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Sub-Committee A: Radio Interference Measurements and Statistical Methods

Working Group 1: EMC Instrumentation Specifications

Subject: Antenna calibration based on time domain measurements

References:
a) CISPR/A/WG1(Secretary)15-03, clause 7.6
b) CISPR 16-1-6:2014-12 (Ed. 1)
c) ANSI C63.5-2016 (unpublished)

At the CISPR/A meeting in Stresa, Italy it was agreed to introduce an antenna calibration method based on time domain measurements. This document provides an introduction of the method, a description of the limitations and measurement results that illustrate the dependencies of the results on critical instrumentation settings.

This document will not provide detailed explanations of the basic theory of time domain measurements and the mathematical background of such measurements.

1. Introduction

Many traditional antenna calibration methods, as described in CISPR 16-1-6 do use site insertion loss (SIL) measurements as the basis for the determination of antenna factors or antenna gain as the result of the calibration process. For example, the Three Antenna Method (TAM) at a free-space calibration site, as defined in clause 7.4.1.1 of CISPR 16-1-6 uses this approach, stipulating that a free-space environment can be created either by absorber placement between the antennas or by elevating the antennas to a large height above the ground plane. Both measures will result in minimizing the ground reflections but do not address other reflections in the calibration environment.

When calibrating antennas in the frequency range above 1 GHz free-space conditions can be achieved relatively easily by utilizing measurement results in time domain and subsequent “filtering” in the time domain to supress unwanted reflections from the environment. The filtered time domain data is then transformed back to the frequency domain to obtain SIL measurement data which has unwanted reflections significantly reduced. This data can then be used to calculate the antenna factor using the stated equations in CISPR 16-1-6 for the TAM.

The application of an Inverse Fourier Transform on site insertion loss measurements that are performed in the frequency domain will provide a display of the average transmission coefficient over time. Such a display offers the distinct advantage to be able to discern different responses, given sufficient resolution, due to their separation in time. The separation in time is due to the different distances signals have to travel between the transmit antenna and the receive antenna. The directly transmitted signal will travel a shorter distance than a signal reflected from the floor or walls or reflective structures close by. Hence the directly transmitted signal (the wanted signal) will arrive before the reflected signals (the unwanted signals). This separation in time can also be calculated as a function of time by applying the velocity of propagation of the medium that the signals travel through.

Most modern VNAs offer a time domain option that conveniently allows the display of measurement results in the time domain. The actual measurements are performed in the frequency domain as reflection or transmission measurements. The VNA internal calibration routines may be applied to minimize systematic errors and thus improve the overall measurement accuracy of results in the frequency domain significantly. The transformation of such results into the time domain offer additional possibilities to improve measurement results by applying a “filter” in the time domain, commonly called a “gate,” which can have bandpass or band stop behaviour, and which can be set by the user to either retain a specific time domain response or suppress a specific response. For antenna calibrations, this means that the use of time-domain allows the removal of unwanted signals from site attenuation insertion loss measurement results to thereby effectively emulate a free-space environment mathematically. The gated time domain response can that be transformed back to the frequency domain to obtain a site insertion loss result in a free-space environment, as required by the SSM for the calibration of antennas above 1 GHz. While the suitability of the measurement approach has been proven, some limitations of measurements in the time domain shall be observed to obtain accurate calibration results, as described in this document.

2. The time domain transmission response

In time-domain transmission measurements, the horizontal axis is displayed in units of time. The response of the through connection used in the calibration is an impulse at t = 0 s and with unit height, indicating that the impulse travelled through this connection in zero time and with no loss. When a EUT is inserted, the time axis indicates the propagation delay or electrical length of the EUT. In time domain transmission measurements, the value displayed on the x-axis of the VNA is the actual electrical length, not two-way travel time as in reflection measurements. The VNA marker still reads out the electrical length in both time and distance. The VNA allows for the entry of the velocity factor defined by the propagation delay of the medium the signal travels through. If no factor is specified, the user shall multiply the distance by the relative velocity of the transmission medium to get the actual physical length.

