QUANTIFYING SIGNAL LEAKAGE - HOW DO CURRENT METHODS MEASURE UP?

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ABSTRACT

Signal leakage continues to be a critical issue for systems operators and hardware manufacturers alike. The FCC's viewpoint and their actions surrounding this issue have been well documented in the past several months, as have been the opinions of several major MSO's. The viewpoint of the manufacturer, however, has been noticeably absent from recent publications documenting the issue. This paper will attempt to make the viewpoint of at least one manufacturer known, as well as discuss and analyze several different methods for measuring RFI isolation.

INTRODUCTION

As mentioned above, the viewpoint of the CATV equipment manufacturer has yet to be revealed to the rest of the cable industry. This silence can be attributed in part to conflicting signals received by the manufacturers from systems operators. On one hand, operators are demanding RF tight equipment; on the other hand, the operators are extremely price sensitive and are not willing to incur the additional cost required to improve the RF integrity of the product. This problem is especially prevalent in the area of subscriber passives, historically significant offenders relative to leakage levels, as approximately 65% of all signal leakage occurs in the drop section of the cable.[1] Little attention has been focused on improving the integrity of these products primarily due to the fractional percentage of dollars invested in the subpassive line as compared with the active and passive lines.

The majority of operators and manufacturers are finally beginning to realize that the RFI issue is a critical one as the fines levied by the FCC continue to increase in both amount and frequency. This realization is providing manufacturers the motivation and impetus to commit themselves to the manufacturing of an RF tight product line. The problem that manufacturers now face is of a different nature: by what process can they measure the leakage levels of their new products to insure that FCC radiation specifications are met and/or exceeded? How, in addition, can they correlate their results with those achieved by systems operators using either the same or different measurement methods?

In order to answer these questions, analysis and testing of several of the more "common" methods has been initiated. All tests were conducted using the same subpassive splitters in order to determine if correlation was possible. The methods analyzed include:

1. An FCC approved open air site
2. A transverse electromagnetic cell (TEM cell)
3. An RFI chamber

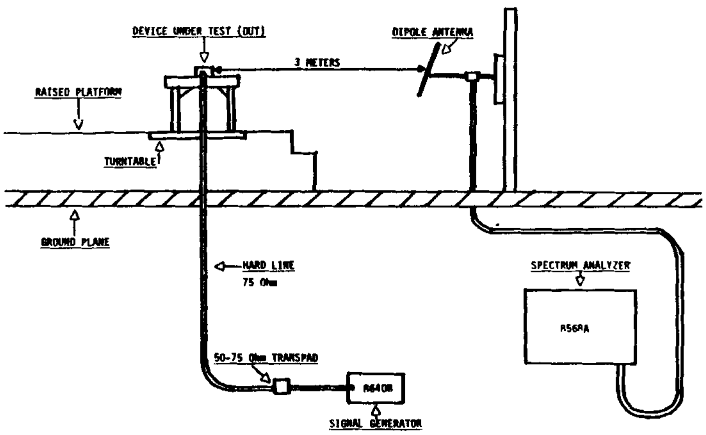
A brief description, as well as measurement results, correlational information, advantages/disadvantages and cost requirements will be included for each method outlined above.

FCC APPROVED OPEN AIR SITE

Description: The open air site is a method in which the device under test (DUT) is placed on a turntable 3 meters (10 feet) from a horizontal calibrated dipole antenna. A signal generator is used to pump a given level of signal into the DUT. The radiated field from the DUT is then measured off the dipole antenna at the far field distance using a spectrum analyzer, field strength meter, or other approved receiver. Because the length of the dipole antenna must be varied with each frequency tested, several discrete points accross the frequency band must be tested in order to create an accurate picture of the leakage levels. The turntable on which the DUT rests should then be rotated and field strength measurements repeated, until a "worst case" view is found and the discrete measurements are recorded. (See open air site measurement.)

