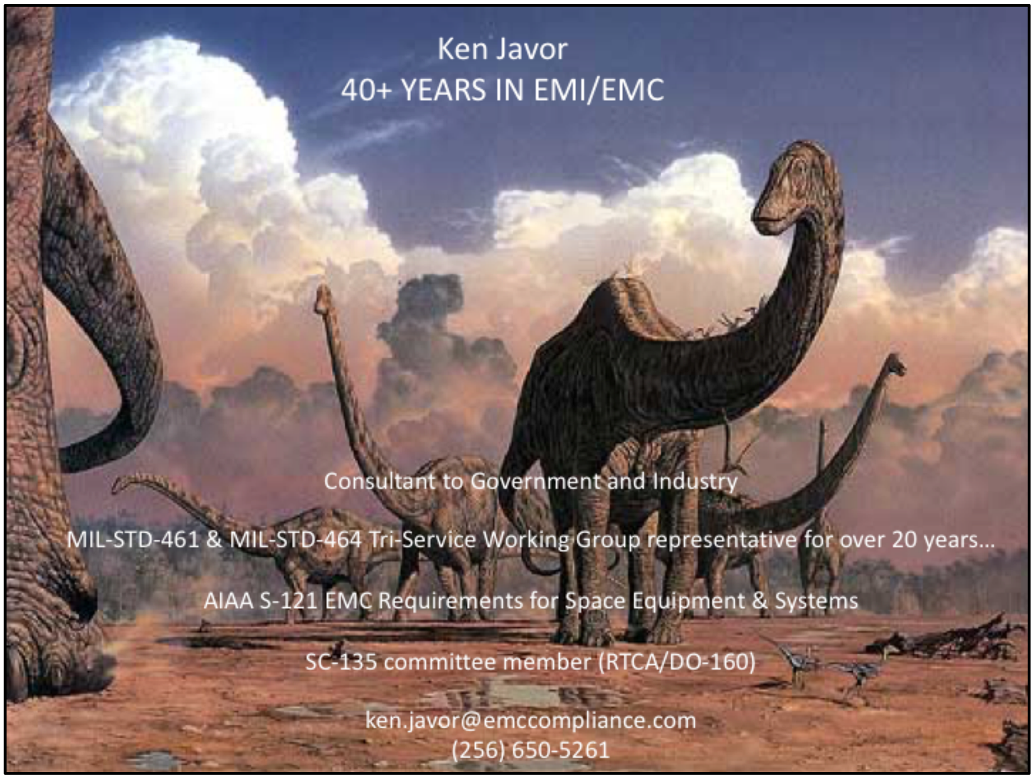
SAE ARP-958 covers the calibration of antennas used at one-meter separation from the test sample. This makes it a near field measurement, which is key to much of what will follow. Examples of such use are CISPR 25, MIL-STD-461, and RTCA/DO-160 for commercial aircraft.

This presentation is about a problematical change in the subject revision to this half-century old document. The proposed “E” revision requires separate horizontal and vertical antenna factor calibration for dipole-type antennas. The original release was in 1968 and covered only log-spirals, so this wasn’t an issue. Revision A in 1992 added other antennas commonly used in shield room tests, including the biconical, log-periodic arrays, horns, and others. Revisions B, C, and D followed with minor changes. Draft E with this new two-antenna factor requirement is another matter entirely. Note the scarlet revision letter: subtlety isn’t our strong suit at EMC Compliance.

This, by the way, is the Liberty Labs antenna calibration facility, in Iowa. It is now Keysight Liberty Labs. Keysight co-chaired the ARP-958E revision along with ETS/Lindgren.



Beyond the pejorative meaning of dinosaur as over-the-hill and out-of-date, remember that dinosaurs were around for over a hundred and fifty million years, much longer than mammals so far and certainly mankind. Further, a big part of my career was researching the evolution of the EMC discipline before my time, mainly as applicable to vehicles.

We can all learn from those who went before us…

Foreshadowing

"…it is easier to run the risk of … being fired … if before long you are going to be dead anyway. This freedom seems to me the chief consolation of old age.

from "But We Were Born Free," copyright 1952.

Elmer Davis, journalist, 1890 - 1958

If the chief consolation of old age is the ability to speak one's mind without fear of consequences, then I have finally arrived. If I don't upset someone in the audience today, I'm probably not getting my point across.

I'm not here to make friends, and certainly not to scare up business, but I am here to influence people.

You need not agree with me today – although I hope you all eventually do – but I am here to plead a case. Not simply inform, but present and persuade.

Preface/Disclaimers/Full Disclosure

Anything discussed in this presentation can be found amongst these well-worn standard texts, which contain information over one hundred years old.

OTOH…

Opinions expressed herein are those of a minority of one.

Opinions expressed herein were cancelled by ARP-958 revision committee members.

Our discussion today is all based on well-known physics of antennas: no new information, no new discoveries – just basic antenna engineering principles that have been known since before many of these books were published.

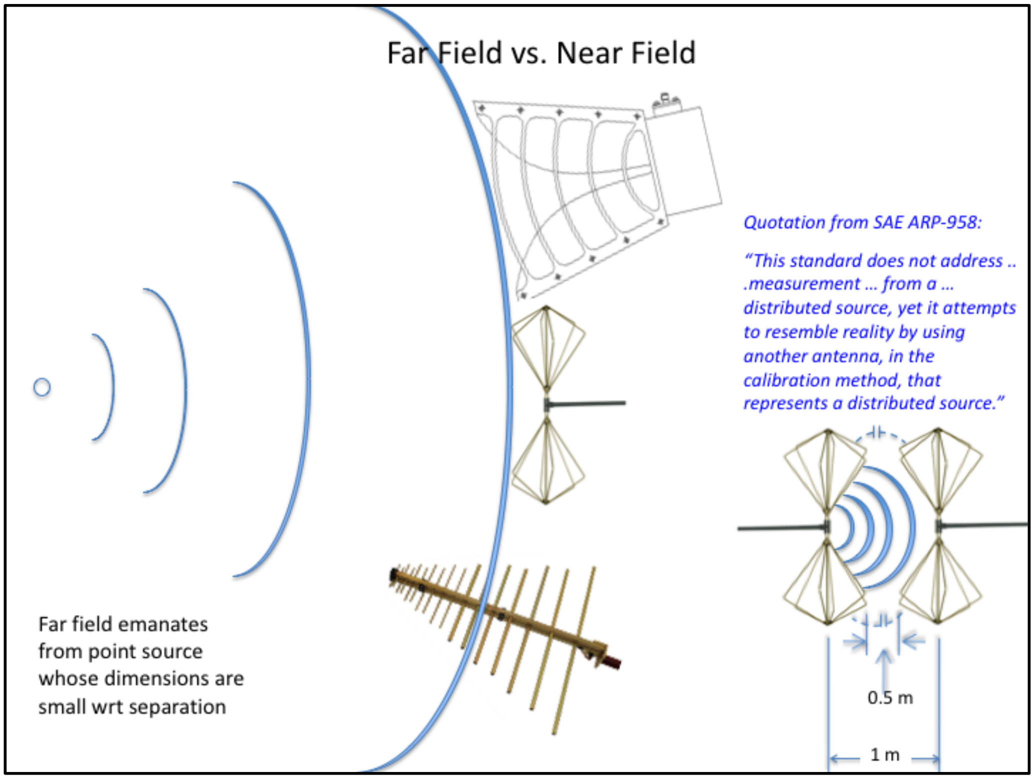
While this presentation is purely factual, from time-to-time an opinion based on facts will creep in. I will endeavor to point out when such an opinion is controversial. This doesn't mean the opinion is wrong, just that some misguided folks don't agree with me. If everyone agreed on this topic, there would be no need for the presentation.

On the other hand…

I seem to be the only person involved in the "E" revision process who had a problem with what is presented herein. I was first instructed to quit messaging on this topic and then after the first two meeting invitations no further invitations followed. My comments on the draft "E" revision submitted through NASA's Marshall Space Flight Center were rejected.

