

# Ground loops during site validation of anechoic rooms below 30 MHz

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**Abstract**—Building up a ground loop is a very common mistake when validating anechoic rooms below 30 MHz, because this is not an issue in the frequency ranges above. It is required to measure a Site Attenuation of nearly 120 dB, but a ground loop can limit this to 63.1 dB. So a large systematic error will occur. There are several possibilities to avoid a ground loop by using battery powered devices, an isolation transformer or an RF transformer. Special care has to be taken to recognize all ground loops which can be formed by communication cables and reference frequency links. Also, a ground loop can be formed by the installed cables which are routed below the ground plane.

**Keywords**—site validation; ground loop; loop antenna; NSA measurement; site attenuation

## I. INTRODUCTION

In the past years the CISPR A standardization committee is working on two new standards for magnetic field measurements in the frequency range from 9 kHz to 30 MHz. An update is necessary to address new technologies like wireless power transfer (WPT) and large TV sets. A new edition of CISPR 16-2-3 [1] for measuring the magnetic field radiated disturbance will be published. New editions of product standards like CISPR 11 [2] will use this material.

Since test site specifications for the frequency range from 9 kHz to 30 MHz are not present, also CISPR 16-1-4 [3] will be updated to address this issue.

In the new CISPR 16-1-4 the normalized site attenuation (NSA) method as well as the reference site method (RSM) will

be used for site validation in the frequency range below 30 MHz. Since the magnetic component of the field is dominant, loop antennas are used to transmit and receive. Similar to the frequency range above 30 MHz a volumetric method with 5 points is used, see Fig. 1. Instead of several transmit heights only one height of 1.3 m above the floor is specified. A height scan on receive side is not required; the antenna is also placed at a height of 1.3 m. The antennas are placed in all three orthogonal orientations X, Y and Z. The distance is specified with 3 m, 5 m and 10 m. Especially for the largest test distance of 10 m and orientation Z a high dynamic range is required.

During the experiments for evaluating the new method the most common mistake was a wrong measurement result due to the effect of a ground loop. Fig. 2 shows the Site Attenuation (SA) deviation of a typical anechoic chamber if a ground loop is present. At 9 kHz the measured deviation is 20 dB too low. The error is decreasing with increasing frequency with a rate of 20 dB per decade. For frequencies above 200 kHz the ground loop does not have an effect and the measured Site Attenuation deviation is correct. It is obvious that the shown measurement result can be interpreted as a bad chamber performance. It is essential for the test engineer to recognize ground loops to avoid erroneous test results.

This paper explains how ground loops are formed and how they impact the measurement results. Several techniques to avoid them are explained. Additional information about site validation below 30 MHz can be found at [4-7].

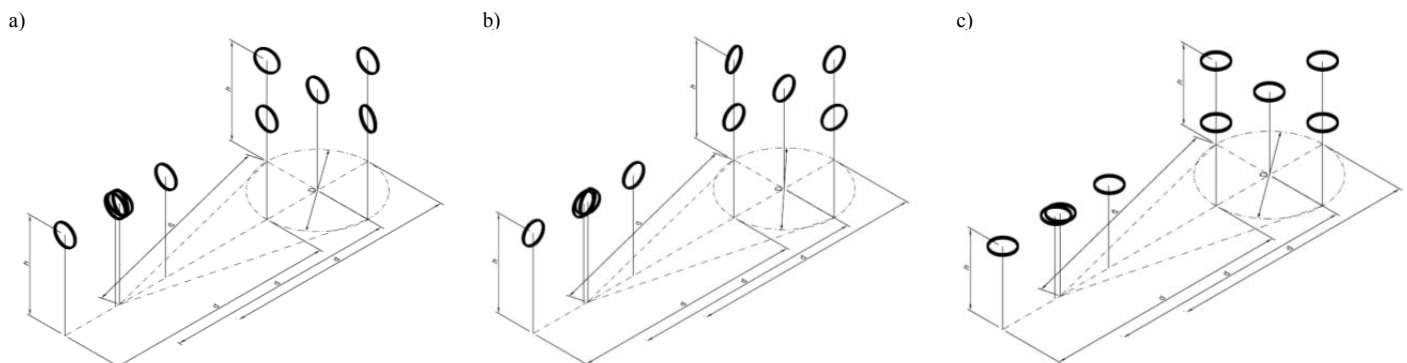


Fig. 1. Test setup for site validation 9 kHz to 30 MHz in orientation a) X b) Y c) Z, see draft standard CISPR 16-1-4 [3]

