Interaction Note

Note 618

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Assessment of and Recommendations for RTCA/DO-160F Section 22 Lightning Induced Transient Susceptibility

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abstract

Radio Technical Committee on Aeronautics (US), RTCA/DO-160F, "Environmental Conditions and Test Procedures for Airborne Equipment, Section 22, Lightning Induced Transient Susceptibility", Dec 2007, defines the US indirect lightning testing of aircraft black boxes with the indirect environments defined in Society of Automotive Engineers Aerospace Recommended Practices, SAE ARP5412A, "Aircraft Lightning Environment and Related Test Waveforms", Revised 2005-02.

After examining the in-flight indirect lightning environments and the physics of cable shielding in IN615, 616, & 617, it was concluded that some tests in DO-160F do not replicate in-flight environments. Also, many modern electronics are not wired the way the standards assume. Specific corrections are made to test set ups and test procedures.

Some recommendations herein are alternatives in DO-160F, others new. They challenge tacit assumptions about broadband transient behavior in these configurations and subsequent simulation in the lab. The legacy mentality from CW testing and CW transfer impedance appears to dominate test design in DO-160. The most important missing feature in DO-160 tests is the Thevinin equivalent source impedance.

A problem in writing and reading this note is that it is intended for three audiences, the subscribers to the note series, the RTCA and SAE committees who write the standards and guidelines, and the engineers and consultants responsible for hardware analysis, design, and test. They have worked in separate worlds too long.

1. Official Indirect Lightning Waveforms

Indirect lightning waveforms from SAE ARP5412A[1] are depicted in Figure 1, below, all normalized to a peak value of one. WF2 is the time derivative of WF1 & 4. WF3 is set at 1MHz for this example although it varies from about 1MHz to 50MHz depending upon system and cable lengths. DO-160[1] sets the WF3 test frequencies at 10MHz and/or 1MHz.

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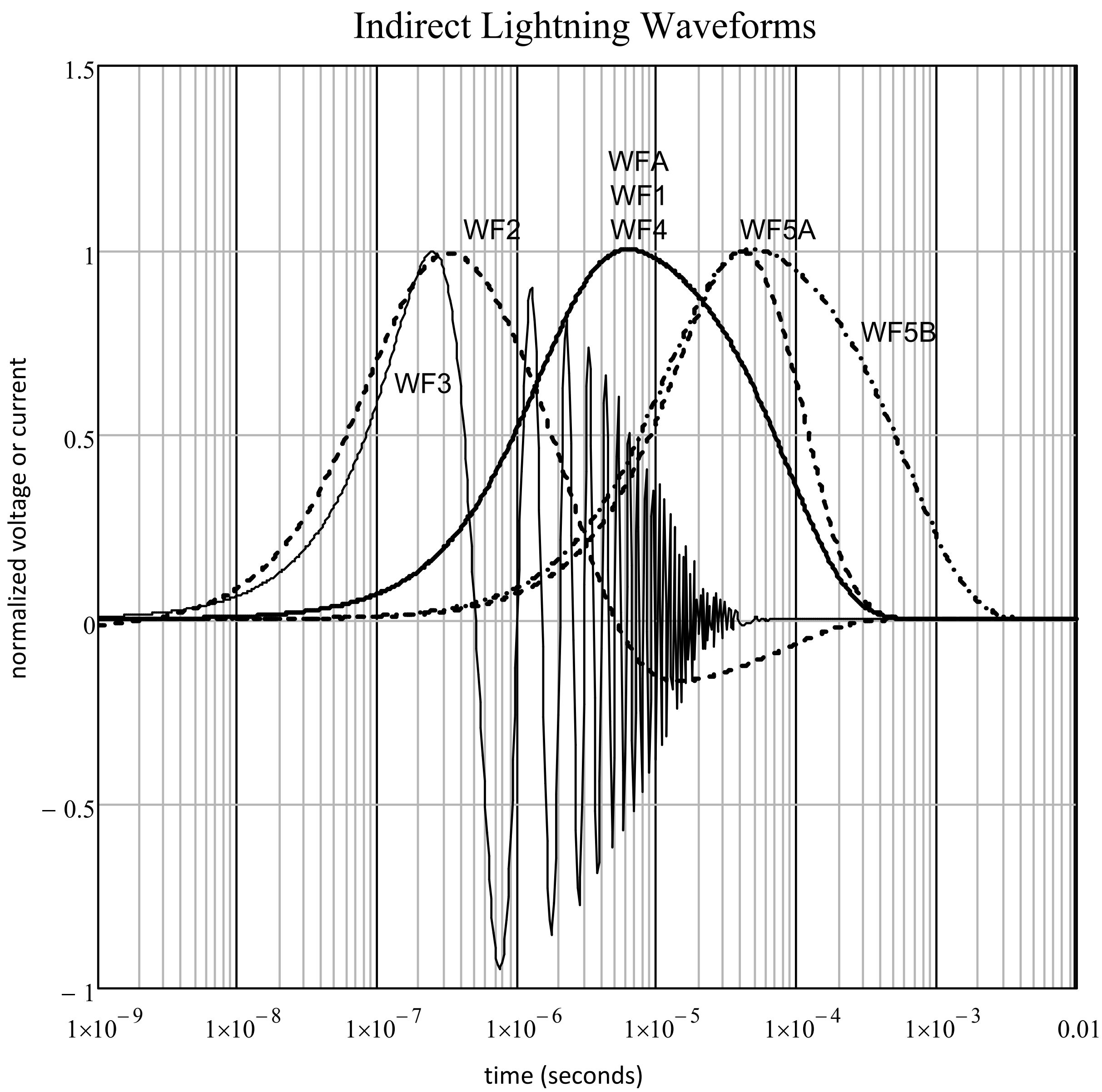

Figure 1. Indirect Lightning Waveforms, WF1 & 4, WF2, WF3, WF5A, & WF5B[6]

The specific formulas for the above waveforms are given, below, in Table 1. Detailed physics and math derivations are in Sections 2.1.1 and 2.1.2 of IN617.

Waveform 5A is a product of system level ground-tests on composite aircraft with well defined current return paths in proximity to the composite system under test.[2] That creates an external inductance which slows the rise time of the induced cable currents in composite airframes. In-flight, there is no current return path, therefore the inductance is the internal inductance of the airframe and it conductors that is roughly two orders of magnitude less than the external inductance present in the ground tests.[2,22] The induced cable currents in-flight are then WF4, the same as the Component A lightning strike criterion.[2,22]

Table 1. Standardized Indirect Lightning Waveforms[1, 6]

Extracted from Table 9 in SAE ARP5412A

- Component A and Waveforms 1 and 4 are the same 1.5µs/88µs double exponential with a x1.094 multiplier, i.e. $I_A(t) = 200kA \cdot 1.094 \cdot (e^{-t/88\mu s} - e^{-t/1.5\mu s})$ peaks at 200kA.
- Waveform 2 is the derivative of Waveform 1 (and A and 4) with a x1.00 multiplier.
- Waveform 3 is a damped sinusoid waveform at 1 and 10MHZ with a damping Q-value of 9-37[Q] with a x1.059 multiplier.
- Waveform 5 consists of two waveforms:

  Waveform 5A is a 23µs/79µs double exponential with a x2.334 multiplier.

  Waveform 5B is a 12.5µs/631µs double exponential with a x1.104 multiplier.

Note: WF2 doesn't graph like the derivative definition, above, but does graph nicely as the following Equation (1) depicted in Figure 1, above, and Figure 2, below, from reference 1 and 6:

(1) $$\boldsymbol{WF2(t) \cong -A \cdot e^{-t/100ns} + B \cdot e^{-t/1.5\mu s} - C \cdot e^{-t/88\mu s}}.$$

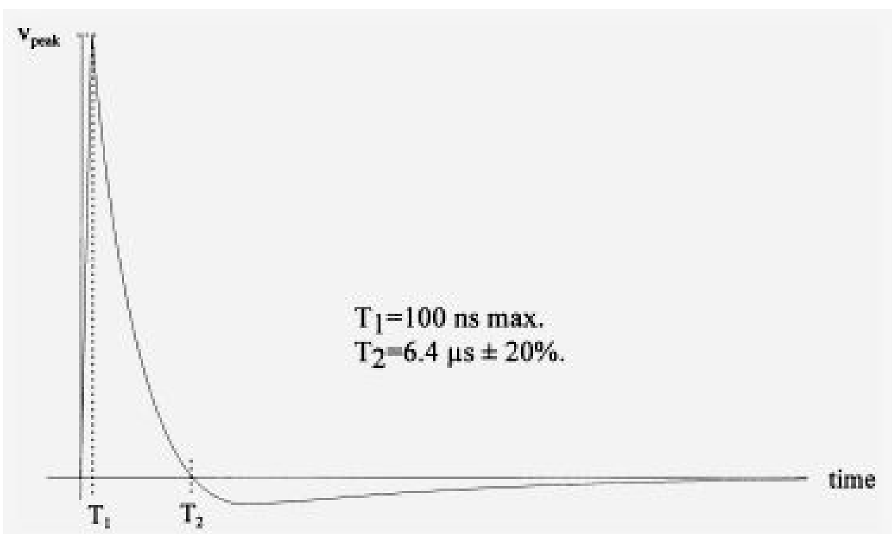

Figure 2. Graphical Representation of WF2[1,6]

2. Organization

This note addresses specific test methods in DO-160F however, in order to develop the rationale, we will treat system level effects first followed by coupling to cables and then to wires and pins. In contrast, DO-160F starts with pin injection tests.

3. Review of the I·R-Voltage Drop in Composite-Skinned Systems, Coupling to Cables, Copper Shielding Performance, and Ground Injection Testing

3.1. I·R-Drop Model. Until a recent analysis,[2,22] the unique physics of the voltage I·R-drop phenomenon in composite airframes was the simultaneous (a) 1.5μs/88μs double exponential Waveform 4 (WF4) external voltage, V_{ext}, along the composite skin and parallel cable shields and (b) the 13μs/88μs double exponential WF5A current, I_{ext}, on the shields.[6] Those parameters have been determined from ground tests with a well defined current return path in close vicinity to the system creating external inductance. In-flight, with no return path, the internal inductance predominates and WF4 replaces WF5A.[2] A simple circuit model, Figure 3, shows the basic parameters governing this phenomenon, the composite skin with resistance, R_{skin}, and inductance, L_{skin}, and the cable braid with resistance, R_{cable}, and inductance, L_{cable}.[2,3,5] These parameters plus the transient current source nature of lightning force a different approach to lightning system analysis, design, and test. It is assumed that exterior and interior joints are electrically bonded as well as possible or, as is the case with large strikes, the lightning "tracks" through the joints thereby lowering their electrical resistance.

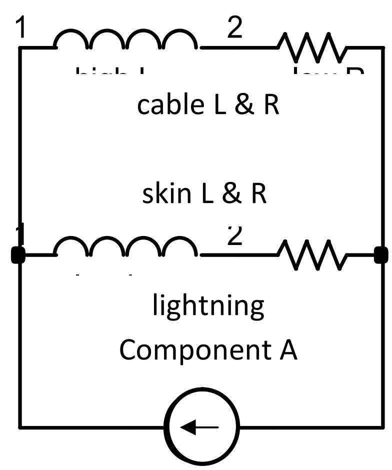

Figure 3. CFC Skin & Cable Shield External Circuit Model[2,3,5]

The division of current in ground test is such that the early time higher frequency current propagates on the exterior composite skin and the late time lower frequency current propagates on the interior cable(s) as illustrated in Figure 4.a, below. The dominant RL time constant is the total loop time constant, $\tau_{loop} = \frac{L_{skin}+L_{ext}}{R_{skin}+R_{ext}}$, because of the parallel circuit and the current source.[2,3,5] In the example used herein, the ground-test loop time constant was 29μs, the in-flight loop constant, τ_d. The in-flight the current waveforms are WF4 in Figure 4.b.

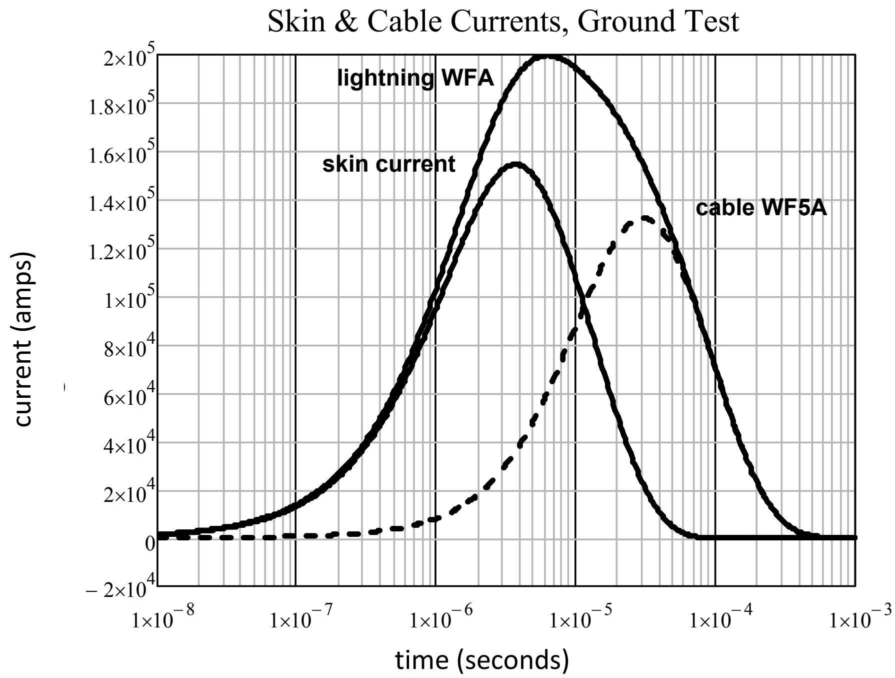

Figure 4.a. Division of Lightning Current between Skin & Cable in System Level Ground-Tests[2,3,5]

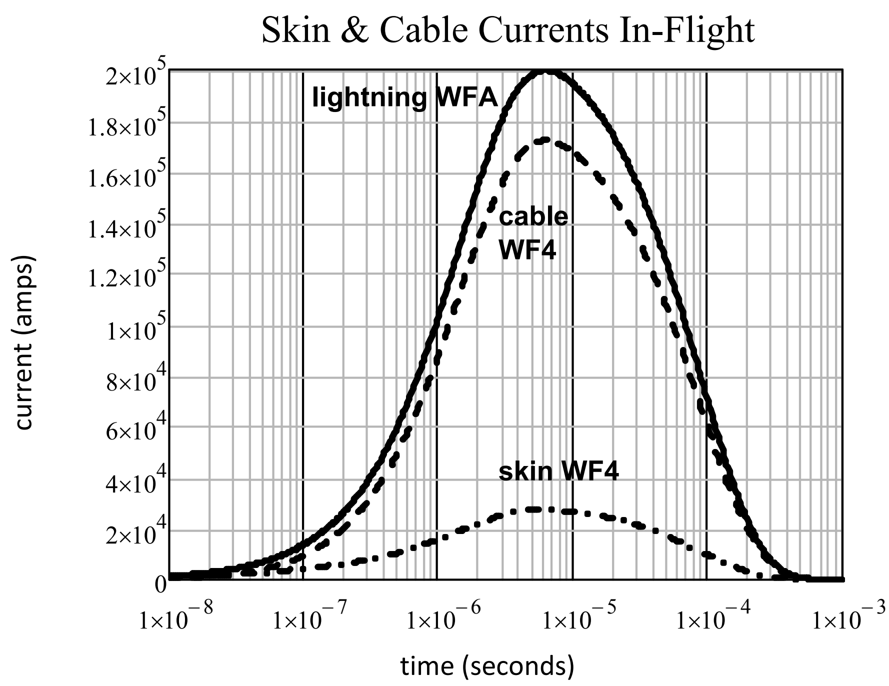

Figure 4.b. Division of Lightning Current between Skin & Cable In-Flight[2,3]

Figures 5 and 6 are the official[6] definitions of Waveforms 4 and 5A and obviously not to scale.

In-flight systems will not experience WF5A therefore it will be set aside in the following except for comparison to WF4. WF5B comes from diffusion of Component A current through aluminum skin. It usually is so low in amplitude, it is omitted from the standards.

