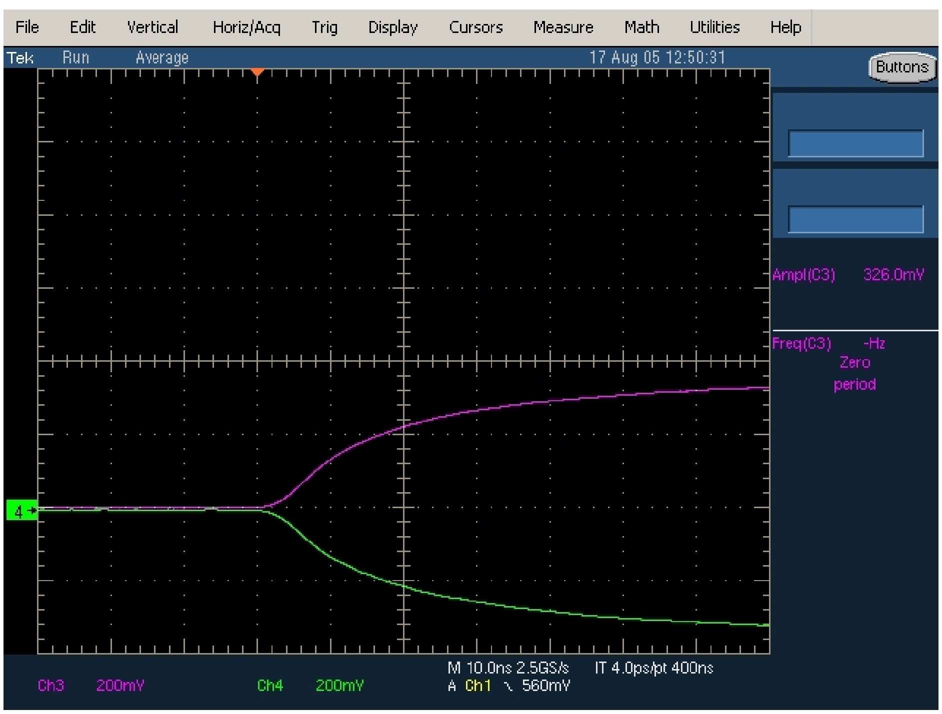

Figure 11: Differential mode intra-pair skew for Purple + White Pair

4.3 Turquoise/Brown + White intra-pair skew

The common mode skew for Turquoise/Brown + White pair is shown in Figure 12. As can be seen, when the purple trace starts to rise, the green trace begins to drop. This is because of the coupling between the two wires of a twisted pair. For this reason, it very hard to decide where on the two traces to measure the delay. The common mode skew here is estimated to be about 15ns.

Figure 12: Common mode skew for Turquoise/Brown + White pair

The differential mode skew for Turquoise/Brown + White pair is shown in Figure 13. The differential mode skew here is estimated to be about 16ns.

Figure 13: Differential mode skew for Turquoise/Brown + White pair

5 TileCal simulation wave measurements

A triangular pulse is also used to simulate the TileCal signal to evaluate the cable response.

5.1 Test setup

The test setup is the same as shown in Figure 7. The differential triangular waveform at the transformer output is shown in Figure 14. The purple trace and green trace represent the signals on the two wires with reference to the common ground point. The orange trace represents the differential signal between the two wires. The trace in the middle represents the common mode signal of the two wires. The rise/fall time of triangular pulse is 29ns. The differential signal amplitude is 710 mV. The common mode signal amplitude is about 1mV. The differential signal to common signal ratio is about 57dB.