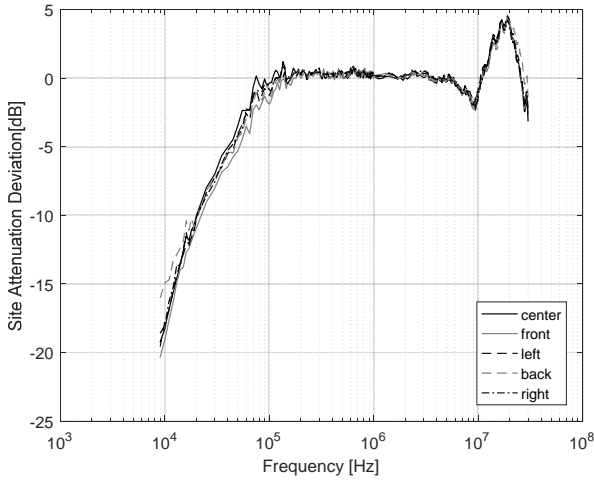


Fig. 2. Typical test result, 10 m, orientation Z, ground loop present [7]

## II. SITE ATTENUATION REQUIREMENTS

The Site Attenuation  $A_S$  is calculated by subtracting the reading where the coaxial cables are connected to the antennas ( $V_{SITE}$ ) from the reading where the coaxial cables are connected to each other ( $V_{DIRECT}$ ), see (1)

$$A_S = V_{DIRECT} - V_{SITE} \quad (1)$$

The typical antenna factor  $F_{aT}$  and  $F_{aR}$  of a 200  $\Omega$  biconical antenna at 30 MHz is 13 dB (1/m). At a test distance of 10 m, horizontal polarization and 1 m transmit height the normalized site attenuation  $A_N$  is 29.8 dB ( $m^2$ ) for biconical antennas. The mutual impedance correction factor  $\Delta A_{TOT}$  for broadband antennas is 0 dB. If we assume a test site with  $\Delta A_s$  of +4 dB, the site attenuation will be 59.8 dB, see (2).

$$\Delta A_S = A_S - F_{aT} - F_{aR} - A_N - \Delta A_{TOT} \quad (2)$$

For loop antennas the situation is much more demanding. At a distance of 10 m the NSA value at 9 kHz for orientation Z is 98.5 dB ( $m^2/S^2$ ). The antenna factor of a typical passive circular transmit antenna with a loop diameter of 50 cm at 9 kHz is 48.5 dB (S/m). Typical active receive antennas are designed to have a flat frequency response. Historically the gain of these antennas is set to have an electric antenna factor of 20 dB (1/m), since older standards are using an electric field strength limit. Recalculating to the actual unit by subtracting 51.5 dB ( $\Omega$ ) leads to -31.5 dB (S/m). So in this case the Site Attenuation is 119.5 dB, nearly 60 dB more than for biconical antennas.

## III. BUILDING UP A MODEL

Typically, engineers will start with a known test setup while developing new methods. For NSA and RSM measurements the used devices, signal generator and spectrum analyzer are placed outside the shielding. The cables are routed via a penetration panel toward the antennas.

In this configuration transmit current  $I_T$  has two return paths. The first over the shield of transmit cable  $I_1$  and the second over the shield of receive cable  $I_2$  where a ground loop is built, see Fig. 3. The loop is closed via protective earth (PE) which connects the chassis ground of the signal generator to the chassis ground of the spectrum analyzer.  $L_L$  is used to model the inductance of the ground loop which is virtually placed outside the shielding of the anechoic chamber.

This model can be used to derive the effect of the ground loop to the measured site attenuation. In the lowest frequency range the impedance of the ground loop is low and the measured site attenuation is harmed by the ground loop. In the high frequency range the impedance of the ground loop is high and the measured Site Attenuation is not harmed by the ground loop.