A level terrain free of metal objects within 50 yards of the site must be selected in order to construct an accurate and effective outdoor site. Once a suitable location is found, a survey of ambient RF signals from 5-1000 MHz must be taken, and the orientation of the facility should be adjusted accordingly. These ambient signals should then be plotted and analyzed against the frequency in which most of the testing will be done. A metal ground plane (often bonded wire mesh) must cover the entire surface of the radiation site to act as a ground plane, and the engineer, field strength meter and other equipment should be located below this plane on a platform which allows the engineer an eye level view of the DUT.[2] A support tower constructed from wood and fiber glass is used to vary the height of the receiving antenna. This tower often has a chain assembly used to raise or lower the antenna depending on the height of the DUT.[3]

OPEN SITE TEST



Measurements:

1. Field strength is measured in microvolts per meter.
2. This measurement is then multipled by a correction factor which includes both an antenna correction factor and cable factor. A chart of the antenna correction factors (ACF), the loss or gain factor of the antenna used, is supplied with the antenna at the time of purchase. The cable factor (CAF) accounts for the length and type of cable used.
3. The resulting number is transposed to microvolts, then to dBmV via the formula:

$$\text{dBmV} = 20 \log_{10} \text{EmV}$$

4. The input level (dBmV) is subtracted from the above result.

You will note in the chart that the input levels are varied in this example due to leakage in the hard line cable at certain frequencies. To determine the input level used, the level was increased until leakage on the terminated cable was seen at each of the above frequencies. This input level was then used for the actual test at each of the frequencies.

Unit: ML-4DR #7

Frequency	Field Strength v/M(CAF+ACF)	Reading (dBmV)	Input Level (dBmV)	Isolation (dB)
30	3.40	-49.35	54.65	104
54	9.16	-40.76	64.25	105
125	11.37	-38.35	54.15	> 93
135	12.49	-38.05	56.95	> 95
185	.05	-85.25	54.75	>140
200	.07	-82.05	63.95	146
216	.10	-80.35	65.65	146
330	.12	-78.25	>64.75	>143
450	.18	-74.85	58.15	133
500	.24	-72.55	64.45	>137

Advantages:

1. The open air site is the approved FCC test method.
2. Test measurements are highly repeatable.
3. The open air site provides an absolute standard.
4. The open air site can be a useful diagnostic tool.

Disadvantages:

1. The open air site cannot discriminate between an egress signal and one that is normal to the external electromagnetic environment.
2. Space requirements are large.
3. The time needed to test one product at several points over the usable bandwidth is extremely high, up to one hour per unit depending on the number of frequencies tested.
4. Weather conditions will effect measurements.

Cost Requirements: The cost for materials needed to construct an outdoor site may run as low as $2000. Test equipment needed includes a signal generator, spectrum analyzer or RF meter and dipole antenna set. Final cost for an outdoor site, then, may be as low as $32,000.

The cost for materials required for an indoor site begins at approximately $70,000, not including test equipment. It should be noted here that most organizations interested in measuring RFI will already own most of the test equipment needed to operate the open air site.

TRANSVERSE ELECTROMAGNETIC CELL (TEM CELL)

Description: The Transverse Electromagnetic Cell (TEM cell) is a shielded two cell chamber used to measure either signal ingress or egress. The two cells, mirror images of each other, are designed to minimize reflections through the use of anechoic material. They are separated by a metal plate (septum) which acts as a center conductor. The cell is typically constructed of

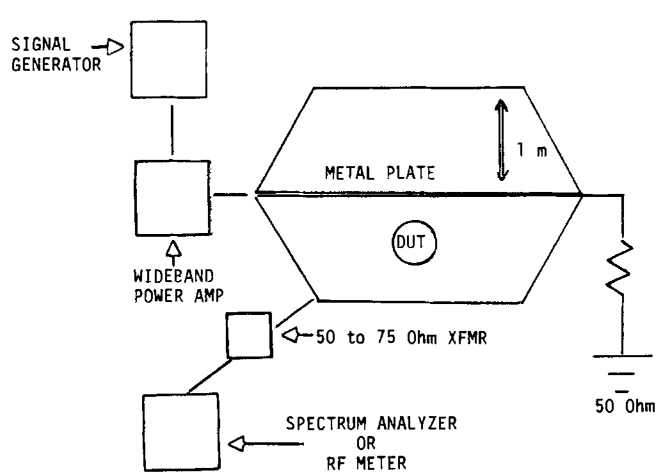
.090 aluminum with vertical delron support rods connected to the septum.

