

Common-Mode to Differential-Mode Conversion in Shielded Twisted-Pair Cables (Shield-Current-Induced Noise)

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ABSTRACT

Neil Muncy [1] has shown that audio frequency current flowing on the shield of twisted-pair audio wiring will be converted to differential mode voltage by any imbalance in the transfer impedance of the cable. He hypothesized that the effect is magnified by the presence of a drain wire and increases linearly with frequency. Whitlock [2] and others have shown that conversion also occurs with capacitive imbalance. This paper confirms Muncy's hypotheses and shows that shield-current-induced noise is significant well into the MHz range.

INTRODUCTION

In his landmark 1994 paper, Muncy reported on his work showing that audio frequency current flowing on the shield of twisted-pair audio cables will be converted to differential mode voltage on the signal pair. His test setup used a sine wave and square wave generator coupled to an audio power amplifier and output transformer to establish 100 mA of current on the shield of 175 ft lengths of an assortment of commonly used audio cables. His results showed that some cable constructions caused considerably more mode conversion than others. In general, cables having foil/drain type shields exhibited the greatest mode conversion and those having braid shields or counterwound overlapping spiral shields exhibited much less mode conversion.

Muncy hypothesized that the conversion mechanism was the imbalance in the transfer impedances of the balanced audio conductors to the shield, and cited the drain wire as the principal cause. He called the mechanism "shield-current-induced noise" and gave it the acronym "SCIN." His measurements used 60 Hz,

600 Hz, and 6 kHz sine and square waves, and indicated that the differential mode conversion was essentially proportional to the frequency of the excitation.

There is considerable anecdotal evidence that foil/drain-shielded cables will degrade the immunity of audio systems to radio frequency interference in the 200 kHz to 2 MHz region, and that replacing those cables with braid-shielded cables will significantly improve the immunity. The authors have long suspected that SCIN is a primary agent, converting common mode current set up by a microphone cable acting as a receiving antenna into differential mode voltage on the balanced audio pair.

An input circuit that has poor immunity to radio frequency signals will then detect the interfering signal by one of several mechanisms. First, square law detection can occur in any of the semiconductor junctions exposed to the interfering signal. Second, detection can occur due to slew-rate limiting. Third, detection can occur due to fundamental overload (that is, clipping or rectification) in any active stage.

SOURCES OF SHIELD CURRENT

Some common causes of shield current in audio cables are:

1. Potential differences between points where shields of opposing ends of an audio cable are connected. The potential differences typically result from IR losses (that is, voltage drops) due to leakage currents of motors, lighting equipment, and electronics equipment.
2. Wiring faults in equipment unrelated to the audio system.
3. Magnetic induction.
4. Ground currents from building equipment such as variable-frequency-drive motors.
5. Radio signals, most commonly broadcast signals, but also noise from lighting circuits and other incidental or unintentional radiators.

Power System-Related Shield Currents

Muncy [11] and Windt [3] have noted that shield currents on the order of 100mA are common in North America where shields are dc-connected to ground at each end. Schmidt [4] has noted that much higher currents have been observed between television studio complexes. These currents have mains power frequencies and lower order harmonics of mains power as their major components, but it is not at all unusual for components at high audio frequencies to also be significant. Impulse noise currents with components throughout the audio spectrum can also be present, most commonly the result of power faults, switching transients, and equipment faults. Impulse noise can, of course, include components well into the MHz range.

A shield current of 100 mA at 5 kHz would produce a differential mode signal of about 1 mV in 38 m of most foil/drain cables, which is enough to wreak havoc in most microphone circuits. Only 1mA of shield current at 2 kHz would produce a differential mode signal on the order of 6 μ V in that same cable.

One common cause of both magnetically induced noise and ground fault current is a wiring fault commonly known in North America as a bonded neutral, whereby the connection of a power system neutral to ground at more than one point sets up a path for neutral currents to flow through parts of the ground system. The neutral of every power circuit is required to be bonded to ground at one, but only one point, either where the power service enters the building, or within the building where that circuit is created by the secondary of a transformer. Any additional connections

violate building codes, but they are an all too common mistake in buildings.

Magnetically coupled noise and ground currents often result from a power distribution system known as 3-phase 3-wire "high leg" delta. In this system, the power company's service to a building grounds the centertap of one winding of a 3-phase 240 volt delta service. The 3 phases are brought into the building but there is no dedicated neutral. Instead, a single conductor serves as both neutral and ground. In such a system any neutral/ground currents from surrounding buildings divide between the path to ground at the utility pole transformer and the path through the neutral/ground conductor and its local path(s) to ground. Muncy has found noise current from industrial equipment in an adjacent building to be flowing on a high leg delta service's ground conductor and along a water service pipe running under a studio, with the resulting magnetic field inducing noise into audio circuits.

Magnetic induction is also produced by properly installed power wiring. For example, phase and neutral conductors are often neither twisted nor symmetrical, thus may not couple equally to nearby conductors, including the shields of audio cables. Even stronger fields can be produced by large triplen neutral currents in 3-phase system feeders.

Shield Currents Due to AM Broadcast Fields

AM broadcast interference is known to occur in sound systems when mic cables run exposed (that is, not within grounded metallic conduit) through the attic or around the floor of a wood frame building, most commonly a church. An important question is, "how much current might be flowing on the shields of balanced audio cables at frequencies that could cause interference if converted to a differential mode signal." AM broadcast stations operating between 0.5 MHz and 2 MHz are a common source of such interference.

The behavior of the random long wire antenna formed by the shield of an audio cable cannot easily be analyzed or predicted because of such complex factors as its radiation resistance, impedance, orientation, proximity to surrounding conductive objects, and exposure to the field. On the other hand, AM broadcast field strength outdoors can be reasonably well predicted on the basis of extensive empirical data, especially within about the first 60 km from the transmitting antenna. Thus, to answer the above question, measurements were made at selected locations of the radio frequency currents flowing on the shields of 125 ft lengths of several test cables. While this

survey is far from rigorous, as we shall see, it is informative.

At each measuring location, the cable shield of a 38m long microphone cable was connected as a long wire antenna to the center conductor of the 50 ohm input of a Hewlett Packard 3856C Selective Level Meter. This instrument is essentially a calibrated radio receiver that can be tuned to any frequency up to 32 MHz with selectable measurement bandwidths of 20 Hz, 400 Hz, and 3.2 kHz. All measurements were made with a 3.2 kHz bandwidth. The chassis of the instrument was connected to the power line safety ground. Measurements were made of the carrier strengths of various local broadcast stations during daytime hours, all of which were being propagated by ground wave. Two locations were used.

At location #1, the analyzer was set up in an open wooden gazebo in the center of a small town park about 29 km from the laboratory. The 38 m cable was run about 2.5 m above moist grassy earth and supported by the branches of three small trees. Location #2 was within 7 km of four omnidirectional AM broadcast transmitters, three of them operating at 50 kW. At location #2, the author's laboratory located in the second floor of his wood frame home, the cable was laid on the floor from the laboratory at the front of the house and zig-zagged through the house to the attic.

The current induced in a receiving antenna (that is, the mic cable) will be directly proportional to the field strength. The primary means of propagation within 100 km of AM broadcast stations is ground wave. The ground wave field strength in volts/meter produced by an AM broadcast transmitter varies with the inverse of the distance and an additional loss due to resistivity of the earth. The additional loss increases with frequency and varies with soil conditions.

The United States Federal Communications Commission (FCC) includes within its Rules for Broadcast services a family of empirically determined curves that predict ground wave propagation for various values of soil conductivity, as well as a map showing soil conductivity for the continental United States. [5] These curves were used to predict, based on measured data at the two different locations, how much current would be induced in the same mic cable shield (antenna) if it were at a distance of one mile (1.6 km) from the transmitting antenna. Latitude and longitude coordinates of the receiving locations, determined using a GPS receiver, and coordinates of each transmitter, obtained from the FCC database, were used to determine path lengths. Measured and computed data are summarized in Tables 2 and 3.

At each location, the RSS (root of the sum of the squares prediction of rms of the combined signals) value of the current and voltage were computed from the data for individual signals. The peak value of the voltage in a circuit establishes how much detection will occur, and can be estimated as 1.4X the RSS value, assuming that no other signals contribute significantly interference (for example, a VHF transmitter).

Analysis of the AM radio data

AM broadcast transmitters use vertical antennas having lengths ranging from 0.2 to 0.625 wavelength. Half-wave and 5/8 wave antennas have the advantage of the greatest field strength in the horizontal plane, providing gain in the vertical plane of 1.9 dB and 3.25 dB, respectively, over a quarter-wave antenna. Many AM broadcast stations use multi-tower arrays to provide directivity in the horizontal plane to optimize their coverage of an intended service area and protect certain azimuths from interference. The horizontal directivity can cause the field strength in a given direction to vary by as much as +12 dB and -10 dB from that for a single tower.

The FCC curves were found to be a good predictor of ground wave field strength over the range of distances traversed by the measured transmitters. At both measurement locations the predicted currents from most of the omnidirectional transmitters varied no more than 3 dB from each other taking into account their transmitter power and antenna directivity, even though the distances from the nearest to the farthest varied from 2 km to 60 km!

Transmitter power / Location	50 kW	5 kW	1 kW
Lab - 2nd/3rd floors of wood frame house	4.8mA	1.5mA	0.6mA
Open park - 2m above earth	5.3mA	1.7mA	.75mA

Table 1 - Predicted AM Broadcast Shield Current

From the two measurement setups, predictions of current at 1.6 km from an omnidirectional transmitting antenna were computed and are summarized in Table 1.

The field strengths from directional antenna systems deviated by about ± 6 dB from those for omnidirectional antennas. Thus, making allowances for transmitting antenna directivity, the range of currents in a typical 38 m mic cable shield unshielded by conduit or building steel might be expected to range from about 1 - 20 mA at one mile (1.6 km) from a 50,000 watt transmitter, from 0.5 - 10 mA at one mile from a 5,000 watt transmitter, and from 0.2 - 2 mA at one

mile from a 1 kW transmitter. Some lengths, heights, orientations, and paths for receiving antennas could easily result in significantly greater currents, perhaps as much as 10 dB. In neither of the test setups could the audio cable shield have been considered a "good" receiving antenna.

CABLE MEASUREMENTS

The laboratory work upon which this paper is based extends Muncy's work on SCIN to 4 MHz. The test setup is shown in Figure 1. A Hewlett Packard 8657A synthesized radio frequency generator or a Hewlett Packard 200CD sine wave generator establishes current on the shield of a twisted-pair cable. A small resistor in series allows a radio frequency voltmeter to measure shield current. The twisted pair is shorted to itself (but not to the shield) at the sending end, and is terminated in 200 ohms at the receiving end. A battery-powered Fluke 199 Scopemeter, connected to the twisted pair at the receiving end measures the differential mode voltage. To allow the use of unbalanced instrumentation, circuit common (and the connection point for the shields of instrumentation) is at the receiving end, where the cable shield and the "low" signal conductor were connected together. A hand-wound balun isolated the Scopemeter channel A input from common mode voltages. The channel B input read the voltage across the small series resistor, which was connected between the generator shield and the cable shield at the receiving end of the cable.

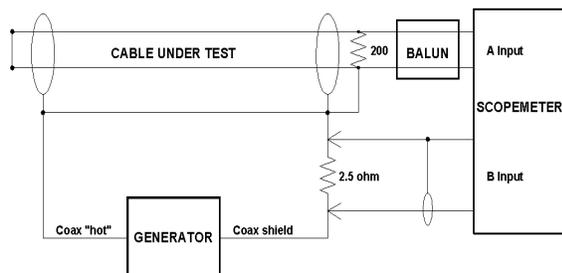


Figure. 1 SCIN Measurement Setup

The range of the measurement is limited by the 5 mv/division sensitivity of the Scopemeter combined with the current drive capability of the generator. The 8657A is rated for 0.7 volt into 50 ohms between 100 kHz and 1 MHz and 1 volt above 1 MHz. The cable shield is a very low resistive load at audio frequencies, gradually becoming an increasingly inductive load as frequency increases. The longer (38 m) cable samples exhibited resonances beginning around 1 MHz. The cable shield was thus a difficult load for the generator to drive below about 60 kHz due to its low impedance, and the current drive capability of the 8657A degrades below 100 KHz. At the lowest frequencies a vintage Hewlett Packard 200CD frequency

generator was substituted for the RF generator. The 200CD was able to produce about 38mA at 10 kHz into all of the cable samples. The voltage readout function of the 199 Scopemeter was used for all differential mode voltages greater than its lower limit of -60 dBV. Below that level voltages were measured by counting divisions on the screen.

