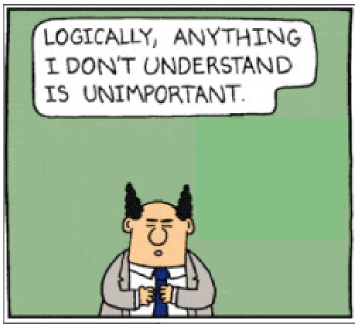
LIGHTNING AND RF ELECTRICAL BONDING

The Origin and Application of the 2.5 mΩ Requirement

The report on which this article is based was put together for internal government use some time ago. But the continued relevance of the information contained in that report recently became apparent when a discussion group on LinkedIn variously labeled the subject matter requirement (2.5 milliohm bond) mysterious, obsolete, "black magic," and ultimately, unnecessary. Apparently, the LinkedIn contributors had little or no idea of the historical context of the requirement, and evoked for this author the quintessential "Dilbert" moment shown here.



The author was also reminded of a famous observation by Arthur C. Clarke, which is paraphrased as follows:

> "Any sufficiently obscure technology is indistinguishable from black magic."

To help provide some context for their discussion and in an effort to curb the all-too-frequent instinct to "move fast and break things," the author posted this report to the LinkedIn group, along with the following advice, which applies regardless of your field of endeavor, engineering or otherwise.

> "A rule of thumb for handling the 'mystery of engineering' is that a lack of understanding is not a condemnation of the misunderstood. Every engineering principle that has made it into a lasting standard had validity at some time. Whether or not it applies in a particular situation depends on the relationship of the problem at hand to the original problem addressed by the requirement.
>
> "Until the original application is fully understood, one has no basis for judging the applicability to any specific case.

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By Ken Javor

> "In the broadest possible terms, reality exists independent of our perception and understanding. Sir Francis Bacon said some 500 years ago that 'Nature, to be commanded, must be obeyed.' The author's corollary to that is 'Nature, to be obeyed, must be understood'."

With that introduction and background, the following report presents everything one needs to know about the origin and application of the 2.5 milliohm electrical bonding requirement.

PURPOSE

The purpose of this report is to document the origins and rationale vs. present practice regarding the now ubiquitous 2.5 milliohm class L & R (lightning and radio frequency) bonding requirements used in aerospace, space, and military vehicles.

REFERENCE DOCUMENTS

Please see Table 1.

Reference	Document Number Date	Document Title
1	MIL-B-5087 09 November 1949	Bonding; Electrical (for Aircraft)
2	MIL-B-5087A (ASG) 30 July 1954	Bonding; Electrical (for Aircraft)
3	MIL-B-5087B (ASG) 15 October 1964	Bonding, Electrical, and Lightning Protection, For Aerospace Systems
4	DOT/FAA/T-89/22 September 1989	Fisher, F.A., Plumer, J.A., & Perala R.A. "Aircraft Lightning Protection Handbook"
5	NAVAER 16-5Q-517 circa 1946	Elimination of Radio Interference Problems in Aircraft
6	N/A 1990	Fisher, F.A., Plumer, J.A., & Perala R.A. "Lightning Protection of Aircraft" Lightning Technologies, Pittsfield, MA.
7	MIL-STD-461G 11 December 2015	Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipments
8	RTCA/DO-160G 08 December 2010	Environmental Conditions and Test Procedures for Airborne Equipment
9	ISBN 0-471-01995 1997	Smith, A. A. "Coupling of External Electromagnetic Fields to Transmission Lines." Interference Control Technologies
10	ISBN 0-471-04107-6 1978	Vance, Edward F. "Coupling to Shielded Cables." Wiley-Interscience.
11	T.O. 16-1-45 25 June 1945	Handbook of Elimination of Radio Noise in Aircraft
12	T.O. 08-10-139 03 January 1943	Radio Transmitter BC-37E & Associated Equipment; Instruction Book for Operation and Maintenance of [Page 6, section 10.d (2)]

Table 1: Reference Documents

Note that, while MIL-B-5087B is long obsolete, the bonding classes survive in MIL-STD-464, and in NASA-STD-4003. MIL-B-5087 is not technologically obsolete, but it contained instructions on how to implement bonds, as opposed to bond performance, and the 1994 SECDEF Perry memo, "Specifications & Standards - A New Way of Doing Business," required military standards to be either performance or interface standards, but not "how to" standards.

HISTORICAL CONTEXT

Reference 1, section 3.3.1, says the rationale for their detailed lightning requirements is:

> "…to achieve a lightning bonding system such that a lightning discharge current may be carried between any two extremities of the aircraft without risk of damaging flight controls or of producing voltages within the aircraft in excess of 500 volts. (These requirements are based on a lightning current surge which reaches a crest wave of 100,000 amperes at 10 microseconds and drops to 50,000 amperes at 20 microseconds.)"