To measure signal ingress in the TEM cell, the DUT is placed in the lower cell, and is connected to the edge of the cell via 75 Ohm hard line cable. A signal generator and power amplifier are used to generate an RF field of 5 volts in the chamber. The ingress levels are then measured off the hard line connection by either an RF meter or spectrum analyzer. It should be noted that while a spectrum analyzer will display peak voltage levels across the entire bandwidth, the RF meter will display RMS values. The FCC uses an Ailtech 37/57 RF meter for their final inspections.

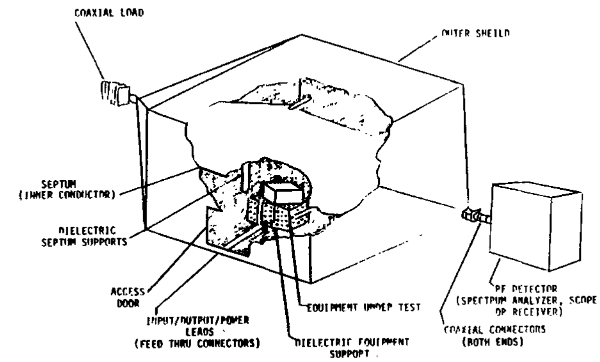
To measure signal egress, the DUT is placed inside the cell in the desired orientation and test configuration. The cell then operates as a transducer to detect emissions from the operating DUT. Energy emitted from the DUT is coupled via the TEM mode of the cell to the cell's terminals where it is measured by a calibrated receiver.[4]

TEM cell size requirements vary depending upon the size of the units to be tested. A general rule of thumb states that the largest product to be tested should never occupy more than one third the total volume of the lower test cell. Reducing the size of the TEM cell will serve to both increase the usable bandwidth and decrease the cost. For example, this particular study utilized a TEM cell large enough to test new televisions. The usable bandwidth of this cell, consequently, is limited to 216 MHz by resonance and multimodes. A TEM cell used for testing expressly subpassive units, conversely, could conceivably have an upper limit of 1 GHz. In addition, the cost of this cell would be much less costly than the above mentioned cell.

TEM CELL



CUTAWAY VIEW OF TEM CELL



Measurements:

1. Measure ingress level of empty chamber to establish noise floor (.15μv at all frequencies).
2. Repeat measurement with DUT in lower cell (microvolts).
3. Transform to dB using the formula:

$$\text{dB Isolation} = 20 \log \frac{\text{Reading } (\mu v)}{\text{Input } (\mu v)}$$

Example (using Ailtech 37/57 RF meter)

Unit: ML-4DR #7

Frequency	Reading (μv)	Isolation (dB)
30	.223	>147
54	.251	146
125	.345	143
135	.345	143
185	.251	146
200	.397	142
216	.629	138

A spectrum analyzer may also be used to sweep the unit across the entire usable bandwidth.

Correlation With Open Air Site: Absolute correlation between the open air site and TEM cell is discussed in Appendix I. For general purposes, however, a correlation factor can usually be found to equate measurements made of the same device by both methods. In the case above, a correlation factor is difficult to find due to the fact that the leakage levels of the DUT are so low that the level of the noise floor is recorded rather than the level of the DUT.

Advantages:

1. The TEM cell has the ability to correlate with both theoretical and open cell measurements.[5] (See Appendix I.)
2. Either automated or sweep testing may be used in taking measurements.

3. The chamber itself is shielded, and may be used for other purposes in which a shielded chamber is required.

4. TEM cell RFI measurements are highly repeatable.

5. The TEM cell may also be used for EMI susceptiblity testing.

6. The TEM cell provides an excellent means for making relative measurements.

Disadvantages:

1. Resonance frequencies and wave guide modes may be encountered in the TEM cell which will negate measurements taken at those frequencies.

2. The TEM cell is not recognized by the FCC as an approved method of measuring RFI; therefore, only relative measurements are presently suggested.

Cost Requirements: The cost of the cell will vary tremendously depending on the size configuration needed. To reproduce the cell used in this study would cost upwards of $60,000; a TEM cell built for subpassive testing would cost as little at $500 once the design is finalized. Test equipment needed includes a signal generator, power amplifier and either a spectrum analyzer or RF meter. A limited number of sources for TEM cells exist at the present time; it is probable, therefore, that lead times may be lengthy.

