ACHIEVING EMC EMISSIONS COMPLIANCE FOR AN AERONAUTICS POWER LINE COMMUNICATIONS SYSTEM

Stephen Dominiak (1), Guus Vos (2), Theo ter Meer (2), Hanspeter Widmer (1)

(1) *Lucerne University of Applied Sciences & Arts (HSLU), Technikumstrasse 21, CH-6048 Horw, (Switzerland)*
Email:stephen.dominiak@hslu.ch, hanspeter.widmer@hslu.ch
(2) *National Aerospace Laboratory (NLR), Voorsterweg 31, 8316 PR Marknesse (The Netherlands),*
Email:guus.vos@nlr.nl, theo.ter.meer@nlr.nl

ABSTRACT

Transmitting data over the power distribution network – Power Line Communications (PLC) – provides an interesting solution to reducing the weight and complexity of wiring networks in commercial aircraft. One of the potential roadblocks for the introduction of this technology is achieving EMC emissions compliance. In this article an overview of the EMC conducted and radiated emissions testing for PLC-enabled aeronautics equipment is presented. Anomalies resulting from chamber resonances leading to discrepancies between the conducted emissions tests and the measured radiated emissions are identified and described. Measurements made according to the current version of the civil aeronautical EMC standard, EUROCAE ED-14F (RTCA DO-160F), show that PLC equipment can achieve full EMC emissions compliance.

1. INTRODUCTION

The transfer in commercial aircraft to electrical systems in order to develop the More Electric Aircraft results in significantly more wiring leading to a considerable weight, complexity and space allocation increase. One of the possible solutions to mitigating the increase in wiring is to enable data transmission over the power distribution network using Power Line Communications (PLC) technology. This solution has been investigated in the European Union project TAUPE (Transmission in Aircraft on Unique Path wirEs). Development has targeted the Cabin Lighting System (CLS) and Cabin Communication System (CCS) as reference applications with the A380 serving as the reference aircraft. The developed solution supports both 28VDC as well as 115VAC variable frequency systems. Ensuring that the PLC solution adheres to the relatively strict Electromagnetic Compatibility (EMC) emissions limits defined by civil aeronautics standards has been an important criterion and is the focus of this article.

PLC is a wired communication technology that is able to use power distribution networks for data transmission. This is accomplished by superimposing a modulated high frequency carrier signal over the standard alternating current (AC) or direct current (DC) power signal. Because of its robustness, PLC technology may generally be employed to reliably communicate over any shielded or unshielded wired networks that would not meet the transmission requirements with respect to delay spread, frequency flatness and noise.

The TAUPE project has successfully demonstrated the use of Broadband PLC (BPL) technology in commercial aircraft by achieving a Technology Readiness Level (TRL) of *four*. In order to achieve that goal, a commercially available PLC technology based on the European standard OPERA was used to develop PLC-enabled aeronautics equipment. Similar to the majority of BPL standards, the OPERA physical layer uses an OFDM modulation scheme with 1536 subcarriers supporting different channel bandwidth and carrier frequency configurations between 2 – 34 MHz, depending upon the transmission mode. Bit loading may be dynamically adapted between 2 – 10 bits per symbol based on real-time channel measurements supporting a maximum raw data rate of 205 Mbps.

2. PLC FOR AERONAUTICS APPLICATIONS

Technologies and standards for PLC are in a very mature state for in-home Local Area Network (LAN) as well as smart grid applications; however its use for aeronautics has received comparatively little attention. PLC has previously been investigated for use in military aircraft, spacecraft as well as commercial aircraft. Reference [1] provides an overview of much of this work. While the topic of EMC is discussed in the majority of these works, only [2] has concentrated specifically on EMC emissions addressing the use of PLC for differential DC power lines in spacecraft. To the best of the authors' knowledge, this is the first paper to publish the results of fully standards conform EMC emissions measurements for commercial aeronautics BPL solutions; thus validating many of the initial findings presented in [2].