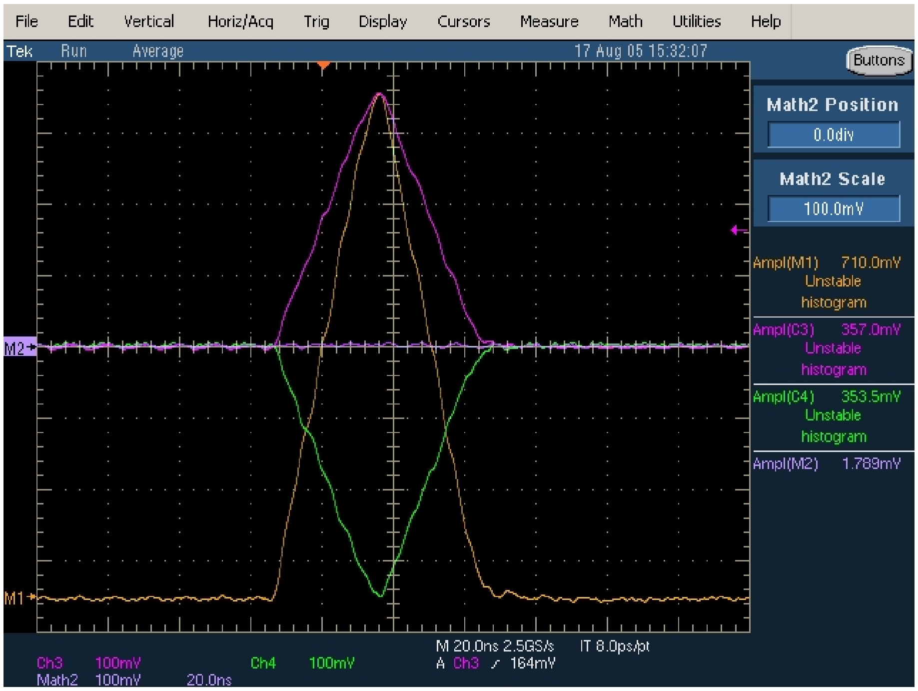

Figure 14: Differential triangular pulse

5.2 Purple + White pair simulation wave result

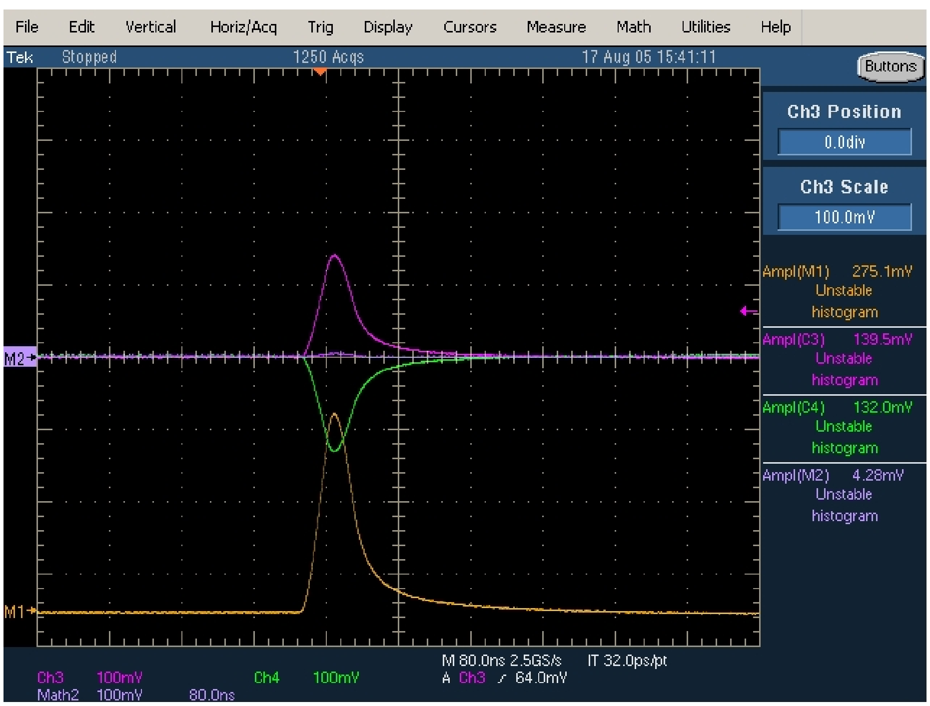

Figure 15: Response of Purple + White pair to triangular pulse input

Figure 15 shows the response of Purple + White pair to the triangular pulse input as shown in Figure 14. The differential output amplitude is 275mV. The propagation coefficient is 38.7% or -8.2dB. The common mode output amplitude is 4.28mV. The differential signal to common signal ratio here is 36.2dB.