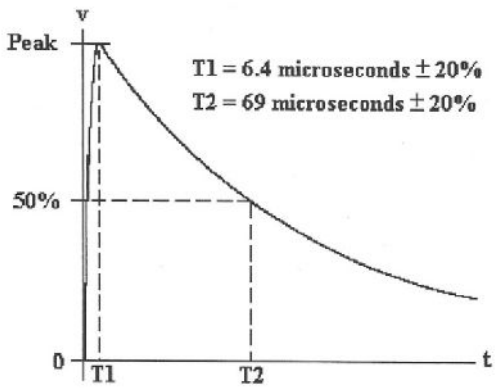

Figure 5[6]. Waveform 4

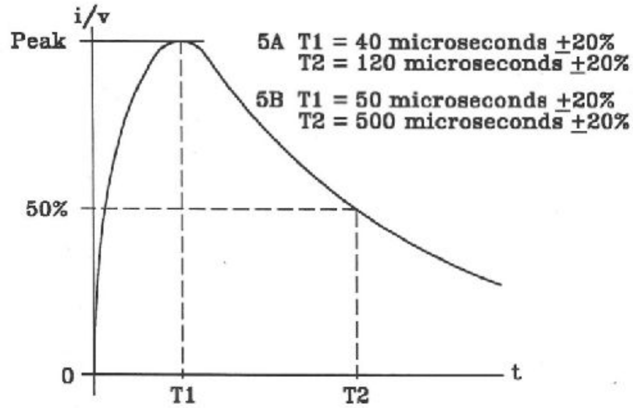

Figure 6[6]. Waveforms 5A & 5B

From reference 6, we define WF5A and WF4 as

(2) $\boldsymbol{V_{WF5A}(t) \equiv V_{5A} \cdot 2.334 \cdot \left(e^{-t/79\mu s} - e^{-t/23\mu s}\right)}$, time-to-peak = 40μs,

and

(3) $\boldsymbol{V_{WF4}(t) \equiv V_4 \cdot 1.094 \cdot \left(e^{-t/88\mu s} - e^{-t/1.5\mu s}\right)}$, time=to-peak = 6.4μs,

where the time-to-peak is the same as ref. 1 & 6 standards in Figures 5 and 6, above. The multipliers are necessary to obtain the correct peak values for the double exponential waveforms.

These are simplifications of the model formulas which are the sum of four different exponentials.

The induced voltage across the airframe and the current induced in the cables running parallel to the lightning current are as follows in the frequency domain:[2,3,5]

(4) $\boldsymbol{V}_{system} = \boldsymbol{I}_A \cdot \frac{Z_{skin} \cdot Z_{ext}}{Z_{skin} + Z_{ext}}$, proportional to the cable length.

The current in the cable shield is as follows:

(5) $\boldsymbol{I}_{cable} = \frac{V_{system}}{Z_{ext}} = \boldsymbol{I}_A \cdot \frac{Z_{skin}}{Z_{skin} + Z_{ext}}$, independent of the cable length.

The allocations of WF4 and WF5A (now WF4) in reference 6 do not reflect the dependence upon the distance between boxes, the induced voltage proportional to the distance, shielded or unshielded, and the independence of the induced WF5 (WF4) current upon the distance, i.e. as the voltage decreases with decreasing separation distance, the current does not.

The standard Component A of the lightning groundstroke used in lightning analyses is as follows in terms of the Laplace frequency variable, s:[6,24]

(6) $I_A(s) = I_A \cdot \left(\frac{1}{s+a} - \frac{1}{s+b}\right)$, where the parameters are defined as follows:

(7) $I_A \equiv 218{,}000$ amps,

(8) $a \equiv 1/88\mu s$, and

(9) $b \equiv 1/1.5\mu s$.

The cable shield internal impedance from both the external and internal surfaces is approximated as follows in terms of the Laplace frequency variable, s:[5,7,24]

(10) $Z_{int/ext}(s) \cong R_{dc} \cdot \frac{\sqrt{s\cdot\tau_d}}{\tanh\sqrt{s\cdot\tau_d}}$.

(11) $\tau_d \equiv \sigma \cdot \mu \cdot t^2$, the shield diffusion time through a thickness, *t*.

The diffusion part of the resistance is usually modeled simply as a DC plus an AC resistance A complete description of this term is never shown, therefore, out of curiosity, we show the real, imaginary, absolute amplitude, and phase of this extraordinary internal impedance term in Figure 7, below, for a 1" 36AWG overbraid. The internal inductance when $\omega \cdot \tau_d \leq 1$ is

(12) $L'_{int} = \frac{\mu_0}{4\cdot\pi} \cdot \frac{t}{r}$ H/m

and when $\omega \cdot \tau_d > 1$ is

(13) $L'_{int} = \frac{\mu_0}{4\cdot\pi} \cdot \frac{\delta}{r}$, H/m, where

(14) $\delta = \sqrt{1/\pi \cdot f \cdot \sigma \cdot \mu}$ is the skin depth.

The latter high frequency term has little use in lightning analyses.

The example composite airframe skin modeled herein has *l* = 10m, *R* = 1m, *t* = 2mm, and $\sigma = 10^4$ S/m. This produces a resistance of 80mΩ an external inductance of 524nH, and an internal inductance of 2nH. A composite general aviation business sized jet can have nose-to-tail as much as 50mΩ while a 787 sized aircraft can have as much as 120mΩ. Add a copper mesh groundplane nose-to-tail, wall-to-wall, and the resistances can drop to 15mΩ and 25mΩ, respectively, along with the induced voltage and current. The example cable is a 36AWG wire braid with length, *l* = 10m, radius, *r* = ½" = 1.27cm, thickness, $t = 8\cdot10^{-5}$mm, and conductivity, $\sigma = 5.8\cdot10^7$S/m. This produces a resistance of 127mΩ, an external inductance of 12µH, and an internal inductance of 25nH.

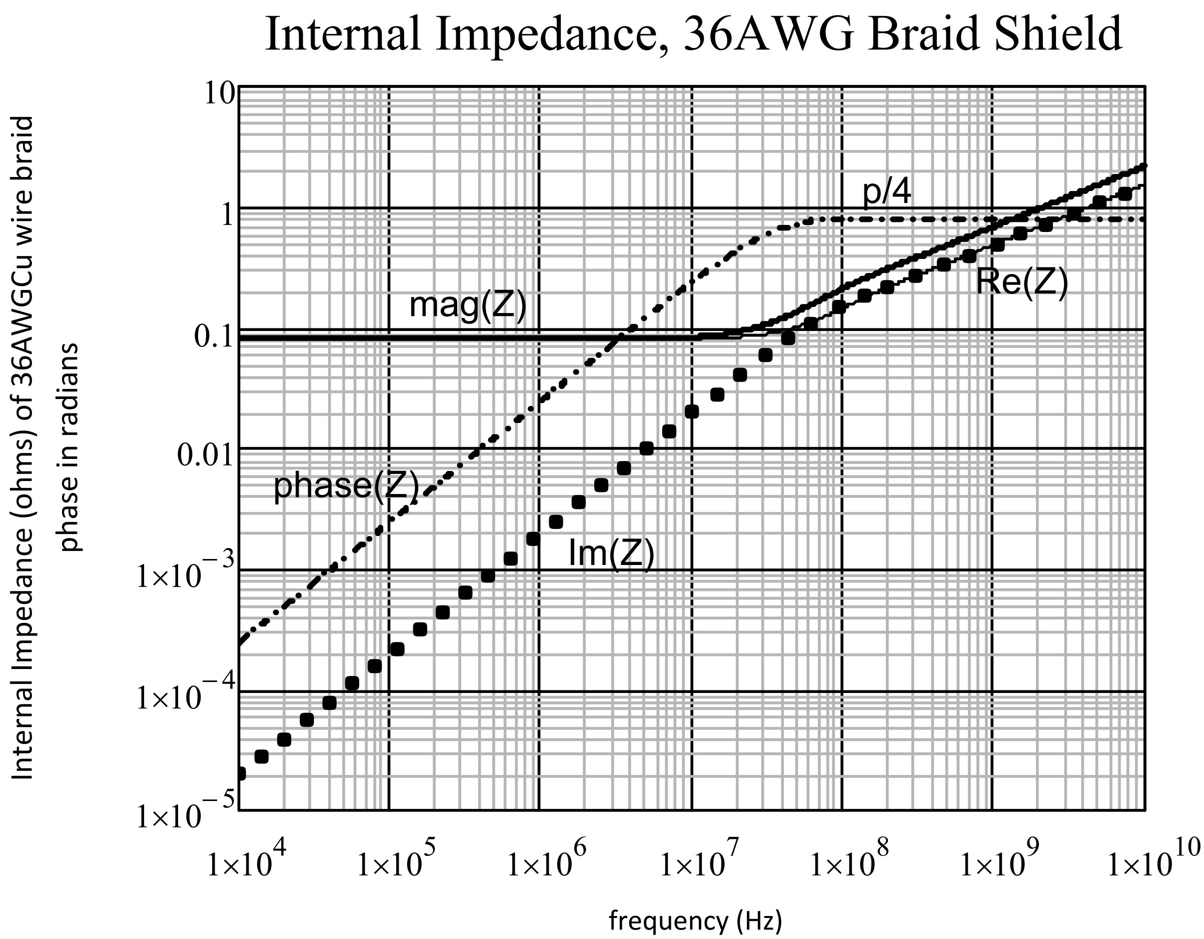

Figure 7. Internal Impedance of a 36AWG Wire Braid Coaxial Shield[7]

3.2 Cable Shield Model. The voltage induced across the inner surface of the coaxial cable shield and in series in the shielded wires is determined by the transfer impedance, Z_T[5,7,13], where

(15) $$Z_T \cong R_{dc} \cdot \frac{\sqrt{s \cdot \tau_d}}{\sinh \sqrt{s \cdot \tau_d}} + s \cdot L_T,$$ where

R_{dc} is the DC resistance of the coaxial cable shield, approximated as follows:[3,5,13]

(16) $$R'_{dc} \cong 1/2 \cdot \pi \cdot r \cdot t \cdot \sigma \cdot K,$$ where

r is the shield radius,

t is the shield thickness, $t << r$,

σ is the shield conductivity,

K is the shield optical coverage, nominally 85%-90%,

τ_d is the shield diffusion time (11), and

μ is the shield permeability.

The transfer inductance, L_T, varies from 1pH/m (a tightly braided shield characteristic of some plated composite fiber braids) to 1nH/m (a looser braided shield characteristic of some wire overbraid cable shields[20]). The transfer inductance will not play a role until we discuss inductively coupled lightning transients later. The low frequency induced lightning then appears as a ground potential, I·R-drop, in the shield, and the high frequency appears as a voltage drop in the shielded wires, Figure 8, below

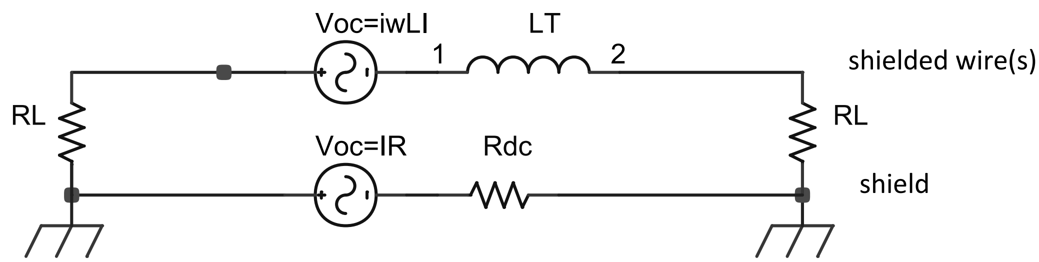

Figure 8. Sources of Lightning and EMI induced through a Cable Shield Z_T

(1) Ground Potential Difference in the Shield, $V_{oc} = I_{shield} \cdot R_{dc}$

(2) Inductive Coupling to Shielded Wiring, $V_{oc} = i\omega \cdot I_{shield} \cdot L_T$

The complete description of the real and imaginary parts of the transfer impedance is never shown, therefore, without comment, we show the complete term in Figure 9. The phase is divided by 50 to keep it on the graph, below. The low frequency approximation is as follows:

(17) $$Z_T(f) \cong R_{dc} \cdot e^{-\sqrt{\pi \cdot f \cdot \tau_d}} \cdot \left(\cos\sqrt{\pi \cdot f \cdot \tau_d} - i \cdot \sin\sqrt{\pi \cdot f \cdot \tau_d}\right).$$ [7]

Schelkunoff discusses this phenomenon in some detail.[7]

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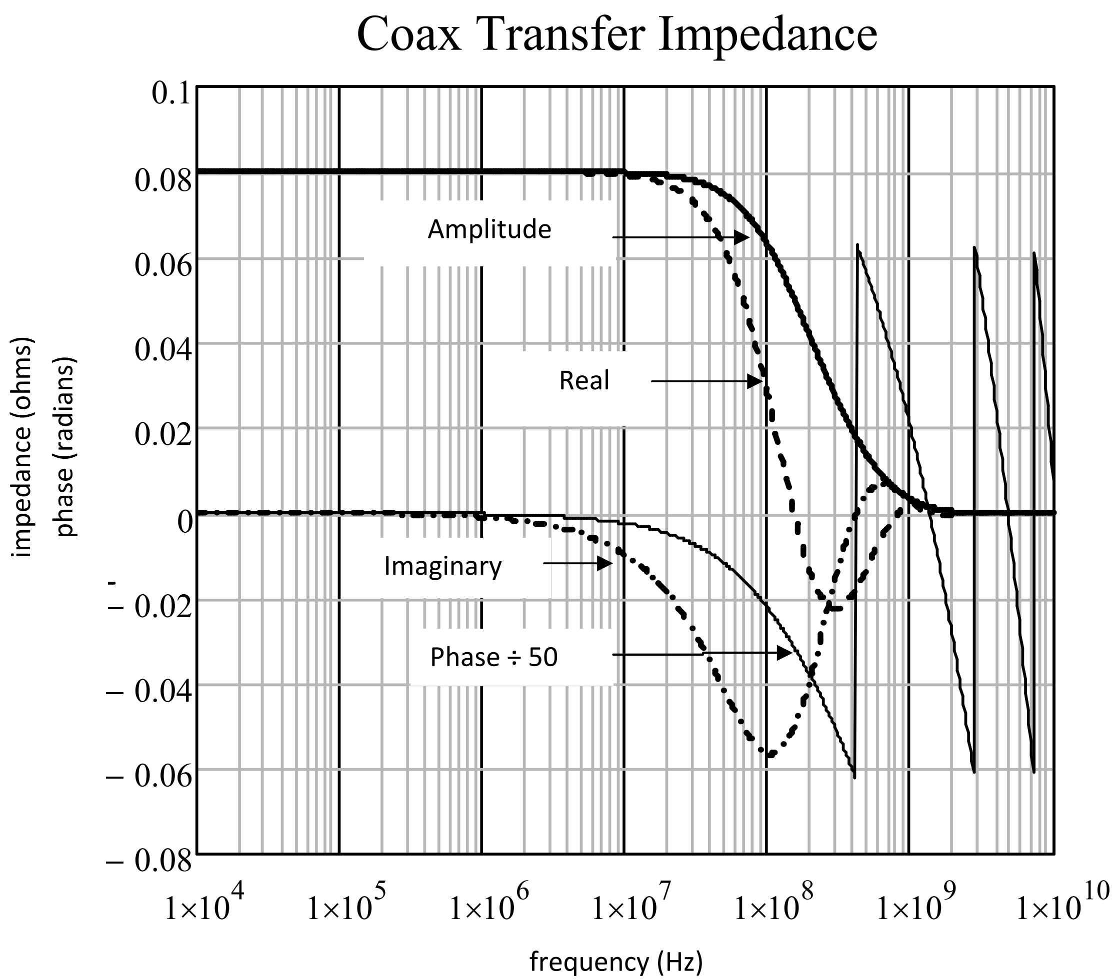


Figure 9. Graph of Magnitude, Real, Imaginary, & Phase of the Diffusion Approximation of Z_T[7]

A simple test circuit model including the cable shield transfer impedance is shown in Figure 10, below.[5] The cable shield internal impedance term is approximately, $Z_{int}(\omega) \cong R_{dc} \cdot \frac{\sqrt{i\omega \cdot \tau_d}}{\tanh \sqrt{i\omega \cdot \tau_d}}$.[7] The transfer impedance is approximately, $Z_T = R_{dc} \cdot \frac{\sqrt{i\omega \cdot \tau_d}}{\sinh \sqrt{i\omega \cdot \tau_d}}$.[7] This note approximates the transfer impedance at low frequencies as

(18) $Z_T \cong R_{dc}/(1 + i\omega \cdot \tau_d)$,[13, 5]

allowing inverse Laplace transforms from tables and capturing the main point of the effect of the diffusion time, τ_d, on the internal rise and decay times. The resulting errors in the higher frequencies have little effect on these low frequency phenomena.

For copper braid shields with thicknesses ranging from 1.5mil ($3.8 \cdot 10^{-5}$m) to 36AWG ($8 \cdot 10^{-5}$m), the shield diffusion times range from 105ns to 1.18µs, therefore, the diffusion will have small effect on the internal voltage rise time, meaning that the internal voltage waveform, V_T, will be close to the in-flight WF4 cable current. See Figure 11, below.