RFI CHAMBER

Description: The RFI chamber is essentially a 4 foot long piece of 50 Ohm coaxial cable used to make relative RFI isolation measurements. This chamber was developed from a device called the "SEED" (Shield Effectiveness Evaluation Device) designed by Belden Cable in their Technical Research Center to evaluate RFI isolation of their shielded cable. The "SEED" provides consistently repeatable RFI test results - generally within 1 to 2 dB from test to test and like sample to like sample. Variations in test location, cable placement, ambient noise, etc. have no significant effect on repeatability. Belden's catalog states that "the SEED system uses a special 5 foot long coaxial fixture....consisting of two concentric copper tubes (outer diameter is 3.125" O.D.; inner tube is 1.315" O.D.) which can provide a 50 Ohm characteristic impedance. A 3 foot cable sample length is centered within the inner tube during testing, assuring that all radiated energy is absorbed. One end of the fixture is terminated; the other end is capped with a removable plate containing feedthroughs for sample and fixture test leads. For multiple tests a signal generator is required to power the cable sample, and a tuned RF voltmeter or field strength meter is needed to measure signal strength".[6]

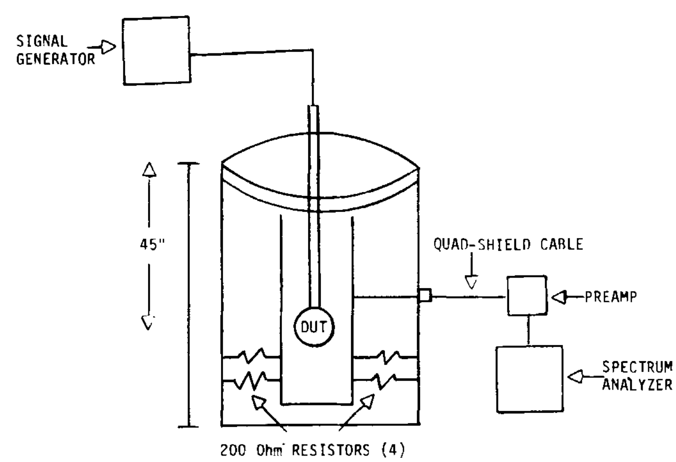
The RFI chamber is merely an adaptation of the "SEED" which allows larger units to be tested. The impedance of the chamber is 50 Ohms, chosen because the dimensions of the inner chamber are larger than that of a 75 Ohm chamber, thus allowing units as large as mainstations to be tested.

During testing a given level of signal (often 49 dBmV) is pumped into the chamber via a tracking generator. The signal level is then measured off the center conductor with a 30 dB gain low noise preamp and a spectrum analyzer. Levels into the spectrum analyzer of 112 dB down from the tracking generator can be measured.

To establish the noise floor of the chamber and the cable, the level is measured using only a terminator on the connector used to hold the DUT. This reference level is graphed. (In our case this level is approximately 112 dB down.) The DUT is then connected and leakage levels are measured.

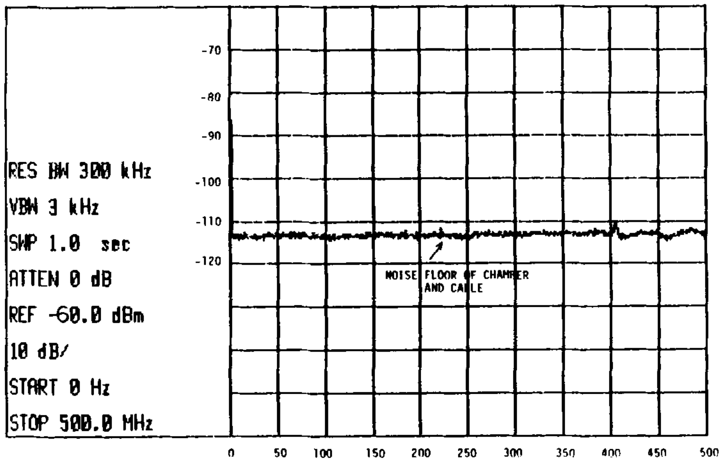
It should be emphasized that at this point in time the RFI chamber provides only a relative measurement when used in this manner; one can say with certain restrictions that one subpassive splitter is 10 dB better than another, and that in our particular chamber the isolation level is -110 dB. We can also correlate one chamber with another (for example a manufacturer correlating with an MSO) to insure that MSO requirements are fulfilled, but one cannot say that the isolation level is absolute at -110 dB when the chamber is used in this method.