The use of commercial BPL technology in aeronautics applications is unfortunately not straightforward. An aircraft PLC solution may suffer from a number of drawbacks including an adverse propagation channel, noise and EMC compliance. The PLC technology operates in a frequency band, which is seen as unwanted Radio Frequency (RF) emissions regarding EMC. In contrast to aeronautics radio equipment, PLC equipment must ensure that out-of-band *and* in-band emissions even in transmission mode are compliant. According to current conventions, a spectrum allocation, i.e. a declaration as intentional emissions, for a wired technology would not be permitted. Out-of-band emissions compliance can be achieved through sufficient hardware design effort, however comparatively little can be done in order to mitigate in-band emissions aside from reducing transmission power which may not be a suitable solution as it will limit performance. For this reason, the findings described in this paper will focus on reporting the in-band emissions from 2 – 30 MHz according to the selected transmission mode of the PLC equipment. Despite these challenges, the advantage of the PLC approach is that dedicated wiring and potentially equipment for data transmission may be completely removed, thus providing reduced weight and wiring complexity.

One major issue of using power distribution networks for data communications in the majority of commercial aircraft systems is related to their ramified single wire structure with a common chassis ground return path. Impedance conditions on such networks are highly varying and generally unpredictable compared to point-to-point topologies in which the impedance may be dominated by a single load. Such networks appear unfavourable for PLC in regards to the asymmetric transmission line structure with relatively high wire-to-chassis distance, undefined characteristic impedance, low noise cross talk attenuation in wire bundles and regarding conducted and radiated emissions and susceptibility of RF radiated fields as defined by existing aeronautical EMC standards such as the EUROCAE ED-14. Different investigations have shown that a single wire system may not support high speed data applications [3], [4].

For these reasons, an alternative approach has been developed that replaces the single wire by a double wire (bifilar approach), providing a homogenous and well defined symmetrical transmission line (differential mode - DM) for data, but maintaining the asymmetric mode with a common ground return path for the distribution of power (common mode - CM). It has been shown that this solution improves the performance of a PLC-based data network dramatically and is also one of the keys to achieving compliance with existing EMC norms [5]. These benefits can outweigh the drawbacks of the required double wire cabling. Without the presence of an existing differential power bus, this solution realizes benefits through differential data signal transmission without comprising the advantages provided by the common chassis ground for power distribution.

Two of the main advantages of the bifilar approach are directly related to the fact that the PLC signal is injected as a DM current on the bifilar wiring pair. This allows the PLC modems to operate with a higher transmission level as benefits can be gained with respect to modal conversion from DM to CM. According to existing conducted RF emission measurement concepts, the current clamp would be placed around both wires in the bifilar pair as they together represent one single power line. In the ideal case this would result in a complete cancellation of the measured PLC signal as the DM currents on each individual wire flow in opposite directions within the clamp. However, due to impedance asymmetries in the bifilar wiring network a fraction of the DM current from the PLC signal will be converted into CM current. This means that the effective transmission power will still be limited in order to be compliant to the applicable CM emission limits. However, the effective data transmission power may be increased above those limits by a factor equal to the modal conversion ratio. A statistical analysis of an ensemble of in situ measurements on a representative power distribution network has shown this ratio to be roughly 23 dB when considering the 80% percentile, which has been found adequate to define the characteristic CMR of a bifilar network [5]. Radiated emissions levels will also be reduced as they can be mainly attributed to CM currents in the relatively large loop created between aircraft wiring harness and ground (aircraft chassis).

3. EMC EMISSIONS TEST SETUP

In the TAUPE project, a series of PLC equipment prototypes were developed. These prototypes integrated commercial PLC modems, customized coupling and power supply modules along with existing CLS and CCS equipment. Highly symmetric inductive couplers have been developed which provide minimal modal conversion and assure that the CM power signal is divided equally among the bifilar wire pair. These couplers also provide an impedance conditioning on the network reducing the influence of the load impedance of the application equipment. All prototypes (Equipment Under Test – EUT) were subjected to equipment level EMC radiated and conducted emissions according to section 21 of EUROCAE ED-14E. Tests were performed at the EMC test lab of the National Aerospace Laboratory (NLR) in Flevoland, The Netherlands. NLR's EMC lab is fully accredited for ED-14 as well as MIL-STD-461 EMC tests by the Dutch Council for Accreditation.