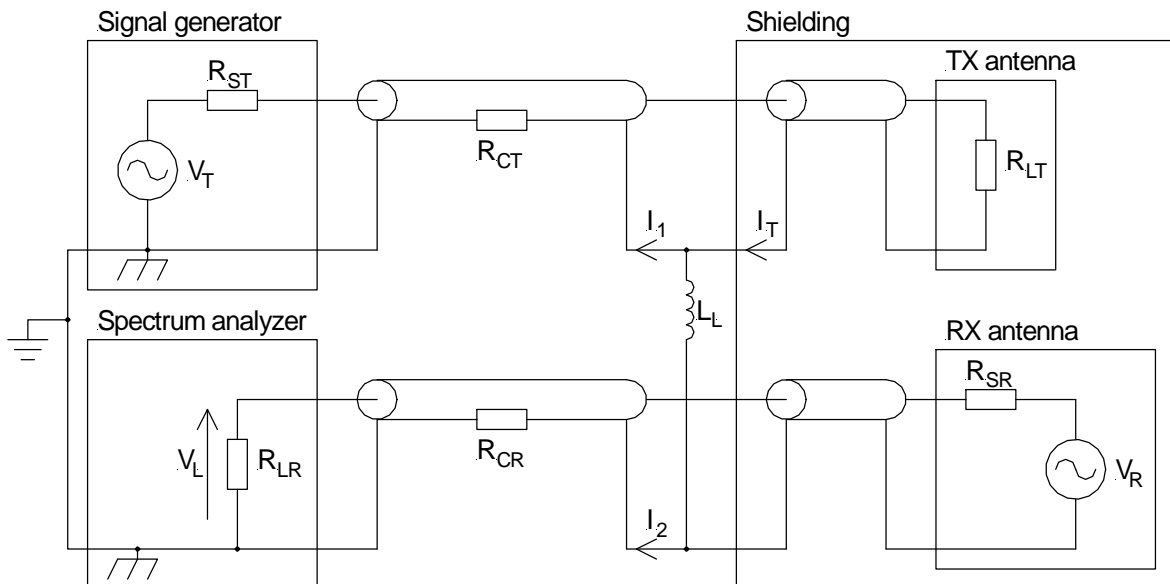


Fig. 3. Model for a ground loop

In the model the correct Site Attenuation  $A_{SC}$  is calculated by the ratio between the voltage of the signal generator  $V_T$  and receive voltage of the antenna  $V_R$ , see (3).

$$A_{SC} = 20 \log \left( \frac{V_T}{V_R} \right) \quad (3)$$

If the ground loop has no effect, the measured Site Attenuation  $A_{SM}$  is equal to the correct Site Attenuation  $A_{SC}$ . This is the case if the impedance of the ground loop is much larger than the resistance of the shielding of the cables, see (4).

$$j\omega L_L \gg R_{CT}, j\omega L_L \gg R_{CR} \quad (4)$$

This condition is met in the high frequency range. In the lowest frequency range, the impedance of the ground loop is much lower than the resistance of the shielding of the cables, see (5).

$$j\omega L_L \ll R_{CT}, j\omega L_L \ll R_{CR} \quad (5)$$

If this condition is met, transmit current  $I_T$  is split into the current on transmit cable shield  $I_1$  and current on the receive cable shield  $I_2$ .  $I_2$  can be approximated by (6).

$$I_2 \approx \frac{V_T}{R_{ST} + R_{LT}} \frac{R_{CT}}{R_{CT} + R_{CR}} \quad (6)$$

The current  $I_2$  thru the resistance of the cable shield  $R_{CR}$  leads to an unwanted voltage on the load  $R_{LR}$ . So both voltage sources  $V_T$  as well as  $V_R$  will affect the voltage  $V_L$ . If the unexpected component caused by  $V_T$  is dominant, see (7).

$$I_2 R_{CR} \gg V_R \quad (7)$$

The voltage  $V_L$  can be calculated by (8).

$$V_L = I_2 R_{CR} \frac{R_{LR}}{R_{LR} + R_{SR}} \quad (8)$$

The input impedance of the passive transmit loop is very low at low frequencies, so we can assume  $R_{LT}=0 \Omega$ . If we assume  $Z_0=R_{ST}=R_{SR}=R_{LR}$  and  $R=R_{CT}=R_{CR}$  the harmed Site Attenuation  $A_{SH}$  is calculated by (9).

$$A_{SH} = 20 \log \left( \frac{2R}{3R + Z_0} \right) \quad (9)$$

The measured Site Attenuation  $A_{SM}$  is equal to the harmed Site Attenuation  $A_{SH}$ , if  $A_{SH} \ll A_{SC}$  is valid. A systematic error occurs, because the measured Site Attenuation is smaller than expected. The error of the Site Attenuation deviation, see (2), is negative. This behavior is also seen in Fig. 2.