The quantity displayed on the vertical axis depends on the format selected. In linear magnitude format, the vertical scale is transmission coefficient units. It represents the average transmission coefficient for the transmission path over the frequency range of the measurement. Logarithmic magnitude format displays the response in units of transmission loss or gain in dB. It represents the average loss or gain in the transmission path over the frequency range of interest.

3. Limitations of time domain measurements

Three major limitations of time domain measurements are briefly discussed below; others like range and response resolution and masking are not addressed and are left for the reader to explore.

a) Aliasing

In the time domain, the range is defined as the length of time that a measurement can be made without encountering a repetition of the same response. This repetition of the response is called aliasing. Response repetition occurs at regular intervals in time, and the aliased responses in any measurement can be viewed by increasing the time span. The desired alias-free range is proportional to the number of points and inversely proportional to the frequency span. To increase the range, the number of points can be increased and/or the frequency span decreased.

b) Windowing

Ideally, the frequency domain measurement would be continuous over an infinite frequency range. Because the VNA is capable of measuring over a finite frequency range, a feature that is designed to enhance time domain measurements in the VNA is windowing. Windowing improves the dynamic range of the time domain measurement by modifying (filtering) the frequency domain data prior to conversion to the time domain, to produce an impulse stimulus with lower side lobes. This greatly enhances the effectiveness in viewing time domain responses that are very different in magnitude; however, the side lobe reduction is achieved with the trade-off of increased impulse width. Because of the limited bandwidth of the VNA, there are abrupt transitions in the frequency domain measurement at the start and stop frequencies. It is this band-limiting (or data truncation) that causes overshoot and ringing in the time domain response.

Two effects limit the usefulness of the time domain response. First, the ability to resolve between two closely spaced responses is impacted and second side lobes, caused by the abrupt cut-off at the stop frequency, limit the dynamic range of the time domain measurement by possibly low level responses within the side lobes of adjacent higher level responses.

A “Window” function is available in the time domain that allows tailoring the resolution in the time domain and the dynamic range through reduction of side lobe levels. A better resolution will lead to a higher side lobe level and thus reduce the dynamic range in the time domain. Usually four or five fixed Windows are available allowing optimization of the two previously mentioned parameters for a specific time domain measurement.

c) Gating

Gating provides the ability to selectively remove or include responses in time. The remaining time domain responses can then be transformed back to the frequency domain with the effect of the “gated out” responses being removed. This can improve the quality of the response, in that the gated frequency response can more closely resemble the EUT response as if it were measured with no other reflections.

However, previous losses or gains do have some effect even when the measurement has been time-gated. Gating also requires the implementation of a windowing function to avoid ringing in the frequency domain. The VNA time domain algorithm compensates for this and other effects. This compensation function works perfectly if the gate is centered at a time response. However, if the gate is not symmetrical around the response in the time domain, then the result will show some errors in approximately the last 10 % of the gated response when compared to the original frequency response. In the bandpass mode, these errors will be present in the first and last 10 % (approximately) of the gated frequency response.

The gate can be thought of as a filter in the time domain. The gate has a passband ripple, a cut-off rate, and side lobe level just like a filter in the frequency domain. The passband of the gate can be selected by the start and stop gate controls. The location of the gate in time can be controlled by setting the center and span times, or the start and stop times, which are the

–6 dB cut-off times. The gate shape controls the flatness, roll-off rate (steepness), and side lobe level of the gate. The minimum gate shape has the highest passband ripple and side lobe level, but has the fastest cut-off rate, for separating closely spaced time domain responses. The maximum gate shape has extremely low side lobes, with almost no passband ripple, but the cut-off rate is not fast.

The unwanted time domain responses will be reduced by the gate, but not totally removed. Even the most simple impulse response does not appear at a single point in time, but can spread out and have side lobe ripples that cannot be completely eliminated by gating.