The cables were uncoiled, one at a time and run freely about a laboratory having wood floors so that their shields present the minimum inductance to the generator, thus maximizing the test current. Measurements were made at discrete frequencies in increments of one octave between 10 kHz and 4 MHz. Because the data was subsequently normalized to a constant shield current, this has no effect on the SCIN properties of the cable, but it does maximize the sensitivity of the test and allows the data to be collected with relatively simple test equipment. Muncy's work was also conducted using unspooled cable. [1]

A variety of cables were tested, including multiple types having foil/drain shields, counterwound spiral shields, shields consisting of both braid and drain wires, one type having a braid shield, and one type having both a foil and braid shield but no drain wire. All cables were measured with XL connectors soldered on, and with all copper shields soldered to pin 1 (and only to pin 1) per AES14.

In the list of cable types tested, a symbolic naming convention was adopted to aid in analysis of the data. The first letter or letters indicates the shield type. B indicates a braid shield, F indicates a foil shield, S indicates a double spiral shield, and D indicates a drain wire. A indicates a cable intended for analog audio, a second letter D indicates a 110 ohm cable, and M indicates a miniature cable. Where multiple products of the same generic type were tested a number is added to differentiate them.

BA - A 0.262" diameter rubber covered portable microphone cable with a braid shield. This cable was Muncy's cable #2. [1]

BDA - A 0.194" diameter 76 ohm twisted-pair braid/drain-shielded portable microphone cable.

BDAM - A 0.138" diameter 60 ohm twisted-pair braid/drain-shielded portable cable.

BD95 - A 0.272" diameter 95 ohm twisted-pair braid/drain-shielded portable cable.

BDD1 - A 0.211" diameter 110 ohm twisted-pair braid/drain-shielded portable cable.

BDD2 - A 0.235" diameter low-loss 110 ohm twisted-pair braid/drain-shielded portable cable.

BDQ - A 0.24" diameter quad-star braid/drain-shielded portable microphone cable.

BF - A 0.14" diameter twisted-pair braid/foil shielded cable for fixed installation.

CP A 0.25" diameter portable twisted-pair microphone cable with a conductive carbon plastic shield.

FDA1 - A 0.135" diameter twisted-pair foil/drain-shielded cable.

FDA2 - A 0.14" diameter 60 ohm twisted-pair foil/drain-shielded cable.

FDA3 - A 0.138" diameter 45 ohm twisted-pair foil/drain-shielded cable. This cable was Muncy's cable #5. [1]

FDA4 - A 0.132" diameter twisted-pair foil/drain-shielded cable.

FDD1 - A 0.143" diameter 110 ohm twisted-pair foil/drain-shielded cable.

FDD2 - A 0.19" diameter low-loss 110 ohm twisted-pair foil/drain-shielded cable.

SA - A 0.19" diameter portable microphone cable with three twisted conductors and two served copper spirral shields wrapped in opposition. This cable was Muncy's cable #1. [1]

SD - A 0.204" diameter 110 ohm twisted-pair cable with two spiral shields wrapped in opposition.

To provide accurate data over the wide spectrum, it was decided to make measurements on cables of various lengths so that effects of wavelength could be studied. Each cable sample was cut into lengths of 50 ft (15 m), 40 ft (12 m), 25 ft (7.6 m), and 10 ft (3 m) and XL connectors were attached. Measurements were then made on all four lengths connected in series via their XL connectors (125 ft or 38 m), and on the 50 ft (15 m), 25 ft (7.6 m), and 10 ft (3 m) samples. No measurements were made on the 40 ft (12 m) samples other than as part of the 125 ft combination. All SCIN measurements were made in co-author Brown's laboratory. An additional length of each (10 ft for most cable types) was sent to co-author Whitlock's laboratory for measurement of basic electrical parameters. Samples of cable types SA, BA, BDAM, and BDD1 were from one of the author's stock of portable cables. The other cables tested were cut from a single roll.

Basic Electrical Parameters

From end to end, a cable shield has both resistance and inductance. Any AC voltage developed across this inductance will magnetically induce a similar voltage in each conductor (as well as any other con-

ductors near the shield), thus effectively forming a three-winding transformer that has a turns ratio of approximately 1:1:1.

In the interest of simplicity, in this paper we discuss only current drive of the shield that is constant with frequency. This results in a voltage across the transformer primary (shield inductance) and an induced common mode voltage in the signal pair that rises linearly with frequency. Magnetic induction is very strongly affected by physical proximity, especially when very near the field source, which in this case is the shield conductor. Ideal cable construction would locate the signal conductors at exactly the same distances to the shield conductor, even when the shield conductor surrounds the signal pair. Thus exactly equal voltages would be induced and a differential (signal) component would not exist. Even with identical induced voltages, impedance imbalances in the driver, cable, and receiver can convert a portion of the induced common mode voltage into differential mode voltage. Twisting is a first order approach intended to "average" the proximity of the two signal conductors to a noise source.

Measurements were made on short samples of each of the tested cables to determine its basic electrical parameters. Most of the samples were approximately 3 m long; a few were on the order of 8 m. Data is summarized in Tables 5 and 6, and includes:

1. Capacitance between each signal conductor and the other signal conductor connected to the shield. Measurements were made at 10 kHz using an Electro Scientific Industries 2100 videobridge.
2. DC resistance of each signal conductor and the shield. Measurements were made in 4-wire mode at 1 mA using an HP/Agilent 34401A multi-meter. Samples having attached XL connectors were measured at solder terminals to exclude contact resistance.
3. End-to-end inductance of the shield with no connections to other conductors. Measurements were made at 50 kHz on an Electro Scientific Industries 2100 videobridge with the cable formed into an approximate circle on the floor.
4. The physical length of each sample.

Measurements of the inductance of the signal conductors were made in an attempt to determine the apparent turns ratio, but they were not of sufficient precision to be of value and are not presented here. The measured electrical parameters were post-processed to determine the apparent electrical symmetry of each cable sample. The post-processed data included:

5. The ratio of the capacitances measured in #1, and that ratio expressed as a signed percent difference to their mean.
6. The ratio of the series resistances of the two signal conductors, and that ratio expressed as a signed percent difference to their mean. This represents a combination of any difference in the lengths and cross sectional areas of the two conductors.
7. Capacitance and resistance per unit length.

Circuit Model

Measured circuit parameters for one of the tested foil/drain cables, cable FDD1, were used to create a simple lumped parameter circuit model treating the cable as a three-winding transformer as suggested by Muncy. An ideal cable would have a 1:1 turns ratio between the signal conductors (measured end to end). It would also have equal values of series resistance for the two windings representing the signal conductors, equal values for the inter-winding capacitances, and equal values for mutual inductance between the shield and each signal conductor.

Shield Construction and Distribution of Shield Current

For each cable having a drain wire, the relative distribution of current between the drain and the shield was

computed from a combination of computed and measured data. For some of the cables, engineering data for the dc resistance of the components of the shield were provided by the manufacturer. For others the values were computed from measured data. When a drain wire was of the same gauge as a signal conductor, resistance measurements on the signal conductor were assumed to also represent the resistance of the drain. Where the drain was a different gauge, the measured resistance was multiplied by the ratio of the resistance per unit length of the drain wire to that of the signal conductor. Manufacturer-provided data tended to correlate well with measurements of the same parameters.

It should be noted that distribution of current throughout a foil or braid shield and between the shield and a drain wire will vary with frequency as a function of their respective geometries. It should also be noted that for most cables having a drain wire the drain is in contact with the more homogenous shield (that is, the braid or drain) along its entire length. An analysis of these more complex issues is beyond the scope of this paper.

MEASURED DATA

Freq kHz	dBV in 50 ohms	Shield current mA	km to ant	1 kW - meas pt mV/m	1 kW - 1.6 km mV/m	Path loss re: 1.6 km (dB)	Extrapolate to 1.6 km (mA)	Ant	Ant vert gain (dB)	Transmitter dB(kW)
RSS	-13.7	4.13								
560	-54.5	0.038	66.6	1.2	95	38	3.0	Dir	0	7
620	-70	0.0064	82.3	0.72	95	42.4	0.84	Dir	1.9	17
670	-25	1.13	6.39	22	95	12.7	4.87	Omni	1.9	17
720	-22	1.59	5.09	28	95	10.6	5.41	Omni	2.3	17
780	-16	3.18	2.82	59	95	4.1	5.11	Omni	2.3	17
820	-40	0.20	21.9	4.1	94	27.2	4.61	Omni	1.5	7
890	-47	0.09	48	1	93	39.4	5.97	Omni	2	17
950	-52	0.051	29.6	2.3	93	32.1	2.05	Omni	0	0
1000	-32	0.504	16.9	5.2	93	25	9.02	Dir	1.9	17
1110	-23.5	1.341	4.6	27	93	10.7	4.62	Omni	3	7
1160	-26	1.006	14.6	6.3	93	23.4	14.9	Dir	0	17

Table 2 AM Broadcast Measurements - Location #1

Freq kHz	dBV in 50 ohms	Shield current mA	km to ant	1 kW - meas pt mV/m	1 kW - 1.6 km mV/m	Path loss re: 1.6 km (dB)	Extrapolate to 1.6 km (mA)	Ant	Ant vert gain (dB)	Transmitter dB(kW)
RSS	-27.1	0.88								
560	-77.4	0.0027	50	1.25	95	37.6	0.21	Dir	0	7
620	-77.5	0.0027	88	0.65	95	43.3	0.39	Dir	1.9	17
670	-43.5	0.134	33	3	95	30	4.26	Omni	1.9	17
720	-44	0.127	30	3.08	95	29.8	3.91	Omni	2.3	17
780	-45	0.113	29	3	95	30	3.58	Omni	2.3	17
820	-37.1	0.286	7	17	94	14.9	1.55	Omni	1.5	7
890	-51.2	0.0555	48	1	93	39.4	1.78	Omni	2	17
950	-54.7	0.0371	12	9.5	93	19.8	4.3	Omni	0	0
1000	-39	0.226	31	1.8	93	34.3	0.36	Dir	1.9	17
1030	-66.5	0.0095	36	1.35	93	36.8	0.7	Dir	0	5
1060	-70.9	0.0058	100	0.12	93	57.8	4.5	Omni	0	7
1080	-68.5	0.0076	37	1.2	93	37.8	0.6	Omni	-1	4.7
1110	-46.2	0.0985	28	1.75	93	34.5	5.24	Omni	3	7
1130	-73.2	0.0044	93.7	0.16	93	55.6	2.7	Dir	0	17
1160	-28.8	0.729	18	3.9	93	27.5	17.4	Dir	0	17
1240	-40	0.201	7	17	91	14.6	1.08	Omni	0	0
1300	-63.8	0.013	34	0.93	91	39.8	1.3	Omni	0	6.5
1390	-58.6	0.0237	26	1.4	88	36	1.49	Dir	0.5	7
1450	-67	0.009	16	3.2	88	28.8	0.25	Omni	-1	0
1490	-58.8	0.0231	14	3.65	88	27.6	0.56	Omni	0.3	0
1590	-47	0.09	6.7	13	86	16.4	0.59	Omni	0	0