It is reasonable to assume I am considered a crank by the balance of the committee membership. Keep that in mind as the presentation unfolds.

Before we get into the details, some background material is pertinent.



Antennas calibrated in the far field can be used to measure any far field signal, and may be used interchangeably, and at any far field distance, even though they are completely different in both kind and size. This is because both calibration and measurement are responses to plane wave illumination, and the only difference between such antennas is their response to the plane wave immersion. This is why nominal far field test methods such as CISPR 22 do not specify antenna type.

Antennas calibrated in the near field are not interchangeable and the calibration is only good for use at the actual calibration distance. This is because the calibration field is not plane but has a wave-front unique to that antenna at that separation. When an antenna so calibrated is used to measure the field from a completely different source – say an EMI test set-up in a shielded anechoic chamber – the resultant "field intensity" is relative to what the antenna picks up at one-meter separation from an identical antenna. It is not a value that can be scaled with distance like a far field measurement. The "field intensity" so measured is only useful to the extent that:

the limit was based on that specific measurement,

the measurement simulates the actual rfi problem the requirement attempts to control, and

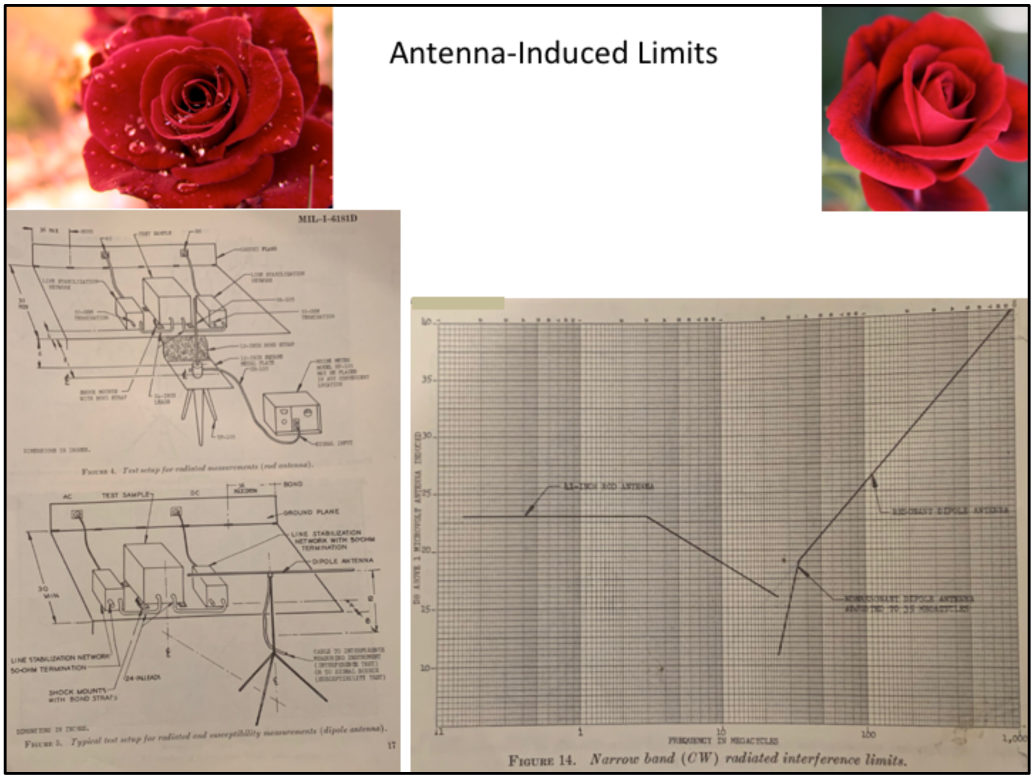
everyone does it the same way.

This is why MIL-STD-461 RE102 specifies antenna type and size. And why (my opinion) RTCA/DO-160 and CISPR 25 should follow suit.

A one-meter antenna factor is a convenient transfer function, that resembles to some degree the response to the electric fields emanating from an EMI test set-up, but there is no uncertainty bound on the difference. It is useful in the sense precisely as stated in the ARP-958 description (this slide and next slide), but we could just as easily use the far field antenna factor, as long as we still made the measurement at one-meter separation and as long as everyone reduced data the same way.

Shakespeare addressed this very phenomenon in Romeo and Juliet: "A rose by any other name would smell as sweet."

For some of you, this material is old hat. Some of you may have never given it much thought. In the backup slides, I have a heat flow analogy specially tailored to be of interest to vehicle EMC engineers. It's in backup because it will not be necessary for some. At the end, if there is time and interest, I will go though the analogy to shed more light on the concept of a measurement where the results depend on how the measurement is made.



Prior to 1964, EMI radiated emission limits were antenna-induced. That means the limit was expressed in terms of the voltage that would appear at the terminals of the antenna, rather than as a field intensity. This required specific antennas to be defined and used: typically the 41” rod antenna and the tuned dipole. These were placed 12” from the test set-up boundary vertically and horizontally, respectively for rod and dipole.

The term “antenna factor” in those days had a different meaning than today. It accounted for any impedance matching and/or balun losses between the antenna element or elements and the actual 50 Ω coaxial antenna terminal. It was simply a loss factor, with units of dB.

Antenna-induced limits made a lot of sense when the antenna was parked 12 inches from the test sample. It’s fairly obvious this is not a field intensity measurement, but borders on a crosstalk measurement, with capacitive and inductive coupling playing a role.

When they backed antennas up to one-meter separation in the mid- to late 1960s, that was when they transitioned to a field intensity limit. An arbitrarily defined new antenna factor was tacked on in order to express the limit as a field intensity, rather than an rf potential. Hence, the original 1968 release of SAE ARP-958. But – this change was still encumbered with all the caveats and limitations described for near field measurements in the previous slides.

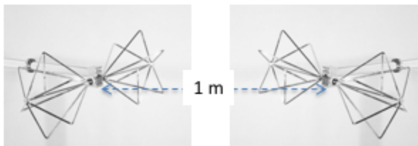
In fact, the military is still making antenna-induced measurements, in that MIL-STD-461 prescribes the kind of antenna, and its separation and orientation. And while the military maybe alone recognizes this, any radiated emission measurement made at one-meter separation from a test set-up longer than one meter is ***still*** a near field measurement.

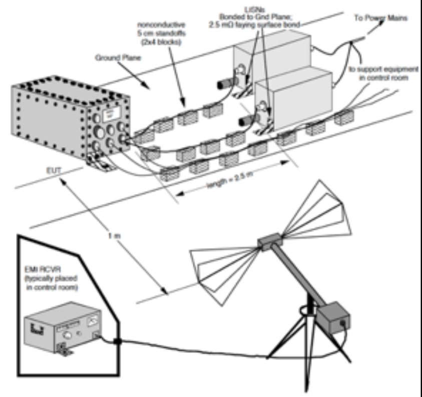
My opinion – It might have been better to stay with antenna–induced limits – people wouldn’t be making the kinds of mistakes we will be describing shortly.

ARP-958: Calibrating an Antenna for a One-Meter RE Measurement

1.1 Purpose

"…a standardized and economical method for the checkout and calibration of electromagnetic interference measurement antennas. *Its application is for use when measuring a source 1 m from the antenna in a shield room.* This is the typical distance used in performing military EMC testing. The influence of the shield room on the measured field strength is not considered. *This standard does not address the measurement of emissions from an unknown distributed source, yet it attempts to resemble reality by using another antenna, in the calibration method, that represents a distributed source…"*





What people want from ARP-958, and what some people think they can get

The best that can be had.