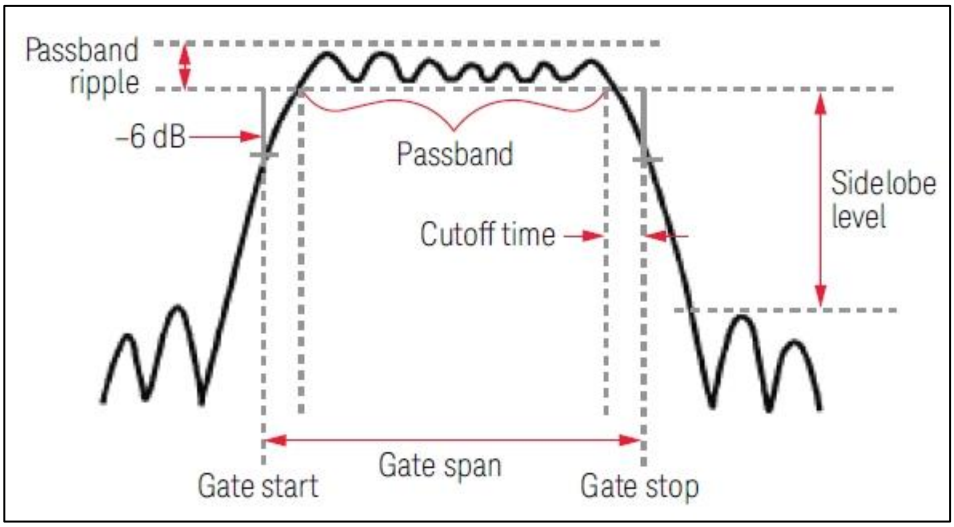

Figure 1: Example of a gate shape and its parameters

4. General steps of time domain measurement

The general steps needed to perform an antenna calibration using time domain with a VNA are described below. Example results obtained during a time-gating process for measurements using a pair of double-ridged waveguide horn antennas are shown in the figures below for the main measurement steps.

The following measurement was performed:

1) AUT:
   DRG Horn Antenna (18 GHz to 40 GHz)

2) VNA instrument state:
   Frequency Span: 18 GHz to 40 GHz
   Number of points: 1601
   IF bandwidth: 300 Hz
   Sweeptime: 5 sec
   Average factor: 30

3) Measurement procedure
   a) Set up the antennas as specified in 9.5.1 of CISPR 16-1-6 (2014), and connect the cables to the network analyzer for a transmission measurement. The use of attenuators, suitable for the frequency range of interest, can be considered to reduce measurement errors due to reflections at the antenna connections. In case attenuators are used, they are to be included in the calibration process of the VNA.

b) Set the frequency range of interest (i.e., 18 GHz to 40GHz), select an adequate number of points to achieve the required alias-free time domain range (see 3.a above) and perform a calibration of the VNA using either a response calibration or a full two-port calibration

c) Connect the antennas to the cables (and attenuators, if used).

d) Perform a transmission measurement to obtain site insertion loss data (see Figure 2)