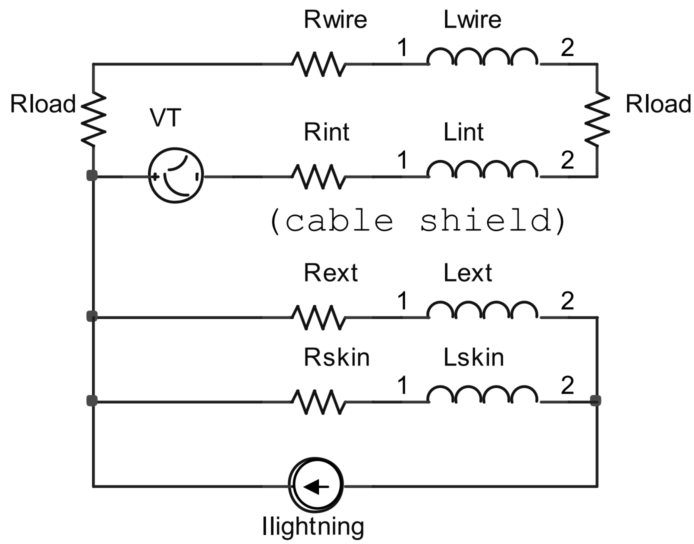


Figure 10. System Circuit Model with Cable Shield[5]

The voltage, V_T induced in-flight along the inner surface of the shield due to the current, I_{shld}, on the shield and in the shielded wiring is as follows in the frequency domain:

(19) $$\boldsymbol{V_T = I_{shld} \cdot Z_T = V_{ext} \cdot \frac{Z_T}{Z_{ext}} = I_A \cdot \frac{Z_{skin} \cdot Z_T}{Z_{skin} + Z_{ext}}}, \text{ or}$$

(20) $$\boldsymbol{V_T(s) \cong I_A \cdot \frac{L_{skin} \cdot R_{dc}}{L_{skin} + L_{ext}} \cdot \left(\frac{1}{s+a} - \frac{1}{s+b}\right) \cdot \frac{s+a_{skin}}{s+\gamma_{loop}} \cdot \frac{1}{1+s \cdot \tau_d}}, \text{ where}$$

(21) $$\boldsymbol{\gamma_{loop} = 2 \cdot \pi \cdot \tau_{loop}^{-1} = \frac{R_{skin} + R_{ext}}{L_{skin} + L_{ext}}}.$$

The difference between Z_{ext} (Figure 10) in the composite system as compared to Z_{ext} (Figure 13) in the bench tests without the composite is the reason why the bench tests simulate the system so poorly with the test cables shielded.

3.3 Induced Voltage inside Cable Shields. The I·R-drop experienced by box electronics is in the interconnecting shields because the boxes' thickness is too large for it to diffuse through the box walls. The induced voltage, V_T, along the inside of a10m long 1" diameter shield for four different copper shield thicknesses is shown in Figure 11 (in-flight), below. The voltage peak along the exterior in this example is about 12-13kV. The current in the shields is over 100kA from Figure 4.b. The "flat braid" is thin 1.5mil copper strips braided around wires like wire braids for less weight, OK for higher frequency EMI effects but a problem for lower frequency lightning shielding. The detailed shield braid parameters are tabulated below in Table 2.

Table 2. Cable Shield and CFC Parameters Governing the Shield Effectiveness

shield type	braid size & type	shield thickness t(m)	cable diam. (inches)	diffusion time τ_d	DC resistance R_{dc} (Ω/m)	f & $t = 1/2\cdot\pi\cdot f$ where $R_{dc}=R_{ac}$
Aracon[21,22,23]	Ni, Cu, Ag plated Kevlar[22] braid	$1.27\cdot10^{-6}$	¼”	35ns	223mΩ/m	100MHz 1.6ns
	Ni, Cu, Ag plated Kevlar[22] braid	$1.27\cdot10^{-6}$	1”	35ns	56mΩ/m	100MHz 1.6ns
Copper foil braid	1.5 mil flat Cu foil braid	$3.8\cdot10^{-5}$	¼”	105ns	36mΩ/m	3MHz 53ns
Copper wire braid	40AWG Cu wire braid	$8\cdot10^{-5}$	¼”	467ns	17mΩ/m	682kHz 233ns
	38AWG Cu wire braid	10^{-4}	1”	729ns	2.2mΩ/m	437kHz 364ns
	36AWG Cu wire braid	$1.27\cdot10^{-4}$	1”	1.18µs	1.7mΩ/m	318kHz 500ns
	34AWG Cu wire braid	$1.6\cdot10^{-4}$	1”	1.87µs	1.4mΩ/m	170kHz 935ns
	30AWG Cu wire braid	$2.54\cdot10^{-4}$	1”	4.71µs	882µΩ/m	67kHz 2.4µs
	20AWG Cu wire braid	$8.1\cdot10^{-4}$	1”	47.8µs	267µΩ/m	6.6kHz 24µs
Copper wire braid over mumetal foil	2 mil µ-foil 38AWG Cu OVB	$7.6\cdot10^{-5}$ mumetal foil	¼”	421ms mumetal foil	13mΩ/m Cu braid	1.9Hz 437kHz

<u>One purpose of this note is to define the bench test simulation in terms of the induced voltage, not the injected voltage or current</u>. The difference in testing (and analyzing) with broadband transients versus CW signals constitutes the underlying difference between the recommendations in this note and the preferred methods in DO-160.

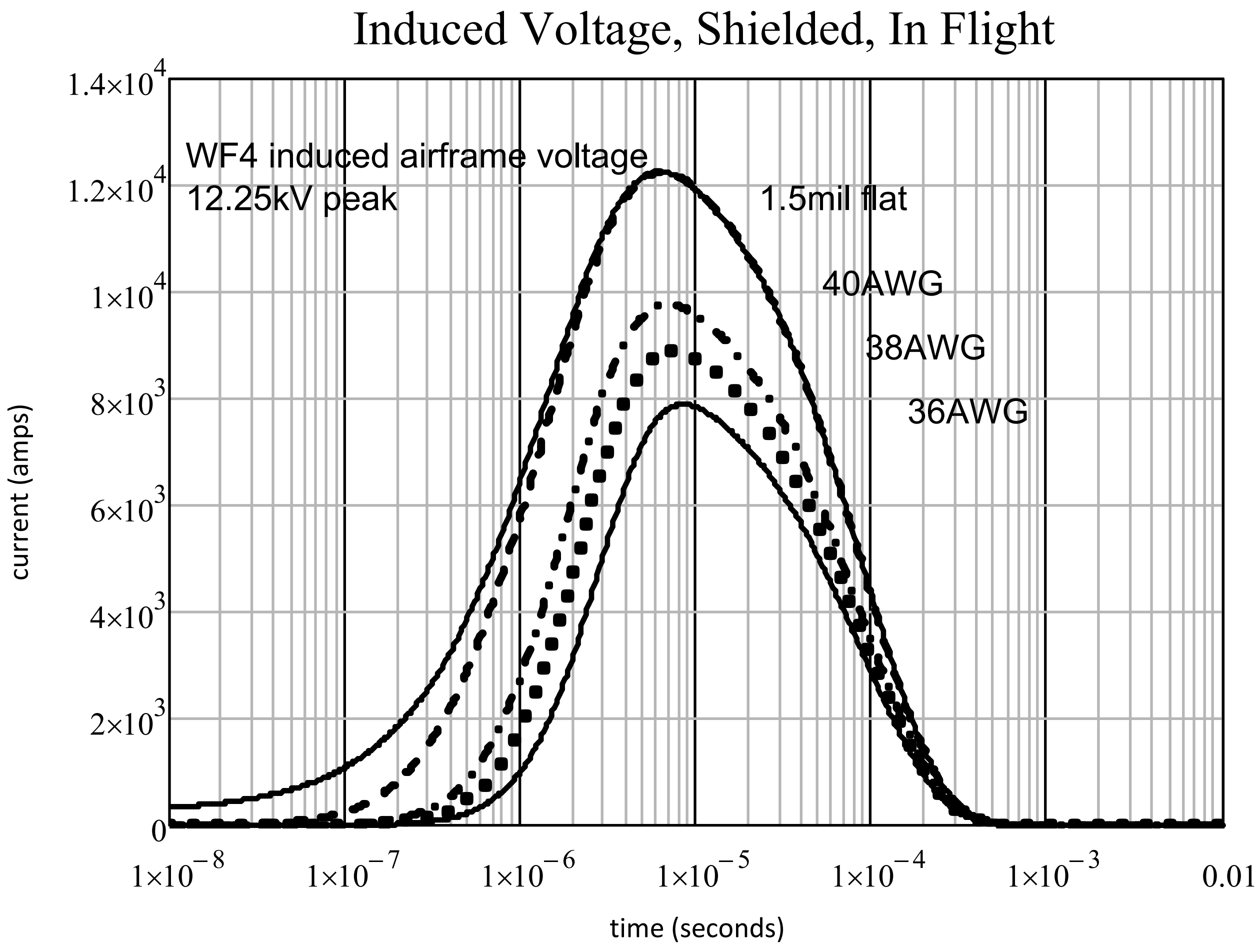


Figure 11. Induced In-Flight Voltage, V_T, with Different Thicknesses of Copper Shield[2,5]

Connectors' and backshells' transfer impedances (2.5mΩ-10mΩ, total) will push the lower peak voltages up closer together. The in-flight rise times are relatively independent of cable resistance due to its inclusion in the loop time constant. All of the in-flight induced voltage waveforms through cable shields are close to WF4, a handy result that we will use later in recommendations about box-level certification testing.

3.4. DO-160F Cable Bundle Tests, Section 22.5.2. This lead off section summarizes the general methods and tacit assumptions of the box level testing.[1] We will quote or paraphrase some of the cogent guidelines (• bullets) with comments (*italics*).

• Cable bundle testing is a technique where transients are applied by cable induction or ground injection.

This means that both ground injection and cable induction test methods are intended to be cable injection ignoring the effects of the ground potential in the chassis ground between boxes.

• This test requirement is satisfied by applying the specific waveforms and limits to interconnecting cable bundle(s) individually or simultaneously.

This more specifically describes the tests as cable injection, again ignoring ground potential effects. As will be shown below, at lower frequencies, the induced voltage along the inner shield surfaces is a ground potential difference and not an inductive coupling to the shielded wires through the shields' transfer inductance even when the source on the outside of the shield is inductively coupled.

• Normally cable bundle tests are done with all shields that are present in the bundle connected at both ends. If the shield current limits cannot be reached by the available test equipment, it is allowable to test with shields disconnected and pulse the core wires directly.

This note points out below that in the ground injection bench tests (without an appropriate composite connection between boxes), the voltage induced within the shielded circuitry can never be close enough to that induced in the system for certification purposes. It goes on further to state that the only practical and accurate way to perform ground injection tests is with the shields disconnected (and with a waveform already well defined).

• Cables with shields needed for functionality during the tests (e.g. data busses, coaxes) shall be maintained and core wires pulsed through a breakout box or tested separately as specified by the system installer. In either case, the relationship between the shield current and core wire transient level must be determined by transfer impedance assessment.

This one is the most problematical. Driving the shield produces poor results. Disconnecting the shield destroys functionality, impedance control, etc. Referring to the transfer impedance will always be misconstrued to mean the CW transfer impedance without regard to the broadband nature of the source transients, perhaps the underlying conflict that gives this note a purpose. Obviously, compromise is needed. Some companies have allegedly developed induction coupling test techniques that are purported to simulate the voltage and/or current needed in the ground injection testing[16]. Injecting on the center wire misses the point of ground injection. See Figure 21, below.

• For cable bundle tests with inductively coupled damped sinusoids, 1MHz and 10MHz to be used.

Only the Antonov 225 aircraft and the ORION manned launch vehicle have external resonances approaching 1MHz. All other manned aerospace vehicles' resonances range up to 20MHz and cable resonances range up to 50MHz. Therefore, it is impossible to relate a 1MHz and 10MHz test to allocated lightning limits and system level test results. It is not too expensive to have pulser modules tailored with component substitutions to specific system sizes and frequencies.

• Waveform 5A (the unique ground test low frequency current waveform induced on cable shields within a composite airframe due to the I·R voltage drop across the lightning path through the airframe) may be defined as a voltage waveform. Although Waveform 5A is defined as a current waveform, the wave shape may also be used for a voltage waveform when the test method specifies lifting the wire shields (*AKA "shield disconnect method"*) for direct core wire pulsing. Waveform 5A may then be defined as a voltage test level.

Other work[2,3] has redefined the in-flight cable current as WF4 instead of WF5A. This test alternative is what this note recommends as the standard, not an alternative, because the simulation fidelity of the voltage induced within the shielded circuitry is so poor with the shields connected as will be explained below.

• Waveform 5 should ideally exist on the cable bundle.

Agreed for shielded cables, but it cannot therefore the attempt to do so is fruitless. This again illustrates that the DO-160 test philosophy that ground injection is really cable injection and a carryover from EMI CW methods. WF5A is now redefined as WF4 with the same problem.[2] The IR-drop experienced by box electronics is in the interconnecting shields, however, because the boxes' thickness is too large for it to come through the box walls.

3.5 DO-160F Section 22.5.2.2 Ground Injection Test. DO-160 Ground Injection bench testing shown below in Figures 12.a.[1] Figure 12.b is from SAE ARP5415A, because it more simply shows the intended nature of the test, i.e. applying a current on the cable shield or applying a voltage between the two boxes connected by an unshielded cable(s).[8]

• Equipment external ground terminals, chassis ground wires and power return leads, which are connected to the groundplane locally in accordance with the applicable installation/interface control drawings, must be isolated from the groundplane during this test.

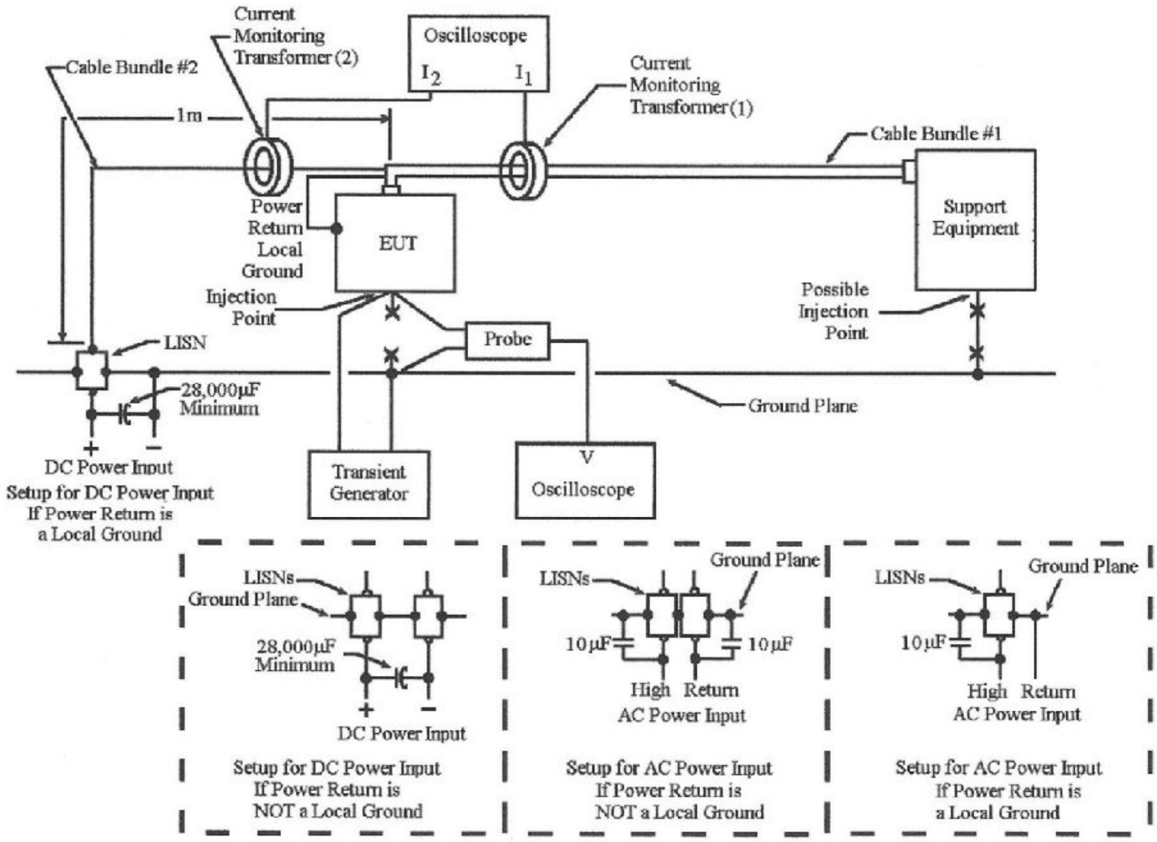
This degrades the fidelity of the box chassis ground so much so as to question usefulness of the ground injection. This exemplifies the fact that it is virtually impossible to perform ground injection of unipolar transients and maintain ground continuity. Recommendations below advocate transformer induction coupling to a continuous ground connection in order to get the box electrical ground to swing both positive and negative as in a system level in-flight I·R voltage drop, albeit with a degraded waveshape.

• The intent of this test is to achieve the applicable test level in each cable bundle.

This is the real intent of the DO-160F ground injection; that is, the test is and is intended to be a cable injection. Recommendations below try to correct this.

• A voltage test is valid when the voltage test level is achieved between the EUT and the groundplane.

This statement can only apply to unshielded cables, not for shielded cables, although the calibrated open circuit voltage is the most desirable test level, not the test voltage as will be explained below.