The purpose of ARP-958, as distinct from other, typical far field antenna calibration regimes, *is for use when measuring a source one meter from the antenna.*

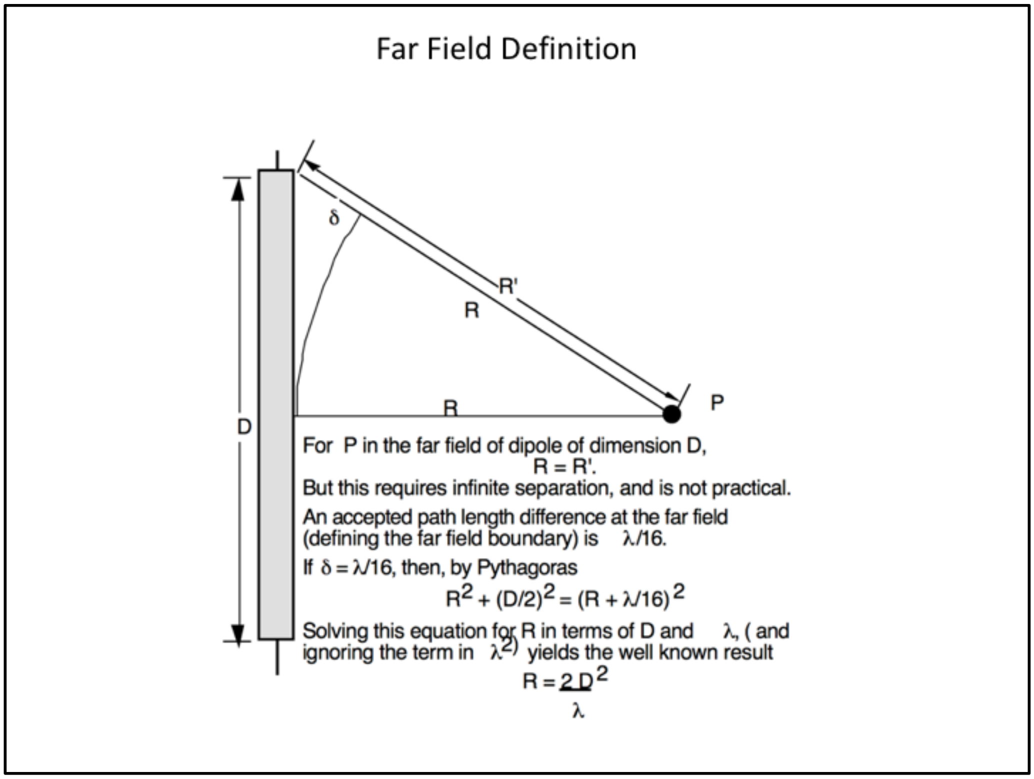
As a direct corollary, this standard cannot possibly provide for the accurate or absolute measurement of emissions from an unknown source whose dimensions exceed the separation distance; the best it can do is provide precise measurement by calibrating using an identical antenna that represents the distributed source at the same separation distance. Precise here means repeatable across various facilities. It's not that you can't hit the bullseye; the bullseye is undefined. The best that can be had is a small group: all test facilities get the same answer.

So for the EMI measurement on the right, antenna terminal voltage, adjusted for any cable loss, preamplifier gain and then antenna factor, is a value based on the response of the antenna to a particular field distribution unique to that antenna at a separation of one meter (shown at upper left), where as stated in ARP-958 section 1.1, the transmit antenna simulates the actual distributed source to be measured.

Further, compare in this case the 137 cm tip-to-tip length of the standard biconical with two meter or longer test set-up boundaries. The simulation is, shall we say, inexact.

We measure an artifact of the test set-up – it is not a true field intensity that can be extrapolated based on distance, as in the far field.

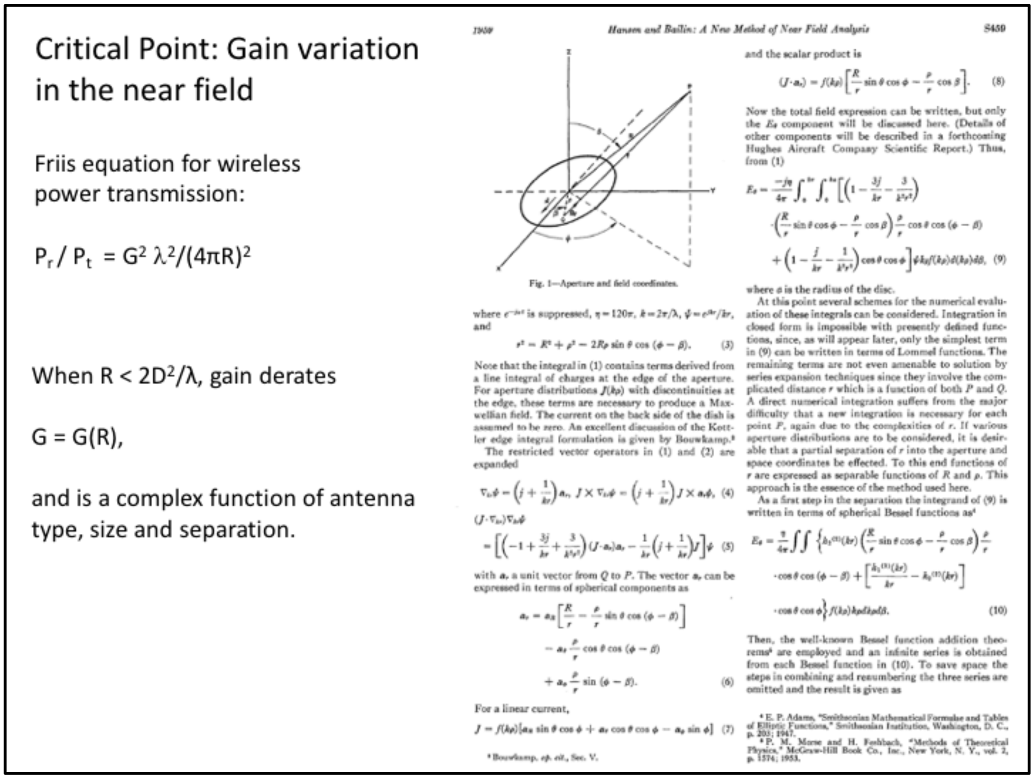
And this is just fine, as long as we all agree to do it the same way and as long as it is a reasonable simulation of the type of interactions we expect on an integrated platform. And as long as we check that the EMI performance measured in the test facility provides EMC on the integrated platform. That is, we verify in a production or pre-production vehicle that all the rf systems operate compatibly and within specification.



The theoretical construct of a plane wave is the curvature of a sphere with infinite radius. A practical description of the far field depends on the need for accuracy, but the criterion can be qualitatively described such that at the far field distance, the phase difference between waves emanating from any two points on the radiating structure is less than some arbitrary amount expressed as some fraction of a wavelength. For a theoretical plane wave, that phase difference is zero wavelengths. For ordinary use, a phase difference not exceeding one-sixteenth wavelength is often used, resulting in the familiar far field boundary cited as twice the square of the maximum physical aperture dimension divided by wavelength.

So you learn two things here, if you haven't seen this before. 2D^2/lambda is not a physical constant but a commonly accepted and useful construct, and also that this only works when D is large compared to lambda, else the second term we ignored can't be.

BTW, for a tuned half-wave dipole, 2D^2/lambda is just equal to a half-wavelength, which is a commonly used far field value for a tuned dipole.



In the Friis equation, notice as R ♑□♏⬧ ⧫□ zero, the ratio on the right blows up.

But conservation of energy says the ratio on the left cannot exceed unity.

Therefore, the equation predicts that gain is not independent of antenna separation as that separation decreases. As R gets smaller, G decreases from its far field value.

Χονσερϖατιον οφ ενεργψ ψιελδσ αν υππερ βουνδ ον ωηατ τηε γαιν χαν βε ασ Ρ αππροαχηεσ ζερο, βυτ ιτ δοεσ νοτ πρεδιχτ τηε αχτυαλ γαιν ϖαλυε.

In the near field, the behavior of gain as a function of decreasing separation is a complex function of wavelength, separation and antenna physical aperture. This is just one page of many involving calculations for a dish antenna.

Bessel functions, anyone?

