Analysis and Optimization of LIGO In-vacuum Shielded Cables

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1. **Overview and Background –** Shielded cables using braided, coaxial shields are in common use at LIGO. Within the optical suspension subsystem, there are additional constraints on the shielded cable assemblies – low mass, low stiffness, ease of cleaning etc. It is desirable to choose copper braiding solutions that are optimal in these regards. A series of measurements have been devised using a customized version of the industry-standard Triaxial Test Fixture as described in NEMA WC 61 and MIL-C-85485.

   The topic of shielding in coaxial cables becomes more complex as frequency increases. This note is written with frequencies from audio to tens of MHz in mind. There is plenty of in-depth literature that explores the esoteric and subtle effects encountered at higher frequencies. This paper doesn't make any claims outside the LIGO frequency band of interest. The data presented extends to 30 MHz due to the test fixture, but it's easy to visually extrapolate the results over the full RF spectrum used at LIGO.

2. **Technique**

   2.1. **Transfer Impedance** - At frequencies below approximately 100 MHz, the effectiveness of a coaxially shielded cable assembly can be quantified by the ***transfer impedance*** parameter. Transfer impedance relates the current induced on the outer shield of a cable to the resultant voltage on the inner wire(s) for a defined length of cable. Transfer impedance has units of volts-out per amps-in per unit length, yielding ohms/meter.

   For systems having multiple inner conductors within a coaxial outer shield, the inner conductors are treated like one large single conductor by shorting the individual wires together. Analysis of balanced-twisted-pairs within a coaxial shield can be addressed by breaking the problem into two parts. Transfer impedance is measured to predict induced voltages on inner conductors, and then common-mode analysis can be used to yield the overall response.

   Quantitative calculation of the induced current in a coaxial shield resulting from an external interfering source requires knowledge of: loop coupling area, loop impedance, incident field strength and field geometry. It's unlikely that these parameters can be anticipated at LIGO, but it is useful to be able to make relative comparisons between different cable shields. This can be reduced to a comparison of relative transfer impedances for different shields.

2.2. **Test Fixture –** A triaxial test fixture was designed that allows testing of a 1 meter length of coaxially shielded cable. Figures 1 to 5 show some details of the fixture.