Table 3 AM Broadcast Measurements - Location #2

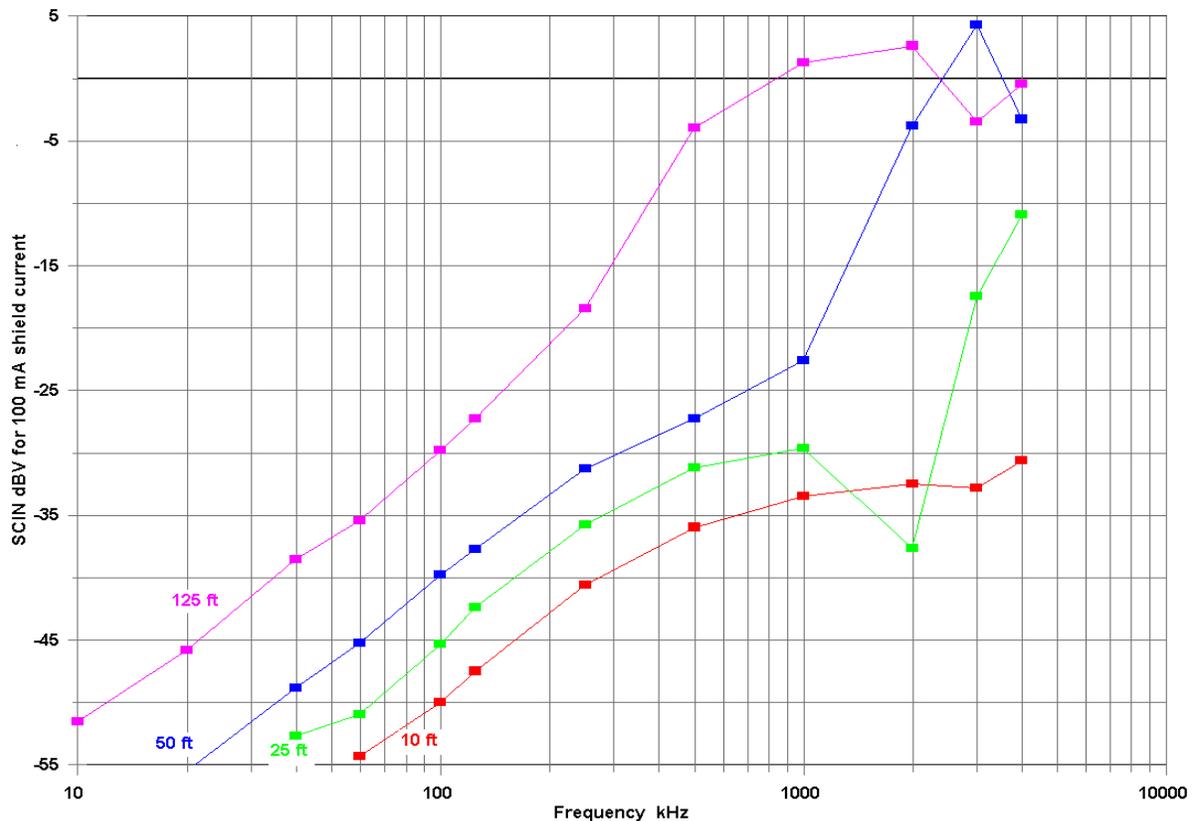


Figure 2 Measured data for the modeled cable, FDD1, normalized for current but not normalized for length.

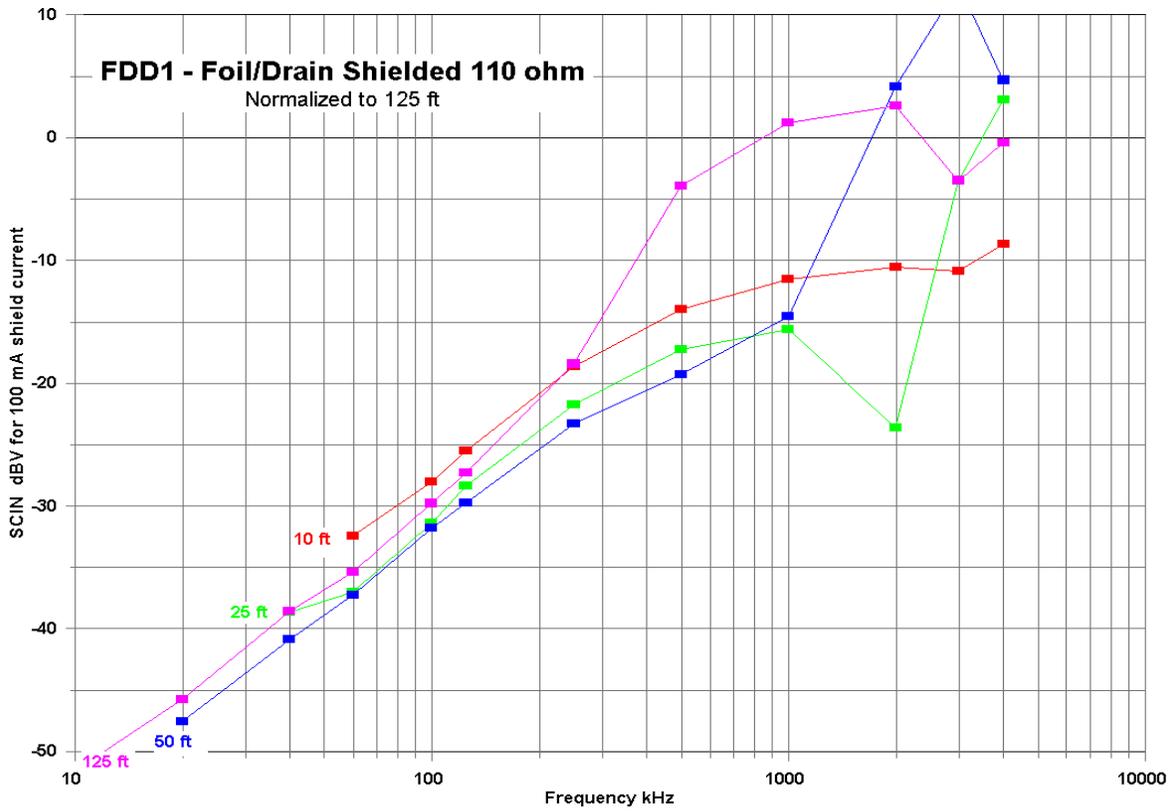


Figure 3 Measured shield-current-induced noise for the modeled cable, FDD1, normalized to 125 ft.

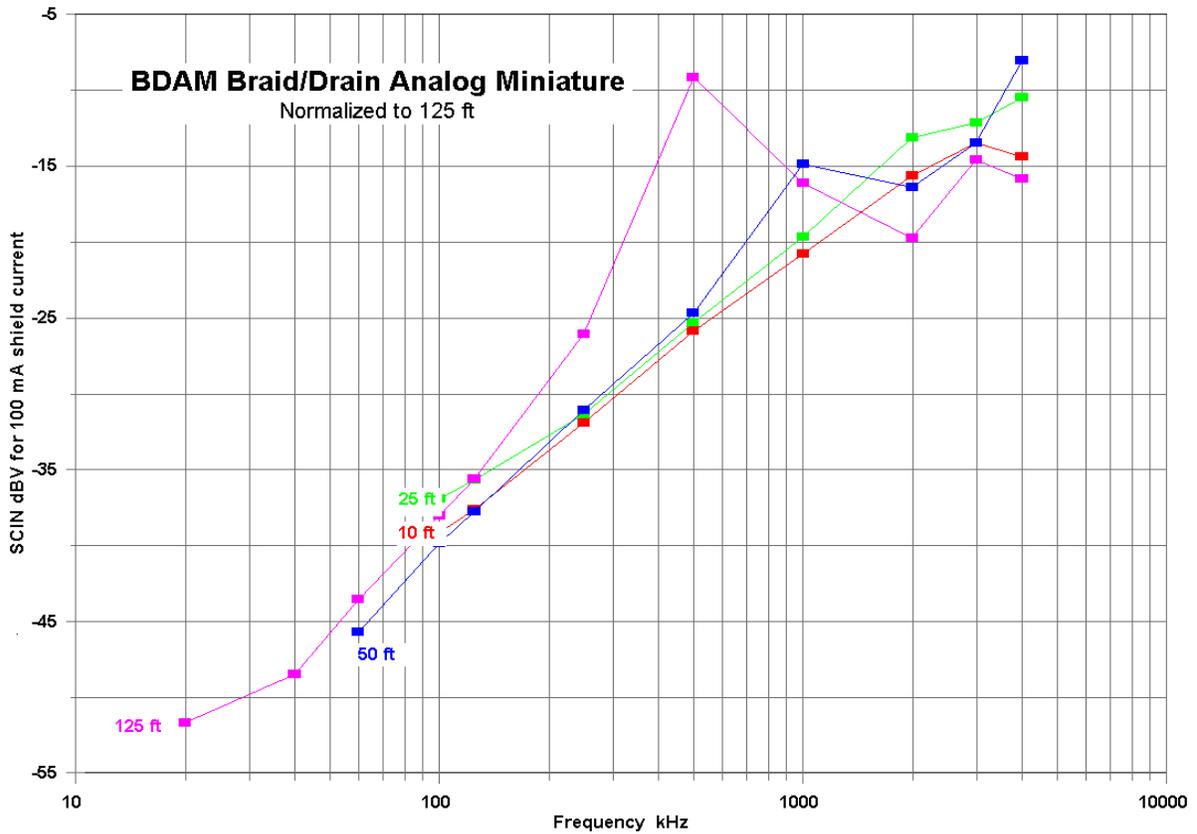


Fig 4 Measured shield-current-induced noise for a miniature braid-shielded cable with a drain wire.

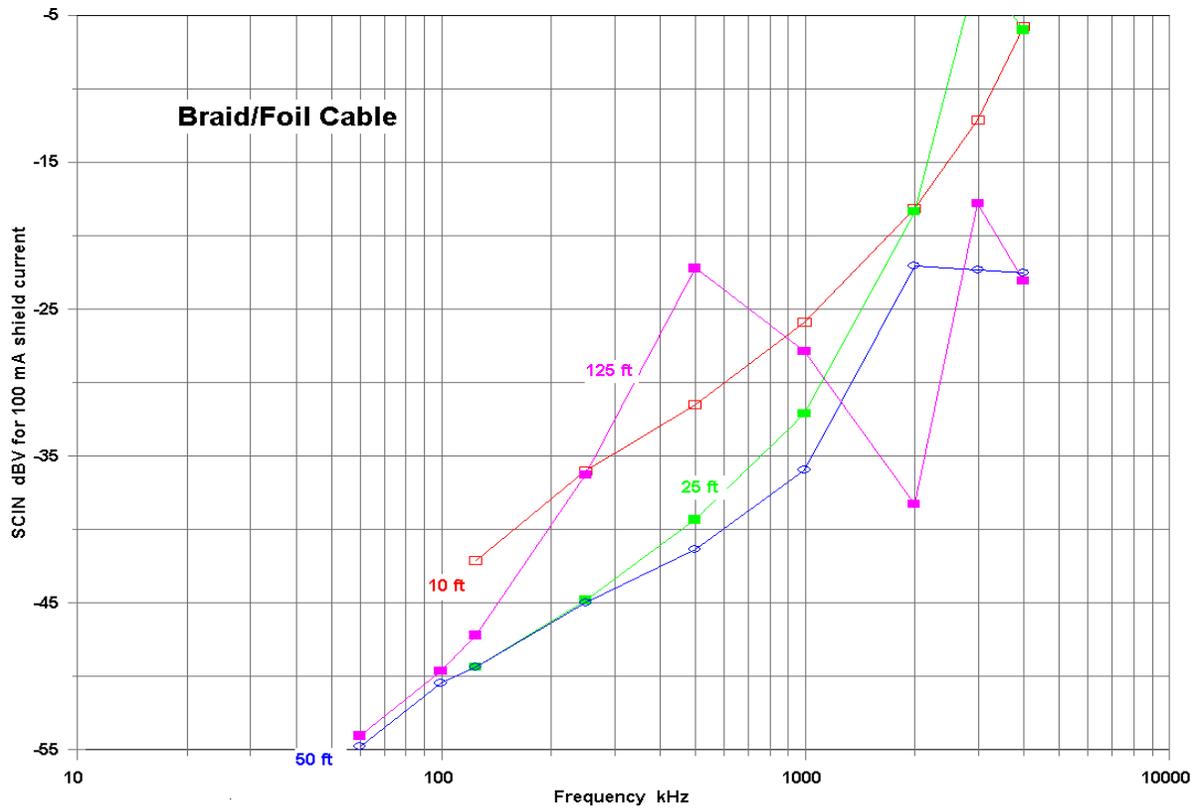


Fig 5 Measured data for miniature foil and braid-shielded cable BF.