Dish and Horn Gain Variation in the Near Field from
NAVAIR Electronic Warfare and Radar Systems Engineering Handbook

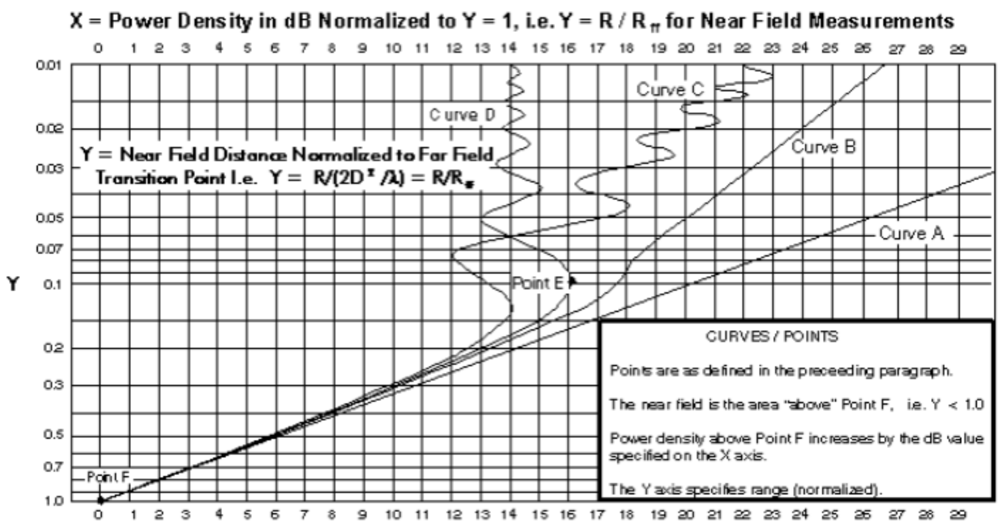


Figure 5. Antenna Near-Field On-Axis Power Density (Normalized) For Various Aperture Illuminations

The end result of several pages of complex mathematics plus numerical integration is this semi-log plot showing gain derating for various aperture type antennas as the separation from the antenna decreases from the far field boundary.

Ordinate and abscissa are backwards from conventional use.

Distance moving in from the far field is on the ordinate axis, with separation decreasing as we move up the axis. Fractional values are normalized relative to the far field distance, which has unity value, and is plotted on a logarithmic scale.

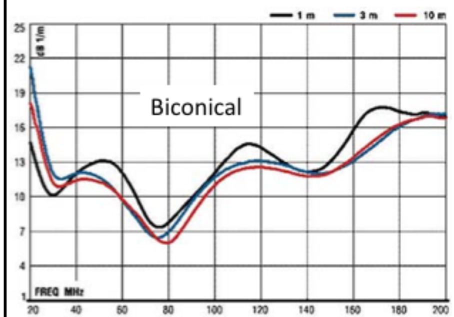
The abscissa shows power density relative to power density at the far field point. It is graduated in dB relative to the power density at the far field point. Therefore it has a value of 0 dB at the far field point.

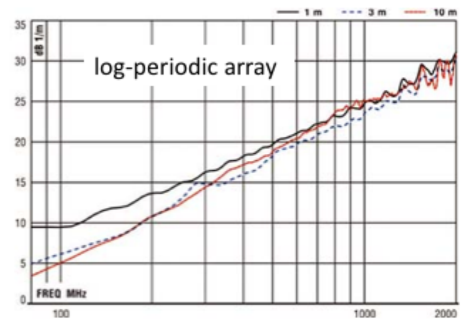
> Point F is our origin – the far field point – from which we count both separation and change in power density.
>
> Curve A is for reference only and shows how power density would vary if it were calculated using the Friis equation with gain independent of separation. It increases without bound.
>
> Curve B isn't very interesting.
>
> Curve C shows power density variations on axis for a uniformly illuminated horn antenna.
>
> Curve D shows power density variations on axis for an antenna aperture like a parabolic dish antenna with tapered illumination.

It is apparent that near field gain decreases with separation, and is a function of antenna type.

EMI Antenna Near Field Gain Comparisons

Courtesy of ETS/Lindgren



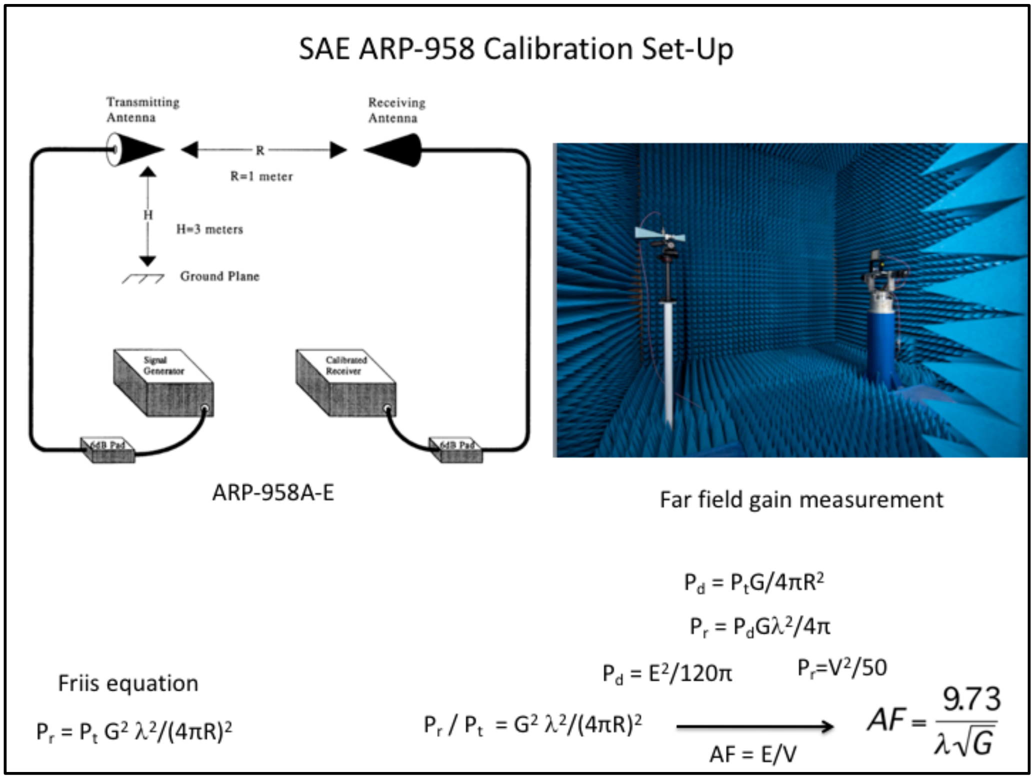


One-meter antenna factor is plotted in black.

Three-meter antenna factor plotted in blue.

Ten-meter antenna factor plotted in red.

These plots show 1, 3, and 10-meter antenna factors for commonly used EMI test antennas. Note that 3- & 10-meter antenna factors are closer to each other than to the one-meter antenna factor. This is because as antenna separation increases, gain asymptotically converges on the far field value.



The drawing on the left is the basic calibration set-up and method in ARP-958 revisions A through E. The difference between the ratio of transmit to receive power is compared with antennas in place vs. disconnecting antennas and connecting two cables together. That sets up the receive power vs. transmit power ratio, zeroing out cable loss. The only difference between this and a far field gain calibration is a) the separation and b) presence of a ground plane. The math is the same.

And the intent on the left is to minimize reflections off the ground plane economically, compared to the facility shown on the right, where cost has not been an object. In both cases, a measurement free of significant reflection error is the goal.

Getting antenna factor from gain is a simple exercise in algebra, spelled out in every version of the ARP from 1968 forward. It relies on two assumptions:

1) The receive power at the antenna port is developed across a matched 50 Ω load, and

2) The impedance of the field impinging on the antenna is that of free space, meaning a plane wave, meaning this is a far field calculation applied to a near field measurement.

This is why near field gain is sometimes referred to as apparent gain.