The NLR EMC laboratory is equipped with a shielded room, measuring 8 m × 4.75 m × 5.5 m. The room is a semi anechoic room (SAR) compliant for MIL-STD-461 and ED-14 EMC testing. It is equipped with EDP 32 RF energy absorbers and ferrite tiles on the walls and ceiling. The shielded room contains a copper-plated test bench measuring 3m x 1m x 0.90m bonded to the wall of the chamber by 8 flat braided copper cables.

According the bifilar PLC approach, it was necessary to make minor modifications to the standard ED-14E conducted emissions test setup as is shown in Fig. 1. As a PLC modem will not generate a PLC data signal on its own, i.e. will not operate in a realistic mode, it was necessary to introduce a stimulating modem which was installed outside of the shielded test chamber. The PLC signal of the stimulating modem was coupled onto the bifilar wiring harness through the bifilar coupler which was located inside the chamber. The power signal was applied by the power supply connected to the bifilar coupler through the standard capacitor and standard Line Impedance Stabilizing Network (LISN). A bifilar wiring harness of length 10 meters was used. Consistent with the specification of a CM current measurement, the current probe was clamped around the twin wire pair.

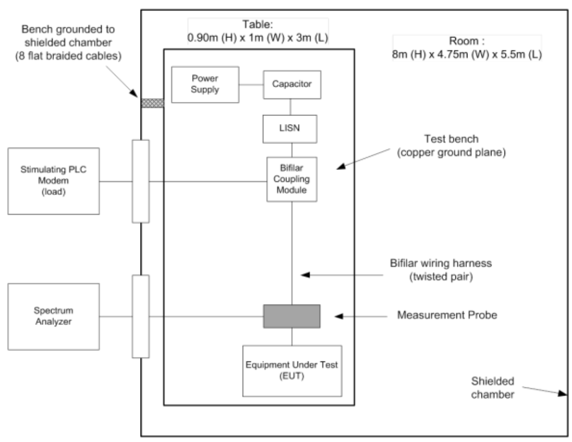

Figure 1. Modified EMC conducted emissions test setup for PLC equipment

A similar setup of the EUT was used for radiated emissions testing with the antenna location and placement following the specification defined in ED-14E. In this setup, a 1 meter long monopole antenna (commonly known as "rod" antenna) was used for measurements up to 25 MHz. The antenna counterpoise was grounded to the copper reference plane of the bench through a metal plate supported by a wooden tripod. A picture of the rod antenna setup is shown in Fig. 2. Measurements from 25 – 200 MHz were made with a biconical antenna (not shown).

The PLC modems in the EUT were configured to use a 28 MHz signal bandwidth between 2 – 30 MHz. No spectral mask was applied meaning that the PLC signal was transmitted with the maximum available power spectral density (PSD) of -50 dBm/Hz in that range. Such a high PSD would not be necessary to achieve a sufficient signal to noise ratio for the PLC transmission, but was used as a baseline for the EMC testing.

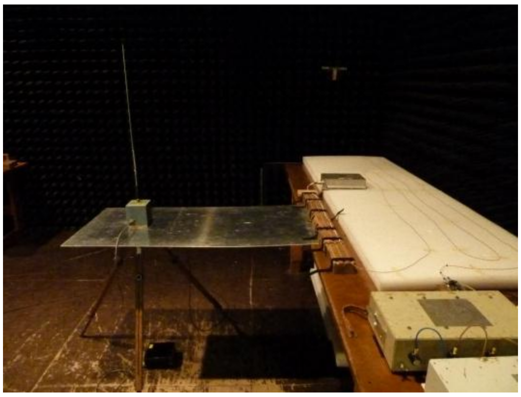

Figure 2. Radiated emissions test setup with the rod antenna

4. MEASUREMENT RESULTS

4.1. Conducted Emissions

The results from the conducted emissions measurement are shown in Fig. 4 in the appendix. The measured interface of the EUT has been designated as a category-M interconnecting bundle as the system is isolated from the primary power bus through filtering. However, the measured levels for conducted emissions show that the bifilar PLC equipment would still be compliant with the more restrictive power line interface limit (20 dBuA in the range between 2 – 30 MHz). Note that this is only measuring the CM component of the PLC signal. For comparison purposes, a DM current measurement was also made by clamping the current probe around a single wire of the bifilar pair. A partial measurement from 10 – 35 MHz of the DM current is shown in Fig. 8. The relatively flat spectrum as well as the drop off around 30 MHz of the OFDM PLC signal is apparent.