This requirement is unchanged in Reference 2 and is equivalent to maintaining 5 milliohms resistance. Reference 3, section 3.3.4, has similar wording, but note the change in assumed worst-case lightning attachment (resulting in a 2.5 mΩ requirement):

> "…to achieve protection against a lightning discharge current carried between the extremities of an airborne vehicle without risk of damaging flight controls or of producing sparking or voltages within the vehicle in excess of 500 volts. These requirements are based on a lightning current waveform of 200,000 amperes peak, a width of 5 to 10 microseconds at the 90-percent point, not less than 20 microseconds width at the 50-percent point, and a rate of rise of at least 100,000 amperes per microseconds (sic)."

The significance of the 500-volt number is explained in Reference 4, section 6.2.5, as follows: "Such a voltage did not present much of a hazard to the electromechanical and vacuum tube components in use when MIL-B-5087B was formulated." It should be emphasized that the 500-volt number goes back to References 1 and 2 in 1949/1954, when relays and vacuum tubes were the building blocks of electronic circuits on aircraft.

The need to limit the structure potential drop to 500 volts is because aircraft at that time used structure not only for power current return but also for signal current return. In the 1940s and 1950s, even the most sensitive signals – those picked up by an antenna and conducted to a radio receiver on an unshielded (no coax) wire – might use structure return. Thus, any noise on structure is in series with the desired signal, as depicted conceptually in Figure 1.

In Figure 1, lightning attaches to the aircraft at one end, and exits the other. In between, based on the lightning resistance requirement, the full-scale lightning current induces no more than 500 V across the aircraft, which potential is in series with any circuit using the lightning current-carrying aircraft structure for a return path (ground plane interference – GPI).

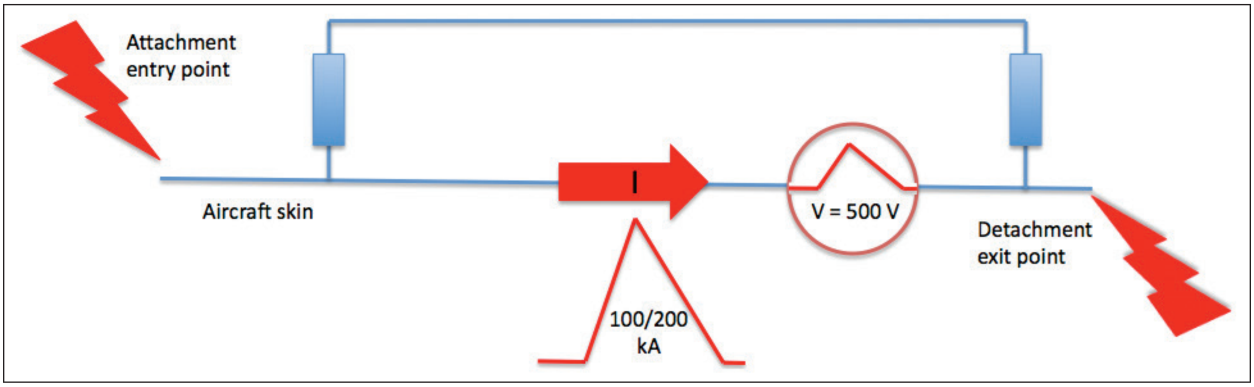

Figure 1: Effect of lightning attachment current on ground-referenced signal

Note that there is no need for any special bond provisions to structure in the circuit of Figure 1, other than that required to make the circuit function in and of itself. Imposing a class R bond does nothing to improve functionality under any circumstances of radiated susceptipility or ground plane noise, such as ground bounce or a lightning transient.

The practical application of the conceptual Figure 1 in the time period when References 1 and 2 were written and applicable is shown in Figures 2a and 2b (taken from Reference 5). These Figures show how noise couples into the receiver front end. Only in our case, it is lightning, whereas the Reference 5 discussion was about radio frequency interference.

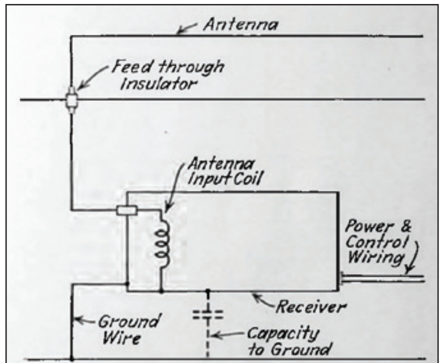

Figure 6—Schematic Diagram of Receiver Input Showing Path to Ground

Reference to figure 6 will show that both the signal currents induced in the antenna, and radio interference currents conducted into the receiver via any path must return to ground via the ground lead and the parallel capacity of the receiver chassis to ground. This constitutes the common ground impedance, and the path to ground is in series with the antenna circuit.