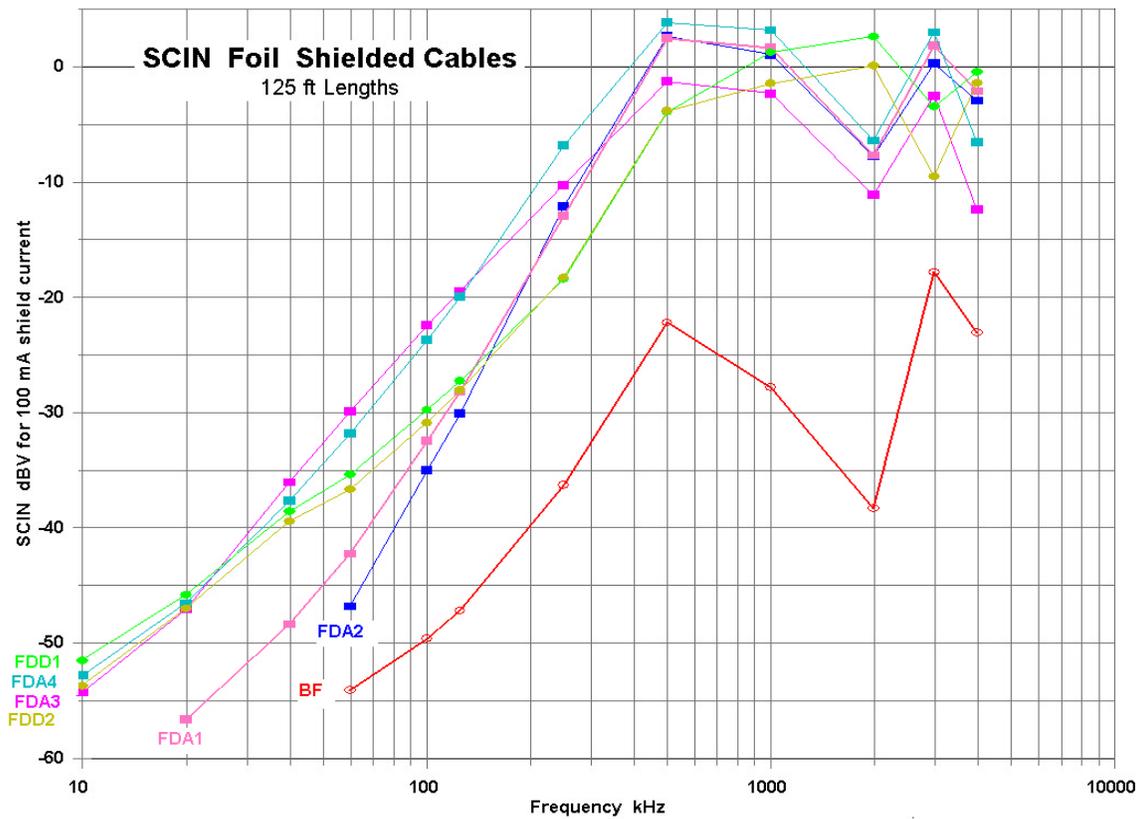


Figure 6 Measured data for 125 ft Foil-Shielded Cables

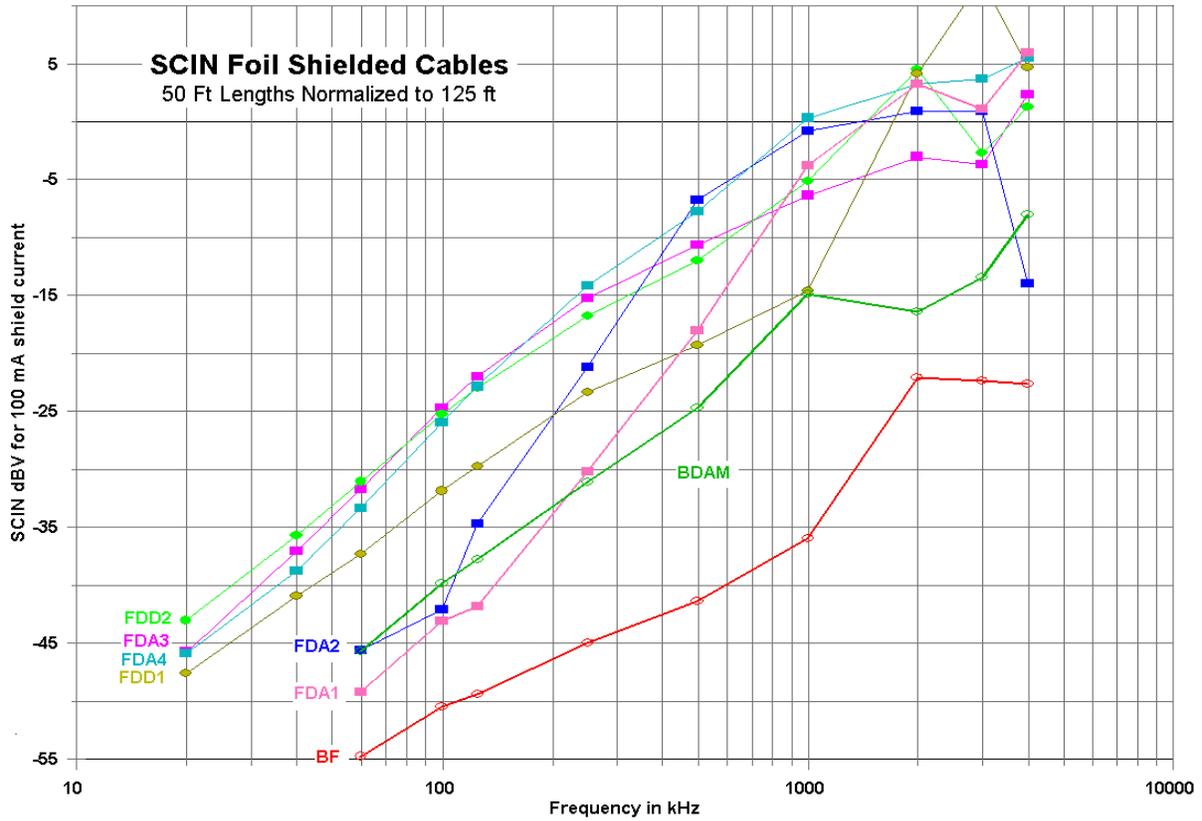


Figure 7 Measured data for 50 ft foil-shielded cables.

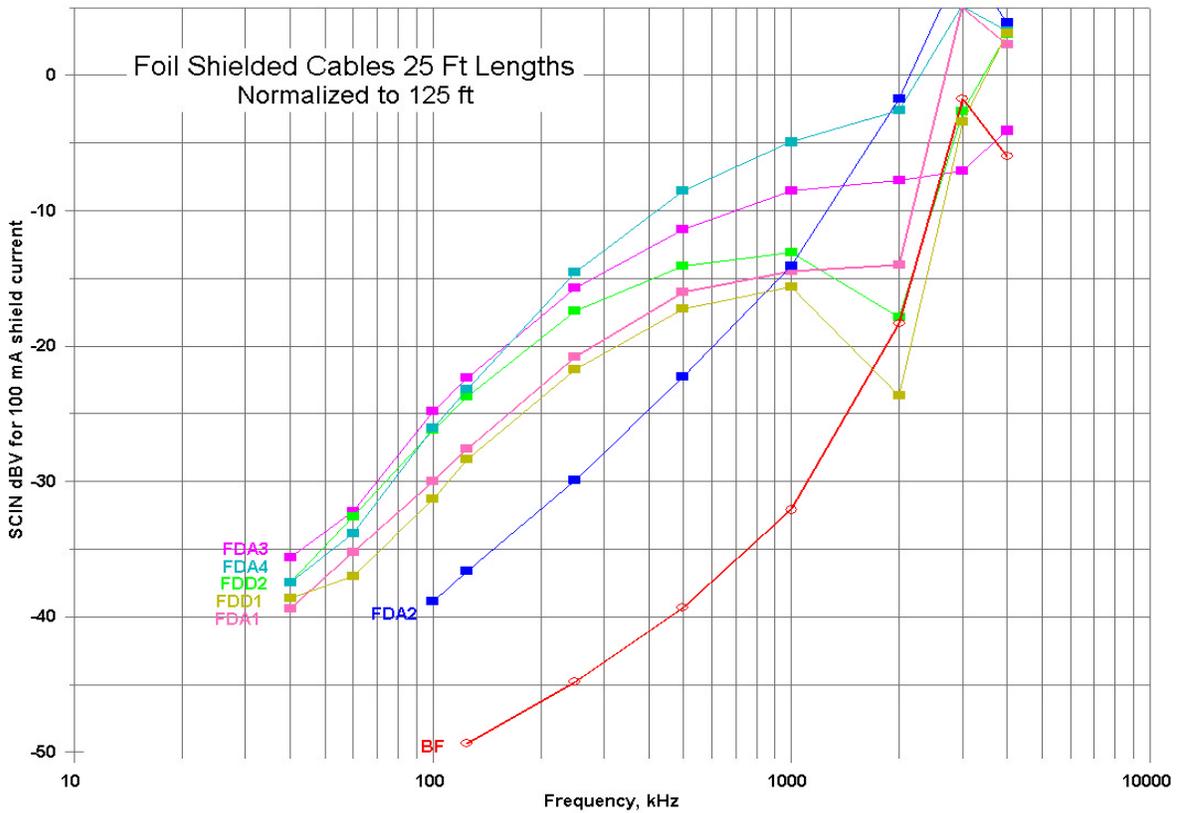


Figure 8 Measured Data for 25 ft foil shielded cables.

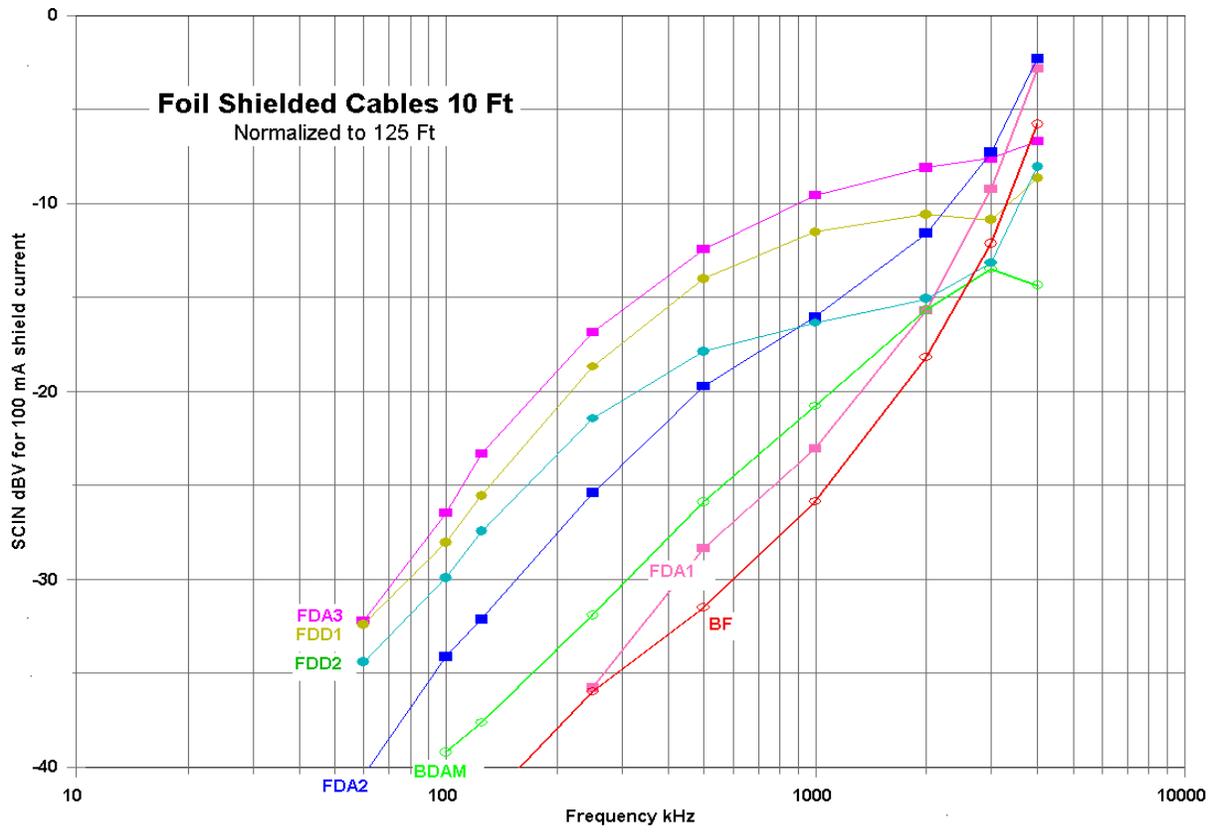


Figure 9 Measured data for 10 ft foil shielded cables.