RFI CHAMBER

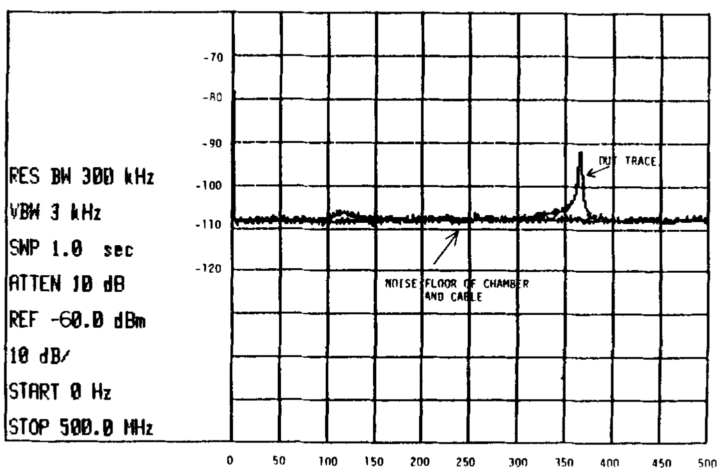


Measurements:

1. The output of the inside connection is terminated; no DUT is present at this time. Measurement is taken off the center conductor, and this level passes through a low noise preamplifier with known gain. A spectrum analyzer then measures and plots this level, which represents the noise floor of the RFI chamber and cable. This noise floor will be the lowest level of isolation that can be detected; in this particular chamber the noise (or reference) level ranges from -108 dB to -112 dB.



2. The above procedure is repeated with a properly terminated DUT. Both the reference trace and DUT are plotted on the same graph.

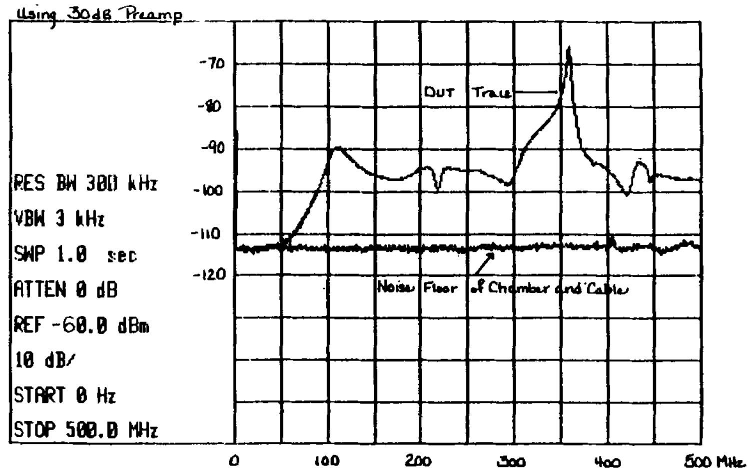


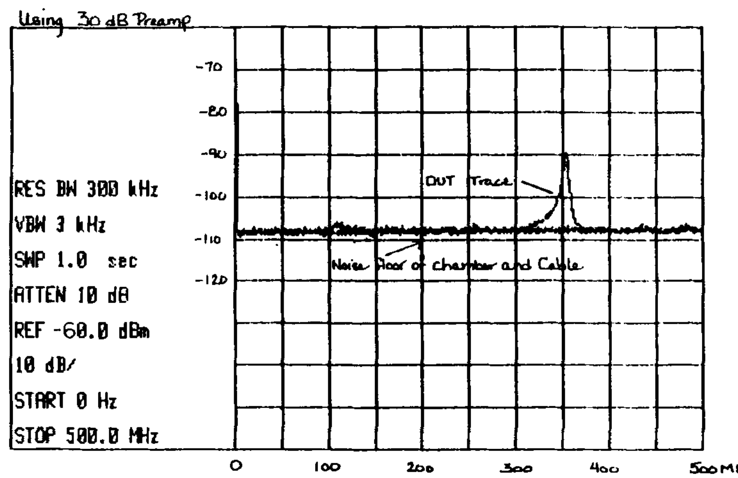
3. The isolation level at worst case will be the highest point on the plot. In the above example, the worst case reading (-92 dB) is taken at 365 MHz, which happens to correspond to a resonance frequency in the chamber.