The impedance presented by this ground path is complex. It may be either inductive or capacitive, depending upon the frequency and the installation; the inductive reactance of the ground lead increases rapidly with frequency, and the capacitive reactance of the capacity between chassis and ground decreases as frequency is increased.

The radio interference voltage developed across the impedance of the ground path depends upon the radio interference current flowing through the impedance, and the value and nature of the impedance at the interference current frequency.

Figure 2a: Grounding excerpt from Reference 5

That this voltage is in series with the antenna circuit is shown in the equivalent circuit diagram, figure 7. The voltage appearing across the receiver input will be the vector sum of the voltages developed across the receiver-input impedance by the currents from the equivalent signal generator and the equivalent radio interference generator.

Because desired signal currents induced in the antenna are usually very small, small radio interference currents, flowing through the common ground impedance, may develop voltages at the receiver input equal to or greater than the signal voltages.

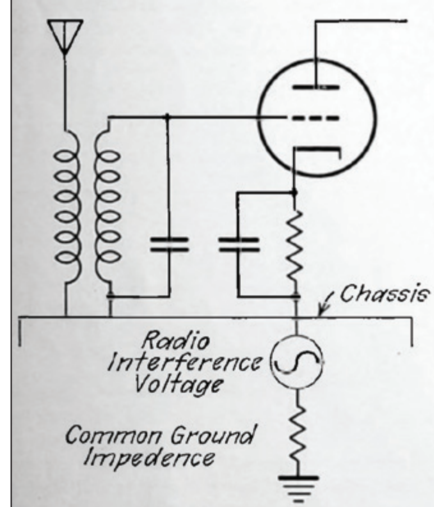

Figure 7—Common Receiver Ground Impedance for Signal and Radio Interference Currents

Figure 2b: GPI excerpt from Reference 5

We should note here that the lightning extremity-to-extremity resistance is precisely that – a resistance – not a single bond value. Figure 3 shows actual values for specific (unidentified and obsolete) aircraft. A comparison of resistance per unit length to total resistance is indicative of the degree to which the various models are "wide-body" or not. The larger the circumference, the more area there is over which the lightning current spreads (in a nose-to-tail strike) and the lower the resistance per unit length. The spread of lightning current over the entire circumference ensures no more than the 500 V criterion is encountered over any nose-to-tail path, and that all cables running fore and aft will see roughly the same end-to-end potential drop, no matter where along the periphery they are placed.

We should also note that the several sub-paragraphs under the lightning bonding sections in the first three references never mention the requirement of bonding an electronic equipment enclosure to structure. Instead, the subsections deal with how to achieve suitably low bonding resistances to protect the 500-volt value, and to ensure lightning currents flow in the intended bond paths. It is of critical importance to understand that this was the only lightning protection design technique of importance to electronic equipment at the time. It is something that References 4 and 6 don't adequately describe.

On this topic, References 4 and 6, section 5.5.1, say in part (the important part is italicized):

> "**Defined lightning threat:** AC 20-53 and MIL-B-5087 each defined the lightning threat as a 200 kiloampere (kA) peak current…
>
> Both documents required tests of critical components, such as fuel tank skins, access panels,

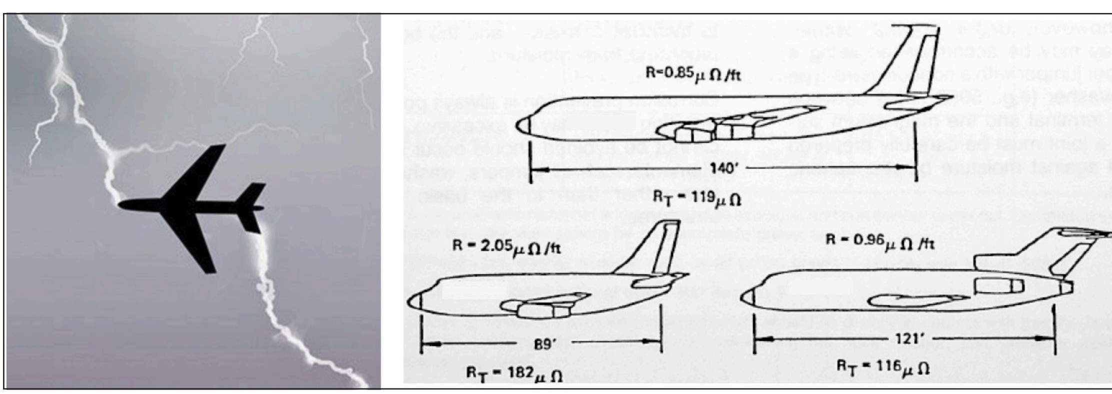

Figure 3: End-to-end resistance of some older aircraft
(photo from https://aviation.stackexchange.com/questions/888/what-happens-when-an-airplane-gets-struck-by-lightning)