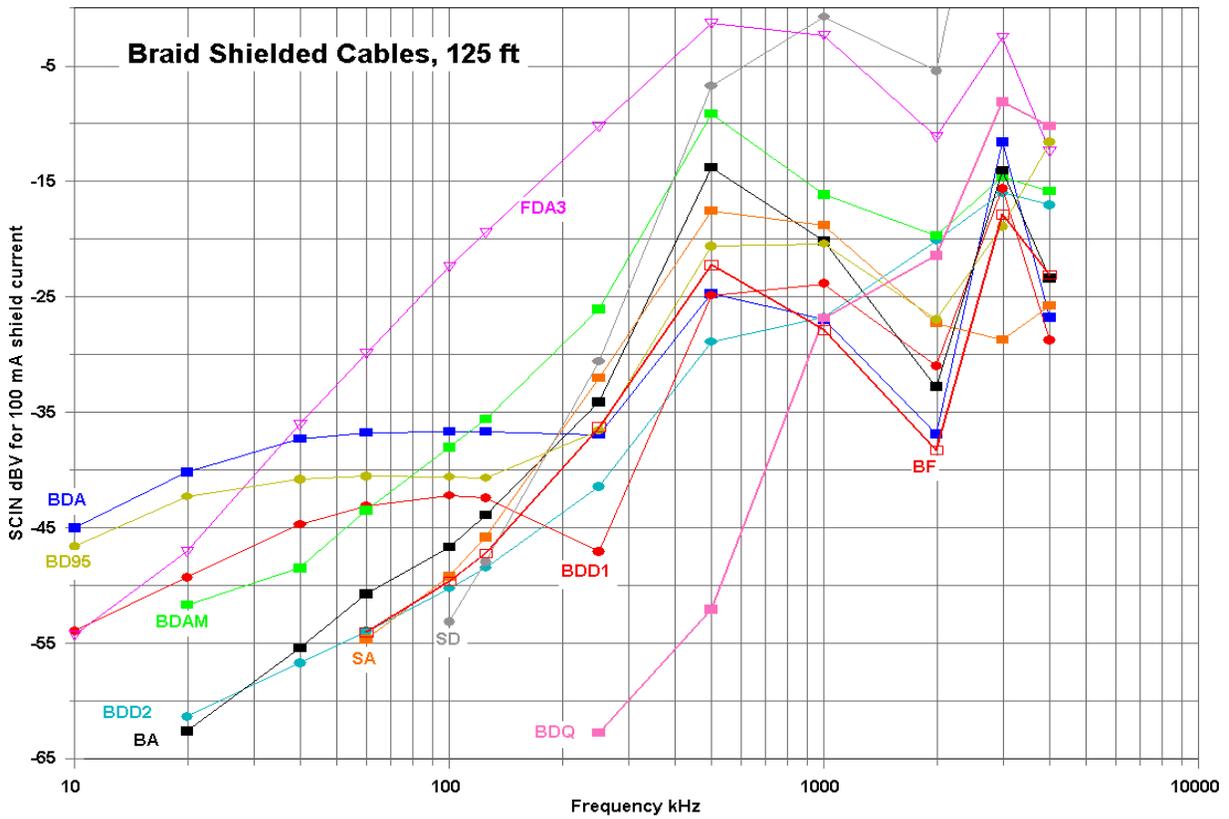


Figure 10 Measured data for 125 long braid-shielded cables.

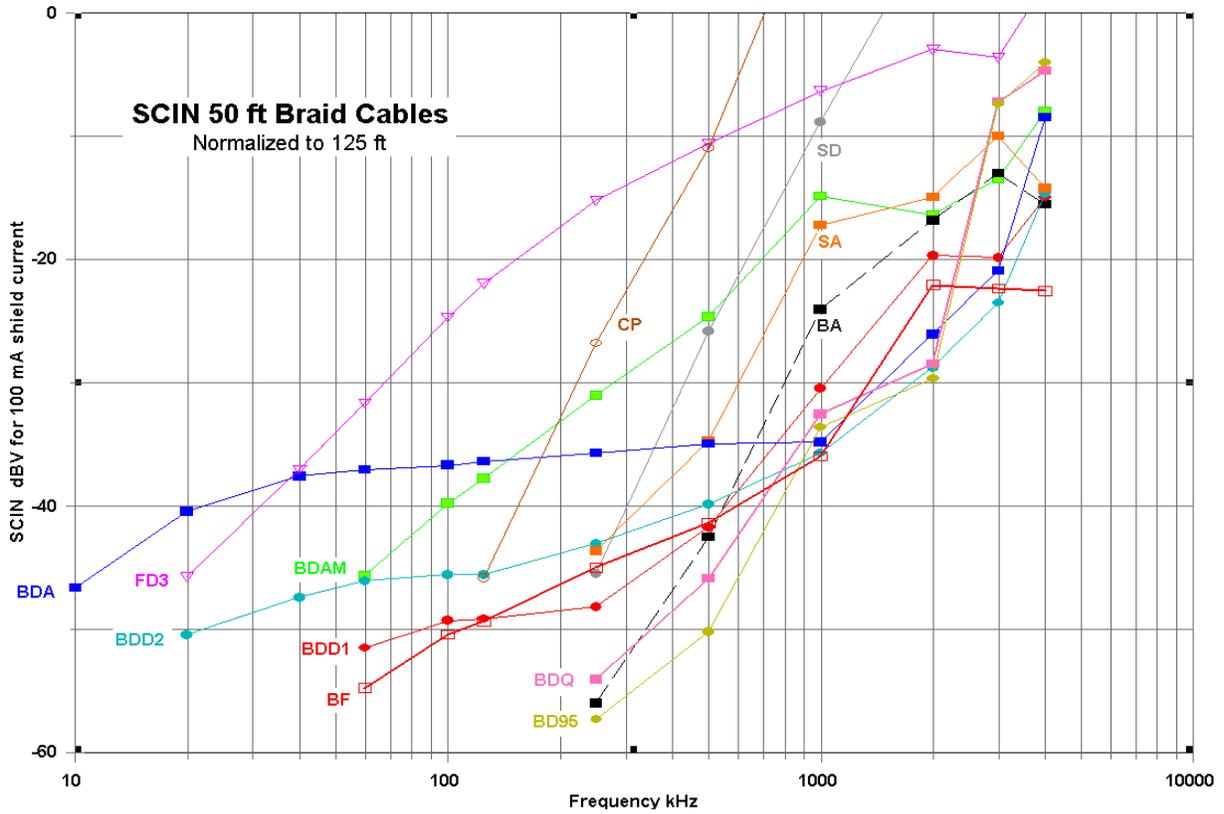


Figure 11 Measured data for 50 ft braid-shielded cables.

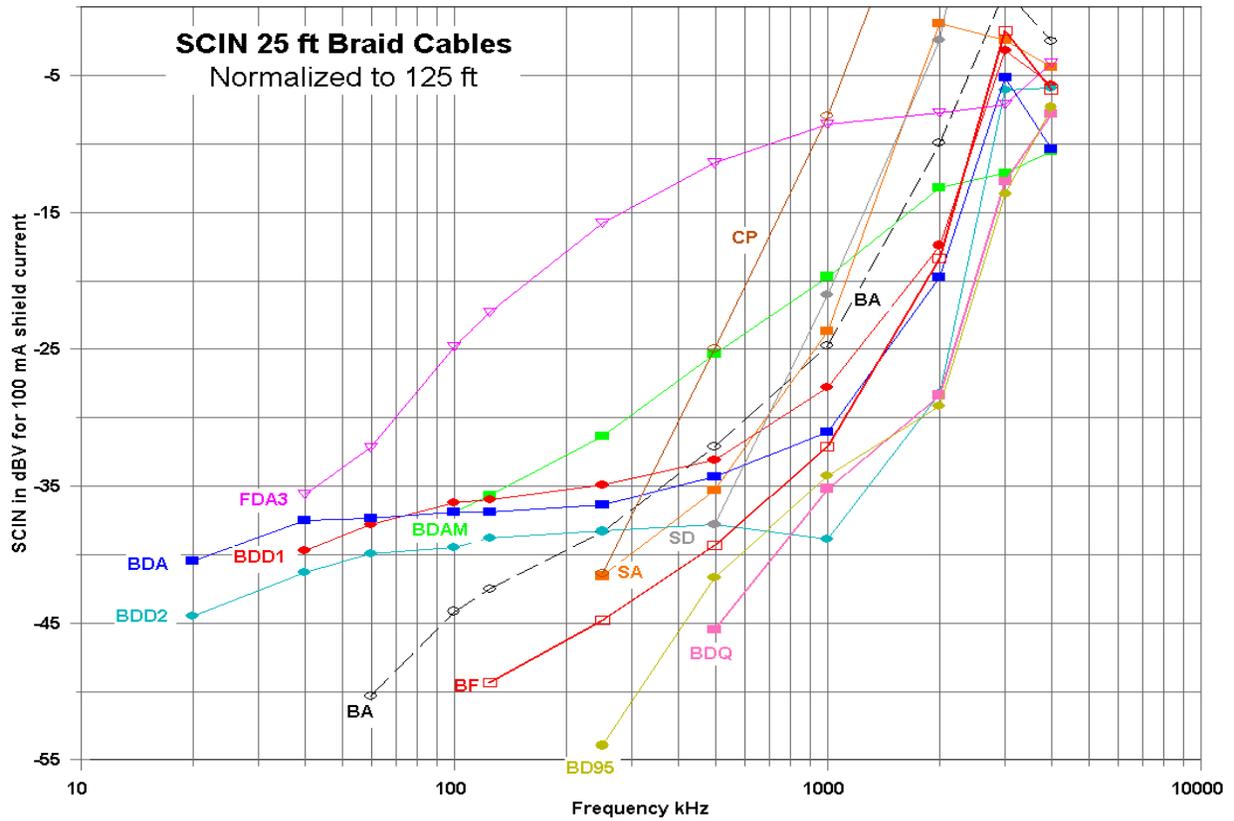


Figure 12 Measured data for 25 ft braid-shielded cables.

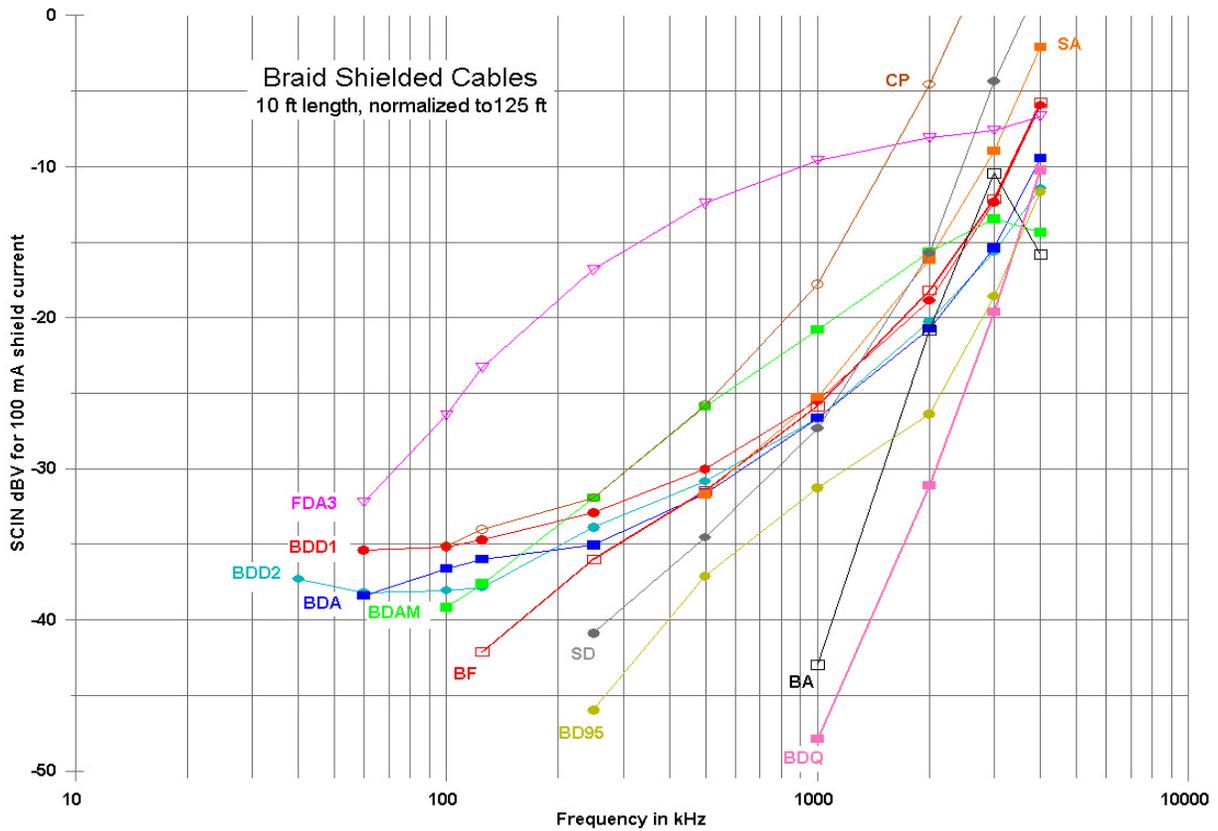


Figure 13 Measured data for 10 ft long braid-shielded cables.