5.3 Turquoise/Brown + White pair simulation wave result

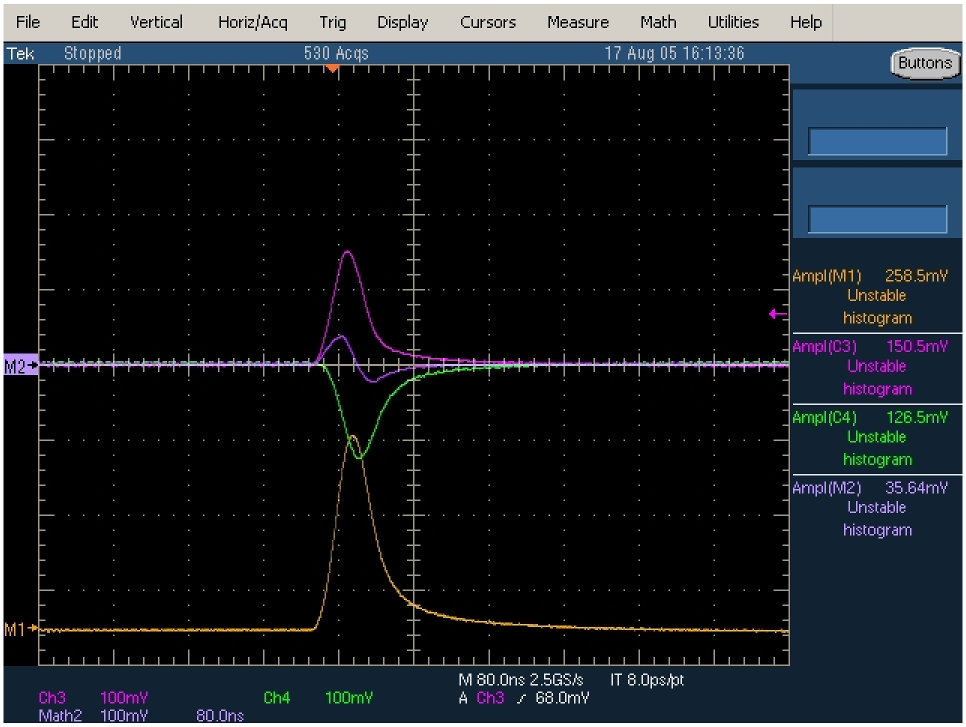

Figure 16: Response of Turquoise/Brown + White pair to triangular pulse input

Figure 16 shows the response of Turquoise/Brown + White pair to the triangular pulse input as shown in Figure 14. The differential output amplitude is 258mV. The propagation coefficient is 36.3% or -8.8dB. The common mode output amplitude is 35.6mV. The differential signal to common signal ratio here is 17.2dB.

6 Conclusions

From the test results above, following conclusions can be made:

1. The differential impedance of twisted pairs of TileCal cable is **72 +/- 3 Ω**, which is consistent between both pairs, but is significantly lower than the nominal impedance **88Ω** of the TileCal cable.
2. S-parameters measurements show that both pairs are very lossy. The attenuation for both pairs tested is much worse than industry standard Shielded Twisted Pair cables.
3. S-parameters measurements show huge differences between pairs, especially in the usable bandwidth. For example, at 15MHz, the differential-to-differential attenuation is -10.3dB for Purple + White pair and -11.9dB for Turquoise/Brown + White pair. The difference here seems not too much. However, the common-to-differential conversion at the same frequency is -36.4dB for Purple + White pair

and -12.2dB for Turquoise/Brown + White pair. The difference in common-to-differential conversion is tremendous, which means that the Turquoise/Brown + White pair has no common mode rejection capability at 15MHz at all while the Purple + White pair works perfectly at this frequency.