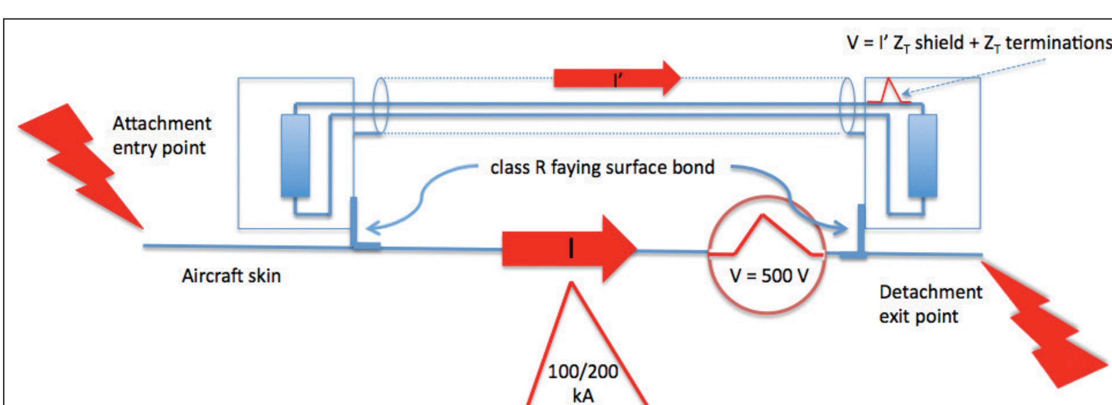

Figure 4: Effect of lightning attachment current on an above-ground signal

> filler caps, antenna installations, and other "points of entry" on the aircraft. *No attention was given to the effects of currents conducted through interior structures or systems, or to indirect effects of lightning on electrical and avionics systems. These latter effects were not well understood during this period*."

It is misleading to say, "*These latter effects were not well understood during this period.*" The only (indirect, resistive coupling) effect on a circuit using structure return was the transient ground potential, which the lightning resistance requirement limited to the target 500-volt potential. They understood what needed to be done, and they did it. The modern techniques of dedicated above ground returns and cable shielding discussed in the next section of this report were not in widespread use, and therefore there were no other indirect effects requiring control. It should be noted that class R bonding was specified, even though it would not have helped the types of circuits shown in Figures 1 and 2. There was some use of coax and EMI filtering. More on this in the next section.

Therefore, we can say that the (implied) 2.5 mΩ class L lightning requirement was the original lightning indirect effects requirement. There are plenty of other class L requirements in each of References 1 – 3 that control direct effects directly, especially fuel ignition.

MODERN USAGE

Modern aluminum aircraft continue to use structure for power current return and 28-volt discretes, but not signals, and definitely not radio signals, which use coax. And NASA spacecraft – at least in the author's personal experience – don't use structure even for power current return. So, our situation isn't as dire as portrayed in Reference 5, but we also no longer use robust vacuum tubes that can handle 500 volts for tens of microseconds. So, we have offsetting trends here. We have much more damage-susceptible circuits, solid-state replacing vacuum tube, but we also don't place structural noise in series with the desired signal.

When using dedicated above ground signal returns, a lightning transient will couple a potential/current onto an entire cable harness. If that harness is shielded, only that potential that couples within due to shield transfer impedance will be seen to be in series with the signal.

So, the use of dedicated returns and shields places two ameliorating conditions at our disposal. The first is that the full lightning current isn't induced across our signal return. The effect of this can be seen looking at Reference 7 CS117[1] transient levels, as compared to the full threat aircraft strike of 200 kA. The very highest induced current is 2 kA.

If we compare Figure 4 to Figure 1, the same lightning attachment to the aircraft skin is present, and the same induced GPI. But that doesn't matter as much anymore because the ground bounce is not directly in series with the above ground circuit. The ground bounce neither interferes with nor can damage the circuit components. A smaller current per Table VII from Reference 7 (Table 2 on page ##)

has coupled to the cable shield and induces a line-to-ground potential which is the cable drive current multiplied by the shield transfer impedance in series with shield termination impedances. As per Figures 5a and 5b, excerpted from References 9 and 10, shield transfer impedance in the lightning spectrum can be worst-case bounded by shield dc resistance, so milliohms per meter. It now becomes critical to control the shield termination impedance, which is comprised of two series impedances: 1) the shield through the connector to the equipment enclosure; and 2) from the equipment enclosure to structure.

Hence, the class R bonding requirements.

The actual effect of increasing the impedance versus the dc resistance is illustrated by a simple transfer impedance measurement.