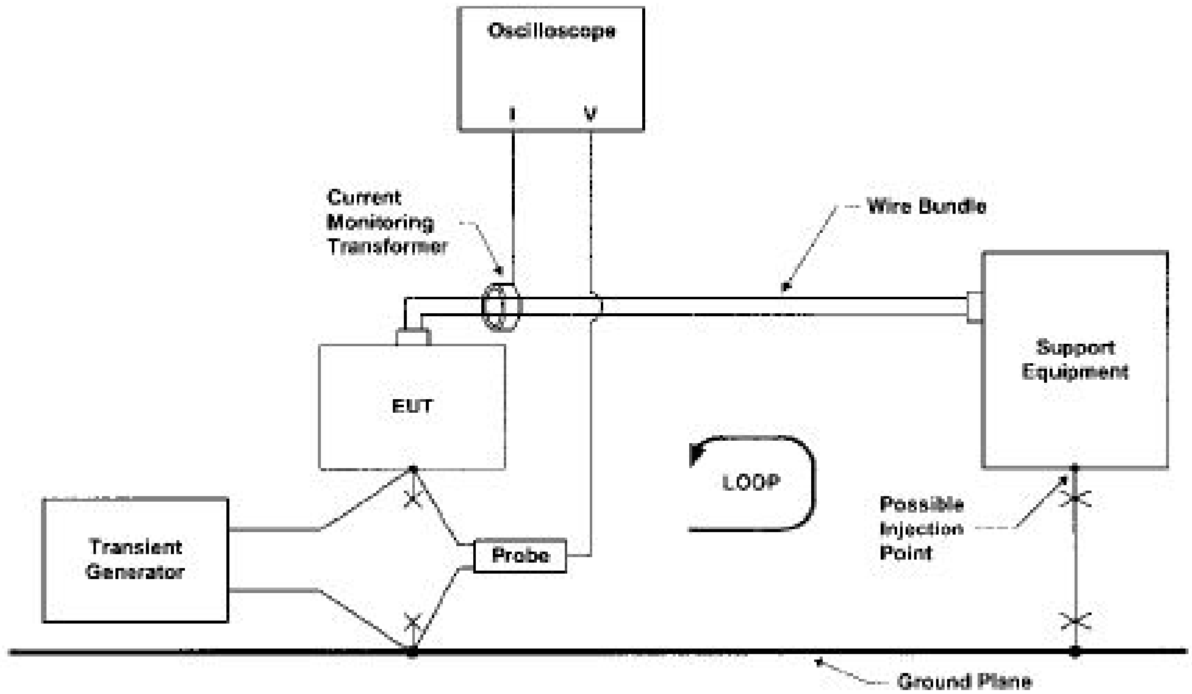
NOTES:
1. Capacitor(s) shall be applied on power inputs to provide a low impedance to ground, as shown.
2. The transient generator output impedance should be low to avoid excessive voltage drop on the power line. The transient generator has to have a low impedance path to allow the power current to flow.
3. A series current-monitoring resistor may be used instead of the current-monitoring transformer.

Figure 12.a. DO-160F Figure 22-19 Ground Injection Cable Test Set Up[1]

The reader should not get too involved with the detailed alternative power connections, above. There are four different power and power return connections depicted:

(1) DC power with the return from the box connected to chassis ground immediately outside the box or to the nearest convenient metallic ground plane designed to do so, a common aircraft wiring practice with primary power in order to save weight,
(2) DC power with the return wired to the power source, a common practice for secondary power,
(3) AC power (usually 400Hz) with the power return wired to the power source, a common practice for secondary power, and
(4) AC power with the power return connected to chassis ground immediately outside the box or to the nearest convenient metallic ground plane designed to do so, a common aircraft wiring practice with primary power in order to save weight.

Also, the idealistic reader should not be overly concerned about the above practice of returning primary power through chassis ground. It works, saves weight, and EMI/EMC, EMP, and lightning protection can be successfully implemented. The large gauge wires in primary power make up the most weight in many wiring subsystems. Shielding constitutes one of the least weights.



NOTE: A series current-monitoring resistor may be used instead of the current-monitoring transformer.

Figure 12.b. SAE ARP5415A Figure 9 Conceptual Ground Injection Test Set Up[8]

• A current test is valid when the current test level is reached on each cable bundle.

This illustrates that the assumption that this is a cable current injection, not a ground injection, and that the amplitude is the only objective. As was shown above, testing with shielded cables with the shields connected degrades the fidelity of the simulation of the induced ground potential voltage in the shielded circuits. Disconnecting the shields allows good simulation of the in-flight induced WF4 voltage in the shielded circuits close enough to what it will be in the system.

The above philosophy and assumptions are why this note was written as it applies to simulating a ground potential in a bench test with cable shields installed. Ground injection pin tests will be addressed similarly below.

3.6. Ground Injection Test Model with Cable Shields, Shields Connected. The equivalent schematic circuit of this test is shown below in Figure 13, below. There is no attempt to simulate the Thevinin equivalent impedance, just the current waveform on the cable shield or the voltage between the box and ground. This concept works for CW injection, not for transient injection where the time constant of the external shield circuit plus the composite skin controls the induced current.

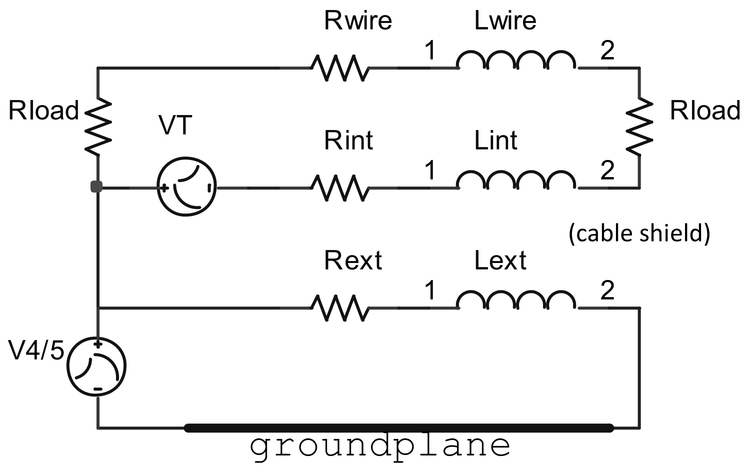


Figure 13. DO-160 Ground Injection Test Circuit Model, Shield Connected

V4/5 Pulser Voltage (WF5A or WF4)

$VT = I_{shld} \cdot Z_T$

In the test set up, the external inductance, L_{ext}, is modeled as a constant 300nH/m (cable height ≈ 2”). With a 1” cable shield resistance, R_{dc}, ranging from 37mΩ/m (1.5mil) to 882μΩ/m (30AWG), the external time constants, $\tau_{ext} = L_{ext}/R_{dc}$, range from 8μs to 340μs unlike the 2-6μs time constant in the system in-flight model, above. The time to peak in the test range from 50μs to100μs, as illustrated below in Figures 14, versus 2μs to 8μs in-flight, Figure 11, above, the better the shield, the worse the simulation. The diffusion times through this set of shields ranges only from 105ns to 1.2μs, too small to cause the increased rise times.

The same model used for Figure 14 is simulated with a WF4 cable shield current injection on a lower resistance TSP and the results are depicted in Figure 15. Again, the rise times are degraded to the point of making the test useless for certification purposes. The TSP has a smaller radius (1/8”) than the overbraid in Figure 14 thereby increasing the radius and decreasing the attenuation.

By comparing Figures 14 and 15 to the system results in Figure 11, simple theory shows that the bench test with shields connected can never simulate the system in-flight results unless a composite groundplane is used and the source current is 200kA (see ref. 5 & Appendix A Figure A.1), a totally impractical method.

Note that the rise times have been decreased from the in-flight case in Figures 14 & 15 by as much as 90μs by the ground-test cable circuit L/R time constant whereas in the in-flight case, Figure 11, the rise times have been decreased by a few μs. The apparent attenuation is due more to the slower rise time than the DC resistance and the shield diffusion constant.

<u>The induced voltage in the bench test in Figure 13 is distorted from that induced in-flight in Figure 10 by as much as 90μs in rise time and as much as 6dB lower peak making bench testing with shields connected a poor simulation of in-flight I·R-drop environments</u>.

Note 3 of DO-160F Figure 22-3, Test and Limit Levels for Cable Bundle Single Stroke Tests, states that “when testing with voltage Waveform 4, the current waveform will be dependent on the cable impedance", but this observation was not followed through to the conclusion, above, that the resulting current waveform and the induced voltage would be distorted from Waveform 4 so much that the simulation was futile. The committee and authors did not have a system level model, Figures 10 and 11, and a test model, Figures 13 and 14, to compare.

Ground injection with shields disconnected is therefore recommended.

■

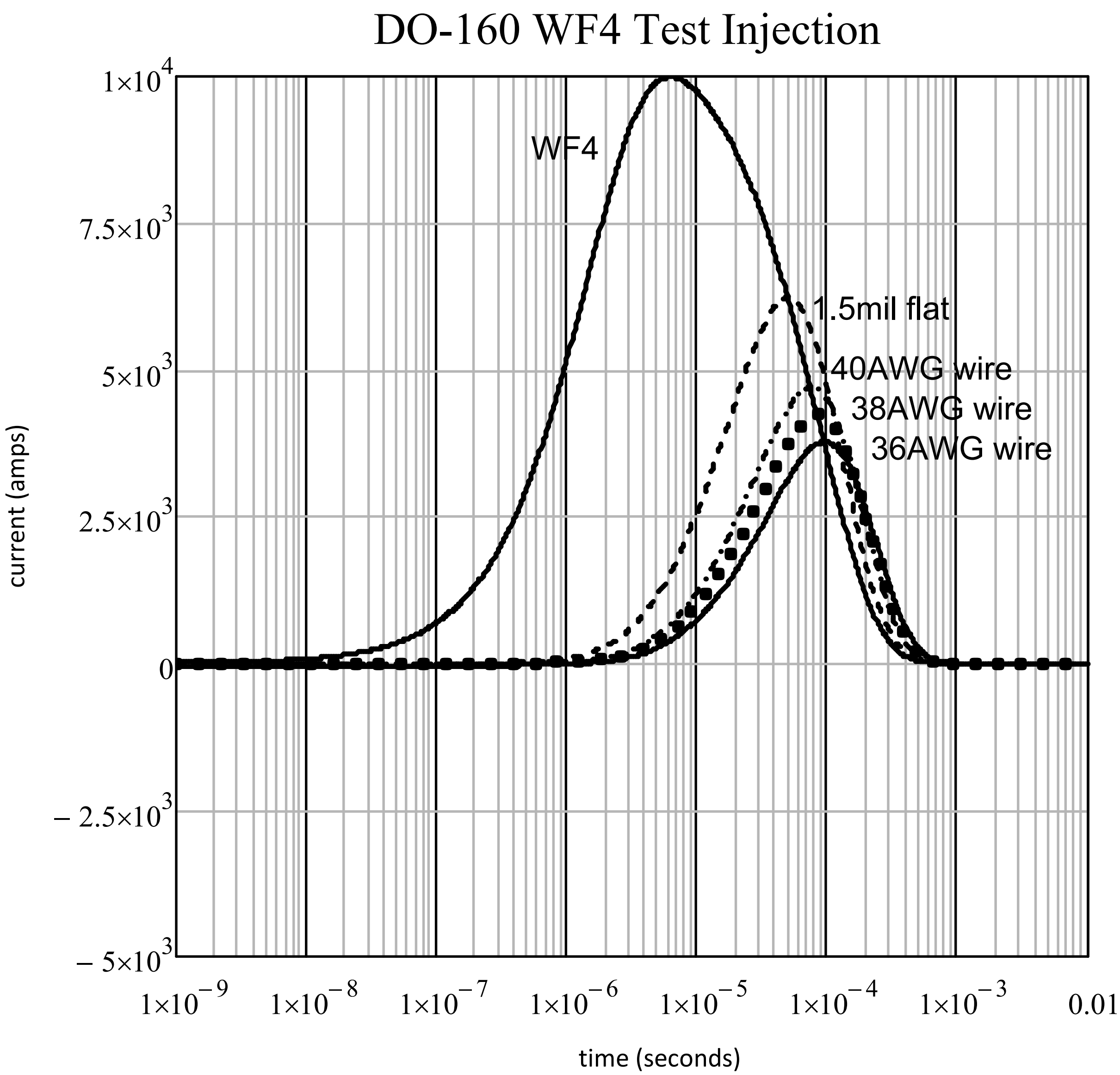


Figure 14. Induced Ground Test Voltage, V_T, with Different Thicknesses of a 1" Copper Shield[2,3]

■

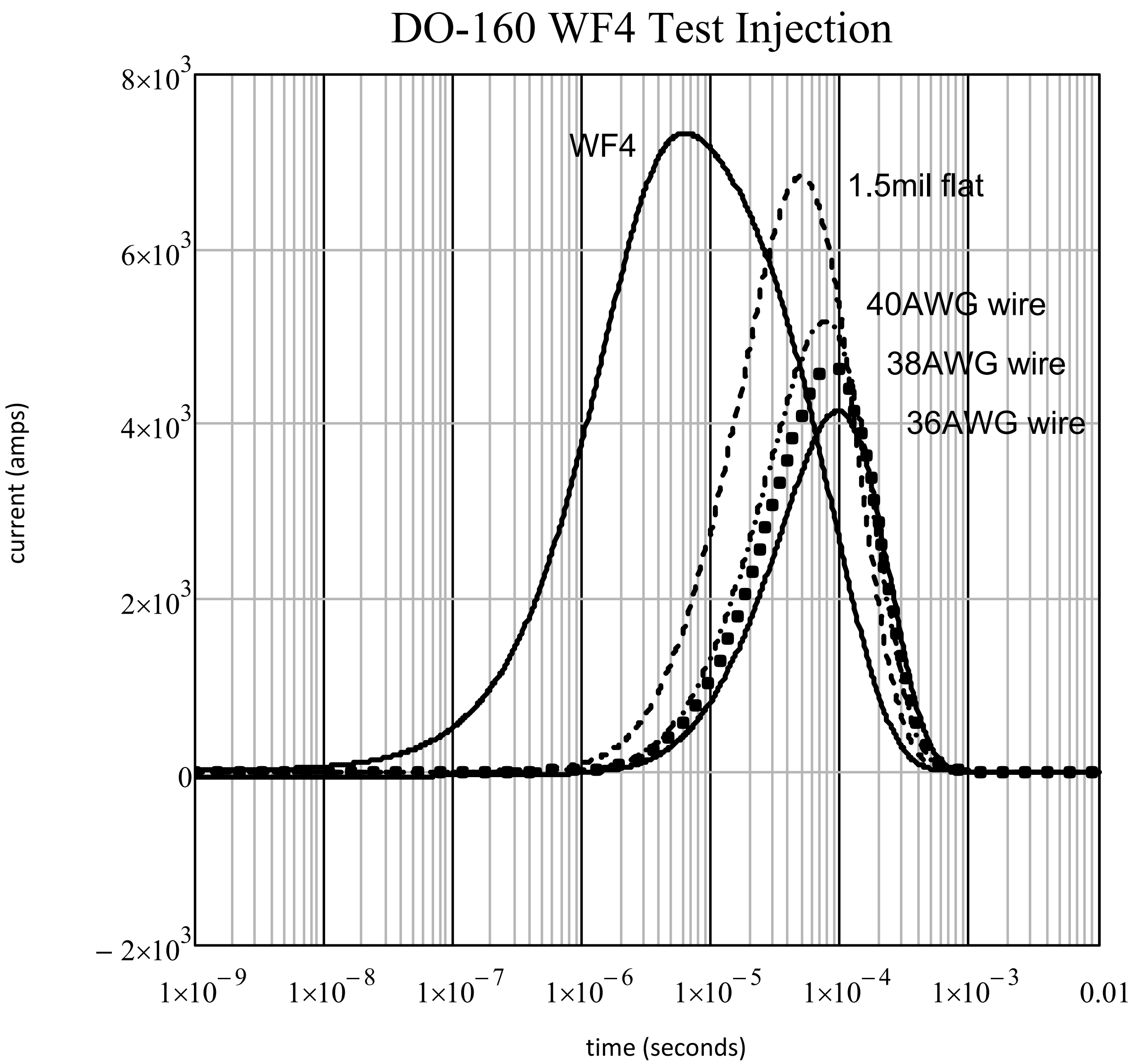


Figure 15. Range of Induced In-Flight WF4 Voltage Waveforms with Different Shield Thicknesses on a ¼" TSP[2,3]

Therefore in the bench ground injection tests it is much easier and more accurate to simulate/inject an in-flight WF4 voltage with the shield-disconnect method, as allowed in RTCA/DO-160F 22.5.2.c & 22.5.2.h (4), i.e. no shields, as illustrated in Figure 16, 18, & 19, below, than to attempt to inject a WF4 current on the shield as in Figures 1.a and 11.b, above.

There is no waveform that can be applied in the DO-160F ground injection test with the cables shielded that would produce the voltages induced in the system. The ground injection test with shielded cables is governed by the external impedance of the cable and its highly variable RL time constant unlike in the system where the induced voltage is governed by the slowly varying loop RL time constant of the parallel composite skin and the interior cables.

3.3 Ground Injection without Cable Shields, "Shield Disconnect" Method Figure 14, below, depicts ground injection with shields disconnected into equivalent common mode loads in two interconnected boxes. See Figure 27 for more detail.