CISPR 25 © IEC: 1995(E)

6.5.1 Antenna systems

The limits shown in tables 10 and 11 are listed in dB(µV/m), and thus theoretically any antenna can be used, provided that it has adequate sensitivity, the antenna correction factor is applied, and the antenna provides a 50 Ω match to the measuring receiver. For the purposes of this standard, the limits … are based upon the following antennas:

a) 0,15 to 30 MHz 1 m vertical monopole (where this is not 50 Ω, a suitable antenna matching unit shall be used);

b) 30 to 200 MHz a biconical antenna used in vertical and horizontal polarization;

c) 200 to 1000 MHz a log-periodic antenna used in horizontal and vertical polarization.

Commercially available antennas with known antenna correction factors (see 3.4) may be used.

CISPR 25:2016 © IEC 2016

6.5.2.2 Antenna systems

Measurements shall be made using linearly polarised electric field antennas that have a nominal 50 Ω output impedance.

To improve consistency of results between laboratories, the following antennas are recommended:

a) 0,15 MHz to 30 MHz 1 m vertical monopole (where this is not 50 Ω, a suitable antenna matching unit shall be used);
b) 30 MHz to 300 MHz a biconical antenna;
c) 200 MHz to 1 000 MHz a log-periodic antenna;
d) 1 000 MHz to 2 500 MHz a horn or log periodic antenna.

In light of the previous discussion, the CISPR 25-1995 text highlighted in red typeface is – my opinion – not just wrong, but fundamentally and embarrassingly so in such a high-profile standard.

Cloaking a near field measurement in field intensity raiment does not make it a far field measurement anymore than me changing my name to Bill Gates will fatten my bank account. I can change my name to Fred Astaire, but it doesn’t alter the fact that I can’t dance. Lipstick on a pig. There are innumerable sayings about dressing something up to appear to be something it is not.

Now back in 1995, the fact that CISPR 25 got this wrong was neither here nor there to someone primarily working aerospace EMC. Not my turf, not my problem. Some of you may in fact be wondering as I speak where this aerospace guy gets off wandering on to your turf and casting aspersions. Well, the answer to that is what is coming up has spilled over from the automotive world into the wider world including aerospace and military EMC via SAE ARP-958, which is used by all disciplines making one-meter separation measurements, and which started out supporting military EMI testing.

The 2016 version of CISPR 25 has removed the errant text, and recommends – but does not require – a standard set of antennas. This is a reasonable first step towards standardization that doesn’t instantly obsolete many test facilities’ existing antennas, but puts them on notice.

So an improvement here, but a similar type error and a massive disappointment is coming up next…

CISPR 25:2016 © IEC 2016

6.5.2.7 Location of the measuring antenna

NOTE 2 The users of this standard are aware that antenna manufacturers can give:

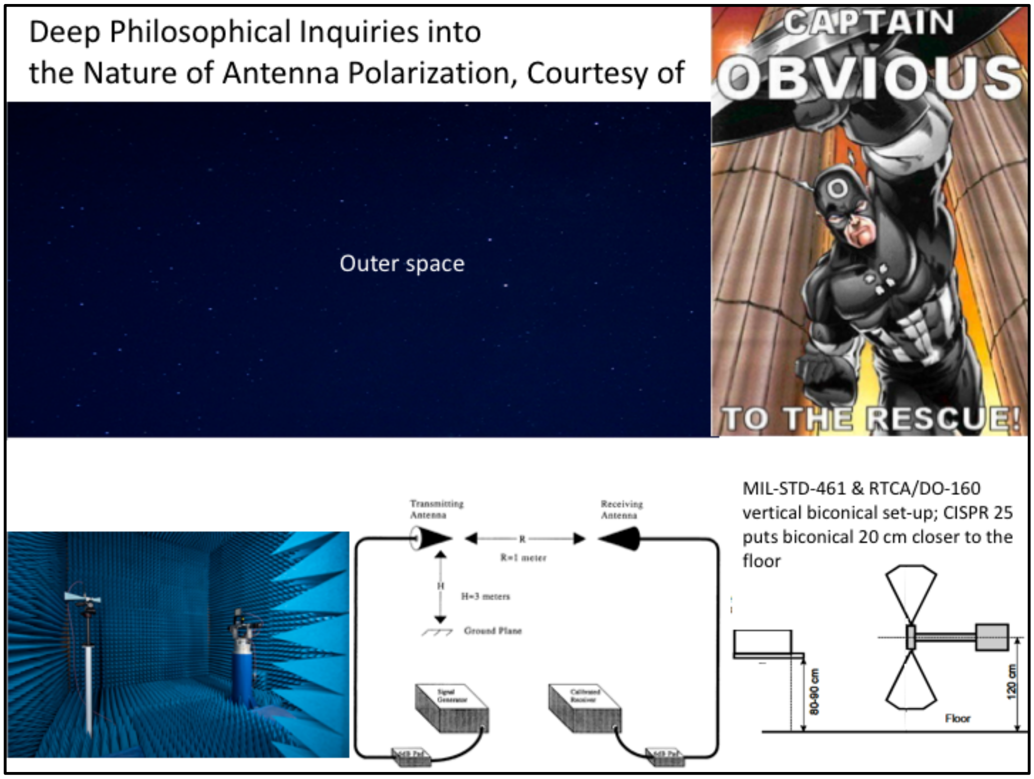
– independent antenna factors for horizontal and vertical polarisations; in this case the appropriate antenna factor are used for measurement in each polarisation.

– a single antenna factor; in this case this antenna factor is used for measurements in both polarisations.

Based on this note, the SAE ARP-958E committee says that polarization specific antenna factors are justified by popular demand. Aside from the – my opinion – ***really*** bad idea of polarization-specific antenna factors, note that this edition of CISPR 25 opens the door to different test facilities doing things in either of two different ways, contributing to lack of repeatability between test facilities.

Not a good thing, especially in light of how much money is pumped into getting a CISPR 25 chamber just right.

Now we are getting down to the issue at hand, for which the foregoing was just an introduction.



We all know that in space, no one can hear you scream.

And absent gravity, there is no up or down.

Likewise, in the absence of any mass capable of causing gravity, there is no vertical or horizontal, either. Vertical on Earth means aligned with the local gravitational field.

Vertical and horizontal are not absolute descriptors, but relative to some frame of reference.

So, far away from any frame of reference, there is no horizontal or vertical, and there can only be one ***orientation-independent*** antenna factor.

If – ***pay attention*** – antenna factor is inherently orientation-independent, and yet there are indeed measured differences between orientations, then the difference is an artifact of the measurement itself.

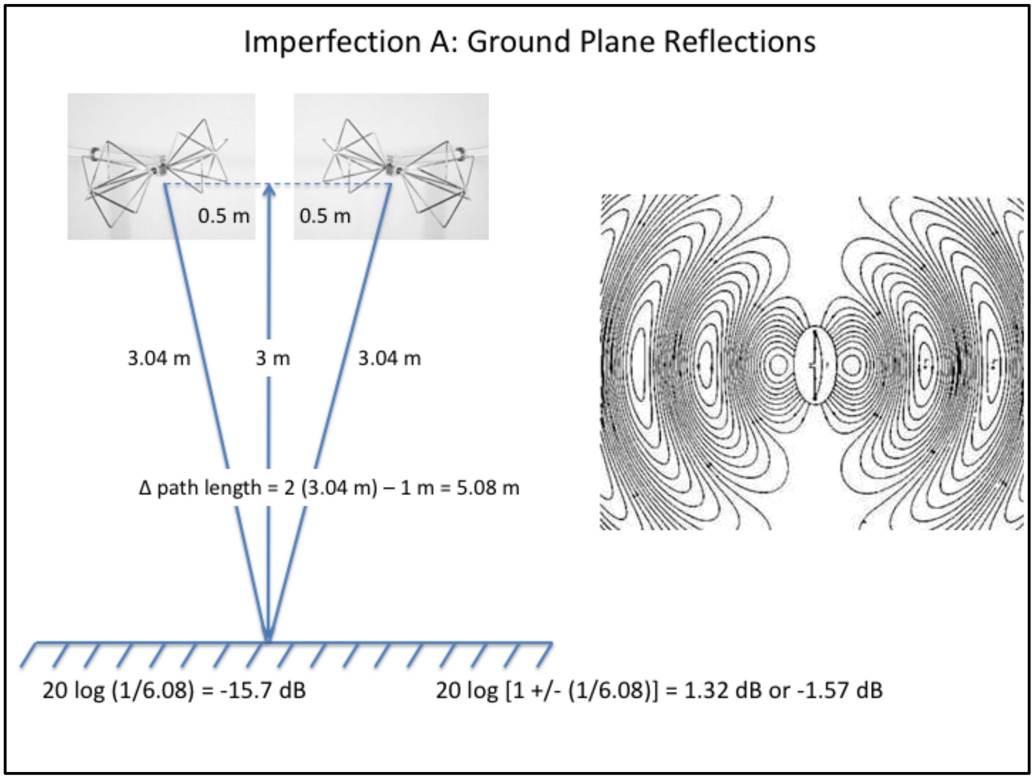
This means that the difference must be due to the presence of the reference – in our case – the ground plane.