According to (9) the harmed Site Attenuation  $A_{SH}$  depends solely on the resistor values. Increasing transmit voltage  $V_T$  or reducing the noise floor of the spectrum analyzer by modifying the bandwidth and input attenuator settings will not reduce the effect the ground loop.

TABLE I. HARMED SA FOR TYPICAL CABLE ARRANGEMENTS

Cable Type	$A_{SH}$ [dB]			
	1 m	3 m	5 m	10 m
RG 213/U	87.3	77.8	73.4	67.3
RG 214/U	88.9	79.3	74.9	68.9
RG 223	83.1	73.6	69.1	63.1
RG 240	83.1	73.6	69.1	63.1

If we assume typical coaxial cable types RG-213/U [8], RG-214/U [9], RG-223 [10] and RG-400 [11] the DC resistance is 4,3  $\Omega$ /km, 3,6  $\Omega$ /km, 7,0  $\Omega$ /km and 7,0  $\Omega$ /km. The harmed Site Attenuation, using (9), for these cable types of 1 m, 3 m, 5 m and 10 m length is given in Table 1.

There are two cutoff frequencies. The lower cutoff frequencies  $f_1$ , see (10)

$$f_1 \approx \frac{R}{\pi L_L}, A_{SM} = A_{SH} + 3dB \quad (10)$$

The upper cutoff frequencies  $f_2$ , see (11)

$$f_2 \approx \frac{1}{2\pi L_L} \left( \frac{V_T R^2}{V_R Z_0} - 2R \right), A_{SM} = A_{SC} - 3dB \quad (11)$$

Between both cutoff frequencies an increase of the measured Site Attenuation of 20 dB per decade is observed.

The estimation of the loop inductance  $L_L$  is difficult since it strongly depends on the cable routing and cable length. Measurements showed values between 1.9  $\mu$ H for 1 m cables and 20  $\mu$ H for 10 m cables.

The simulation tool SPICE was used to calculate the example shown in Fig. 4. A correct Site Attenuation of 120 dB, a ground loop inductance of 20  $\mu$ H and two RG 223 cables of 10 m length were assumed. The result shows an error up to 56.9 dB in the simulated frequency range from 100 Hz to 10 MHz. Above 9 kHz an error of up to 38.6 dB is observed.

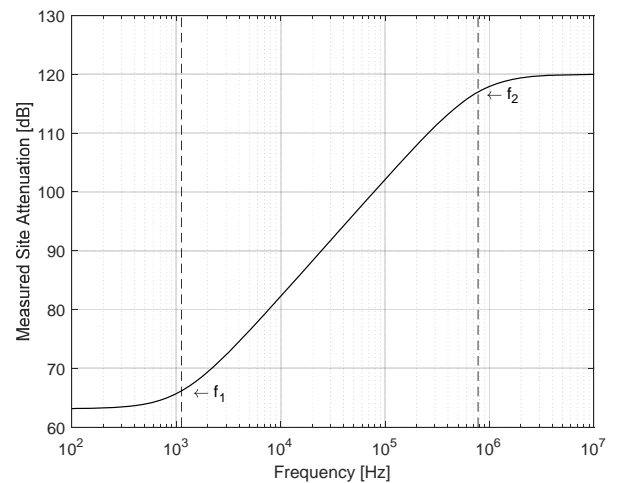


Fig. 4. Calculated measured Site Attenuation for 2x 10 m RG223 cables, 20  $\mu$ H ground loop inductance,  $A_{SC}=120$  dB

#### IV. CIRCUMVENTING GROUND LOOPS

There are several methods to eliminate or reduce the effect of a ground loop.