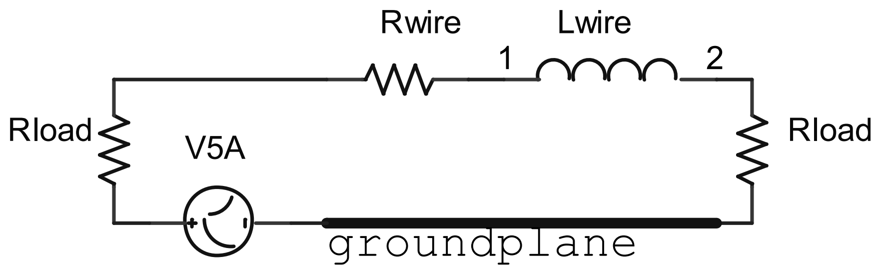


Figure 16. DO-160 "Shield Disconnect" Ground Injection Test Circuit Model

V5A Pulser Voltage (WF5A)

For unshielded operational cables, ground injection of a WF4 voltage is, of course, recommended.

The misapplication of the bench CW test physics and results to the system physics and the bench tests has resulted in (1) erroneous allocated I·R voltage drop lightning in composite airframes' shielded cables, (2) wrong designs of box qual tests, and (3) the subsequent disconnect between system allocations, system test, and box test results. All of these errors add up in an uncontrolled manner. Misapplication of the CW transfer impedance concept for these broadband transients allocates wrong waveforms and amplitudes for system design and likewise to the bench tests.

3.4 Mumetal Shields. IN616 showed that the transfer impedance was about 10μΩ/m for layered copper braid over a mumetal foil cable shield.[5] That means that the connectors and backshells will contribute all of the induced voltage. That also means that a short mumetal shield has no merit. For the 100kA WF4 current in this example and that of IN616, a 5mΩ connector produces a WF4 voltage of 500V, still big but easier to clamp than 5-13kV. The value of 100kA on the cable shield is abnormally large. It is more like 100kA divided by the number of cables and other conductors in the same parallel path, say for example, 10. That results in 50V induced in each shielded cable, a much easier transient to clamp. Include a system groundplane and the induced voltage drops more. Transformer isolation of circuits have 1kV standoff capability therefore such an interface is desirable in these transient environments where high data rates defy use of highly capacitive diode voltage limiters. Even then, it is not clear that capacitive isolation in the interconnecting lines and/or common voltage limiting is sufficient to mitigate susceptibilities to a ground potential between boxes.

The recommended ground injection test for mumetal shields is with shields disconnected using a WF4 voltage waveform because the connectors control the induced voltage. The test limit should be the calibrated open circuit voltage.

3.5 Coaxial Signal Lines. For interfaces with coaxial cable connections where the shield is the signal return, the situation is more complicated. Induction testing through a break out box onto the wire in the cable is the official option as stated in DO-160F Section 22.5.2, above:[1]

• Cables with shields needed for functionality during the tests (e.g. data busses, coaxes) shall be maintained and core wires pulsed through a breakout box or tested separately as specified by the system installer. In either case, the relationship between the shield current and core wire transient level must be determined by transfer impedance assessment.

This statement again demonstrates that the DO-160 philosophy about ground injection is actually cable injection. Pin injection is <u>not</u> ground injection.

If testing proves impossible, analysis supported by engineering tests should be considered for certification. A low level test depicted in Appendix B can be used to characterize the coax cable in realistic environments and the results can be extrapolated.

Coax lines usually carry RF signals therefore the circuits can be adequately protected with high-pass filters with the front component an inductor to ground, Figure 17.a, or, better yet, quarter-wave stubs (a mechanical version of a band-pass filter), Figure 17.b, plus their own band-pass filters therefore ground injection test issues are moot.

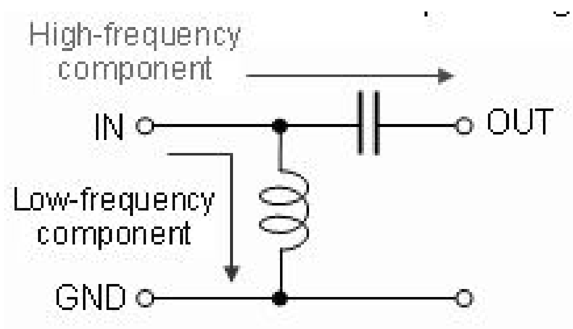


Figure 17.a. High-Pass Filter

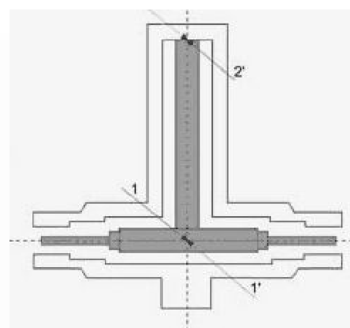


Figure17.b. Quarter-Wave Shorted Coax Stub

3.6. Recommended Ground Injection Alternatives. The following ground injection with cables connected and cable shields disconnected are depicted in Figures 18 and 19, below.. The purpose is to make the EUT "ground" rise above and below zero volts as it would in a system with a lightning I·R-voltage drop between boxes. The lab ground at the STE end of the cable will hold that end as close to zero volts as possible. The STE (special test equipment) may require protection. The test voltage should be the calibrated open circtuit voltage.

Because we cannot hook up a unipolar pulser in the ground connection between the EUT and STE, the alternative is transformer coupled bipolar pulse with over damping as feasible and necessary. We gain continuity of the chassis ground connection, obtain as much of a realistic I·R-drop through the EUT chassis, produce a ± ground potential at the EUT, but lose fidelity of the unipolar waveform.

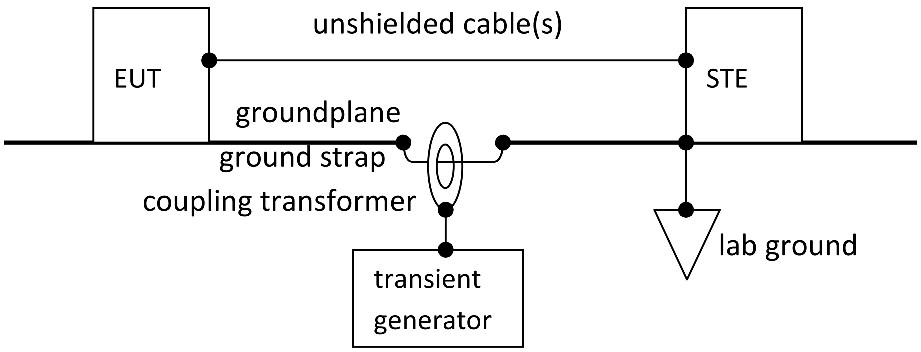


Figure 18. Simple Conceptual Alternative Ground Injection Diagram

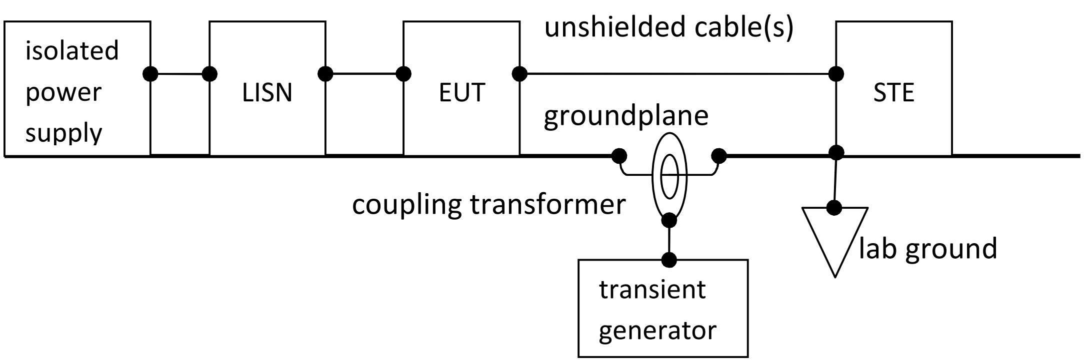


Figure 19. Conceptual Ground Injection Diagram with EUT Power Supply and LISN(s) Ground the EUT Power Return as in the System

One company has developed special injection probes for such testing although their technology and fidelity is not advertised.[18] The blurb on the Thermo Scientific DCI-1 coupler states that it provides coupling to cables for injection testing using Waveforms 1 (recommended), 5A & 5B (acceptable).[18] It sounds like a coupling transformer with waveshaping circuitry.

4. DO-160F Section 22.5.1 Pin Level Ground Injection Test.

From DO-160, pin injection testing is a technique whereby the chosen transient waveform(s) is applied directly to the designated pins of the EUT connector, usually between each pin and case ground.

The ground injection test on pins is problematical, anyway. Therefore clarification required. It may be that the only credible ground injection test is at the box level as depicted in Figures 18 & 19, above, where the entire box circuitry is affected by the ground potential difference between boxes as it is in the system. When systems connect their power returns through chassis or structure as most aircraft do, then pin level ground injection makes sense as long as the ground pin is part of the test circuit.

4.1. Power Pin Ground Injection The DO-160 power pin ground injection test set up is depicted as follows in Figure 20 (EUT ≡ equipment under test). The reason for this test set up is that many aircraft connect their power returns through chassis ground or structure. Unless there is a near short circuit connection through the transient generator output, the power cannot be turned on. This quandary is part of any ground injection of unipolar transients.

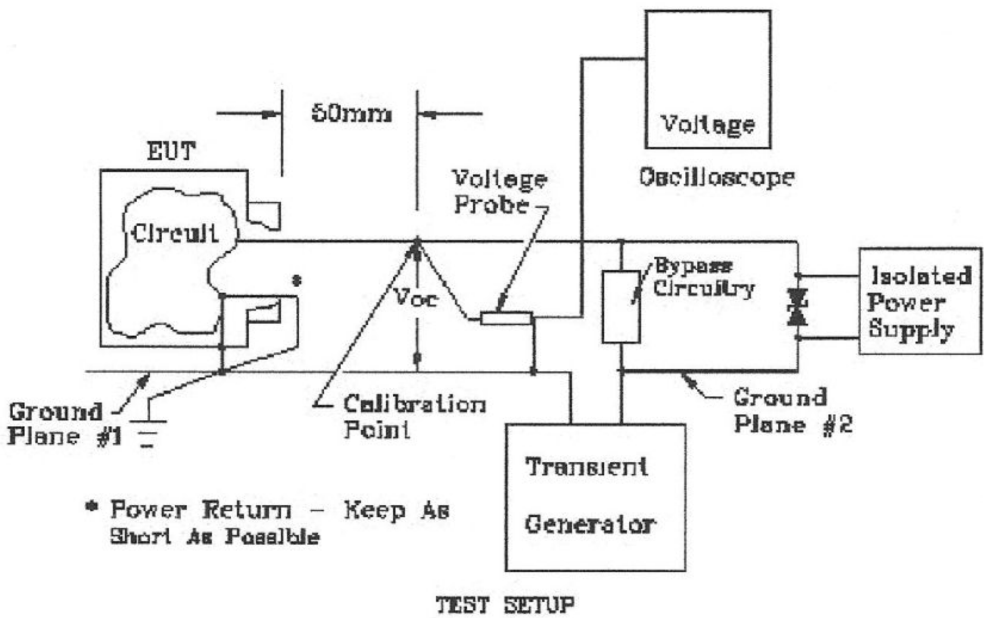


Figure 20. DO-160F Figure 22-15 Power Pin Ground Injection Test[1]

Grounding the EUT to a zero voltage facility ground as depicted above defeats the purpose of the test; that is, the EUT ground must swing above and below zero volts in order to induce the real effects of the IR-voltage drop in the structure between boxes. The test above is simply a power-off common mode pin injection with little relationship to in-flight I·R-drop environments.

If Ground Plane #1 is connected to Ground Plane #2, then the power can be applied. However, the Transient Generator will then drive a short circuit current through the ground connection and the EUT will pass with flying colors. An isolated power supply is not what's on aircraft primary power.

Ground injection may only be possible with transformer coupling in order to (1) maintain power return or chassis ground continuity and (2) swing the EUT ground above and below zero. Such a technique will lose waveform fidelity. The EUT cannot be grounded to the facility during the test. Such a concept is illustrated below in Figure 21. The test voltage has to be the calibrated open circuit voltage adjusted by whatever impedances are in the EUT and test circuitry. The voltage measurement in the figure may be useful only for diagnostics.

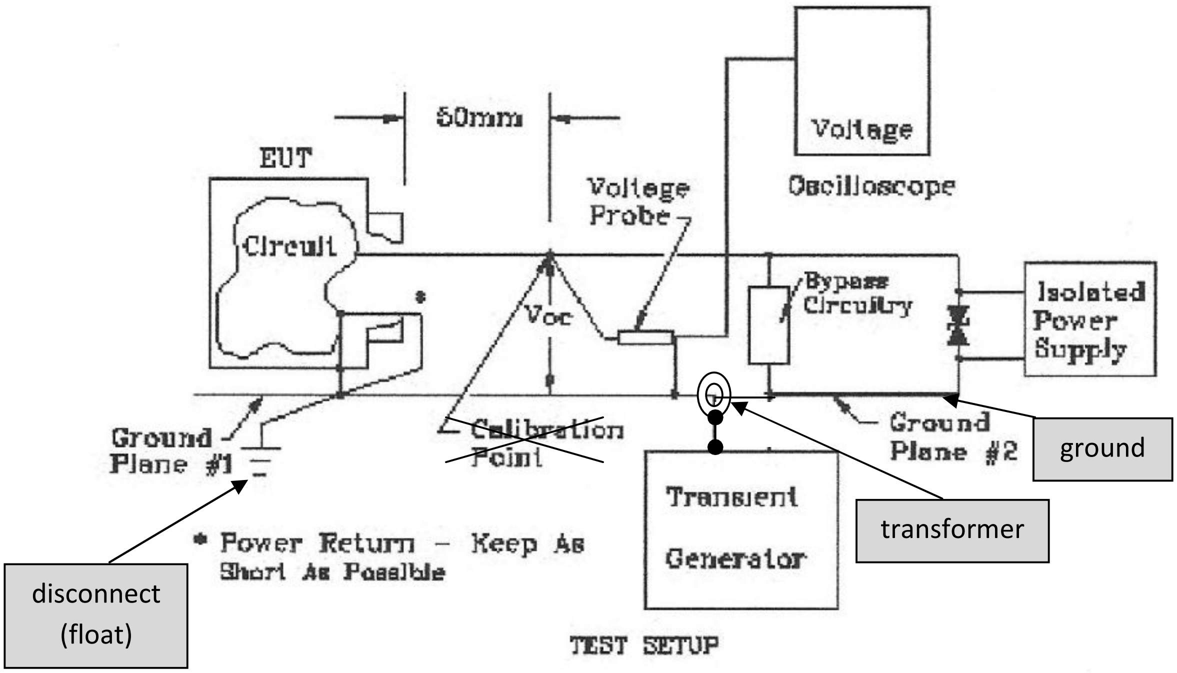


Figure 21. DO-160F Figure 22-15 Alternative Power Pin Ground Injection Test[1]
Alternative Transformer Coupled Ground Injection
EUT Floating/Ungrounded, Power Supply Grounded

4.2. Signal Pin Injection For signal pins, DO-160 pin injection test (presumed to be for ground injection but not so stated) set up is as follows in Figure 22, below.[1] Again, this test set up assumes that the power return is connected through chassis ground or structure, a rare practice in modern electronics.

This test should be set up with the EUT and a test set connected by a common cable(s) and the ground injection made about the same as Figure 21, above, transformer coupled into the common chassis ground, with the EUT chassis floating/ungrounded.

Recommend that this specific test method in Figure 22 be dropped for ground injection certification testing because it doesn't simulate ground injection or any other allocated environment, as is. It should only be used for engineering tests like testing surge suppression design.

Ground injection testing has to be at the box level and not directly coupled to an I/O pin. All of these tests have to be designed carefully. The recommendations herein are conceptual; the actual hook ups require detailed design.

(As an aside, a friend ran such a test of his surge suppression on a circuit card. The surge suppressor worked fine, no components were damaged, but the trace on the card melted. Reason enough to run engineering tests ahead of time.)

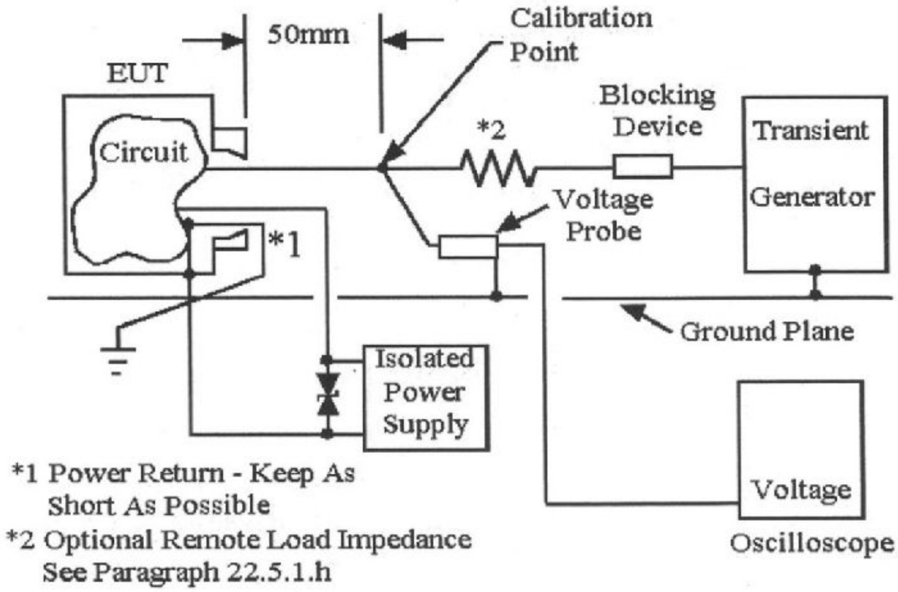


Figure 22. DO-160F Figure 22-13 Signal Pin Injection Test[1]
<u>Recommend Deletion for Ground Injection Certification</u>

For all other I/O power and signal circuits, wired up as twisted pairs with the signal and power return connection, pin ground injection is moot since applying the ground potential difference will affect the entire box circuitry.