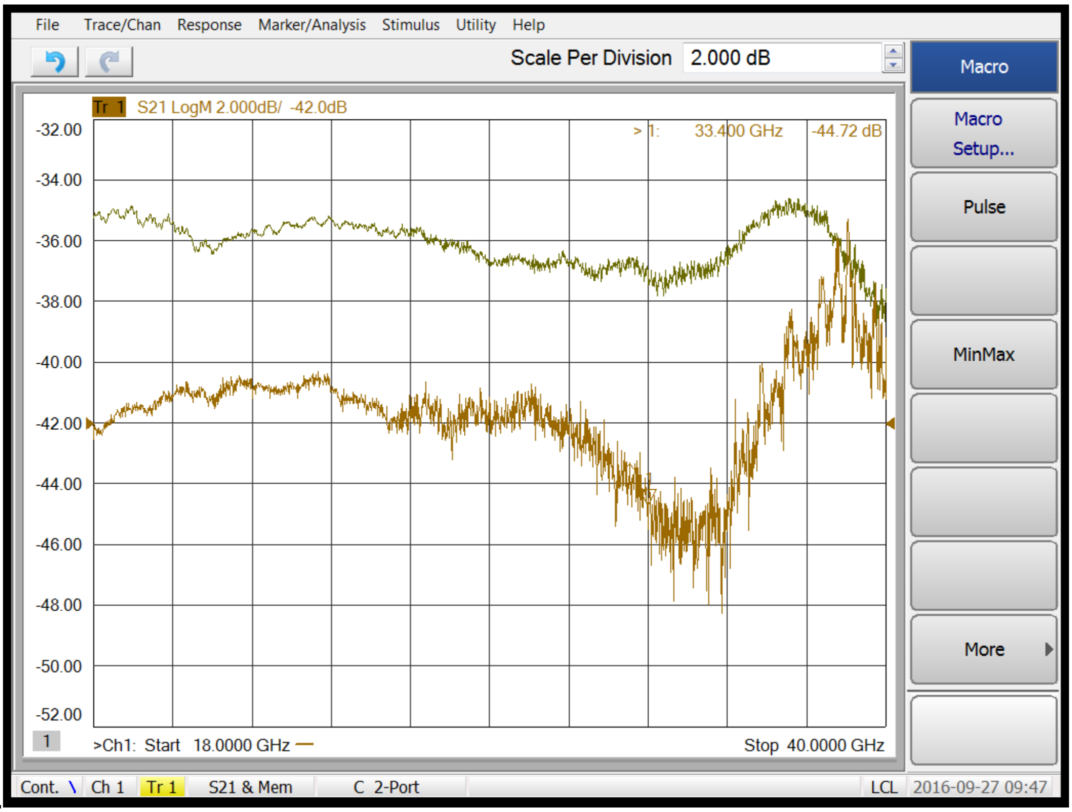

Figure 2: SIL measurements performed at 1m and 3m separation distance

Measurements were performed at an indoor area with no particular absorber treatment (allowing reflections). The top trace is the SIL for a 1m separation distance (with 30 averages) and the bottom trace is the 3m SIL without averaging.

e) Transform the site insertion loss data into time domain, using time domain bandpass mode (see Figure 3). Determine the direct transmitted signal (wanted signal) which is located closer to the start time of the display, due to the shorter signal path. This is the response to be retained; all other responses, caused by reflections, are to be suppressed.

The following transformation parameters were used:
1) Time domain Bandpass mode
2) Normal Window
3) Start time: 3 nsec and stop time: stop 5 nsec

4) Gate type: Bandpass
5) Gate shape: Normal
6) Gate start time: 3.1 nsec and Gate stop time: 4.9 nsec

f) Center the gate on the response to be retained, and ensure that the gate span is sufficiently wide to retain the complete response within the passband of the gate. Note that improper gate positioning does introduce additional measurement errors. While viewing the time domain data, select the gate start and stop times at zero crossing points, so that all of the first pulse is enclosed. Turn on the gating function to suppress all unwanted (i.e., reflected) signals (see Figure 3).