##### A. Avoid current flow

If  $R_{LT}$  is increased the current  $I_T$  will be decreased and the impact of the ground loop is minimized. However, this is a theoretical approach since active antennas with high input impedance are not commercially available. The use of an unmatched termination is not common practice in RF engineering.

##### B. Decrease ground loop resistivity

As derived in chapter III the harmed Site Attenuation  $A_{SH}$  (9) and both cutoff frequencies  $f_1$  (10) and  $f_2$  (11) depend on the resistor values  $R$ . By using cables with a smaller resistance of the cable shield or shorter cables the harmed Site Attenuation  $A_{SH}$  can be reduced. Cutoff frequencies  $f_2$  which is more important for site validation can be reduced.

##### C. Increase loop inductance

As derived in chapter III both cutoff frequencies  $f_1$  (10) and  $f_2$  (11) depend on the loop inductance  $L_L$ . To decrease the important cutoff frequencies  $f_2$ , the loop inductance  $L_L$  has to be increased. This can be either done by increasing the loop area or by using magnetic materials. EMC engineers usually use clamp on ferrites or ferrite beads to suppress common mode currents. Typical EMC ferrite material for the desired frequency range is Manganese-Zinc (MnZn). If a high inductance is desired, there are two possibilities, either using multiple ferrite beads on the cable or using a ferrite core with multiple turns. For a slim-line ring core (12) is valid.

$$L = \mu_r \mu_0 N^2 \frac{A}{l} \quad (12)$$

So it is more effective to have a ring core with several turns instead of having a cable with several ferrite beads.



Fig. 5. Bulkhead connector with isolated ground

##### D. Open ground loop

If the ground loop is opened, the Site Attenuation is not harmed and its maximum value is determined by transmit power and signal to noise ratio. There are several possibilities to avoid a ground loop:

- Use a bulkhead connector with isolated ground, see Fig. 5. In this case the shielding effectiveness of the room is harmed, so the measurement devices should be operated in a shielded control room, otherwise ambient noise could influence the measurements. Typically, this should not be an issue, since the large majority of anechoic rooms have a shielded control room.
- Use an isolation transformer to power one of the measurement devices. Protective earth (PE) for primary and secondary side shall not be connected; otherwise this measure is not effective. Electrical safety rules must be followed.
- Use an RF transformer  $T$  on one of the RF cables. An example is shown in Fig. 6. The transformer  $T$  prevents the return current via the inductance  $L_L$  and no unexpected voltage  $V_L$  is produced. Receive voltage  $V_R$  due to  $V_R$  is not influenced, expect a small amount of insertion loss. Suitable transformer products are already commercially available.