4. Step-delay measurements, as a qualitative indication, show huge differences in intra-pair skew between pairs.
5. Triangular pulse tests show no much difference in differential signal amplitude attenuation for both pairs tested. This is because the main spectral components of the triangular pulse stay below 10MHz; below this frequency point the attenuations for both pairs are almost the same. However, the bad pair generates a significant amount of common mode signal output. In real ATLAS TDAQ system, the TileCal cable is only terminated in differential mode. Hence, this common mode signal will bounce back and forth between the front end and the receiver end and eventually convert into differential noise at the receiver end.

7 Appendix: LAr analogue cable measurement results

A 21 meters LAr analogue cable is also tested at RAL using the same setup as for TileCal cable testing. The measurement results are presented here for the purpose of comparison.

7.1 LAr cable differential impedance

The TDR waveform for the differential impedance measurement of the LAr cable is shown in Figure 17. The reflection ratio is 180/980 = 0.184. After taking into account the transformer primary parallel resistance effect and the coax RG174 impedance tolerance, the differential impedance of the LAr cable is calculated to be in the range of **78 +/- 3 Ω.**

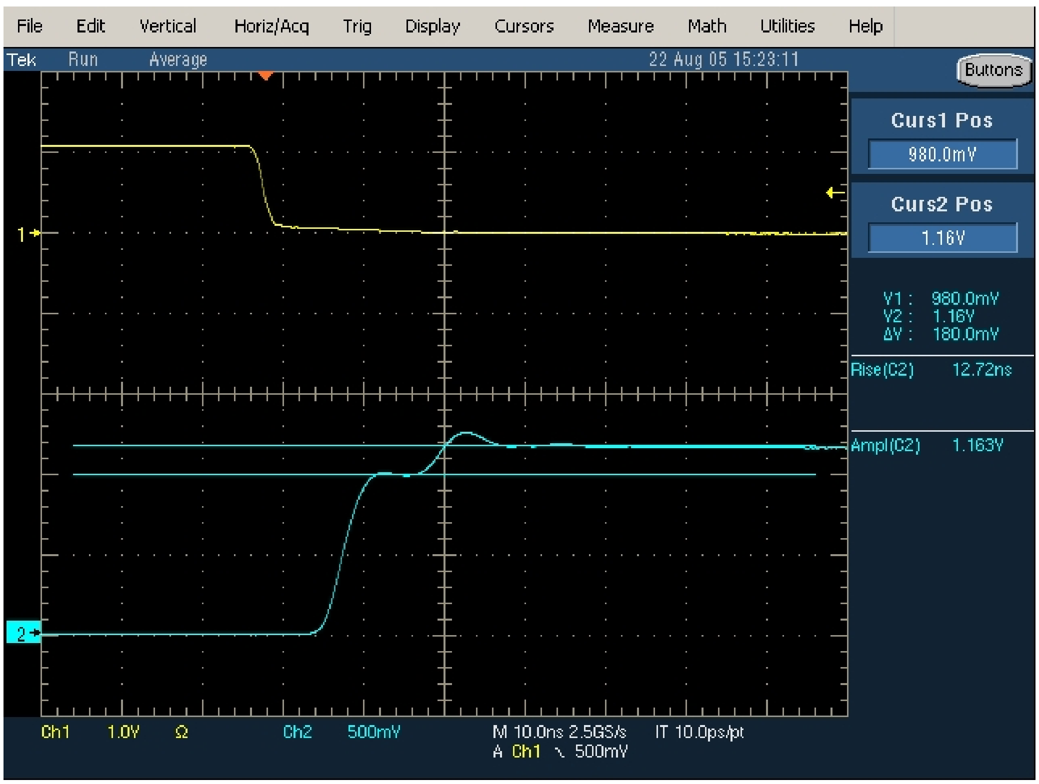

Figure 17: TDR waveform for differential impedance measurement of LAr analogue cable

7.2 LAr cable intra-pair skew

The common mode intra-pair skew is less than 0.5ns for all the 16 pairs of the 21 meters LAr cable. A typical scope shot of the intra-pair skew is shown in Figure 18.