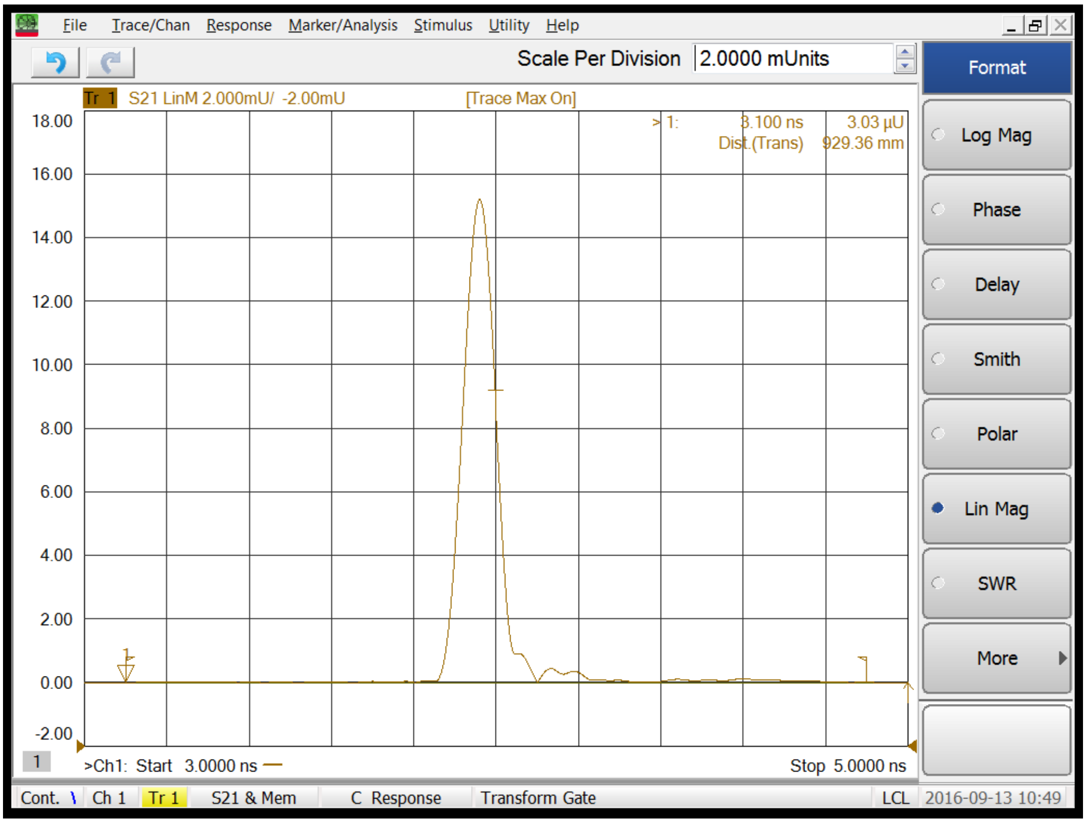

Figure 3: Time domain representation of 1 m SIL with Gate turned on

g) (see Figure 4). The gated response is then transformed back into frequency domain as a SIL which has unwanted reflections largely removed (see Figure 4). Note that the frequency domain data with the reflected signals removed appears much smoother.

h) Record the gated site insertion loss data (Figure 4) and use general procedure and data processing as described in CISPR 16-1-6 (2014) for TAM to determine free-space antenna factors.

5. Antenna ring down time

The antenna ring-down time is an oscillatory response after the main peak (in time domain). It is a characteristic of an antenna caused by internal reflections. For antenna calibrations using the time domain response it is important to set the gate in the time domain such that the ring down time is enveloped by the gate. If this is not the case then measurement errors are introduced in the frequency domain SIL data. Figure 5 shows an example of a ring-down signature of a mini-biconical antenna with a bandwidth of 1 GHz to 18 GHz with a the ring-down time less than 1 ns. Antennas with long ring-down times may not be suitable for TD calibration because long ring-down responses may obscure a nearby site reflection which could cause considerable error.