In Figures 6a and 6b on page ##, the transfer impedance of the white 50 Ω coax was measured using its bnc connectors, and then inserting at the interrogated end a pair of bnc-to-banana adapters to simulate a shield pigtail termination. In this case, the dc resistance of the plug and jack adapters is at least as

TABLE VII. CS117 Test and limit levels for multiple stroke and multiple burst lightning tests.

Multiple Stroke			
Applicability	**Test Description**	**Internal Equipment Levels****	**External Equipment Levels****
All equipment installations	Waveform 2 (WF2)/ Waveform 1 (WF1)	First Stroke V_L = 300 V (WF2) I_T = 600 A (WF1) I_T = 60 A* Subsequent Strokes V_L = 150 V (WF2) I_T = 150 A (WF1) I_T = 30 A*	First Stroke V_L = 750 V (WF2) I_T = 1500 A (WF1) I_T = 150 A* Subsequent Strokes V_L = 375 V (WF2) I_T = 375 A (WF1) I_T = 75 A*
All equipment installations	Waveform 3 (WF3) – 1 MHz and 10 MHz	First Stroke V_T = 600 V (WF3) I_L = 120 A (WF3) I_L = 24 A* Subsequent Strokes V_T = 300 V (WF3) I_L = 60 A (WF3) I_L = 12 A*	First Stroke V_T = 1500 V (WF3) I_L = 300 A (WF3) I_L = 60 A* Subsequent Strokes V_T = 750 V (WF3) I_L = 150 A (WF3) I_L = 30 A*
Equipment installations routed in areas with composite skin/structure.	Waveform 4 (WF4)/ Waveform 5A (WF5A)	First Stroke V_L = 300 V (WF4) I_T = 1000 A (WF5A) I_T = 300 A* Subsequent Strokes V_L = 75 V (WF4) I_T = 200 A (WF5A) I_T = 150 A*	First Stroke V_L = 750 V (WF4) I_T = 2000 A (WF5A) I_T = 750 A* Subsequent Strokes V_L = 187.5 V (WF4) I_T = 400 A (WF5A) I_T = 375 A*
Multiple Burst			
Applicability	**Test Description**	**Internal Equipment Levels****	**External Equipment Levels****
All equipment installations	Waveform 3 (WF3) – 1 MHz and 10 MHz	V_T = 360 V (WF3) I_L = 6 A (WF3)	V_T = 900 V (WF3) I_L = 15 A (WF3)
Equipment installations that utilize short, low impedance cable bundle installations.	Waveform 6 (WF6)	V_L = 600 V (WF6) I_T = 30 A (WF6)	V_L = 1500 V (WF6) I_T = 75 A (WF6)

Table 2: CS117 test and limit levels for multiple stroke and multiple burst lighting tests (Table VII from Reference 7)

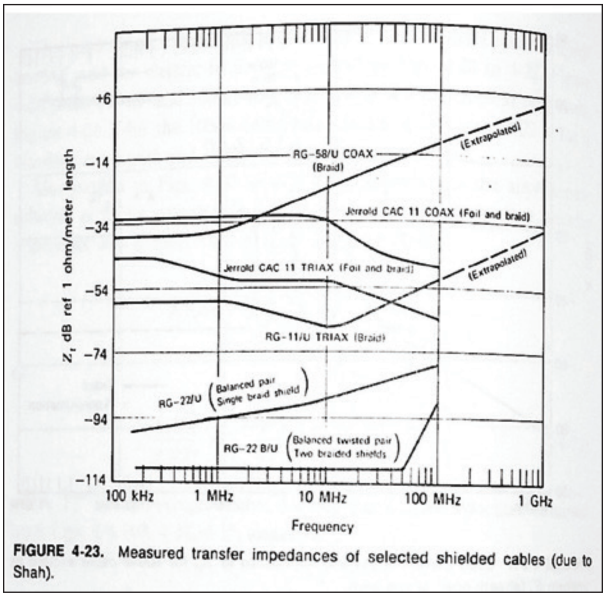

Figure 5a: Typical braided shield transfer impedance from Reference 9

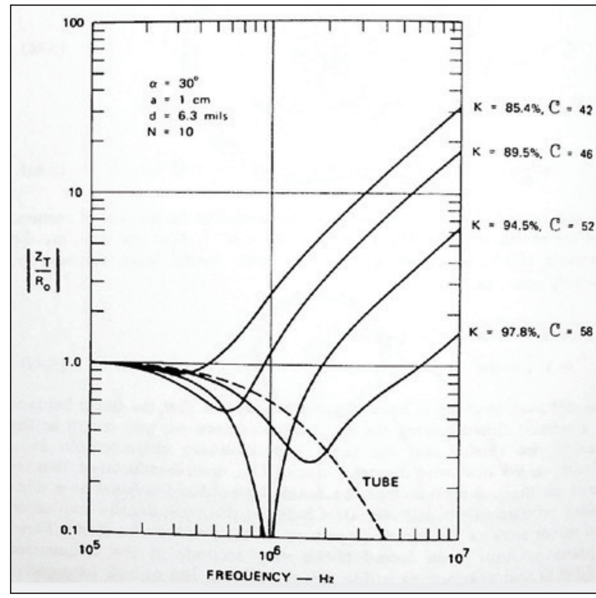

Figure 5b: Braided shield transfer impedance behavior from Reference 10

low as that of an equal length of braided shield. The difference measured is in the impedance of the termination.