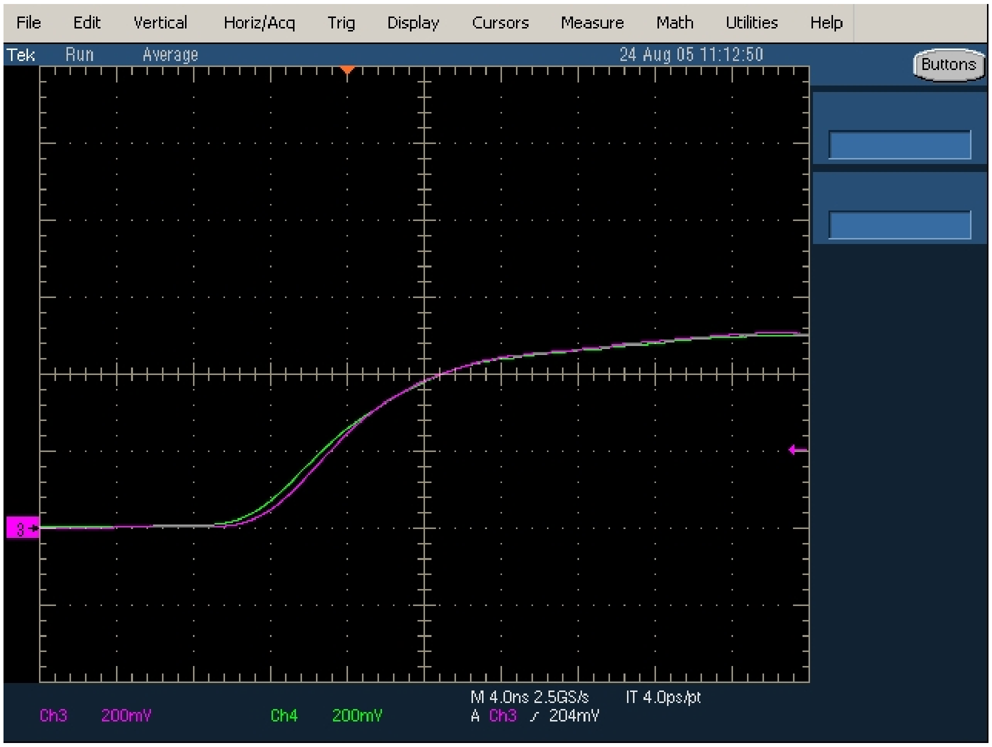

Figure 18: Common mode intra-pair skew for 21 meters LAr analogue cable

7.3 LAr cable S-parameters

Since the intra-pair skew tests above show that all the 16 pairs of the LAr cable are well balanced, only one pair (pair 2) is chosen for the S-parameters test. Figure 19 shows the S-parameters plot for pair 2 of the LAr cable, and the corresponding data is listed in Table 5 and Table 6.