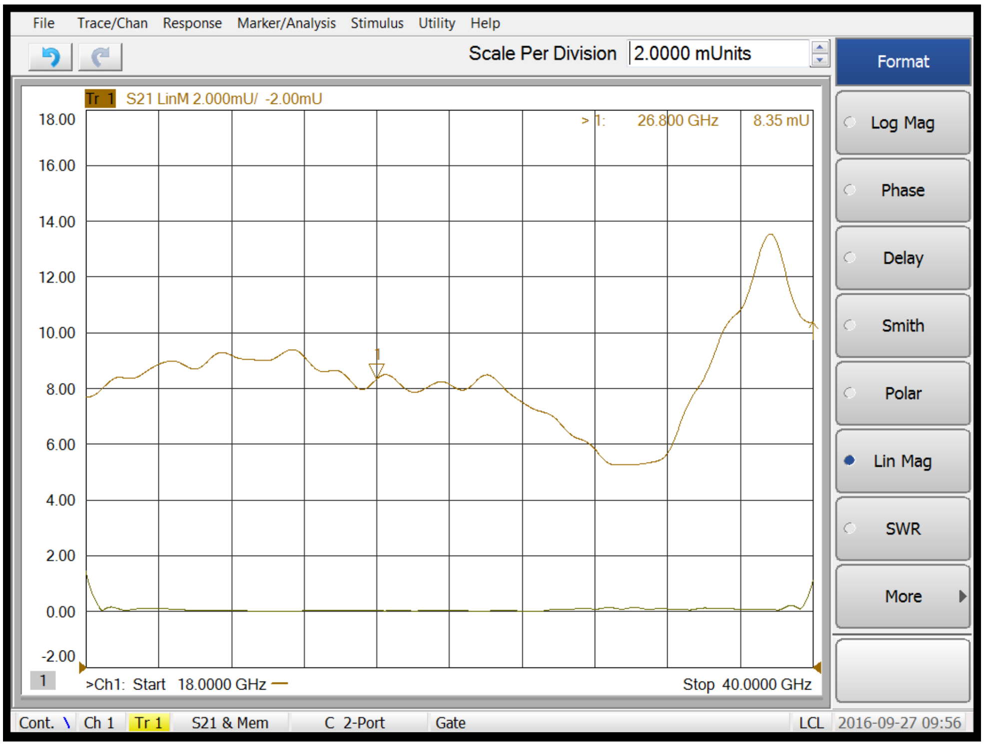

Figure 4: Frequency domain representation of gated 1 m SIL with Gate turned on (Disregard the bottom trace since which is an unwanted display memory content)

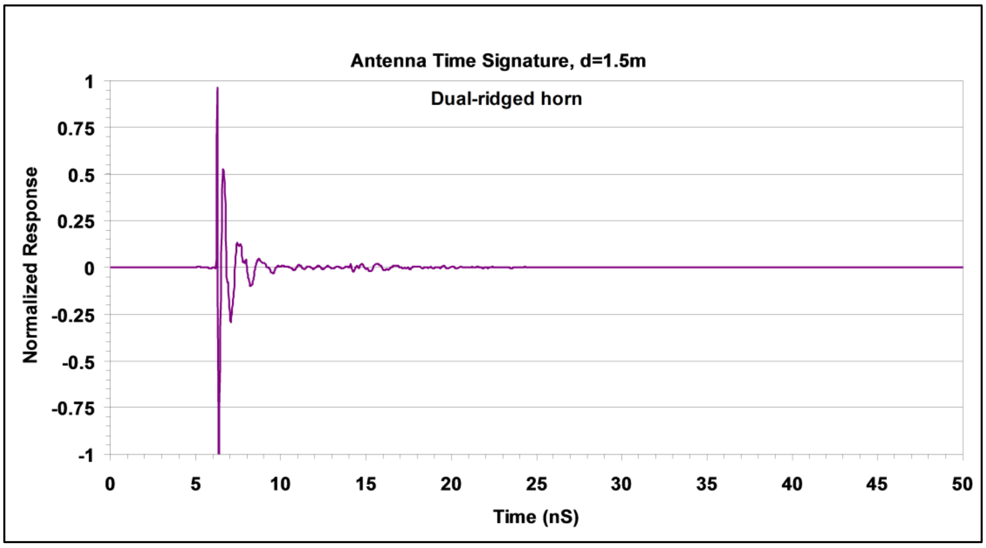

Figure 5: Ring down time of mini-biconical antenna

6. Impact of VNA settings on time domain antenna calibration results

a) Change of Windowing function (see 3.b above).
The following transformation parameters (similar to 3.e) were used:

1) Time domain Bandpass mode
2) Minimum Window
3) Start time: 3 nsec and stop time: stop 5 nsec