As noted, the far field gain measurement at lower left goes to a lot of trouble to remove the ground plane as a source of perturbation.

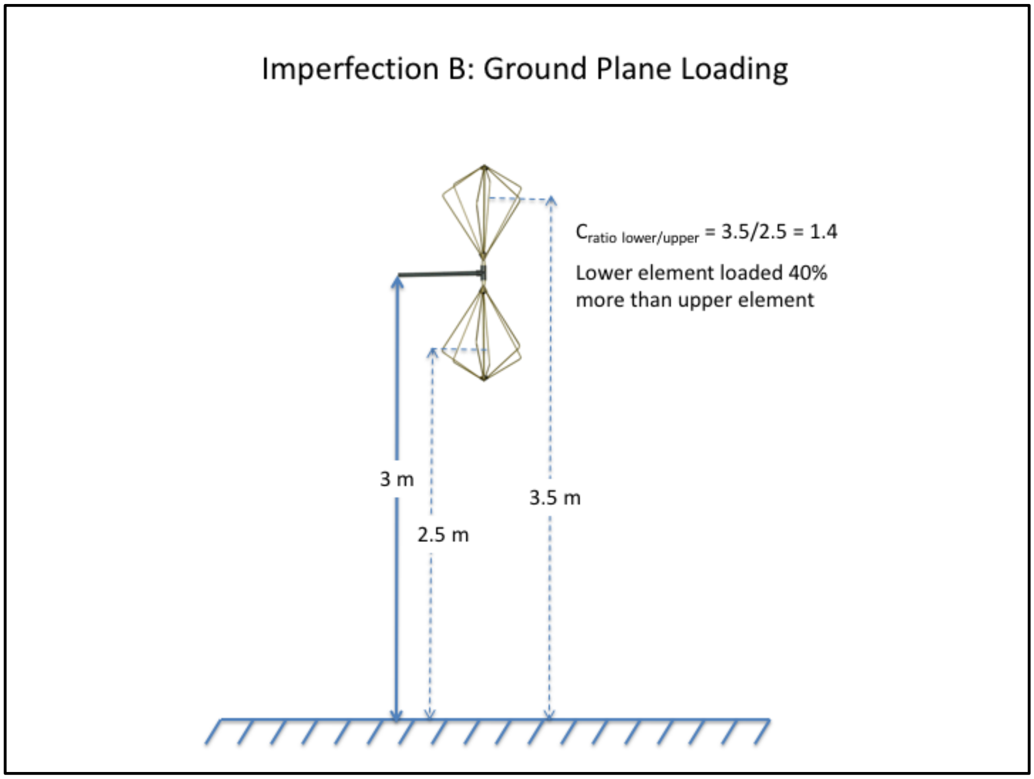
The ARP-958 calibration at center tries to minimize ground plane-induced perturbations, but in a more cost-effective manner.

The EMI test set-up at the lower right has the lower extremity of the vertical biconical antenna within 52 cm of the floor in the depicted military measurement, but within 32 cm of the floor in the CISPR 25 set-up.

If our antenna calibration routine minimizes the effect of the ground plane reference using a three-meter separation from the ground plane, but our EMI radiated test method on the lower right does not, then what are we doing reducing EMI test data to account for the minor imperfections of the calibration site?



ARP-958 since the "A" revision includes a ground plane, so two effects must be taken into account. The first is reflections off the ground plane, shown on this slide, and the second is capacitive loading, on the next slide. Ray tracing math reveals that the bounced ray is about 16 dB down from the direct ray, and that this results in less than 2 dB change relative to no reflection. This isn't really a problem in the vertical polarization, because when vertically oriented, antenna gain in the direction of the ground plane is much lower than broadside.



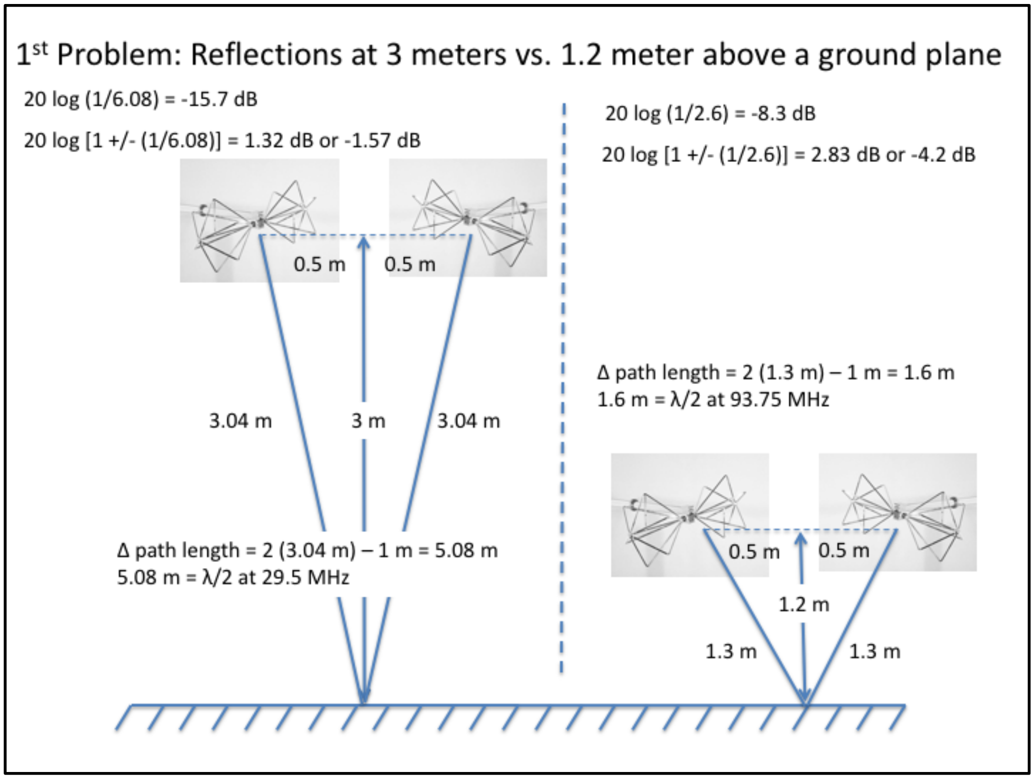
Differential ground plane loading is an issue for wire-type antennas whose separation from the ground plane varies between vertical and horizontal polarization. For aperture type antennas this issue doesn't exist, or is negligible due to symmetry. The next slide quotes section 4.1.1 of ARP-958E saying that for vertical polarization, the ground plane effect is negligible, which implies that the degree of differential loading this far from the ground plane is acceptable, and that the major issue with the ground plane is reflections, which as we noted are going to be more a factor with horizontal polarization.