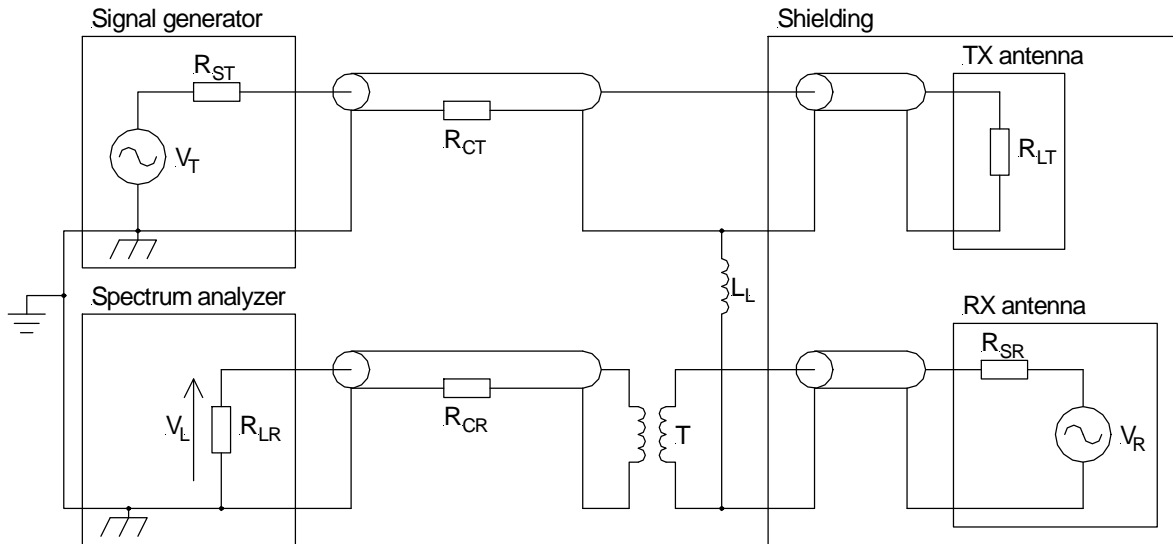


Fig. 6. Open the ground loop using a RF transformer

- Use a battery powered signal generator or spectrum analyzer, or an uninterruptible power supply (UPS) to power one of the devices. The UPS shall not be connected to ground via PE.
- Use a signal generator which has isolation between chassis ground and signal ground. Some arbitrary waveform generators offer this feature. For typical RF signal generators this is not the case.
- Operate the signal generator inside the anechoic chamber and the spectrum analyzer outside the anechoic chamber. In this setup the ground loop is opened, if there is no conducting contact of the transmit cable shield and the shielding. Barrel connectors lying on the ground plane could form a ground loop and must be taken into consideration.
- Use a fiber optic RF link to bring the signal to the transmit antenna. Power levels have to be taken into consideration, so an additional amplifier will be required.

#### V. "SECONDARY" GROUND LOOPS

In a typical setup there will be other cables which could form a ground loop, additional to the ground loop shown in Fig. (3).

Typically, auxiliary cables for communication are used, since the devices are controlled by measurement software. Optical or galvanic isolation of GPIB, Ethernet and USB cables is necessary if battery, UPS or isolation transformer powered devices are used. The same applies for setups where the inductance of the ground loop is increased by ring cores on the power cables.

Since a high dynamic range is required for measurements at 10 m distance, the resolution bandwidth has to be set to a small value to maintain sufficient signal to noise ratio. In this case synchronization between the signal generator and the spectrum analyzer may be required. The required cable for the 10 MHz frequency reference signal will form a ground loop like other cables mentioned before.

Another secondary ground loop could be formed inside the anechoic room. Typically, RF cables are routed beneath the ground plane from the penetration panel to the floor panel. On both sides of the cable the shield is connected to the shielding. This ground loop can be easily avoided by disconnecting the cables from the bulkhead of the floor panel and connect it directly to the next cable with a barrel connector. The same effect can be seen if the cables are routed above the ground plane and barrel connectors are used to extend the cables. If these have a conducting contact to the ground plane, a ground loop is formed. To avoid them electric isolation of the barrel connectors is required.

To increase the signal to noise ratio a power amplifier inside the anechoic room may be used. There is no issue as long there is any contact to the shielding, so battery powered amplifiers are recommended. If the amplifiers chassis ground is connected to the shielding via PE, a ground loop is formed if the receive antenna cable has a second contact to the shielding.

On receive side an issue could be none battery powered active receive antennas. Often they are powered via a shielded power cable. The cable shield of the RF cable and the cable shield of the power cable are connected via the antenna chassis. The power supply is connected to the shielding by PE, and the power supply chassis to the power cable shield. If the transmit antenna cable has a second contact to the shielding, a ground loop is formed.

An effective method to check if a ground loop is present is to remove the cable from the transmit antenna and to connect a termination instead. In this case the ground loop is not opened and the spectrum analyzer will show the harmed Site Attenuation. Disconnecting the receive cable from the spectrum analyzer and connecting a terminator there will open the ground loop. The spectrum analyzer will show only the noise floor.

#### VI. CONCLUSION

Ground loops can lead to severe problems for magnetic field site validation. Measurement results show errors up to 20 dB. It is very important for test engineers to recognize ground loops and to avoid their impact. Overlooking ground loops will lead to wrong validation results, causing compliant anechoic chambers to fail.

A model for ground loops is presented and analyzed. A principle agreement with measured data is found. The model is helpful to understand how ground loops are built and react.

Knowledge and experience are required to detect and avoid ground loops. A method to detect ground loops is given. Several techniques to avoid ground loops are presented. Depending on circumstances and available equipment the one or other is easier to apply.

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