Figure 1

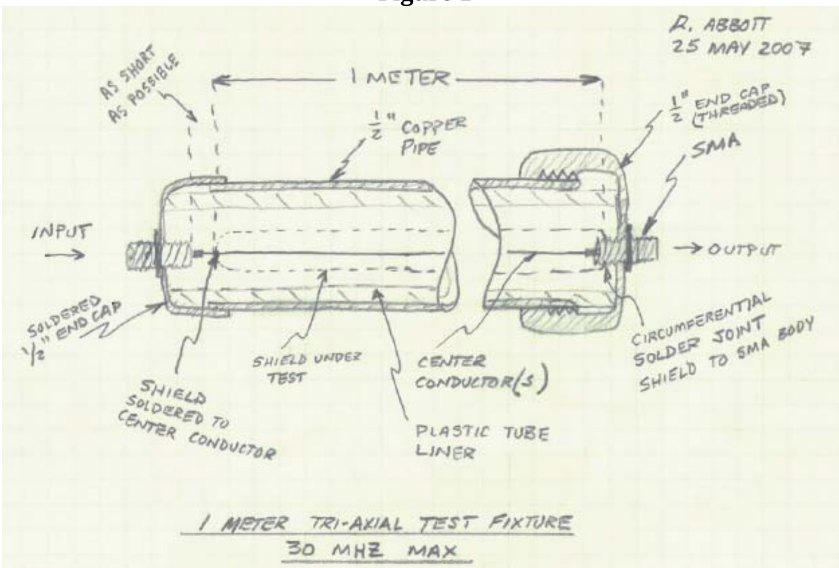


Figure 2 One Meter Triaxial Test Fixture

Figure 3 Removable End of Triaxial Test Fixture and Braided LIGO Cable Sample

Figure 4 Soldered End of Triaxial Test Fixture

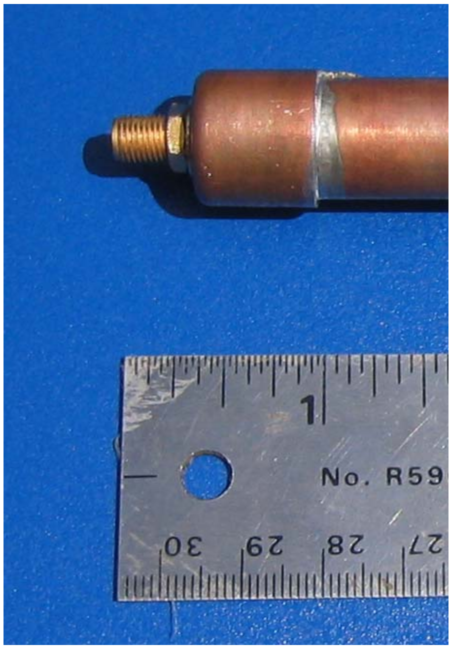
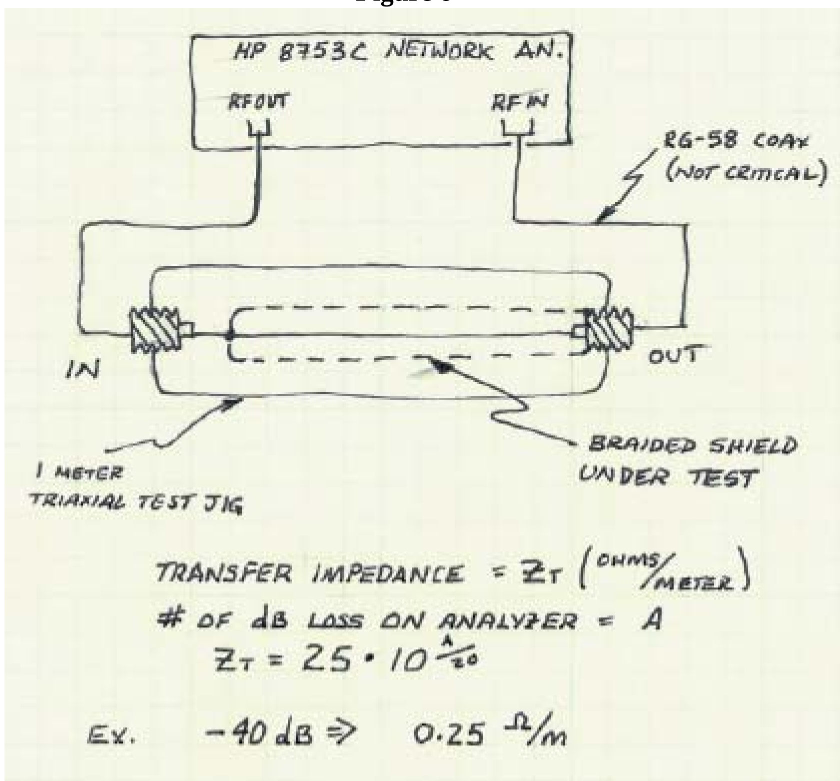


Figure 5 LIGO Braid and Reference Belden 1671 Sample

3. **Measurements**

3.1. **Test Setup –** Figure 6 shows the test setup used to obtain data from 300 kHz to 30 MHz. Data was taken over lower frequencies using the triaxial test jig with the Stanford Research SR-785 dynamic signal analyzer. The comparative results of these two instruments agree well.

Figure 6



3.2. **Interpretation of Results**

3.2.1. **Sample Preparation** - Several 1 meter samples were prepared. Within the ohmic region ranging from DC to approximately 300 kHz, the transfer impedance is the same as the copper loss associated with the shield braid. Above this range, there are significant differences depending on the nature of the shield (solid, braid, double braid etc.).

A sample of Belden 1671, Solder-soaked braid, was used as a "best-case" comparison. The other results are from a LIGO copper braid consisting of 12 picks per inch, 5 wires per carrier, 24 carriers, 0.005 inch individual wire, 120 total ends. 18, 28awg Teflon insulated wires were contained within the LIGO braid. At each end of the LIGO assemblies, the 18 wires were stripped and soldered together to form a single internal conductor. The inclusion of the 18 internal wires is important because the internal wire bundle distorts the weave of the copper braid, increasing the visible aperture size and changing the braid angle.

The first LIGO braided sample was prepared using circumferential soldering and the best possible workmanship. The second sample had a 1 inch section of the braid removed and bridged by a soldered section of 28awg wire. The third sample had an additional 1 inch gap and wire bridge. These gaps offer insight into the effect of passing the shield through an unshielded Sub-D connector, as is common practice at LIGO.