Formally, the problem in **E**

Section 4.1.1 Apparatus

"…The area in which the setup is situated shall be clear of obstructions and reflections. Chambers or variations from the setup shown in Figure 3 are allowable if there is a demonstrated correlation of under 1dB from the reference setup of Figure 3. The methodology as described in clause 5.1.3 of ANSI C63.5-2017 is an acceptable process for determining correlation. It also needs to maintain a ground plane to simulate open field sites. Note that for 3 m height and vertical polarisation, the influence of the ground is negligible, so the ground should not be taken to be essential, rather the emphasis should be on achieving free-space conditions. A 3 m height for the center of the antenna is defined as the initial antenna calibration height. *For dipole like antenna, antenna factor will vary with polarization, both polarizations should be considered and shall be supplied unless otherwise specified.* For aperture type antenna (horn), the antenna factor found using the methods of this document should vary less than 1dB between polarizations."

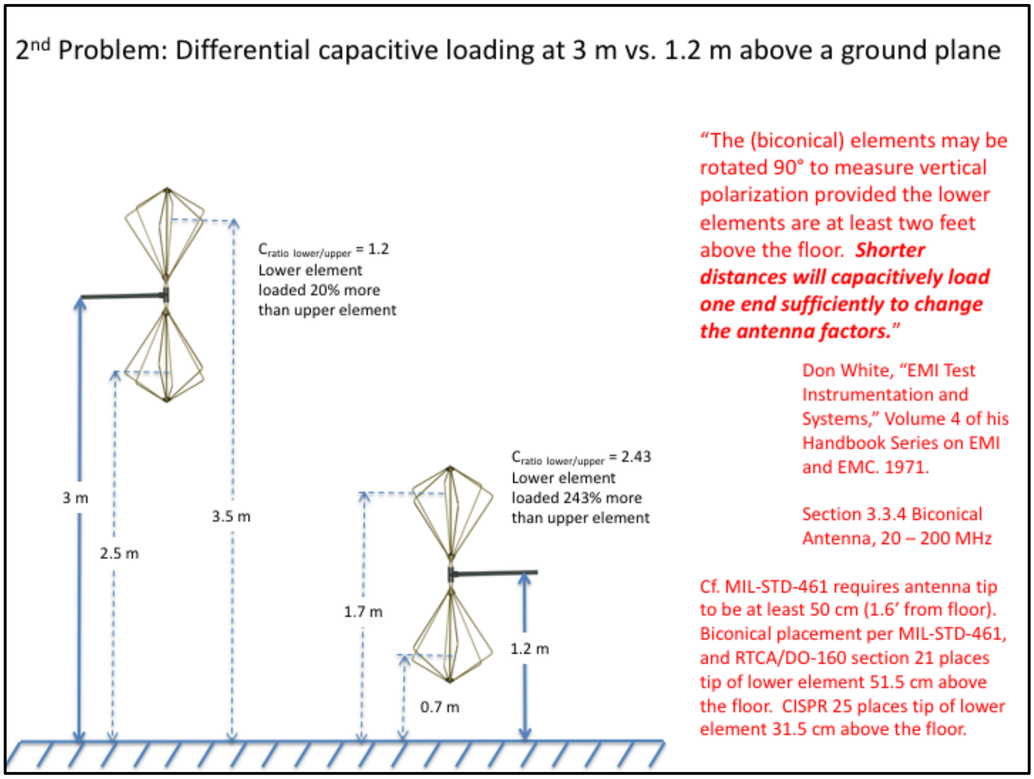
The blue type face text is where SAE ARP-958E says that ground plane effects for vertical polarization are negligible, with calibration performed three meters above the ground plane. The problem in E is the new red text requirement for separate horizontal and vertical polarization antenna factors. As noted, these problems are associated with the presence of a ground plane.



On the left is the situation for an SAE ARP-958 calibration three meters over a ground plane. On the right is a better simulation of the actual test set-up. One can see that if the correction factors are applied for reflections based on the 3-meter high calibration set-up, they do not at all correct for the reflections encountered 1 or 1.2 meters over the floor. My opinion – it is essentially false advertising to claim otherwise.

Note that in addition to the magnitudes of reflection amplitudes being quite different, so is the spectrum of reflection errors, due to the different path lengths traveled. There will be reflection errors at lower frequencies three meters above the floor than at 1.2 meters above the floor.

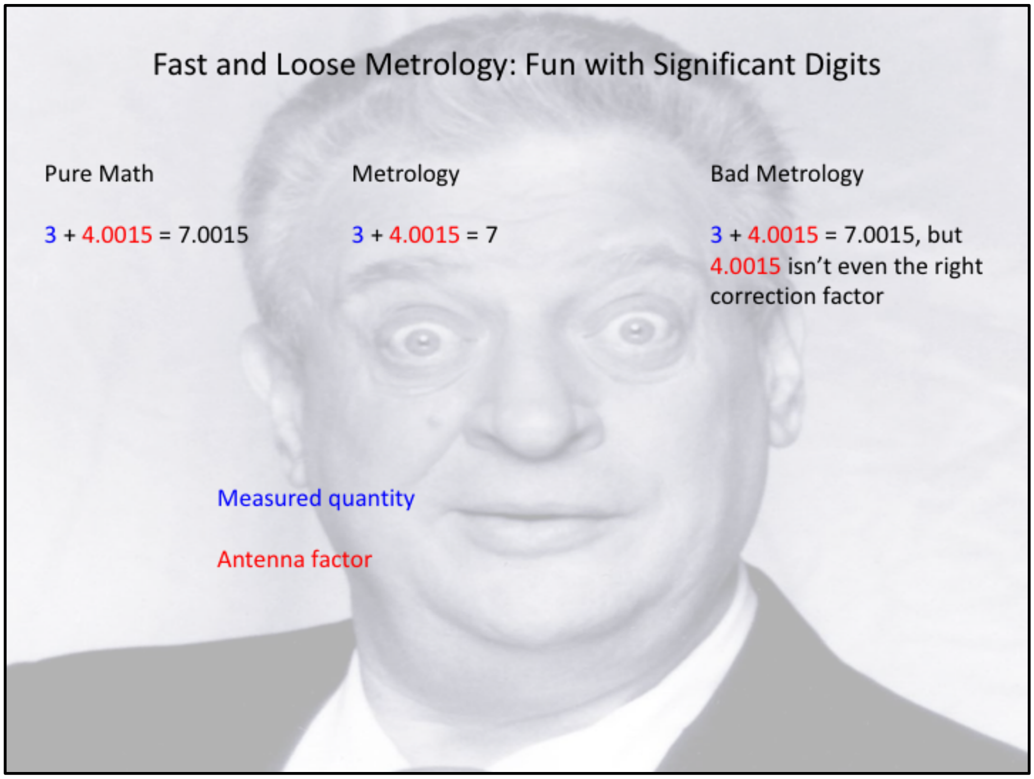
My opinion – If you are hell-bent on providing reflection corrections as a function of polarization, then it must be done at the actual height in test usage, not at a height picked purposely to minimize the quantity being corrected.



On the left is the situation for an SAE ARP-958 calibration three meters over a ground plane. On the right is the actual situation during test. One can see that if the correction factors are applied for differential capacitive loading based on the calibration set-up, they do not at all correct for the differential capacitive loading encountered 1.2 meters over the floor.

Once again – my opinion – it is false advertising to claim otherwise, and if it ***is*** somehow now essential to provide differential capacitive loading corrections as a function of polarization, then again it must be done at the actual height in test usage, not at a height picked purposely to minimize the differential loading.

Note red text, citation, and date. The antenna factor as used will differ materially from that calibrated. The citation is from the well-known six-volume Don White EMC handbook series. Handbooks are not forums for advancing the state of the art, but collections of what is already known. In this case **–** ***fifty years ago, in nineteen hundred and seventy-one***. We are ***not*** blazing a new trail here, folks…



This entire slide is on the one hand factual, but controversial so we will say it's my opinion.

Consider the train of logic – or illogic – presented so far.