Figures 7a and 7b show that degradation is strongly frequency dependent. At 100 kHz, degradation in transfer impedance is 15 dB, while at 30 MHz degradation is 37 dB.

Figure 8 shows another common application that requires a class R bond: the use of filters with capacitive bypass to the equipment enclosure, and hence to structure. In order for the capacitor to be able to short noise currents to ground and provide an attractive path for said currents instead of the circuit component behind the filter, the capacitor plus all connections to structure must be very low impedance.

Well before Reference 1 was released, Reference 11 was recommending 2.5 mΩ bonds for communication electronics, and when using bond straps, ensuring a maximum 5:1 length-to-width ratio.

Because class R bonds are somewhat indiscriminately specified and used, it is worthwhile to quote exact wording for this requirement in References 1–3, as tabulated in Table 3 at the end of this report on page ##.

Several interesting facts may be gleaned from this tabular comparison of the three different revisions of MIL-B-5087:

- The first two revisions express the rationale or purpose of the requirement. The final revision does not.
- MIL-B-5087A's unique wording explains the rationale for the class R dc bond. It is clear that low rf impedance is the goal, and that the MIL-B-5087 2.5 milliohm value is a means to an end, not an end-in-itself. The 80-milliohm value is hard to fathom, since it is less than a nanohenry at 20 MHz, the upper end of the specified range. It is likely not coincidental that the range over which the bond impedance is specified is that of the Reference 12 WWII-era BC-375 transmitter that was designed

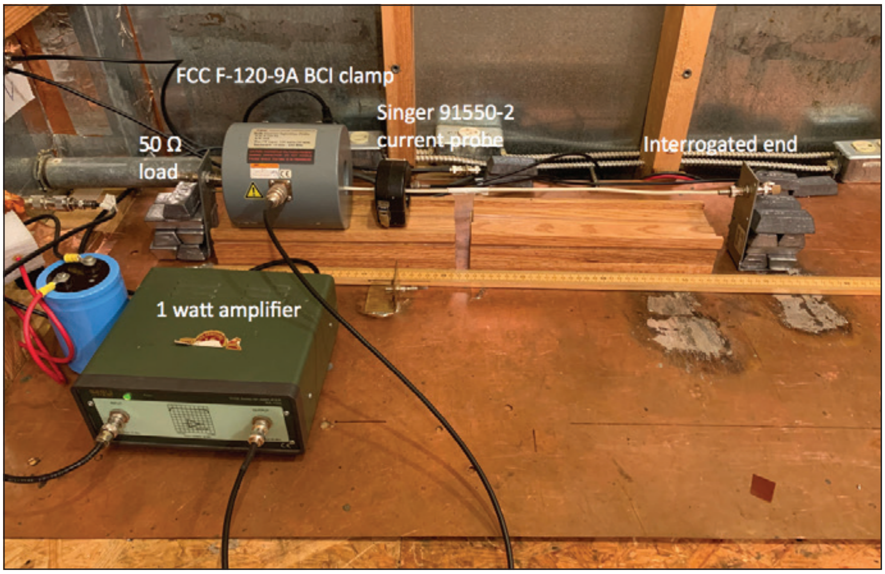

Figure 6a: Baseline transfer impedance measurement set-up

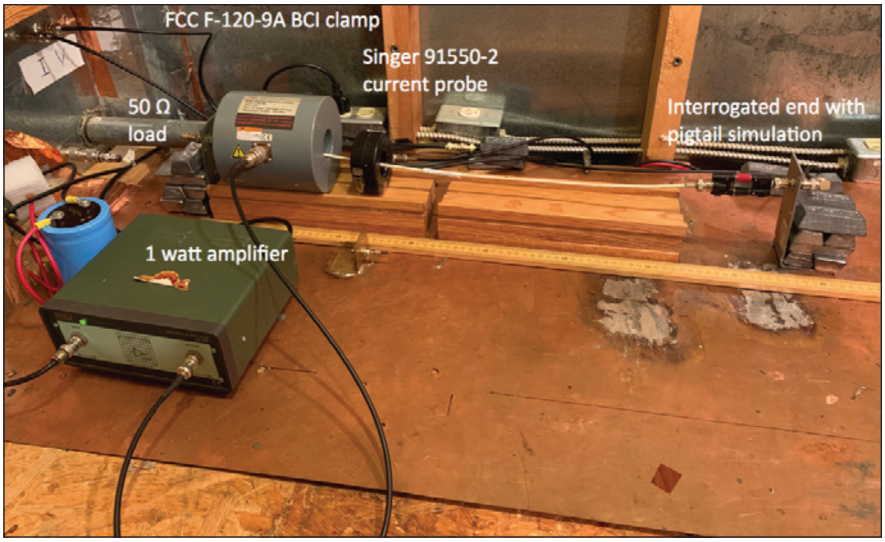

Figure 6b: Identical to baseline measurement except banana adapters added to simulate pigtail shield termination