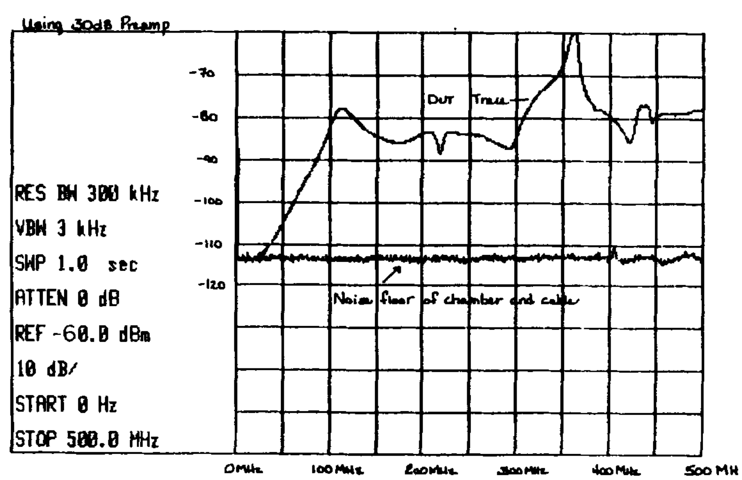
Advantages:

1. The chamber's small size (48" by 28.5") is convenient for the manufacturer or MSO with little space.
2. The chamber is lightweight and mobile.
3. The simple design of the RFI chamber allows the unit to be built in-house.
4. The chamber provides a quick and easy method for comparing isolation levels of like products. The great majority of RFI chambers in the CATV marketplace today are used for this purpose. An MSO or manufacturer will typically gather together as many competitive samples as can be found, run them through the chamber and analyze the results. For example, a quick study of this kind performed recently at Magnavox yielded the following results:

3-WAY SPLITTERS







As can be seen, the difference in the isolation levels of like products can vary tremendously.

Disadvantages:

1. The noise floor of the chamber will vary depending on the connector used; therefore, several connectors should be tried to establish the lowest possible noise floor.
2. The measurement is a relative measurement, not absolute.
3. Resonance frequencies may be present in the chamber, making actual readings at those frequencies somewhat questionable.
4. The chamber is relatively fragile, and should be moved with care.

Cost Requirements: The RFI chamber is an extremely economical method of measuring RFI. The chamber itself costs only a few hundred dollars: the cost of the can itself, double shielded cable, resistors, hard line cable and connectors. The cost of test equipment will begin at approximately $30,000, but as mentioned before, in most situations the organization will already own some or all of the equipment needed.

Correlation Between Open Air Site and the RFI Chamber: Correlation between an open air site and an RFI chamber is precluded by one important detail: the measurement field. To illustrate this one needs only to compare the methods of measurement in the two cases.

An open air site is designed to measure device field strength levels located in a specific circumferential arc about the vertical axis of the device. The rotation of the device on its axis or the rotation of the axis itself can have significant effects upon the detected field strength levels. This is attributable to the fact that most devices will exhibit varying field strength levels as the device is rotated about any particular circumferential path. For example: A four way tap will display vastly differing detected egress levels when the f-ports are turned away from the detector. Thus, the device orientation is critical in achieving egress measurement accuracy and repeatability.

The RFI chamber is designed to measure device field strength levels located in a specific cylindrical area about the vertical axis of the device. The rotation of the device on its axis will have no effect on the detected field strength levels. While rotation of the device's axis will effect the detected field strength level, the magnitude of these effects will be far below the variance seen at the open air site. Therefore, with the RFI chamber, device orientation is far less critical in achieving egress measurement accuracy and repeatability.

Based on this analysis it is logical to assume that detected egress levels from an open air site will be significantly lower than those levels detected from an identical device in an RFI chamber. Also, because the fields from a circumferential arc are detected in one case and that fields from a cylindrical area are detected in the other, correlation of the two measurements is impossible.