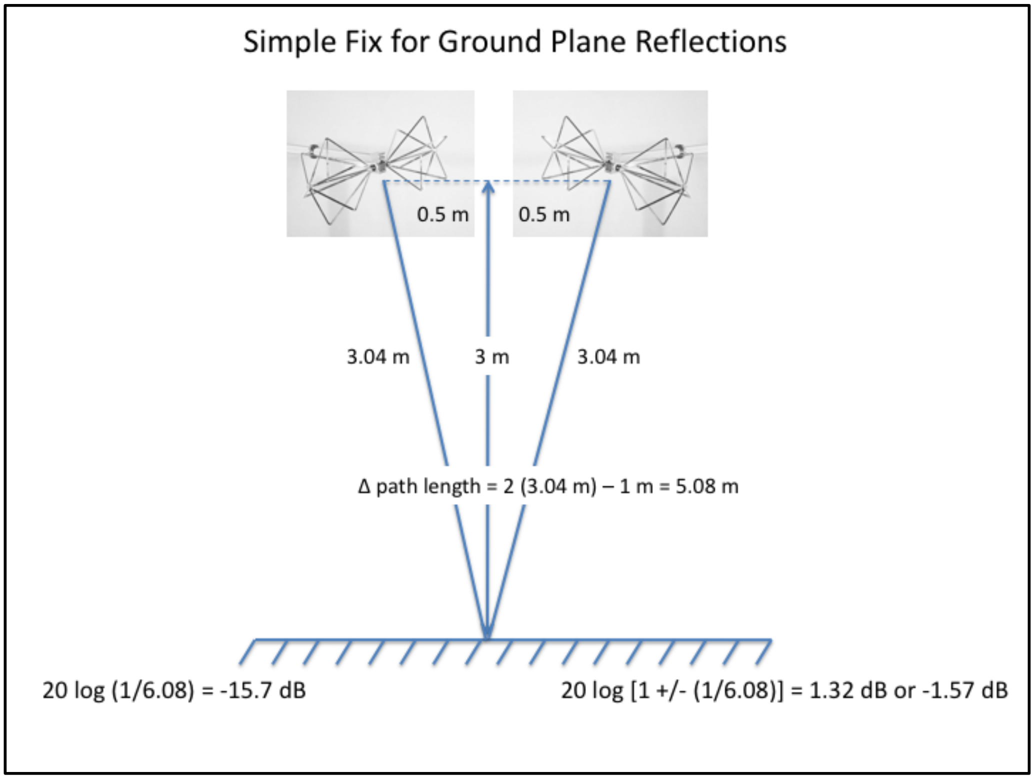
We must quantify something which cannot be quantified in an absolute sense, because the measurement result depends on the tool we use to measure it. The best we can do is agree to a standard measurement so that we all get the same answer.

To the result from this standard method, we add minor corrections based ***not*** on the measurement itself, but on the tool's calibration, which purposely minimizes effects that are present to a much higher degree in the measurement set-up.

It is bad enough to ignore the concept of significant digits.

It is adding insult to injury to require a correction factor that doesn't represent the measurement itself, but only a minor imperfection of the tool's calibration site.

In summation, if we as an engineering discipline wish to avoid what one colleague calls the Rodney Dangerfield effect, i.e., "EMC don't get no respect," it behooves us to have requirements and measurement protocols in accordance with the laws of physics and metrology.

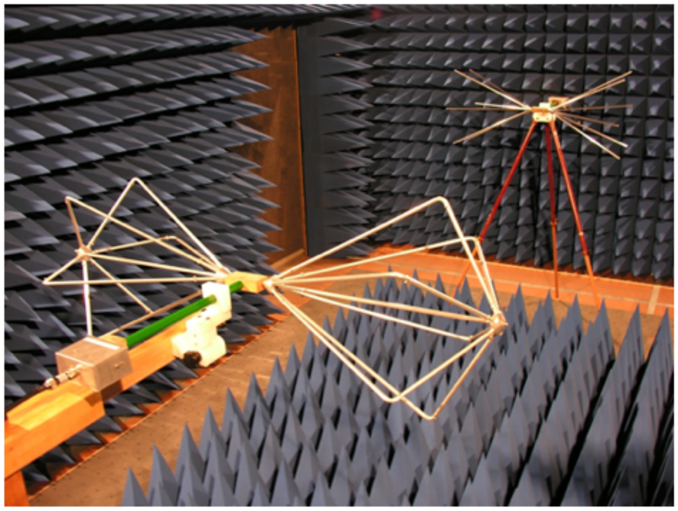


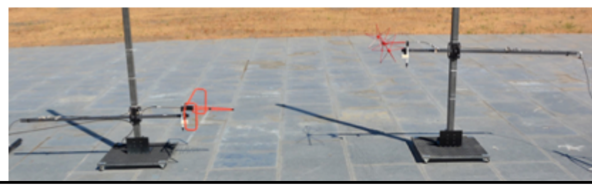
Now my opinion – if it isn't already obvious – is that we are doing just fine with three meter height antenna factor calibrations. Nothing is broken here, and nothing needs fixing.

But – purely as an exercise following this thought process to a logical conclusion – it is interesting to consider how ARP-958 might have been written differently in the first place if it had been written say, post-2000, instead of in 1968.

Instead of trying to get the antenna away from the floor to minimize errors from reflections, today we can economically make the floor go away. This wasn't practical for the typical EMI test facility in 1968, and was still expensive in 1992, but post-2000, at many EMI test houses eliminating the floor and other complications could be done with existing test facilities…

Better Set-Up?





Pyramidal absorber isn't the best solution down to 30 MHz: ferrite tile works much better. Both in terms of specified absorption, but also because pyramidal absorber only achieves specified absorption when the electromagnetic field Poynting vector is parallel to the direction of the cones, which is certainly not the case for the floor bounce here. For this facility, the pyramidal absorber would have to be backed up with ferrite tile. Below 1 GHz, the floor would only need ferrite tile.

Notice that with an absorber-lined chamber, there is no need for a mast to raise antennas to three-meter height. If an EMI test facility has a test chamber with ferrite-backed cones, antenna calibration could become a ***do-it-yourself*** proposition, which was the original intent back in 1968.

But note that even if you don't have this high-end chamber, a ground plane laid down on a parking lot free of obstructions and some ferrite tile absorber would suffice (no cones necessary for the floor alone below 1 GHz).

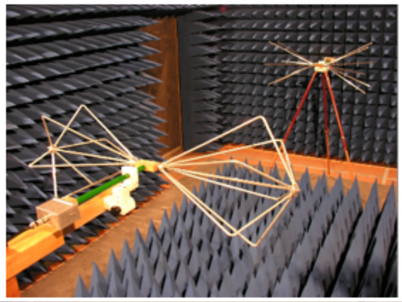
Maybe it's time to write a new SAE ARP-958**D-I-Y**…

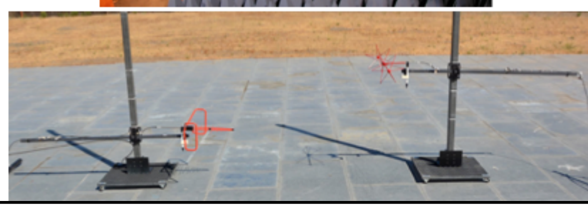
Conclusion

Free field (not far field) antenna factors are desirable and practical.

SAE ARP-958D is better with respect to not providing polarization-specific antenna factors

Consider a calibration site that eliminates/controls reflections/loading.





We have arrived at the end. Conclusions – all my opinions:

Antenna factors should be measured in the complete absence of reflections and loading – or practically speaking – under conditions where the errors due to reflection and loading are controlled to an acceptable level.

SAE ARP-958D is better with respect to not providing polarization-specific antenna factors.

Maybe it's worth considering reducing these errors not by trying to inadequately quantify incorrectly measured differences, but by providing a calibration site that eliminates polarization-specific errors. And one that – not coincidentally – is part of many existing EMI test facilities.