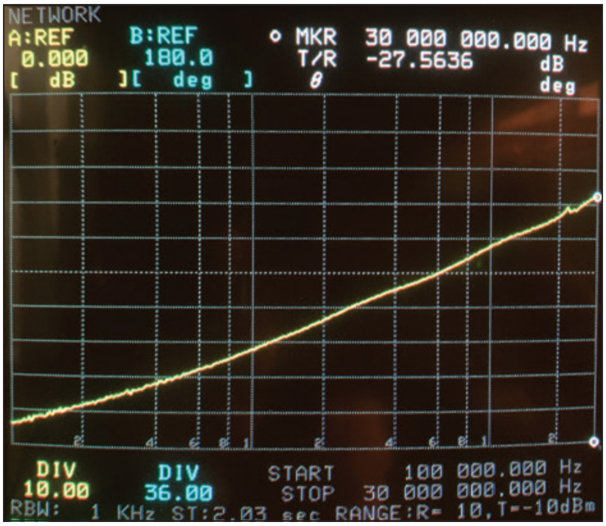

Figure 7a: Baseline transfer impedance test results for set-up in Figure 6a. Ordinate scale is transfer impedance in dB Ω. The network analyzer is taking the ratio of the coupled potential (T-input) to the induced shield current (R input).

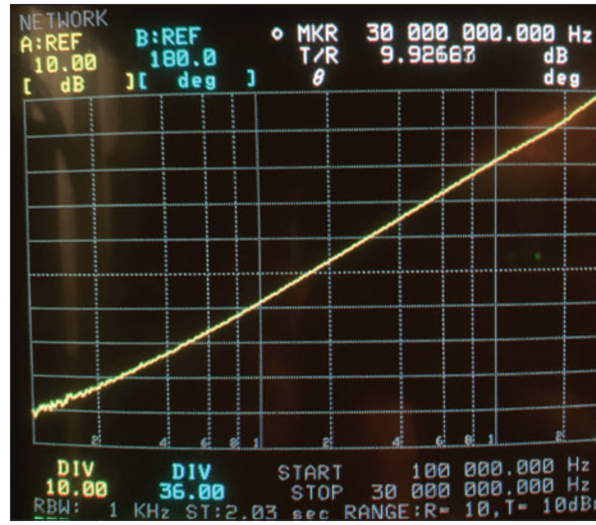

Figure 7b: Pigtail transfer impedance test results for set-up in Figure 6b. Ordinate scale is transfer impedance in dB Ω (note 10 dB offset in reference level)

to drive a high impedance antenna through an open-wire lead-in to the antenna.

- The addition of the rf impedance verification might have been the first such instance, certainly not the last. This particular approach has been attempted to be inflicted on many programs over the years, including the International Space Station. It doesn't end well. Very difficult to instrument in practice, the approaches of design in Reference 1 and dc measurement and design in Reference 3 work best, that is, the design is low impedance: faying surfaces, wide area to short length ratio bond topology.
- MIL-B-5087B is the only version to require a specific dc resistance (the now ubiquitous 2.5 milliohm requirement) for class R. This is the first place the value appears in any revision of MIL-B-5087, even though it was an end-to-end resistance requirement for lightning protection, but not so stated.
- It is often the case that a design looks good (faying surfaces) but doesn't quite meet the 2.5 milliohm target. Values will range from just over to several