4) Gate type: Bandpass
5) Gate shape: Normal

6) Gate start time: 3.1 nsec and Gate stop time: 4.9 nsec

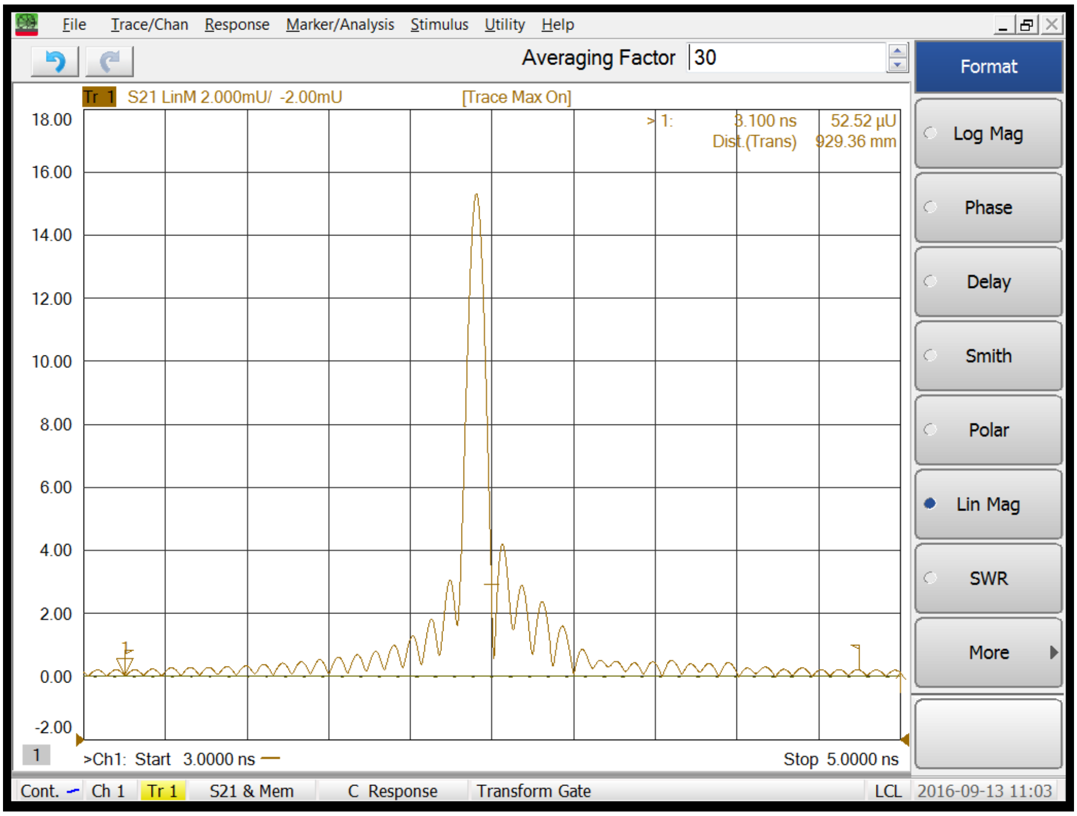

Figure 6: Time domain results with minimum Window function

As to be expected the minimum Window function introduces higher side lobe levels but provides better resolution. For antenna calibrations lower side lobe levels are preferred to be able to determine the ring down time of the AUT. Other Window functions (e.g., Maximum) did not deliver a response significantly different from the one in Figure 3 but the width of the main response.

b) Change of Gate Shape and Gate Span (see 3.c above)
The response in Figure 3 was evaluated by changing the Gate shape only (e.g., Gate Shape "Minimum" and "Maximum") and no appreciable difference was noted due to this change.

Then the Gate Span was reduced and the following VNA settings were implemented:

Time domain Bandpass mode
Normal Window
Start time: 3 nsec and stop time: stop 5 nsec

Gate type: Bandpass
Gate shape: Normal
Gate start time: 3.955 nsec and Gate stop time: 4.07 nsec

The time domain representation can be seen in Figure 7 below.