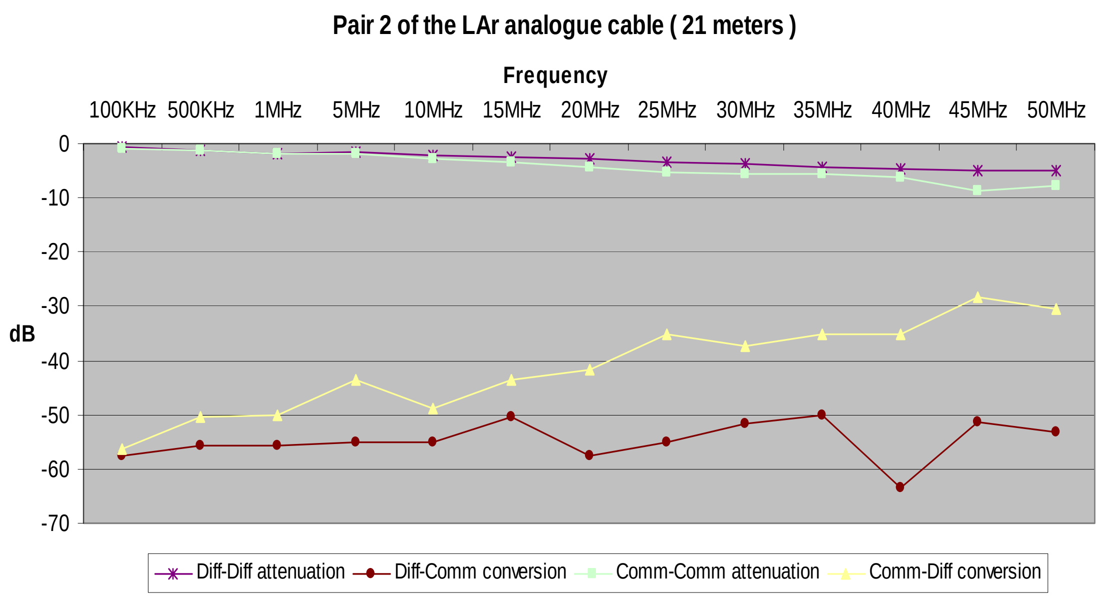

Figure 19: S-parameters for the LAr cable (21meters)

Frequency	Differential input (mV)	Differential output (mV)	Common output (mV)	Diff-to-Diff (dB)	Diff-to-Comm (dB)
100KHz	660	612	0.9	-0.7	-57.6
500KHz	660	572	1.1	-1.2	-55.6
1MHz	662	534	1.1	-1.9	-55.6
5MHz	664	562	1.2	-1.4	-55.1
10MHz	666	526	1.2	-2.0	-55.1
15MHz	664	496	2.0	-2.5	-50.2
20MHz	662	475	0.9	-2.9	-57.6
25MHz	662	453	1.2	-3.3	-55.0
30MHz	660	430	1.7	-3.7	-51.5
35MHz	660	404	2.0	-4.3	-50.2
40MHz	662	387	0.4	-4.7	-63.6
45MHz	656	364	1.7	-5.1	-51.5
50MHz	657	365	1.5	-5.1	-53.1

Table 5: Differential to Differential and Common mode data for pair 2 of the LAr cable

Frequency	Common input (mV)	Differential output (mV)	Common output (mV)	Comm-to-Comm (dB)	Comm-to-Diff (dB)
100KHz	660	1.0	601.4	-0.8	-56.4
500KHz	662	2.0	568.6	-1.3	-50.4
1MHz	660	2.1	535.8	-1.8	-49.9
5MHz	660	4.4	528.5	-1.9	-43.5
10MHz	660	2.4	477.5	-2.8	-48.8
15MHz	658	4.3	437.4	-3.5	-43.7
20MHz	660	5.5	404.6	-4.3	-41.6
25MHz	664	11.8	364.5	-5.2	-35.0
30MHz	662	9.1	349.9	-5.5	-37.2
35MHz	664	11.7	342.6	-5.7	-35.1
40MHz	666	11.8	320.8	-6.3	-35.0
45MHz	664	25.7	240.6	-8.8	-28.2
50MHz	662	19.8	266.1	-7.9	-30.5

Table 6: Common to Common and Differential mode data for pair 2 of the LAr cable

7.4 Conclusions

1. The intra-pair skew tests show that all the 16 pairs of the LAr cable consistently have very low skew.
2. S-parameters measurements of the LAr cable show much better performance than the TileCal cable. In particular, the Differential-to-Differential attenuation of 21 meters LAr cable at 50MHz is -5.1dB. Whereas the Differential-to-Differential attenuation of the bad pair of the 75 meters TileCal cable reaches -26.6dB.