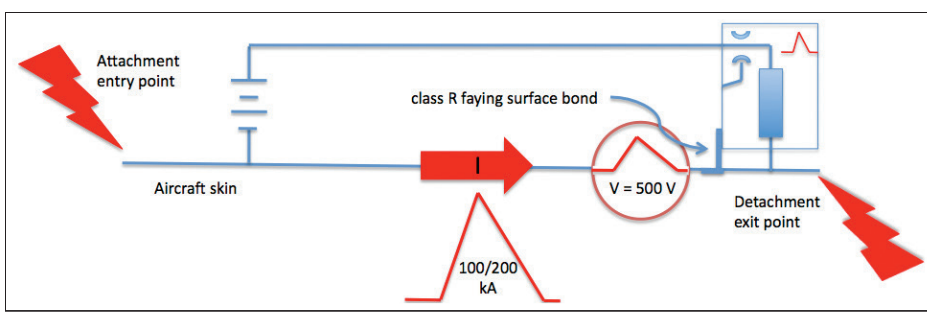

Figure 8: Effect of lightning attachment current on ground-referenced power

Ref.	Class R Bond Purpose	Class R Bond Requirement
1	3.2.1(d) Prevent the development of r-f potentials on conducting frames and enclosures of electrical and electronic equipment and on conducting objects adjacent to unshielded transmitting antenna lead-ins.	3.3.4.1 Equipment containing electrical circuits which may produce radio frequencies, either desired or undesired, must be installed so that there is a continuous low impedance path from the equipment enclosure to the aircraft structure. Bonding shall be accomplished by bare, clean metal-to-metal contact of all mounting plate, rack, shelf, bracket and structure mating surfaces so as to form a continuous, low impedance ground from equipment mounting plates. Bonding jumpers shall not be used. … 3.3.4.2 All conducting items having any linear dimension greater than 12 inches that are within 3 feet of unshielded transmitting antenna lead-ins shall have a low impedance bond to structure. Direct metal-to-metal contact with structure is desired, but if a jumper must be used, it shall be as short as possible.
2	Same as Reference 1 wording	3.10.1 Equipment containing electrical circuits which may produce radio frequencies, either desired or undesired, must be installed so that there is a continuous low impedance path from the equipment enclosure to the aircraft structure. Bonding shall be accomplished by bare, clean metal-to-metal contact of all mounting plate, rack, shelf, bracket and structure mating surfaces so as to form a continuous, low impedance ground from equipment mounting plates. If it is proposed that bonding be accomplished by other than metal-to-metal contact of the mating surfaces, the contractor shall demonstrate by a laboratory test that his proposed method results in an r-f impedance of less than 80 milliohms over a frequency range of 0.2 to 20 mc for 1 bond applied in the proposed manner. Bonding jumpers shall not be used… 3.10.2 All conducting items having any linear dimension greater than 12 inches that are within 1 foot of unshielded transmitting antenna lead-ins shall have a low impedance bond to structure. Direct metal-to-metal contact with structure is desired, but if a jumper must be used, it shall be as short as possible.
3	No rationale provided	3.3.5.1 All electrical and electronic units or components which produce electromagnetic energy, shall be installed to provide a continuous low-impedance path from the equipment enclosure to the structure. The contractor shall demonstrate by test that his proposed bonding method results in a direct current (dc) impedance of less than 2.5 milliohms from enclosure to structure. The bond from the equipment enclosure to the mounting plate shall also comply with these requirements, except that suitable jumpers may be used across any necessary vibration isolators. 3.3.5.2 All conducting items having any linear dimension greater than 12 inches or more installed within 1 foot of unshielded transmitting antenna lead-ins shall have a bond to structure. Direct metal-to-metal contact is preferred. If a jumper is used, the jumper shall be as short as possible. 3.3.5.3 Vehicle skin.- Vehicle skin shall be so designed that a uniform low impedance skin is produced through inherent rf bonding during construction. Rf bonding must be accomplished between all structural components comprising the vehicle, i.e., wings, fuselage, etc. Hatches, access doors, etc., not in the proximity of interference source or wiring shall be either bonded to or permanently insulated from vehicle skin, except for the protective static bond. Consideration shall be given to the design to operational vibration and resultant breakdown of insulating finishes or intermittent electrical contact.

Key: Unique to MIL-B-5087A   Unique to MIL-B-5087

Table 3: Tabulation of requirements in References 1-3

tens of milliohms. There is always a desire to waive the discrepancy with an excuse to the effect that the real goal is low rf impedance of a few ohms and the design by inspection meets that. The danger here is that a metal-metal faying surface bond should easily come in under 2.5 milliohms and, if it doesn't, a likely suspect is dirt, corrosion, or possibly inadequate etching away of paint or another surface contaminant. Long term, such impurities can contribute to bond degradation by allowing more impurities in (i.e., keeping the bond from being gas-tight), or galvanic action, especially combined with the bond not being gas tight.

- Similarly, bond meters come in different varieties. Those geared towards lightning verification often use quite high potentials, which can punch through a thin layer of insulating contamination and show a low resistance where a meter optimized for EMI work, with maximum potential of a few tens of millivolts, accurately records the behavior of the bond for EMI currents.
- MIL-B-5087B uniquely tries to make the aircraft skin a perfect ground plane and shield.
- The second paragraph in each version is in reference to the Reference 12 100 W rf transmitter that could output as much as 5000 V on an open wire antenna lead-in at a few hundred kilohertz; hence, capacitive coupling to nearby metal would have been issue.

ENDNOTE

1. Borrowed almost intact from Reference 8, section 22.