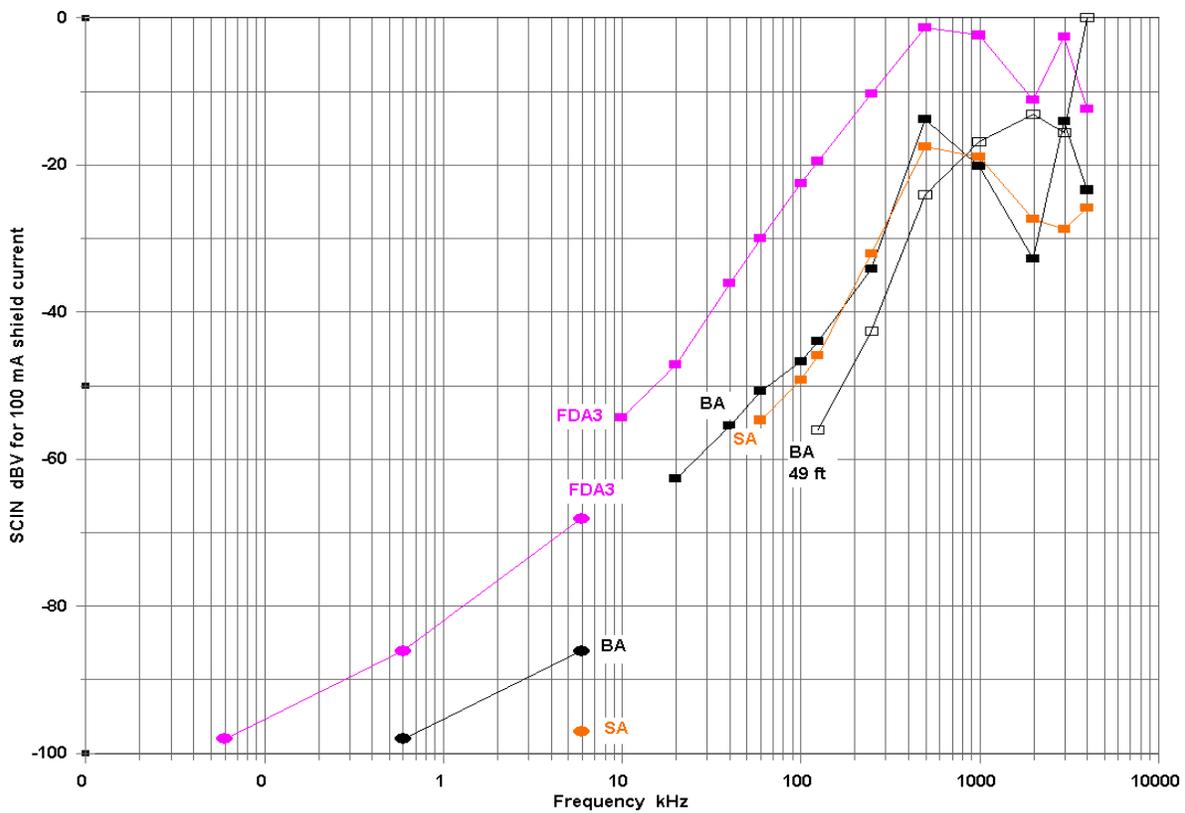


Figure 14 Measured data compared with Muncy's data.

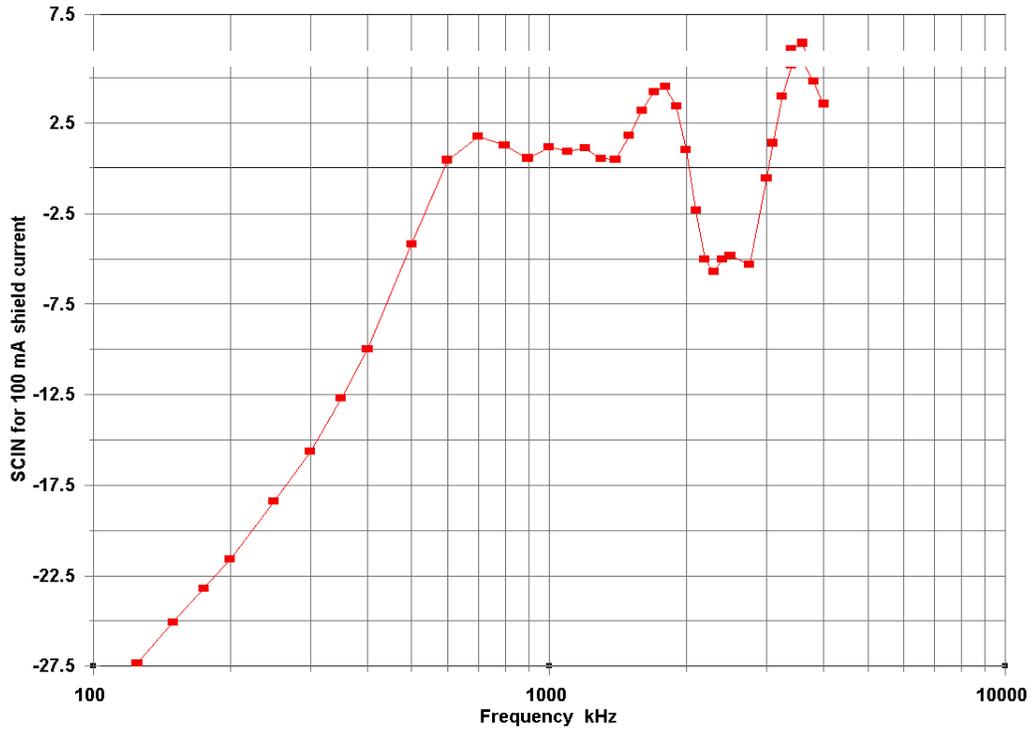


Figure 15 More closely spaced data points for 125 ft cable FDD1 shows resonance and transmission line effects.

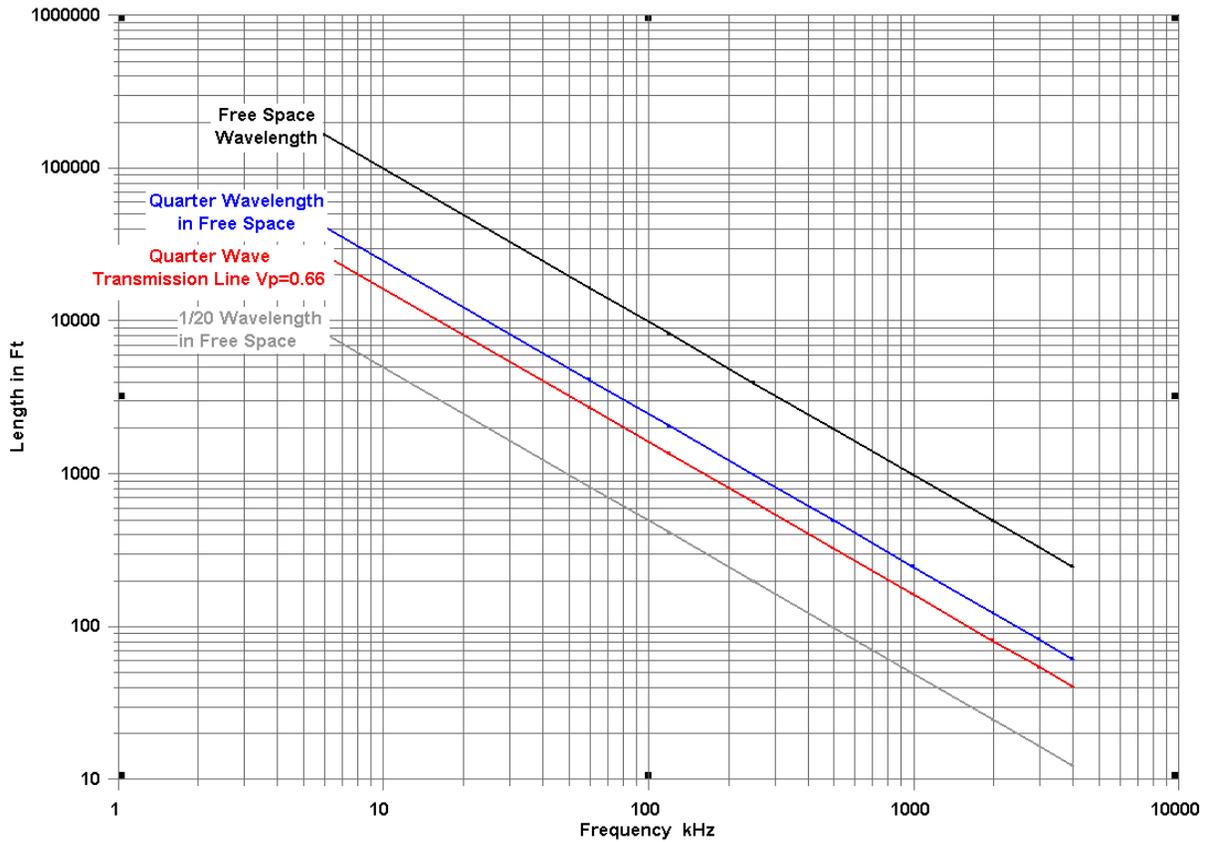


Figure 16 Wavelength and frequency relationships.

Type	Sample Length ft	Cap High to Low+Shld pF	Cap Low to High+Shld pf	Cap diff	Shield R m Ω	Signal High m Ω	Signal Low m Ω	Shield μ H
BA								
BD95	10.58	295.2	307.4	-4.05%	39	155	160	3.24
BDA	10.42	412.2	402.9	2.28%	44	284.5	294	3.51
BDAM	25.25	1195	1203	-0.67%	181.5	685	675.5	10.42
BDD1	25.08	684.5	669.8	2.17%	137.5	608	582	9.423
BDD2	10.33	213.6	208.6	2.37%	33	240	239.5	3.14
BDQ	10.5	606.5	636.1	-4.76%	32.5	135.5	136	3.485
BF	138.5	5800	6280	-9.21	460	3360	3470	
CP	10.92	464.2	460.8	0.74%	151.5	151.5	151.5	4.7
FDA1	16.25	942.2	927.2	1.60%	329	267.5	266	6.78
FDA2	14.92	894.5	899.7	-0.58%	196	220	219	6.221
FDA3								
FDA4	28.17	2408	2349	2.48%	605	464	470	124
FDD1	10.46	271.2	258.3	4.87%	265.5	399.5	399	4.145
FDD2	10.46	230.1	240.4	-4.38%	175	245	244	3.75
SA	10	659.8	656.3	0.53%	48.5	271	269.5	3.595
SD	10.5	249.4	246.9	1.01%	80	362.5	355	3.58

Table 5 Cable parameters - part 1

Note: Cable BF data courtesy of Ray Rayburn, who used a Data Precision 938 for capacitance measurements and a Fluke 87 series IV in difference mode to measure the resistance parameters. To measure the low values, the cable was clamped into a Johnson double banana plug. Reference for the difference measurement was a heavy short wire clamped into the plug.

Type	R diff %	O.D. inch **	Shield OD in. **	Shield Type	Drain AWG **	Z _o Ohms **	Pf/ft Pair **	Loss dB/100m 6 MHz **
BA		0.262	0.192	Braid	None		30	
BD95	-3.13%	0.272	0.2	Braid	22	95	15	5.4
BDA	-3.23%	0.194	0.122	Braid	24	76	20	
BDAM	1.41%	0.138	0.121	Braid	24	60	26.1	
BDD1	4.47%	0.211	0.137	Braid	26	110	13	9.88
BDD2	0.21%	0.235	0.155	Braid	24	110	11	5.25
BDQ	-3.7%	0.24	0.16	Braid	24		39	
BF	-3.17%	0.135		Braid/Foil				
CP	0.03%			Cond Plastic	22			
FDA1	0.56%	0.135	0.095	Foil	24		32	
FDA2	0.46%	0.14	0.1	Foil	22	60	25	
FDA3		0.138	0.098	Foil	22	45	34	
FDA4	-1.28%	0.132	0.092	Foil	24		37	
FDD1	0.13%	0.143	0.101	Foil	26	110	14	10.3
FDD2	0.41%	0.19	0.134	Foil	24	110	11	5.25
SA	0.56%	0.189		Spiral	24	150	56.4	
SD	2.11%	0.204	0.13	Spiral	none	110	12	7.08

Table 6 Cable parameters - part 2 (**) Indicates data from manufacturer, not measured.