5. Discussion of Ground Potential Susceptibilities and Protection

Assuming there is at least one chassis ground reference in each box for all circuits and chips in the box, ground potential, $V_{gnd} = I \cdot R_{gnd}$, between connected boxes, literally all chips in a box are exposed, differences are manifested as voltage stresses across chip junctions and substrates, and all components on a chip are directly or indirectly connected to the substrate. Figure 23 is a notional illustration of a box-to-box hook up with internal box circuit grounding with a ground potential in between them.

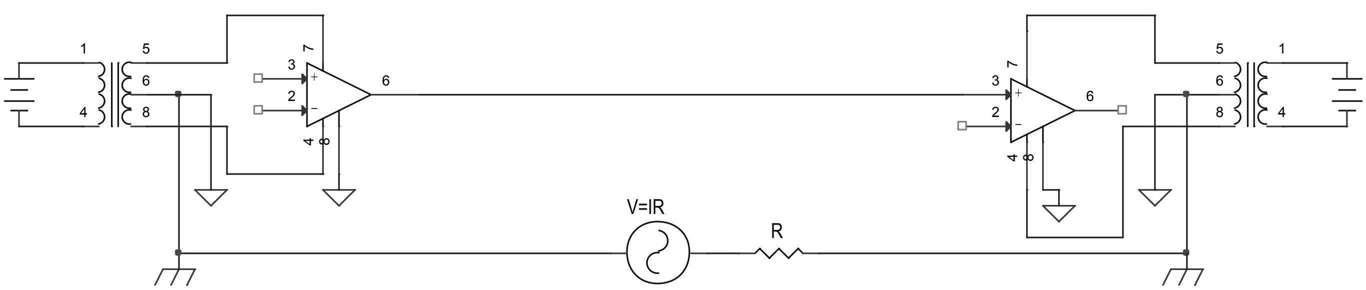


Figure 23. Notional Box Hook Up with a Ground Potential In Between

Chips use a reverse biased PN junction for the substrate. Oxide isolated devices use an oxide layer that is also built on a P-type substrate. When an input or output pin is taken below ground (which is one side of the substrate PN junction), the normally reverse biased isolated regions between components become forward biased and electrically connect the normally isolated components, possibly leading to latchup. at worse, bit errors, at a minimum. See Figure 24, below.

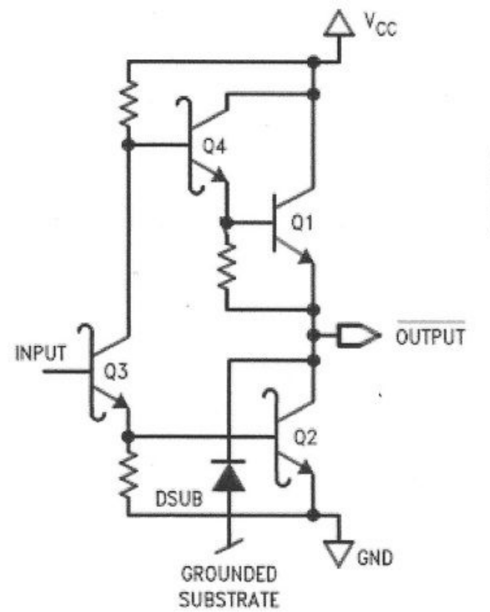


Figure 24. Typical Parasitic Substrate Diode (DSUB) Connection within Chip Circuitry

One chip vendor[16] has a simple prescription for protection against ground potential differences: "e_{gnd} can be minimized only by maintaining a relatively short distance between the transmitting and receiving locations." Unfortunately, that is easier said than done. There are several ways to mitigate the lightning transient ground potential, e.g. (1) heavy shielding, (2) true single point ground at one location only, or (3) transformer isolation. Ethernet solved the problem in their 100m "premise wiring".

The ground potential applies a voltage through the back door of chips, though the power supply and chip ground. Voltage clamps across the I/O pins and chassis ground may not clamp low enough for the max ratings of the power and ground pins and substrate overstress.

A circuit fix proposed for ground injection or the I·R-drop is a combination of common mode clamping diodes and circuit isolation, Figure 25. <u>Installing a combination of current-limiting resistors, TVS voltage clamping, and isolation is the best way to lower induced load voltages below CMR limits</u>.

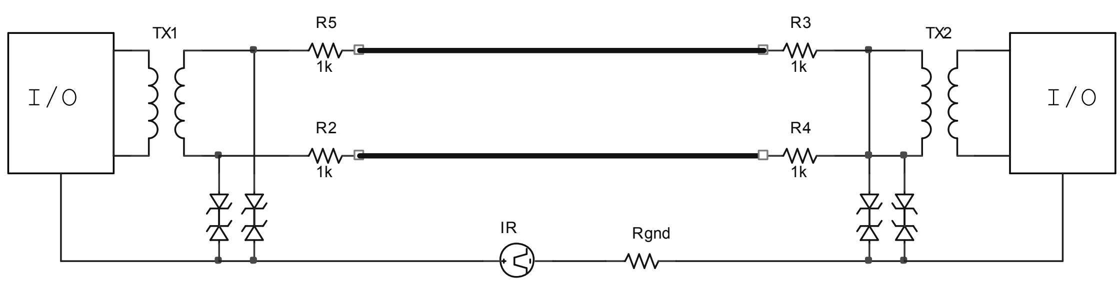


Figure 25. I/O Circuit Fix for the IR-Drop

The current-limiting resistors limit the TVS current and clamping voltage, the TVS protects the isolation components and the loads from overstress, and the isolation components act as voltage dividers further lower the load CM voltage to less than 1V.

6. Review of Inductive Coupling of Lightning into System Cables, Copper Shielding Performance, and the RTCA/DO-160 22.5.2.1 Cable Induction and 22.5.1 Pin Injection Tests

6.1 Sources of Inductive Coupling. There are three sources of inductive coupling to cables in airborne systems[3], (1) the time derivative inductive coupling of the external 1.5µs/88µs double exponential WFA, i.e. WF2, (2) the inductive coupling of the external resonant damped sinusoidal WF3, and (3) inductive coupling cable-to-cable from the internal WF4 and WF3 I·R-drop cable currents. The first is a broadband transient WF2 that will couple to the resonant frequencies of interior cables or raceway-like cables, where $f_{res} = c/2 \cdot l_{cable}$. The second is WF3 is the resonance(s) of the external system, $f_{system} = c/2 \cdot l_{system}$ coupling to cables. The third is a cable crosstalk excitation from cables conducting WF4 and WF3 due to the I·R-drop phenomenon to those less exposed. Most airborne systems have external resonances between 1MHz and 20MHz in the HF band. Figure 26 is a simple RLC circuit model of the airframe external electrical parameters, i.e. a capacitance across the airframe resistance and inductance. Figure 26 depicts the first four natural resonant modes of a Boeing 707 modeled as a stick figure where the distributions of currents are shown for each part of the exterior - fuselage, wings, and empennage.

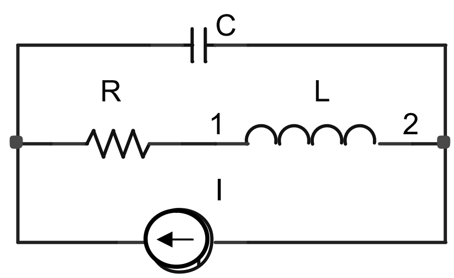


Figure 26. First Resonance of a Cylinder

Driving this circuit with a 35kA Component A 1.5µs/88µs double exponential lightning current from Figure 3.b results in the following for the resonant excitation scaled by the frequency which is inversely proportional to the external length.[3]

(22) $\boldsymbol{I_3(peak) \approx 3.7kA \cdot l_{system}/150m}$ times the appropriate damped sinusoid.

The effect on the Component A current is negligible, less than 1%.

For an aluminum aircraft, the Component A lightning current, 200kA, will result in a max WF3 external resonance current is about $I_3 \approx 21kA \cdot l_{system}/150m$.[3] Few cables run the entire length of a system without running through bulkheads thereby breaking them up into shorter lengths. These three sources of WF3 then compete with each other for design criteria and limits in box level qual/cert tests.

At the lowest aircraft resonance, the WF3 damped sinusoid currents peak around the center of the aircraft and null at the extremities. See Figure 26, below, for the natural resonant frequencies of a Boeing 707.[13]

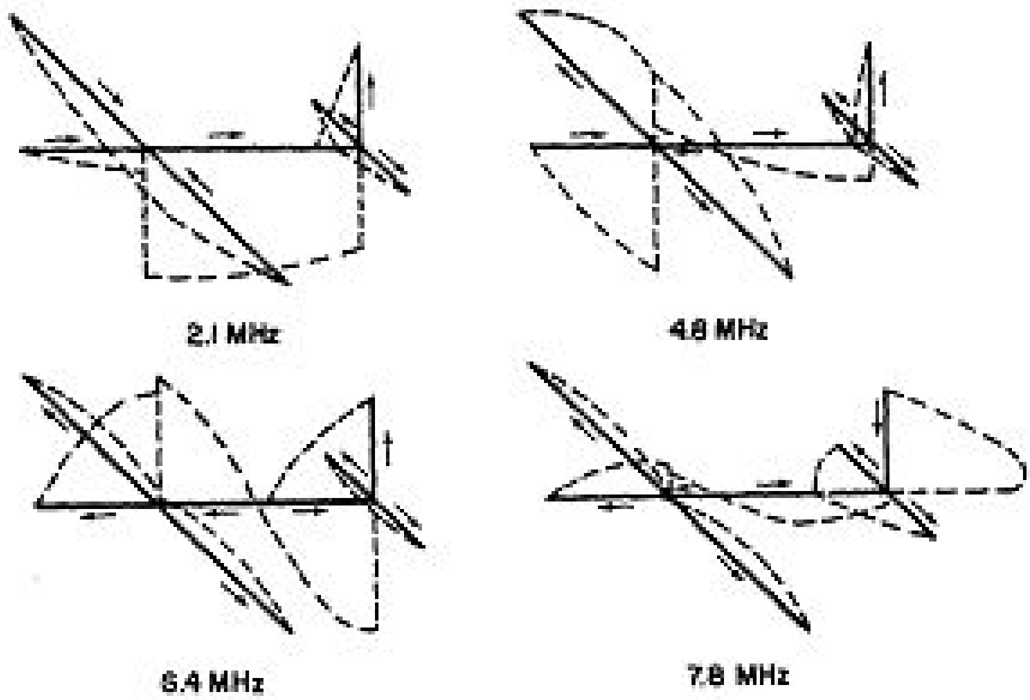
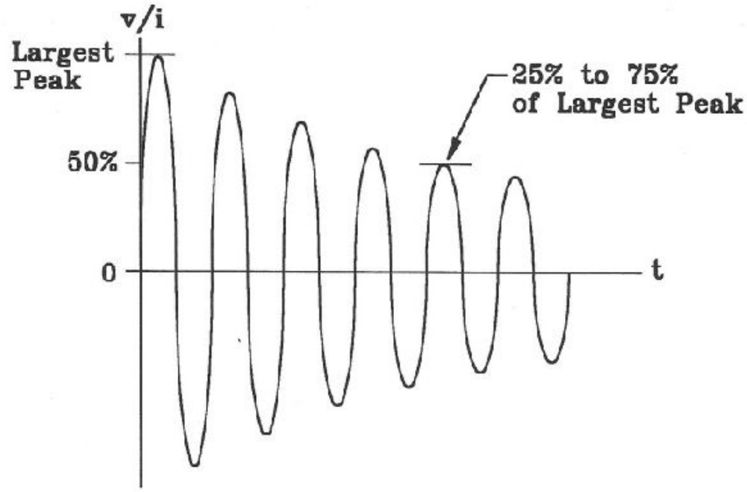


Figure 27. Resonant Modes of a Boeing 707[13]
Dashed Lines represent Distribution of Current on the Aircraft Segments at each Resonance
Arrows represent Directions of Current Flow

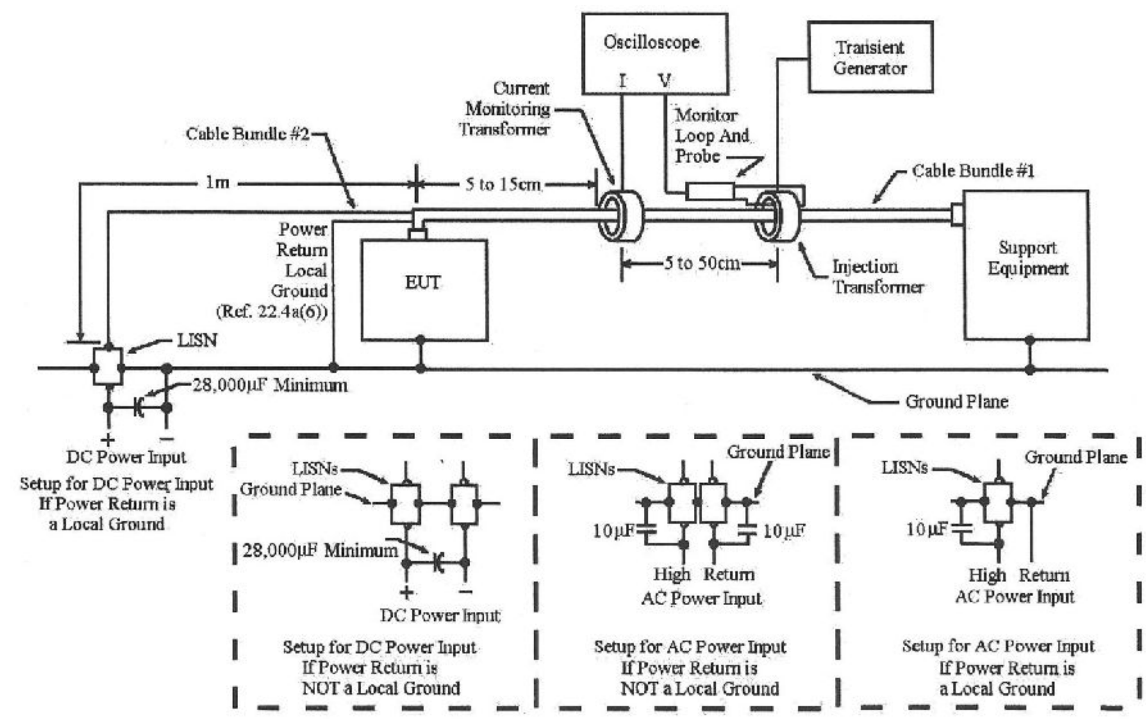
Figure 28, below, is the official Waveform 3 used in lightning certification of boxes. Figure 29, below, is a test set up designated for the inductively coupled injection to box cables. Note that the range of amplitudes at the fifth half cycle corresponds to a range of resonant Q-values of 9 to 37. Experience is that the external Q-value of aluminum airframes is about Q ≈ 20 and the Q of resonant cables is Q ≤ 10, at most. Also note that the frequency range of 1-50MHz corresponds to system or cable lengths of 3m (9´) to 150m (450´). The longest aircraft is the 84m Antonov 225 which corresponds to 1.2MHz lowest resonant frequency. The 7.67m Beech Bonanza resonates at 20MHz. The 380´ ORION space vehicle during launch resonates at 1.4MHz.



NOTES:

1. *Voltage and current are not required to be in phase.*
2. *The waveshape may have either a damped sine or cosine waveshape.*

Figure 28. Official Waveform 3 for Lightning Certification[1]



NOTES:

1. *Capacitor(s) shall be applied on power inputs to provide a low impedance to ground, as shown.*
2. *A series current-monitoring resistor may be used instead of the current-monitoring transformer.*

Figure 29. Test Set Up for Certification to Waveform 3[1,8]
Taking the Power Return to Ground, above, is <u>not</u> Universal
Follow the As-Built Design not DO-160

Again, the reader should not get too involved with the power connections.

Commercial transient generator modules are designed to produce Waveform 3 voltage on the cable at 1 & 10MHz per DO-160. These frequencies should be expanded in order to include the actual frequencies characteristic of systems and cables otherwise the simulation is off and the comparisons to allocations and system test are meaningless.