When setting a very narrow gate span of about 0.075 nsec around the main response the difference compared to a much wider gate that encompasses the complete ring down time leads to a maximum deviation of about 1.2 dB in the antenna factor. Setting a wider gate span (1.2 nsec) only yielded an antenna factor variation of about 0.15 dB compared to a gate span of about 4 nsec.

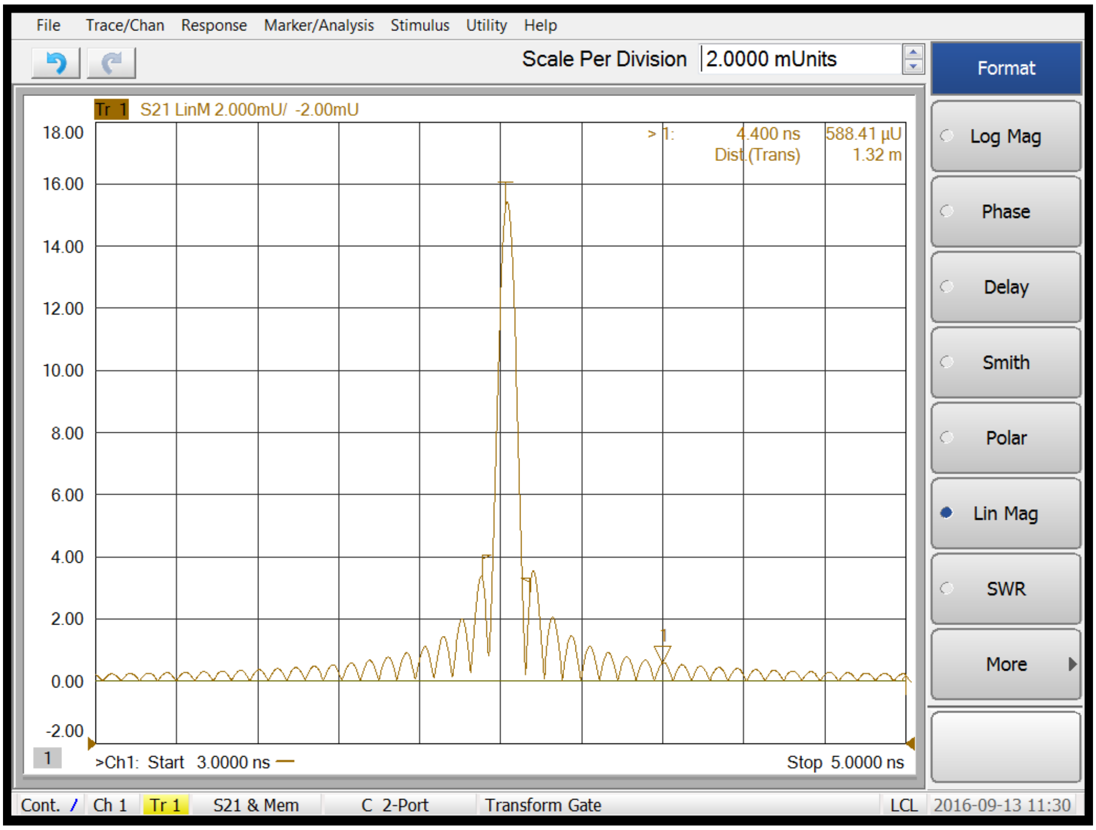

Figure 7: Time domain representation of a very narrow gate

6. Conclusion

The processing of SIL data in the time domain for the purpose of antenna factor determination is a very viable approach to significantly reduce unwanted reflections from the antenna calibration environment and therefore improve the accuracy of the calibration result. Calibration sites of lesser quality may be used if sufficient resolution and spacing of responses in the time domain can be assured. In addition, the gating in the time domain must be performed such that the main response of the antenna includes the antenna's ring down time. In order to identify the ring down time in the time domain a windowing function with minimum side lobe levels should be used to avoid masking. When these restrictions are observed the time domain approach is to be considered as an antenna calibration method in the frequency range above 1 GHz.

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