Cable Type	Drain Resistance (R) $\Omega/318$ m	Shield R w/o drain $\Omega/318$ m	Total Shield R $\Omega/318$ m	Drain current re total	Measured shield R $\Omega/318$ m	Signal conductor R $\Omega/318$ m	Shield O.D. in	Lay Length in
FDA1	26.18	86.5		-2.2 dB	20.246	16.462	.095	2.5
FDA2	14.75	111	13.1	-2.4 dB	13.137	14.745	0.1	
FDA3	19.08	60.4	14.5	-2.4 dB			0.098	1.75
FDD1	38.19	75.7	25.4	-3.5 dB	25.38	38.19	0.1	
FDD2	23.4	120	16.7	-2.9 dB	16.73	23.423	0.134	
BDAM	27.13	10	7.3	-11.5 dB	7.188	27.129	0.121	1
BDA	27.3	4.8	4.1	-16.2 dB	4.23	27.3	0.122	0.5
BDD1	44.4	6.2	5.4	-18.2dB	5.48	24.24	0.137	1.5
BDD2	23.23	4.0	3.4	-17.2 dB	3.195	23.23	0.155	
BD95	14.65	4.6	3.5	-12dB	3.686	14.65	0.2	2.75

Table 4 Cable shield Data

ANALYSIS OF SCIN DATA

Data are presented in Figures 2-15. The results are consistent both with Muncy's measurements of specific cable types and with his hypothesis that SCIN increases with frequency for nearly two decades above the audio spectrum. In fact, it continues to increase for most cables to at least 4 MHz, an arbitrary upper limit chosen for this experiment, and the authors have no reason to believe that it will not continue to increase further. It was, for example, necessary to limit the bandwidth of the Scopemeter to 20 MHz to prevent corruption of the data by VHF television signals for many of the foil/drain-shielded cables, even though the author's laboratory is in an area of only moderate field strength from these transmitters.

The measurements show that a few foil/drain-shielded cables offer better performance than others, but that, in general, all foil drain cables perform much more poorly than all braid shield cables. In general, any braid cable that also has a drain wire had greater mode conversion than a cable of similar construction without a drain wire.

In general, the degree of common mode conversion appears to be directly related to the conductance of the drain wire as compared to the conductance of the shield (i.e., foil, braid, or spiral) with which it is associated. For example, the braid-shielded cable having the poorest SCIN performance is a miniature cable with a drain wire whose cross sectional area is approximately one quarter the effective cross sectional area of the braid. As will be seen, the magnitude of this factor appears to be limited to about 30 dB.

In general, measurements made on short lengths of cable correlate reasonably well with those taken on longer samples as long as the measured lengths are less than 1/20 wavelength at the test frequency. In any given real world cable installation, just as in the labo-

ratory setup, the distribution of voltage and current along the cable will vary with the wavelength of the interfering signal, the length of the cable, and boundary conditions established by surrounding objects and electrical terminations. For greater electrical lengths, the data becomes increasingly non-linear with respect to frequency due to voltage and current distributions along the cable acting both as an antenna and as a transmission line, and due to variations in distribution of the shield current with frequency. No attempt has been made to model or analyze these complex relationships.

Normalization of Data

To allow correlation of this data with Muncy's measurements, made with a current held constant at 100 mA, all data were normalized to a shield current of 100 mA. To allow comparison of data for cables of varying lengths, all data were normalized to the length of the longest samples measured, 125 ft (38 m) samples. Normalization for current was accomplished by multiplying the measured voltage by the ratio of 100 mA to the measured current. Figure 2 shows data normalized for 100 mA shield current, but not normalized for length, for the modeled cable, FDD1. Normalization for cable length was accomplished by multiplying the voltage already normalized for 100 mA shield current by the ratio of 125 ft to the actual length of the sample. Data are plotted as SCIN in dBV as a function of frequency for each cable type and for several cable lengths. Figure 3 is a plot of data for cable FDD1 normalized both for 100 mA shield current and for 125 ft (38 m) length, and all subsequent plots are normalized in this manner.

Since the cable is a linear system with respect to the magnitude of the excitation, there is no potential error in normalizing the data for current. Normalizing for length is not quite the same, in that it depends on the assumption that the voltages induced at every point in the line are in phase, and that the currents are of equal

magnitude and in phase at every point on the cable. Such assumptions are generally good where the cable is shorter than $1/20$ wavelength at the frequency of the interference, but becomes increasingly erroneous as the electrical wavelength of the cable increases. Thus the normalization for length is simply an analytical convenience that may or may not be valid for any given cable and any given length. An analysis of the data suggests that normalization for length is valid for some cable types, frequencies, and cable lengths but is not valid for others.

Precision of Balance

In general, measurements normalized for length yielded rather consistent results for cables having relatively high levels of SCIN (that is, cables with foil/drain shields and miniature braid-shielded cables with a drain wire), but gave inconsistent results for cables with relatively low levels of SCIN (most cables having braid shields). The authors suspect that this is because the very precise balances required in cables and their wiring required to achieve low levels of SCIN can easily be upset by relatively small variations in cable production tolerances and relatively small variations in how cables are terminated.

This can be more readily understood by remembering that balance in a system is the result of very precise cancellation of signals that are of precisely equal amplitude, out of polarity, and with very little phase difference between them. Cancellation by 60 dB requires a level match of 0.1%. Although the cable itself may have good balance, that balance will be changed when connections to it are routed through an XL connector, because the signal contacts are physically asymmetrical to the shield contact by virtue of their spacing. Small variations in how the signal conductors and shield are arranged at the connector can also have an effect. Depending on the balance of the cable itself, the connector may either degrade or improve the balance of the capacitance between contacts and inductive coupling between the contacts. All of these effects were noted in the process of collecting and evaluating the data.

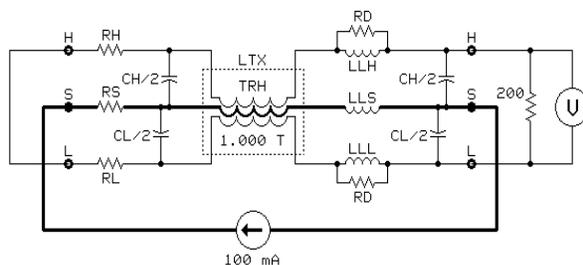


Figure 17 – The Circuit Model

Analysis Using the Circuit Model

The circuit used to simulate behavior of the cable and test setup is shown above. H, L, and S indicate the signal high, signal low, and shield connections respectively at the cable ends. RH, RL, and RS are the dc resistances of the signal high, signal low, and shield conductors respectively. CH and CL are the capacitances to the shield of the signal high and signal low conductors respectively (the signal high to signal low capacitances are insignificant to the analysis have been omitted). Each of these capacitances is halved and placed as shown to crudely approximate their distribution over the length of the cable. LTX is the mutual inductance of the ideal 3-winding transformer. This transformer has a primary (heavier line) to signal-low secondary turns ratio of 1:1 (indicated at 1.000 T). TRH is the turns ratio of the signal-high secondary. LLH, LLL, and LLS are the leakage (uncoupled residual) inductances of the signal high, signal low, and shield conductors respectively. Resistors RD are included to approximate the damping caused by skin effect in the conductors and dielectric losses in the capacitances in actual cables.

Various lengths of cable FDD1 were simulated using the circuit values in Table 5.

Length	10 ft	25 ft	50 ft	125 ft	
RH, Ω	0.400	1.00	2.00	5.00	
RL, Ω	0.400	1.00	2.00	5.00	
RS, Ω	0.265	0.662	1.325	3.313	
CH/2, pF	125	313	625	1563	Note 1
CL/2, pF	125	313	625	1563	Note 1
LTX, μ H	3.50	8.75	17.50	43.75	
TRH	1.012	1.012	1.012	1.012	
LLH, μ H	1.02	2.56	5.12	12.80	Note 2
LLL, μ H	1.00	2.50	5.00	12.50	
LLS, μ H	0.50	1.25	2.50	6.25	
RD, Ω	100	100	100	100	Note 3

Table 5 Circuit Values for Model

Note 1: CH to CL imbalances of 5% were used in some simulations.

Note 2: LLH is proportional to the square of TRH.

Note 3: RD value was changed in one simulation to show the effect of damping.

Since the impedance of an inductor rises linearly with frequency, a voltage with this characteristic will be produced across LTX. This will induce similar voltages in the two signal conductors. If they are equal, of course, there would be no differential and no SCIN. However, inasmuch as the effective turns ratio of signal high and signal low "windings" of the trans-

former are mismatched, a fraction of the induced common-mode voltage will appear as differential. At audio frequencies, this is the dominant coupling mechanism. In the cable simulated here, a turns ratio mismatch of 1.2% ($TRH = 1.012$) produced an excellent correlation with the measured values at low frequencies. Figure 18 shows simulated SCIN for the four different lengths tested.

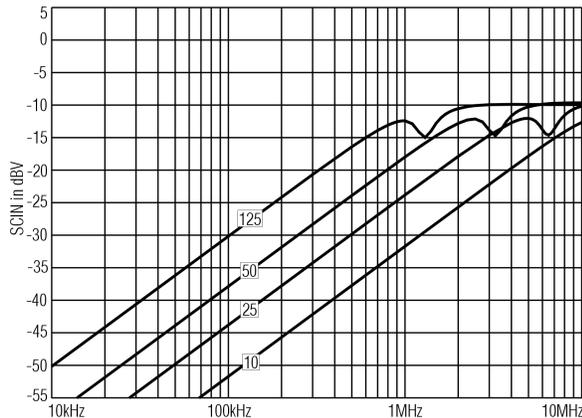


Figure 18 - Simulations of various lengths of cable FDD1 with 1.2% turns ratio error, matched capacitances, and $RD = 100$ ohms.

At some high frequency, roughly inversely proportional to cable length, an electrical resonance occurs. The main elements which resonate are leakage inductances and cable capacitances. At frequencies well below this resonance, the simulations tracked the measured data within about 3 dB. As frequency approaches and exceeds this resonance, behavior becomes quite complex and is strongly influenced by capacitance imbalances in the signal pair and damping (losses) in the resonant elements.

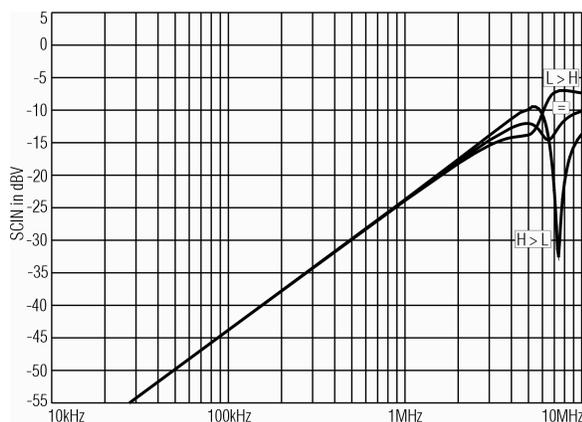


Figure 19 Simulation of 25-foot length of cable FDD1 under same conditions as Fig 18 above, but with 5% mismatch in capacitances

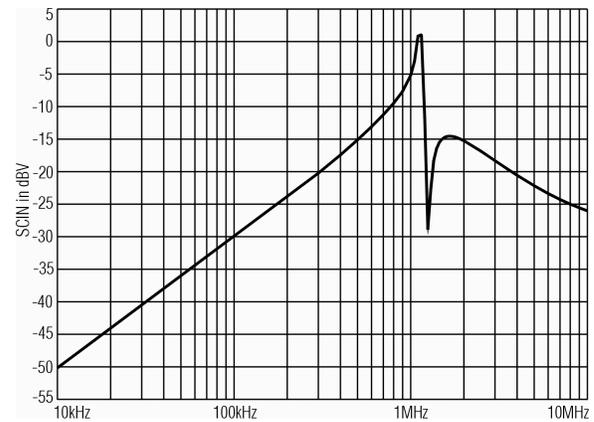


Figure 20 - Simulation of 125-foot length of cable FDD1 under same conditions as Fig 18, but with $RD = 1000 \Omega$.