MIL-STD-461 CS116 damped sinusoidal testing is often considered to be an alternative to lightning induced WF3 however the pulser current levels and source impedance are not the same. It has possible uses but must be evaluated. CS116 is a carryover from nuclear EMP criteria.

6.2 Internal Cable Mutual Coupling and Resonances[3] The current induced on cables in the IR voltage drop coupling is now Waveform 4 instead of Waveform 5A. The rise time is therefore 1.5µs instead of 18µs and the current amplitudes are about 30% larger. The mutual inductive coupling between these cables and others is increased proportionally, therefore, there will be more WF2 and Waveform 3 damped sinusoid transients on the interior cabling.

On a cable-by-cable basis, the amplitude of a resonant WF3 current on a cable carrying WF4 current is approximately as follows:[3]

(23) $|I_{WF3}| \cong \frac{\beta}{\omega_3} \cdot I_{WF4} \cong \frac{2 \cdot l_{cable}}{2 \cdot \pi \cdot c \cdot 1.5\mu s} \cdot I_{WF4}$, where

(24) $\beta^{-1} \equiv 1.5\mu s$, the rise time of WF4 and

(25) $f_3 \cong c/2 \cdot l_{cable}$, resonant frequency of a cable a half wavelength long, $c \cong 3 \cdot 10^8\, m/s$.

The longer the cable, the higher the amplitude of WF3 and the lower the resonant frequency and vice versa. The WF4 cable currents can range from 20-100kA for a single cable with no underlying groundplane down to 2kA on one cable out of ten following the same cable routing.[3] The induced WF4 current is independent of the distance between ground connections. Mutual inductive coupling between the cables with high WF4 currents and nearby cables will increase virtually eliminating “protection levels’ from consideration. Crosstalk of 2kA-100kA WF4 current to a parallel 3m cable will result on 800V-40kV of WF2 inductive coupling.[3]

6.3 Effect of Thin Copper Shields. Modern trends in aerospace are towards lighter weight. That means less metal in cable shields which increases the transfer impedance resistance and the frequency where the resistance equals the transfer inductance out to the DO-160 Waveform 3 Induction Test frequencies of 1 & 10MHz. An example of different transfer impedance characteristics of cable shielding is shown in Figure 30, below, where the 1” diameter overbraid has its break frequency below 1MHz while the 1.5 mil twisted shielded pair (TSP) foil flat braid has its break frequency above 10MHz. That means that the induced voltage within the TSP shielded circuit is an I·R-drop, ground potential voltage, $V_{oc} = I_{shield} \cdot R_{dc}$, not the inductively coupled voltage, $V_{oc} = i\omega \cdot I_{shield} \cdot L_T$ in the wiring, that we are used to dealing with, both illustrated in the circuit model in Figure 31, below. This holds even up to 38AWG (4mil) thick copper wire TSP braid shields with modest transfer inductance. Tighter braiding reduces the transfer inductance but also makes the TSP heavier and stiffer. 85% optical coverage and a 30^0 weave angle are the norm.

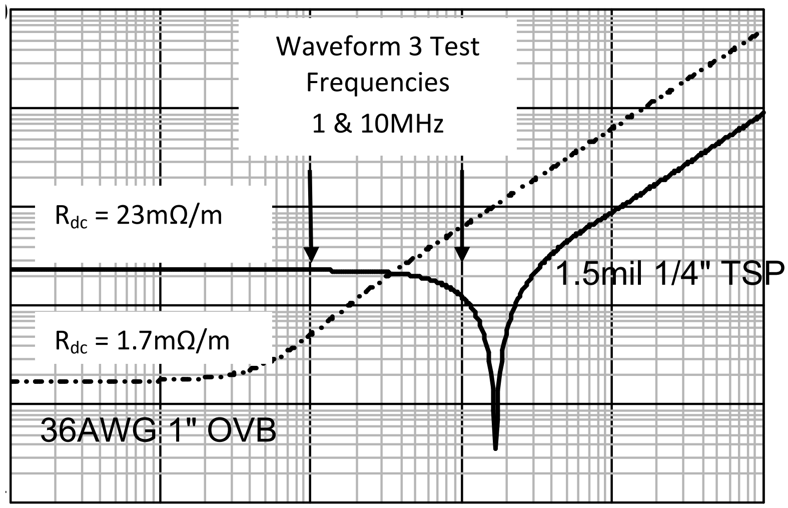


Figure 30. Cable Shield Transfer Impedance Model Results
Examples 1.5mil ¼" Diam. Flat Braid and 36AWG 1" Diam. Overbraid

Thinner lighter weight Aracon[10] cable shields[12] are in use that apply nickel, copper, and/or silver plating to thin Kevlar[11] fibers/threads. Thicknesses of Aracon[9] plating are about 11 microns of Ni, 24 microns of Cu, followed by 11 microns of Ni or 13 microns of Ag, all on Kevlar[5] fibers about 16 microns in diameter.[9] A 1" Aracon[7] overbraid exhibits about 60-70mΩ/m DC resistance and a transfer inductance of about 1pH/m therefore the DC resistance runs out to about 10MHz before the transfer inductance takes over.[15] The low transfer inductance is due to the tighter braid because the plated fibers are more flexible than solid copper wires and can be woven tighter. In order to provide better low frequency shielding, Micro-Coax weaves copper wires into the Aracon[10] braid. The resulting DC resistance is in between the pure Aracon[7] and a pure copper braid with the transfer inductance about the same.

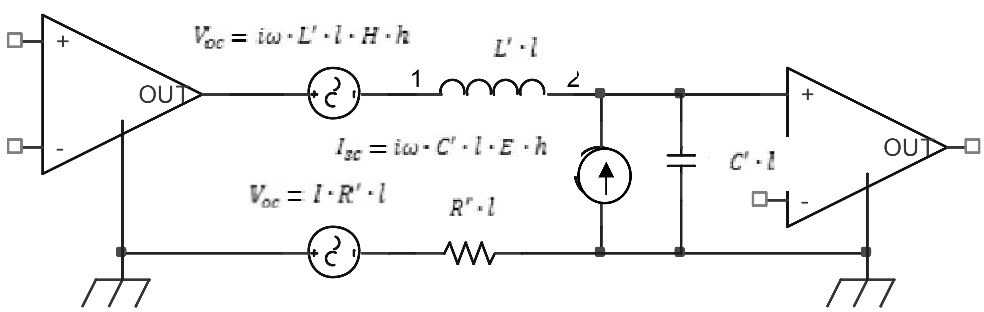


Figure 31. EMI & Lightning Common Mode Voltage & Current Sources

$\boldsymbol{V_{ov} = i\omega \cdot L' \cdot l \cdot H \cdot h}$ in wires from magnetic fields coupling directly or through a shield.

$\boldsymbol{V_{oc} = I \cdot R' \cdot l}$ from current running through a common chassis ground and/or a cable shield.

$\boldsymbol{I_{sc} = i\omega \cdot C' \cdot l \cdot E \cdot h}$ from an electric field between the cable and nearest chassis ground, coupling directly or through a shield.

In such shielded configurations, applying an inductively coupled voltage to the unshielded wire(s) for pin certification testing is applying the wrong voltage in the wrong place as illustrated in Figures 8 & 30, above. Electric coupling, $I_{sc} = C_T \cdot \dot{V}$, through cable shields is much smaller than magnetic therefore it's ignored. $C_T \approx$ 1pF/m doesn't allow much E-field coupling.[20]

6.4. DO-160F Section 22 5.1.d, Pin Induction Test[1]

DO-160F 22.5.1.d states that for pin injection testing, Waveform 3 shall be limited to 1MHz. This incredulous limitation destroys any presumption of simulating the effects in systems and doesn't relate to allocations or the system test results. The lowest Waveform 3 test frequency should be that of the lowest system resonance, $f = c/2 \cdot l_{system}$, i.e. 20MHz for a Beech Bonanza, 2MHz for a stretch Boeing 777, and 1.2MHz for the Antonov 225. Cable resonances run up over 50MHz.

DO-160F 22.5.1.h states that to account for cable characteristic impedance effects, the maximum inserted series impedance shall be limited to 75 ohms during Waveform 3 tests. This erroneous assumption is applied to cables 3.3m in length at frequencies with wavelengths the length of a football field to 1 mile. The wire resistance isn't even 1ohms.

7.5 The Power Pin Induction Test Figure 32, below, is OK for power connections with the power return connected through chassis ground or structure. Otherwise, use the methods in Figures 34 or 35.

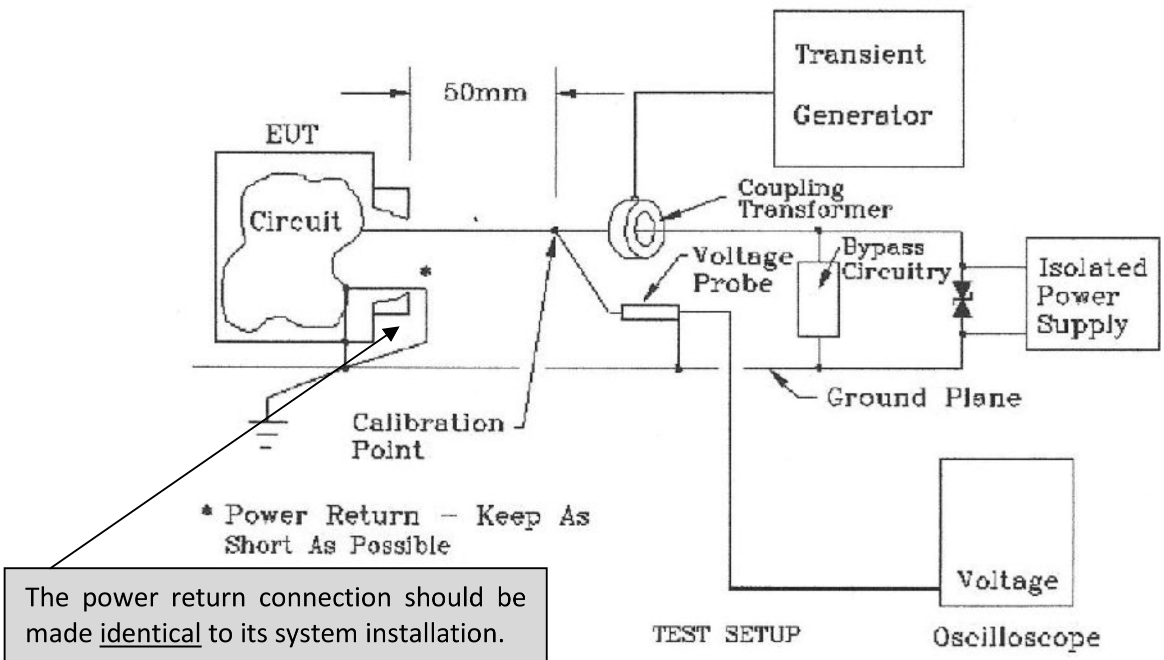


Figure 32. DO-160F Figure 22-14 Power Pin Induction Test[1]
For Unshielded Power Circuits with Returns connected through Chassis Ground
For Twisted Pair Power and Signal Connections, the Transformer must be placed around the Pair
The Test Voltage should be the Open Circuit Calibration Voltage
For Shielded Connections, see Figures 34 & 35, below.

6.6 Signal Pin Injection Test The DO-160 signal pin induction test set up is shown in Figure 33, below.

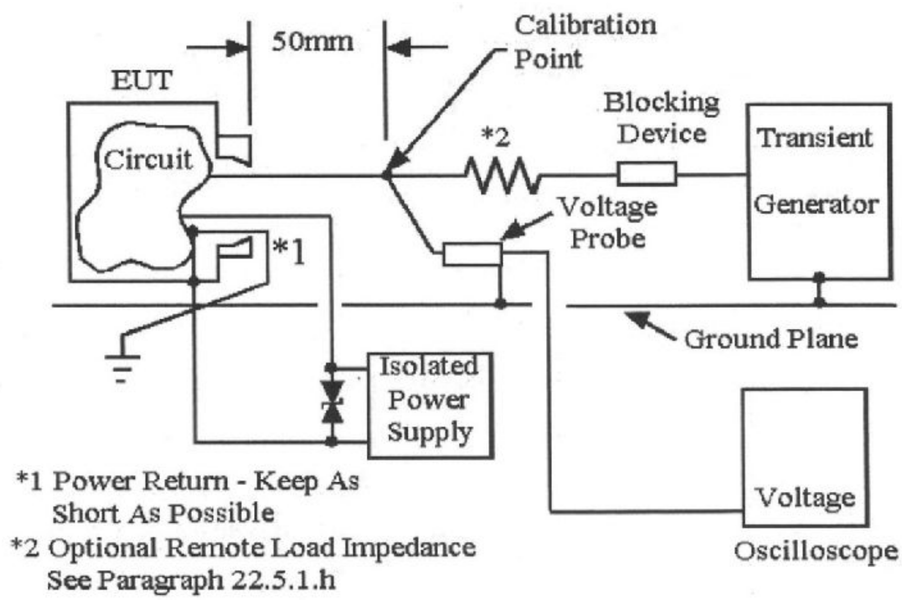


Figure 33. DO-160F Figure 22-13 Signal Pin Injection Test[1]

<u>Recommend Deletion for Pin Induction Certification</u>

6.7 Recommended Alternative Lightning Induction Signal Pin Injection The lightning induction pin injection tests should be transformer coupled Waveform 3 common mode voltages on unshielded signal and power pairs (UTP ≡ unshielded twisted pair) as shown in Figures 34 or 35. Injecting on both wires of a pair ensures simulation of the common mode induced environment.

The test limit should be the calibrated open circuit voltage.

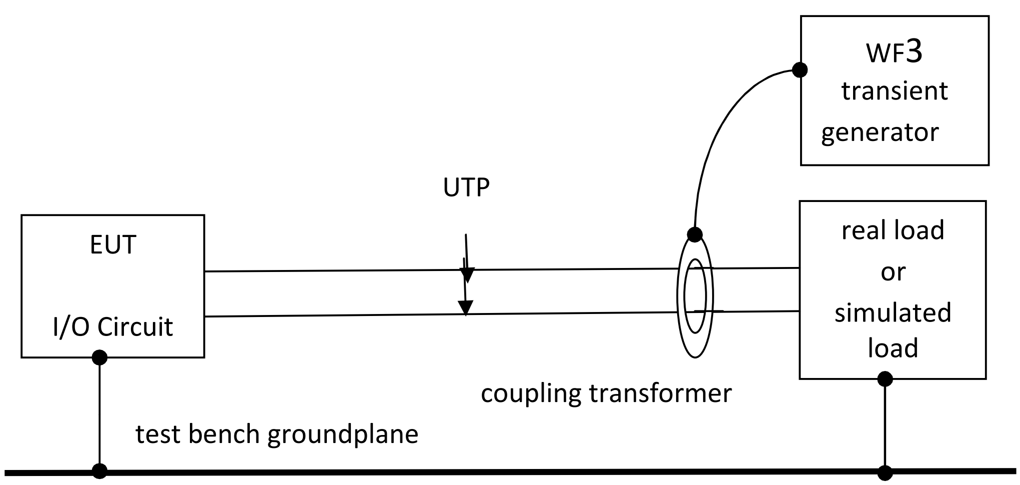


Figure 34. Lightning Induction Pin Injection Test Set Up (Waveform 3)

(For cables shielded with transfer impedance parameters $\frac{R_T}{2 \cdot \pi \cdot L_T} < \text{test frequencies}$

& unshielded cables & cables with shields grounded at one end only (SPG).)

When the transfer impedance is resistive out to 10MHz or other test frequencies, a ground injection test is called for as illustrated in Figure 31, below.

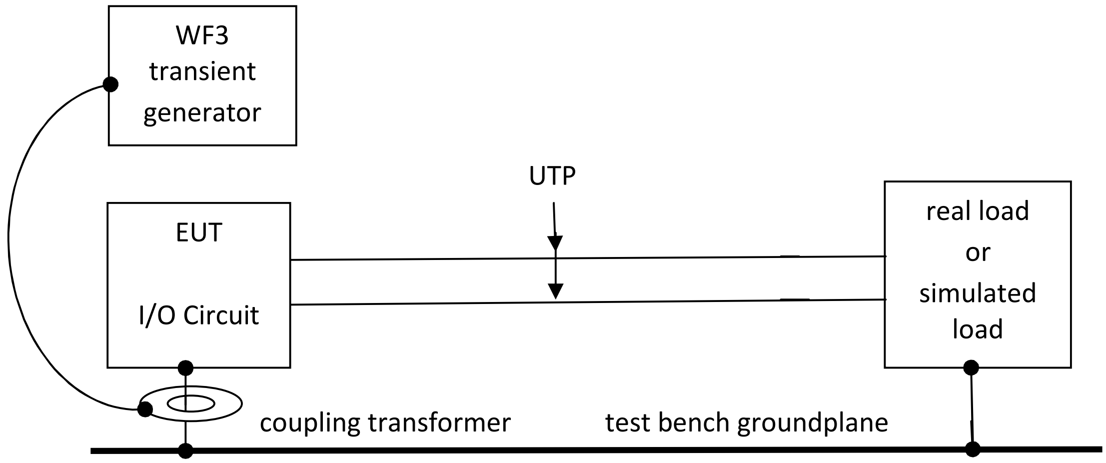


Figure 35. Lightning Induction Pin Injection Test Set Up (Waveform 3)
Modified as Ground Injection, Shield Disconnected, for Thin TSP Shields
(For cables shielded with transfer impedance parameters $\frac{R_T}{2\cdot\pi\cdot L_T} \geq \textbf{test frequencies}$.)