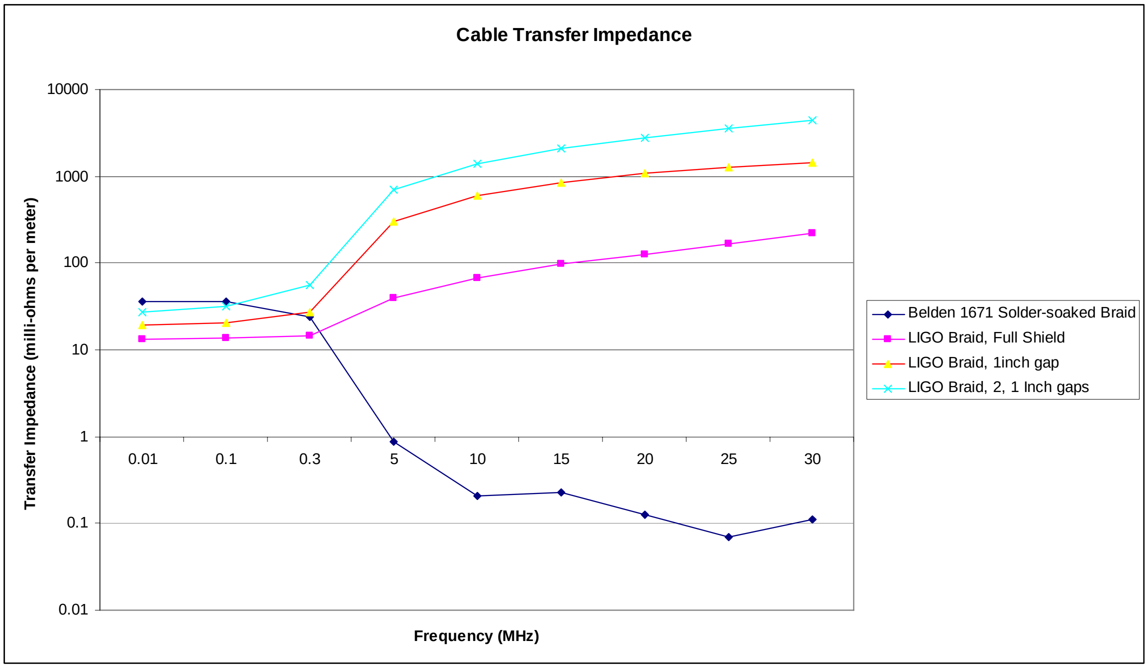
3.2.2. **Graph of Results**

Figure 7 shows the comparative results of measurements on the different cable scenarios. The Belden 1671 more closely resembles a solid tubular shield, and shows a completely different high frequency response that is explained to in cable shielding literature. The fully shielded LIGO cable shows better low frequency performance simply due to the lower copper losses associated with the higher copper cross-sectional area.

The pair of 1 inch bridged gaps in the shield reduces the performance of the 1 meter sample by more than an order of magnitude from several MHz up to the limit of this measurement.

Visual extrapolation of this result to the higher Advanced LIGO modulation frequencies (~55 MHz) is reasonable.

Figure 7



3.3. **Next Steps**

3.3.1. A calculation was done to check the DC resistance of the braid against a calculated value based on the LIGO wire braid parameters. The formula used was obtained from the Alpha Wire Inc. website. This formula yields the percent coverage of the braid as well as the DC resistance per unit length

Figure 8

D1 = 0.15; (*Average diameter of cable under shield, inches*)

D2 = 0.005; (*Diameter of single 36 awg strand, inches*)

P = 12; (*Number of "picks" per inch*)

Nn = 5; (*Number of strands per carrier*)

Ca = 24;(*Number of carriers*)

dR = 414.8 / 1000 / 12 / 2.54 * 100; (*Resistance of 1 strand per 1000 ft, conversion to meters*)

$$a = \mathrm{ArcTan}\left[\frac{(2 * \pi\, (D1 + 2 * D2) * P)}{Ca}\right];$$

$$F = \frac{Nn * D2 * P}{\mathrm{Sin}[a]};$$

$$angle = a * \frac{180}{\pi} \quad \text{(*This is the braid angle in degrees*)}$$

$$Coverage = (2 * F - F \wedge 2) * 100 \quad \text{(*Percent coverage for braid*)}$$

$$Resistance = \frac{dR}{\mathrm{Cos}[a] * Nn * Ca} \quad \text{(*Resistance per meter of the braid at DC*)}$$

For the LIGO braid, the calculated parameters are:
Braid Angle = 26.7 degrees
Braid Percent Coverage = 89%
Braid DC Resistance = 12.7 milli-ohms per meter

The calculated value of 12.7 milli-ohms per meter agrees well with the measured value of 13.4 milli-ohms per meter given that some contact resistance will be added in the relatively short test fixture.

3.3.2. Any number of trade-off scenarios can now be made. One such scenario is to consider the shielding afforded by the pair of 1 inch gaps associated with our in-vacuum connectors as a baseline. A fully circumferential back-shell design could be implemented thus allowing the percent coverage in the braid to be reduced without changing the overall performance.

Calculations show that a 50% coverage braid resulting from using only 3 strands per carrier will likely perform similarly to the existing braid without overall performance degradation. This would have to be verified, but the resulting braid would be lighter, more flexible and easier to clean.

Any number of other combinations may prove useful, but this is an example starting point.

4. **Conclusions**

A relatively simple test fixture has been constructed that allows characterization and comparison of LIGO cable assemblies. Further tests can be conducted on reduced coverage braids to establish their shielding effectiveness.

The test method could be extended to include twisted-pair inner conductors by changing the output connector from an SMA to a balanced differential connector. This would allow the evaluation of total shielding effectiveness in the LIGO differential transmission environment when used in conjunction with a differential receiver. The common practice of unbalanced impedances in differential pairs could then be seen in its true light.