It is possible, however, for an organization to use the RFI chamber in a manner by which adherence to FCC specifications may be recognized. To accomplish this, a pinpoint unidirectional source is used as a worst case device. Measurement of this device in an open air site can be directly compared to an RFI chamber measurement. This measurement should be made with the unidirectional source's emission calibrated at FCC regulations. It can then be inferred that any omni directional radiator having a detected level at or below the standard will meet or exceed FCC requirements.

SUMMARY

Of the RFI measurement methods discussed above, only the open air site is approved by the FCC for use in determining whether FCC isolation requirements are met. Correlation with the open air site is critical for any MSO or manufacturer using an alternate method of making RFI measurements. Methods in which to correlate the RFI chamber and TEM cell with the open air site as they now exist are somewhat cumbersome. With additional research these methods may be refined to provide the MSO or manufacturer the ability to make absolute measurements quickly and inexpensively in a TEM cell or RFI chamber.

APPENDIX I

Correlation Between Open Air Site and TEM Cell

Significant research has been done by the National Bureau of Standards to provide a means for correlating open air and TEM cell measurements. To insure significant results, NBS suggests using as the DUT a spherical dipole because its radiation characterictics can be analytically determined. The theoretical value may then be compared with actual test results to provide a correlation between actual test fixtures.

To relate the field measurement from the open air site (μV/m) to the TEM cell measurement, one must first convert the radiated field to the equivalent free space or direct path field (E_d) via the formula:

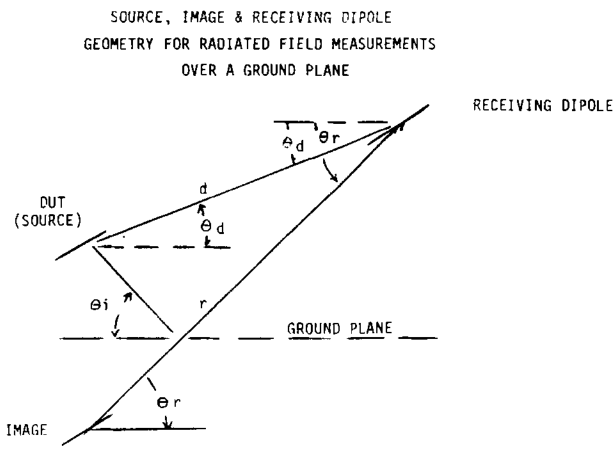
$$|E_d| = \frac{|E_m|}{1 + B^2 + 2B\cos\alpha}$$

Where:

$$B = p\frac{d}{r},$$

$$\alpha = \frac{2\pi(r-d)}{\lambda} + \phi, \text{ and}$$

$p + \phi$ are the magnitude and phase of the ground screens reflection coefficient. λ is the wave length in meters, and the parameters d and r are shown in the following:



Likewise, the measurements taken in the TEM cell are related to equivalent free space radiated field, E_d via the formula:

$$E_d = \frac{b n_o V_m}{\lambda_o \, d \, Z_o \, K(I) \, \tilde{E} \cos\theta} \sqrt{\frac{2G}{3}}$$

Where:

b = separation distance in meters between septum and the cell floor.
n_o = intrinsic wave impedance = 377 Ohms.
V_m^o = RMS voltage (volts) measured at one port terminated into 50 ohms.
λ_o = wavelength at measurement frequency in meters.
d = separation distance in meters between spherical dipole and measurement point in free space.
Z_o = characteristic impedance of TEM cell as a transmission line, 50 Ohms.
$K(I)$ = change in equipment under test (DUT) radiation current caused by enclosing the DUT inside the TEM cell.
$\tilde{E}$ = normalized electric field at any location inside the cell, relative to the field strength at the center of the test region of the cell.
$\cos\theta$ = polarization of radiated field from DUT relative to the TEM mode electric field of the cell.
G = gain characteristics of the cell.

The results obtained from the above procedures are compared to the theoretical value computed, and studies indicate that, at least for the DUT used, results between the 3 measurements correlated within a few dB at those frequencies below mode resonances in the cell. At higher frequencies, larger differences (up to 12 dB) exist due to cell multimoding.[7]

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