Levels are TBD from shield transfer impedance, shield/cable length, and the induced current on shields, i.e.

(23) $$\boldsymbol{V_T = [R_{dc} + i\omega \cdot L_T] \cdot l \cdot I_{shld}}.$$

The transfer impedance, $Z'_T = R_{dc} + i\omega \cdot L_T$, should include the cable connectors, box connectors, and backshells, i.e. the complete cable assembly plus box connectors. A simple two-probe method[15] with a general network analyzer is sufficient to determine as-built transfer impedance without elaborate test fixtures, one for each cable.

7. RTCA/DO-160F Tables 22-1.1 and Table 22-1.2 Revised

DO-160F Tables 22-1.1 and 22-1.2 have been revised with notes in order to summarize the foregoing discussions and recommendations and because they provide definitive direction in DO-160. The tables in DO-160 overlapped aperture coupling and resistive (I·R-drop) coupling thereby creating the illusion that they were comparable. The only overlap is when aperture coupled WF3 frequencies are lower than the cable shield transition from resistive to inductive; then, the injection should be WF3 as a ground injection.

Table 2. Pin Injection Test Requirements, Revised

DO-160F Table 22-1.1 Pin Injection Test Requirements, Revised				
Waveform Set	**Test Type**[a]	**Test Levels**[d]	**Test Waveform Nos. (V_{oc}/I_{sc})**[b,d]	**Notes**
A (shielded aperture coupling)	Wire injection on twisted pair, triad, etc.	See Paper #3 Tables 15-19	3/3	$\omega_3 \cdot L_T > R_{dc}$ See Figure 34.
	Ground Injection	See Paper #3 Tables 15-19	3/3	$\omega_3 \cdot L_T < R_{dc}$ See Figure 35.
B (unshielded I·R coupling; shielded see Table 2 F, J, K.)	~~Pin~~	~~Table 22-2~~	~~4/4~~	Meaningless[c]
	Ground Injection	See Paper #3 Tables 20-23	4/4	If only one pin; Cable if multi-pin.

Notes:

(a) Inductively coupled WF3 voltage appears in the pin wires when the cable shield transfer impedance is inductive at WF3 frequencies and appears in the shield when the transfer impedance is resistive at WF3 frequencies. (See Appendix B for a simple inexpensive test of the transfer impedance of as-built cable shields.)

(b) I_{sc} depends upon the shield's transfer inductance, the wire resistance, and the clamping diode equivalent resistance.

(c) IR-drop pin injection is a contradiction because the I·R-drop voltage is in the shields/chassis ground between boxes.

(d) WF3 frequency, $f_3 \approx c/2 \cdot l_{cable}$; WF3 level $\approx l_{cable}$. See IN616. (l_{cable} = cable length.)

Table 3. Cable Bundle Test Requirements, Revised

DO-160F Table 22-1.2 Cable Bundle Test Requirements, Revised				
Waveform Set	**Test Type**	**Test Levels**	**Test WF Nos.**[a,b,c,d,e,i,k]	**Notes**
C (unshielded, aperture coupling)	Single Stroke	See Paper #3 Tables 15-19	2, 3	Use 3 instead of 2.[g]
D (unshielded, I·R coupling)	Single Stroke	See Paper #3 Tables 20-23	3, 4	
E (shielded aperture coupling)	Single Stroke	See Paper #3 Tables 15-19	1, 3	shield disconnected.[j] See Figures 18, 19, 34 & 35
F (shielded, I·R coupling)	Single Stroke	See Paper #3 Tables 20-23	3, 4	shield disconnected.[j] See Figures 18, 19, 34 & 35
G (unshielded, aperture coupling)	Multiple Stroke	See Paper #3 Tables 15-19	2_D, 3	Use 3 instead of 2.[g]
	Multiple Burst	See Paper #3 Tables 15-19	2_H, 3	Use 3 instead of 2.[g]
H (unshielded, I·R coupling)	Multiple Stroke	See Paper #3 Tables 20-23	3, 4_D	
	Multiple Burst	See Paper #3 Tables 20-23	3, 4_H	
J (shielded, aperture coupling)	Multiple Stroke	See Paper #3 Tables 15-19	1_D, 3	shield disconnected.[j] See Figures 18, 19, 34 & 35
	Multiple Burst	See Paper #3 Tables 15-19	1_H, 3	shield disconnected.[j] See Figures 18, 19, 34 & 35
K (shielded, I·R coupling)	Multiple Stroke	See Paper #3 Tables 20-23	3, 4_D	shield disconnected[j]
	Multiple Burst	See Paper #3 Tables 20-23	3, 4_H	shield disconnected[j]

Notes:

(a) 1_D and 4_D have the same waveform as Component D.

(b) 1_H and 4_H have the same waveform as Component H.

(c) 2, 2_D, and 2_H have the same peak levels.

(d) 2, 2_D, and 2_H have the waveforms of the derivatives of Components A, D, and H, respectively.

(e) 3 has the same waveform and peak level for Components A, D, and H.

(f) Aperture or inductive coupling has three different sources: 1) apertures, 2) raceways and wing spars, and 3) cable cross coupling from other nearby cables with WF3 and/or WF4 currents.

(g) Applying WF2 inductively will result in a WF3 frequency characteristic of the test cable, not the in-flight cable, therefore injecting the in-flight WF3 is preferred.

(h) Aperture/inductive coupling scales by aperture size, cable distance from the source, cable height, and the system circumference at the coupling location.

(i) I·R-drop WF4 (A, D, & H) voltage is proportional to the distance between boxes along the lightning current path; the WF4 (A, D, & H) cable current is not.

(j) Ground injection with shielded cables should be WF4 voltage with shields disconnected.

(k) WF3 frequency, $f_3 \approx c/2 \cdot l_{cable}$; WF3 level $\approx l_{cable}$.

8. Concluding Remarks.

Some recommendations herein are allowed alternatives in DO-160F, some new.

Ground Injection should be with a WF4 voltage for shielded cables with the “shield disconnect” method and with a WF4 voltage for unshielded cables. Transformer coupling may alter the waveshape but that is an acceptable compromise in order to create a voltage swing in the boxes grounds.

Pin level ground injection is meaningless since ground injection is a box level phenomenon, i.e. stressing the entire box circuitry through the chassis ground connection(s) within the box. Except for isolated power pins, this test method should be dropped except as an engineering test.

Coax lines usually carry RF signals and can be adequately protected with high-pass filters or quarter-wave stubs to chassis ground plus their built-in band pass filters. That renders the near-impossible ground injection test a moot issue. Pin injection is not ground injection.

There is remarkably little published data on ground injection susceptibilities at the box level. Most published work addresses ESD threats on the box I/O pins and ground bounce within chips and circuits. The inter-box ground potential stresses within the box and chips on the cards suggest that (1) substrate latchup is a concern and (2) common mode isolation in the lines or common mode voltage clamping across the I/O circuits can only partially protect this susceptibility.

The DO-160F Cable Induction Test method is OK, as is, except for the frequency range. Certifying a box at 1MHz makes it acceptable for the Antonov 225.

The Pin Induction Testing ignores the fact that most TSP (twisted shielded pairs) cable shields are quasi-resistive out to 10MHz rendering the coupling into the shielded circuits a ground potential along the inside of the shields not an inductive voltage in the wires. Ground injection of WF3 is much easier that the formal ground injection because the chassis ground connection remains intact through the coupling transformers.

Finally, the Induction Tests with the damped sinusoidal WF3 need to be expanded in frequency to cover actual resonances on and in the systems commensurate with design allocations and assessment of safety margins. That would also get the induced voltages past the TSP transfer impedance resistive region and into the transfer inductance region, a stronger reason for extending the frequency range of WF3 testing, i.e. simulation fidelity at the cable and pin level with lower levels.

These test recommendations reduce costs by reducing the number pin injection tests, even replacing most with tests at the box level. They reduce risk by making the box certification tests more comparable to theoretical allocations and system level test data.

The author is grateful to Tom Pierce (JPL) and Roxanne Arellano (USC ECE) for many substantive discussions and for Carl E. Baum’s review and corrections. The influence of many years of knowing and being associated with Ed Vance cannot be expressed adequately.

Appendix A. Test Set Up with Composite Panel and Shielded Cable Simulating System Induced Voltage within the Shielded Cable[5]

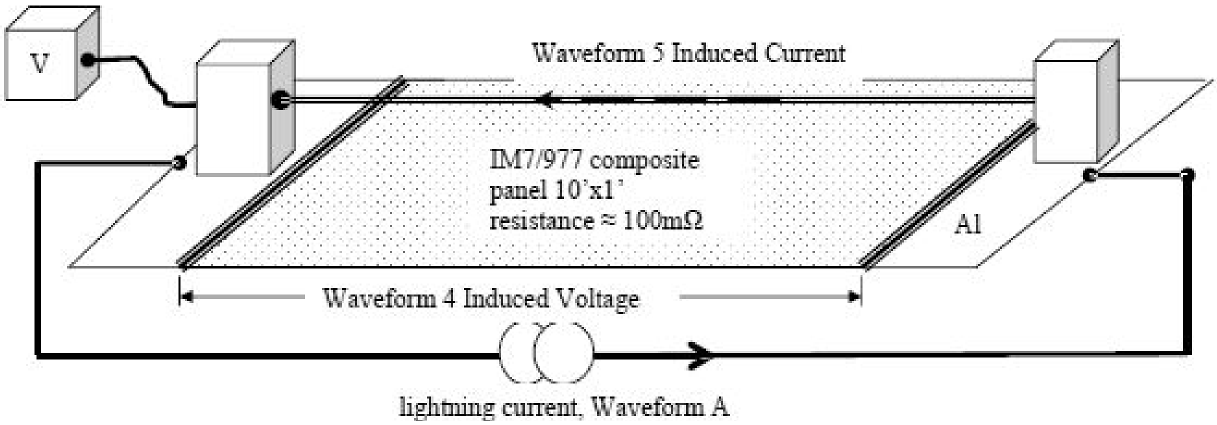


Figure A.1. Bench Simulation of the Waveform 4 I·R-Drop across the CFC Structure and Waveform 5A Current on the Shield from IN 608[5]

The composite resistance scales proportional to the length and inversely proportional to the width.

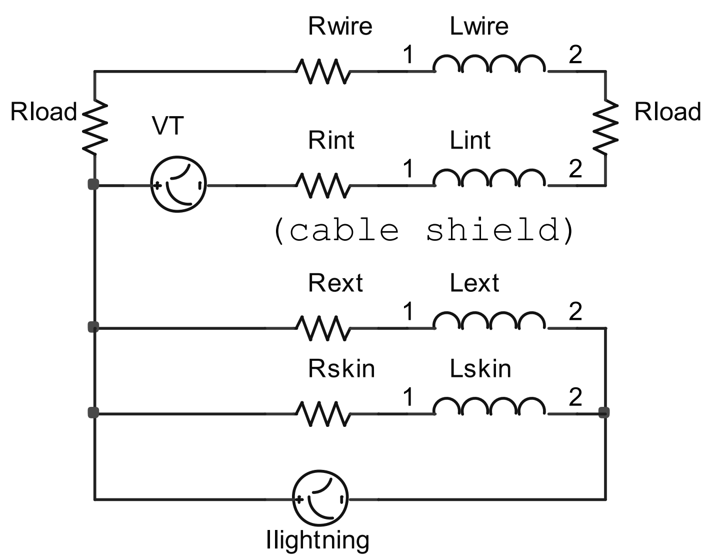


Figure A.2. Circuit Model of the System and the Test with Cable Shield

Appendix B. Two Probe Method for Measuring As-Built Cable Shield Attenuation

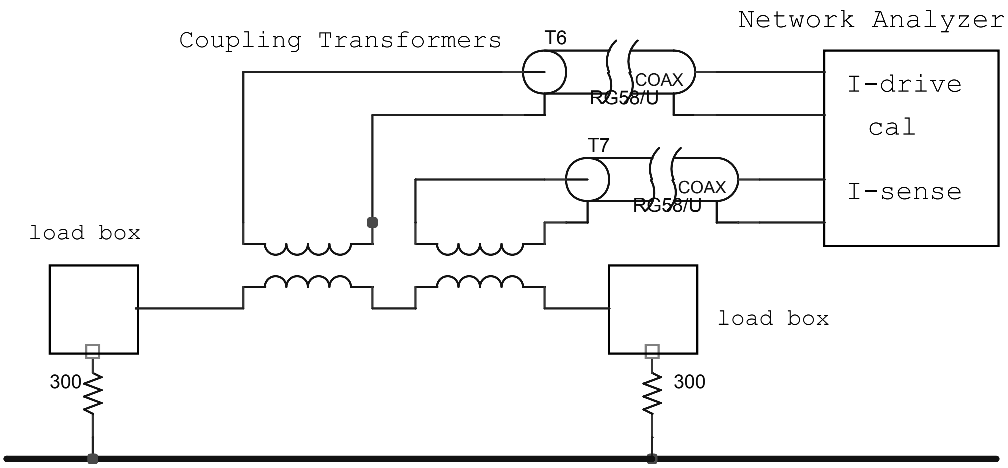
(This method requires only load boxes and a groundplane for a fixture.)

Connect the cable to load boxes, both grounded to the ground plane with 300Ω each. Terminate the shielded wire(s) with 50Ω (CM impedance of TSP pairs) inside the load boxes.

Turn network analyzer on.

Install current probes on cable relatively close together; (Ignore P-Spice RG58/U nomenclature.)

Set analyzer to S21, insertion loss;

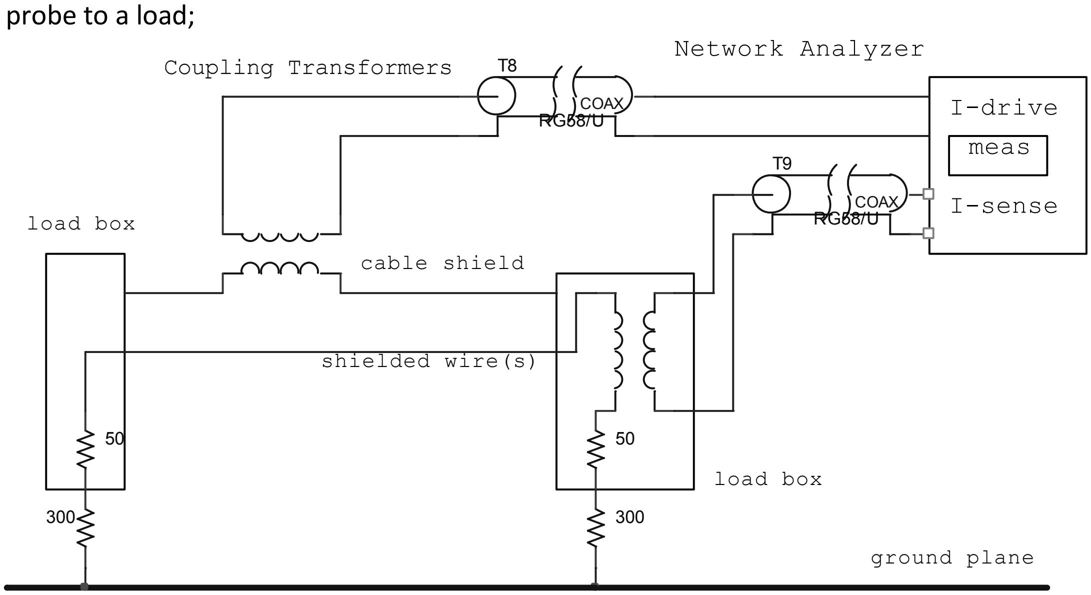


Configuration to "cal" Current Probes & Cables

Run a calibration on the current probes and test cables by pushing “cal” on analyzer;

The analyzer should display a straight line;

Move sense probe to a load;



Configuration to "meas" Cable Shield Attenuation

Measure the shield attenuation (SA) by pushing “meas” button on analyzer;

The analyzer should display a shield attenuation curve, actually display $\boldsymbol{SA} = \frac{I_{load}}{I_{shield}} = \frac{|R'_{dc} + i\omega \cdot L'_T| \cdot i}{100}$;

The two parameters needed for setting up WF3 lightning tests are (1) R_{dc} and (2) $\omega = R_{dc}/L_T$.

Transform to transfer impedance by multiplying by x100 or adding 40dB depending upon the scale.

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9. Bill Gaffney, Micro-Coax, verbal communication, 6/11/10: Thickness of Aracon[5] plating is rounded off to 50 microns; the fibers have about 11 microns of Ni, 24 microns of Cu, followed by 11 microns of Ni or 13 microns of Ag, all on Kevlar[5] fibers about 16 microns in diameter. Total diameter is 108-110 microns.

10. ARACON® and MICRO-COAX® are registered trademarks of MICRO-COAX, Inc.

11. KEVLAR® is a registered trademark of E.I. du Pont de Nemours and Company.

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