Figure 19 shows the typical effect of a fairly common 5% capacitance imbalance, while Figure 20 shows the effect of much less damping than used in the other simulations. No attempt was made to simulate this high-frequency behavior since the test setup was intentionally configured to minimize the effects of cable capacitance and utilize an unbalanced instrument for output measurement. The simulation assumes, for example, that the balun used in the measurements is ideal (infinite CMRR) while we know that the real balun has unknown characteristics at high frequencies when the impedance of the driving source (the cable) rises. Using an instrument with a balanced input requires that it have extremely good CMRR at all the frequencies of interest, a requirement not easily met. However, the authors are eager to extend both the frequency range and the accuracy of these measurements.

Wavelength

Figure 16 shows the relationship between frequency and electrical wavelength over the range of 1 kHz to 10 MHz. It should be noted that the electrical length of a conductor is a function of its diameter, and is typically on the order of 0.97 times the free space wavelength. The arbitrarily chosen value for the velocity of propagation, V_p of 0.66 is typical of shielded audio cable, but is by no means a standard.

The model is a simple one, and does not consider wavelength or the distribution of the excitation signal along the length of the cable. A 125 ft wire would be 1/4 wavelength long at approximately 2 MHz. A 125 ft transmission line having a velocity of propagation of 0.66 would be 1/4 wavelength at approximately 1.3 MHz. In general, voltage and current distributions along a wire or line can be ignored for line lengths less than about 1/20 wavelength and are still relatively minor for lengths up to about 1/10 wavelength.

This translates to roughly 250 kHz and 500 kHz respectively for a 125 ft transmission line.

An analysis of the data in this light suggests that the measured data reasonably well reflect pure SCIN to at least 250 kHz for 125 ft samples, and may still be a reasonable first approximation up to about 500 kHz. Likewise, for 50 ft cables the data would appear to be valid to at least 500 kHz and a first approximation to 1 MHz, the 25 ft cable data should be valid for an octave above that, and the 10 ft data should be valid to at least 1.5 MHz and a first approximation to about 3 MHz.

It is important to realize that it is the electrical length of the cable at the frequency of the interfering signal that is important. Each individual audio cable run in an installation will behave differently as a result of its electrical length. Also, each individual audio cable run will behave differently as an antenna by virtue of its electrical length, its proximity to surrounding objects, as well as its geometric orientation and exposure to the interfering field. The interfering voltage present at the input to electronic equipment will be the complex algebraic sum of all of the responses of the cable to all of the fields to which it is subjected.

Foil, Drain, and Braid

Figures 2 and 3 show the SCIN performance of foil/drain-shielded cable type FDD1. Figure 4 shows the performance of the miniature braid/drain-shielded cable type BDAM, and Fig 5 shows the performance of foil/braid-shielded cable type BF. These cables are all nearly the same physical size and have the same size conductors, but their SCIN performance differs by nearly 30 dB. The differences are due to the drain wire or lack of it, and its resistance relative to the braid or foil. The relative resistances of foil and braid suggest that cable BDAM should have about 9 dB less SCIN than cable FDD1. The measured data show a difference of 8-10 dB over a broad frequency range, when resonances associated with various cable lengths are discounted.

Figure 14 compares the authors' data with Muncy's. Muncy measured 175 ft (53 m) samples and expressed results in dB (u). The longest samples measured here are 125 ft (38 m) and expressed in dB (V). Thus 5.1 dB was subtracted from Muncy's data and the result is plotted here. When noting the roughly 6 dB offset between the two sets of data, consider that all three cable types have been manufactured for at least three decades, and that cable samples for types BA and SA were from a stock of cables accumulated over a period of 25 years. Thus although the same nominal cable types were measured, they were almost certainly from very different manufacturing runs and

probably even from different factories. What is most consistent between the data are its trends -- foil/drain-shielded cables have at least 20 dB more SCIN than braid-shielded cables and measured SCIN increases approximately linearly with frequency.

AM Broadcast Data

Measured SCIN data indicate that 20 mA of shield current at 0.5 - 1.5 MHz in typical braid-shielded cables 38 m long would produce differential mode voltages at equipment inputs on the order of 10-50 mV, and 100 - 500 mV in most foil/drain-shielded cables. Cable lengths of 175 - 500 ft will exhibit quarter-wave resonance in the AM broadcast band, a condition that will further increase current because the cable is a "better" antenna.

At first glance 20 mA might seem to be a lot of shield current for real world environments. A survey of cities and suburbs around North America suggests that it might not be all that unusual. When AM broadcast stations were first built, their transmitters were surrounded by corn fields and swamps. Now the corn fields have been pushed much farther from cities, many of the swamps have been drained, and most of those same transmitters are surrounded by homes, businesses, and churches. Thus 20 mA of shield current is not at all out of line for audio system wiring running exposed through the ceiling of a church in such a neighborhood.

THE MECHANISMS OF SCIN

The authors propose that shield-current-induced noise is the additive result of two basic sets of factors.

Shield Symmetry to Signal Pairs

The first set of factors are those establishing the precision of the balance of the coupling of shield current to the signal conductors (that is, the precise value of the ratio of the nominally 1:1:1 transformer). The most important of these factors are the makeup and construction of the shield and the absence or presence of a drain wire that is twisted in the same direction as the signal pair. **For foil/drain-shielded cables and for very small diameter braid-shielded cables having a drain wire, the drain wire is almost always the dominant factor.** For braid-shielded cables the presence of a drain wire generally increases SCIN but the effect is of much lesser significance than with foil shielded cables.

The Balance of the Signal Pair

The second set of factors is related to the construction of the signal pairs and their relationship to the shield.

These factors are the precision of the symmetry and balance of the signal pair's:

- length and diameter (and thus their turns ratio to the shield)
- inductance
- mutual inductance to the shield
- capacitance to the shield
- physical positioning of the pair within the shield (influencing mutual inductance and capacitance)
- twisting
- insulation (dimensions and dielectric constant)

Thus to have low SCIN, a cable should have a braid shield and should be well manufactured to maintain a high degree of precision of the balance of all of its physical and electrical parameters with various conditions of installation, handling, and use.

SCIN is, by definition, a purely inductive mechanism, and thus increases linearly with frequency up to the frequency range where transmission line and antenna effects come into play. Other factors may be present and may also be causing mode conversion. For example, by virtue of IR drop along the shield a voltage gradient will exist along the length of the shield. Likewise, voltage gradients along the shield when the shield is a significant fraction of a wavelength will establish corresponding voltage gradients along the signal conductors and the capacitances between those conductors and the shield.

To the extent that skin effect and other similar factors do not modify the behavior of the cable at higher frequencies, the actual contribution of SCIN in a cable at high frequencies can be computed from its measured value at low frequencies and applying a linear multiplier for the frequency difference.

Relative Magnitudes of the Effects

Logic suggests that the magnitude of SCIN resulting from an asymmetrically coupled drain wire should be proportional to the fraction of the current flowing in that drain wire. When there is poor symmetry for shield current (as with a foil/drain shield) the contribution to SCIN from shield asymmetry is large and overwhelms the contribution of all of the remaining imbalances by something on the order of 10-20 dB. These remaining imbalances can include the line driver, line receiver, cable capacitances, cable resistances, and cable inductances. The measurements of

SCIN vs frequency in such cables tend to be fairly good approximations of straight lines.

When there is good symmetry for shield current, the shield imbalance contribution to SCIN is small and the contribution of the other imbalances dominates. SCIN vs frequency data for these cables tend to be far more varied, as the various reactive effects push and pull against each other, adding in some frequency ranges and at least partially canceling in others.

UNANSWERED QUESTIONS

Some important questions remain. First, what happens above 4 MHz? Do braid-shielded cables lose their advantage? The trends of the data suggest that they might. Are some constructions better than others? Is the significantly better performance of foil/drain-shielded cables FDA1 and FDA2 simply the result of a good day on the production line, or are they a superior design that can be duplicated and maintained?

Improving Foil-Shielded Cables

Replacing the drain wire with a braid clearly improves SCIN performance to the level of good braid shielded cables. One manufacturer suggested that such cable would be more expensive to manufacture, but another did not. A major reason for the recent popularity of a drain wire in a braid-shielded cable is the ease of terminating the shield if only the drain wire is soldered. The authors strongly recommend against this practice. While the braid and drain may make reasonably good contact initially, over time corrosion can degrade the quality of that connection. The authors found that the presence of the relatively light braid of cable BF increased termination time only slightly as compared to a foil/drain-shielded cable.

The manufacturer of FDA1 also manufactures cable FDA4, and the manufacturer of FDA2 also manufactures FDD1 and FDD2. Engineers from both companies have been made aware of this data. To date, neither had any idea why FDA1 and FDA2 should have much better SCIN performance than other foil/drain cables.

The authors suggest the following as a possible explanation. If the drain wire were to have the same lay (that is, number of twists per unit length) as the signal pair, and if it were to lie precisely midway between the two signal conductors, it would couple equally to the two signal conductors and the induced voltages would cancel. Twisting the drain wire in the opposite direction from the signal pairs might also reduce the imbalance of the coupling between the drain and the

two signal conductors. Either of these constructions might explain the results.

If such construction could be maintained to reasonable tolerances and not made an accident, it might be possible to significantly improve the SCIN performance of foil/drain-shielded cable. Because detection of radio frequency interference is non-linear, a 10 dB reduction in the interfering signal can cause a 20-30 dB reduction in the audible interference or even eliminate it entirely.

CONCLUSIONS

The implications of the data are clear. They are:

1. Current flow on the shield of a twisted-pair cable produces a corresponding differential mode voltage on the twisted pair that is proportional both to frequency of the current and the length (therefore its inductance) of the cable for cables that are shorter than $1/20$ the wavelength of the interfering signal. This differential voltage is called shield-current-induced noise or SCIN after Muncy.
2. Between $1/20$ and $1/10$ wavelength, SCIN will continue to increase approximately in proportion to frequency and cable length.
3. When a cable is longer than $1/10$ wavelength at the frequency of the interfering current, complex, frequency-dependent terms will dominate and no easy prediction of SCIN can be made.
4. SCIN appears to include an additive term whose magnitude is approximately proportional to the fraction of the shield current that flows through a drain wire to the total shield current. The data suggest that the maximum degradation caused by a drain wire is on the order of 25-30 dB.
5. SCIN appears to include algebraically additive reactive terms that result from imbalances in the lengths of the signal conductors, imbalances in the inductance of the signal conductors, and imbalances in the capacitances between the signal conductors and the shield. Because these reactive components have both positive and negative sign, because magnitude and phase of voltages and currents vary along the length of a cable longer than $1/20$ wavelength, and because the mechanism of production of the current is so variable from one installation to another, prediction of these terms is a complex undertaking and unlikely to be worthy of the effort.
6. For cables less than $1/10$ wavelength at the frequency of the shield current, reactive factors

are insignificant for foil/drain-shielded cables, and relatively low in influence with braid/drain-shielded cables.

7. For foil/drain-shielded cables, SCIN attributable to the drain wire is on the order of 20-30 dB greater than SCIN attributable to other factors. For most braid-shielded cables having a drain wire, SCIN attributable to the drain wire is on the order of 10 dB greater than SCIN attributable to other factors.
8. Any asymmetry in the termination of a cable can degrade SCIN performance. This is most significant with cables having relatively good SCIN characteristics.
9. Manufacturing tolerances should be expected to cause variations the SCIN performance from one sample to another of braid-shielded cables.
10. Improved SCIN performance of foil-shielded cables is possible and should be a goal.

And most important:

- **Foil/drain-shielded cable should be avoided in any installation that could be subject to significant levels of shield current at frequencies above 1 kHz.**
- **Drain wires that carry a significant fraction of shield current should be avoided.**
- **Until foil/drain cable is universally replaced by braid-shielded cable for permanent installation, it is critical that audio equipment have good immunity to differential mode signals above the audio spectrum.**
- **The bandwidth of audio systems should be limited to the minimum required to achieve good amplitude and phase response within the audio spectrum. In no case should the bandwidth of an audio system exceed 200 kHz**
- **SCIN is probably active at UHF, so circuit topologies should reject differential mode voltages to at least 1 GHz.**

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