4.2. Radiated Emissions

In-band radiated emissions measurements are shown in Fig. 5 and Fig. 6. Contrary to expectations, two interesting anomalies were observed. The first anomaly was a high peak (resonance) in the radiated emissions 20 dB above the allowed limits at 12 MHz (see Fig. 5). An apparent null can also be observed around 18 MHz with the signal again peaking towards 25 MHz. Such a pronounced resonance peak was neither apparent in the CM nor the DM conducted emissions measurements. While resonances could potentially be caused by a combination of the coupling hardware and wiring harness, this effect would have to be observed in the conducted measurements.

The second anomaly observed was a strong discontinuity (15 – 20 dB) at 25MHz between the measurements with the rod and measurements with the biconical antennas which can be seen by comparing Fig. 5 with Fig. 6. The measured signal is approximately 5 dB above the limit for frequencies just below 25 MHz, but under the limit according to the measurements just above 25 MHz made with the biconical antenna. When considering the limits defined in the ED-14E specification, a change in slope of the limits occurs at 25 MHz, however no discontinuity is present. Therefore, one would expect that the different antenna test setups would be calibrated such that a major discontinuity should not be present.

5. DISCUSSION

The injection of the PLC signal in DM as part of the bifilar approach has played an integral role in reducing the amount of CM conducted current allowing the PLC system to operate with a relatively high PSD while still remaining compliant with the ED-14E limits for conducted emissions. It was believed that, due to the relatively small CM current of the PLC signal, the radiated emissions would also remain below the limits defined by ED-14E. On the contrary, due to the anomalies described in the previous section, this was not the case. These effects have the potential to provide a significant negative impact on the performance of the PLC system as the transmitted power level would have to be decreased by more than 20 dB in order to achieve compliance. In certification testing of standard aeronautics equipment, these resonance effects are less of a problem since emissions are unintentional, often narrowband and only occasionally close to the specified limits. Therefore, the probability of exceeding EMC limits due to a narrowband noise peak falling directly onto the resonance frequency or near to the discontinuity region is relatively low. However, for intentional use of spectrum on power lines such as in the PLC case, the effect is more pronounced particularly for the case of a broadband OFDM-based technology injecting power at constant PSD over a large band.

Similar issues with resonance effects have been previously observed and the inherent problems with the use of the rod antenna are known and have been reported in [6–9]. Resonances can be generated by a number of sources including the capacitance between the ground plane and the test chamber walls (C_G), inductance of the shield of the RF cable of the rod antenna (L_C) and inductance of the ground bonding of the test bench (L_G) as shown in Fig. 3. Cavity resonances are also possible due to deficiencies of anechoic treatments especially at low frequencies [6]. Resonances have been found to be dependent upon the size of the chamber, the size of the copper ground plane, grounding technique and the configuration of the RF absorber material. This has led to sometimes significant variations from one test site to another as reported in [8]. Larger chamber and table sizes have typically led to a lower resonance frequency.

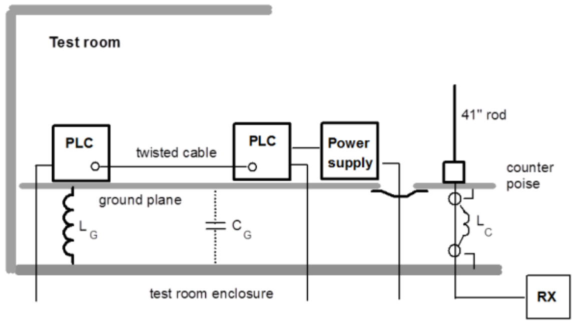

Figure 3. Potential sources of chamber resonances for the ED-14E test setup

Some mitigating techniques have been proposed. Reference [9] proposes the use of adequate absorber material which performs well even below the chamber resonance frequency. It is stressed that full ferrite tile coverage is necessary in order to provide an adequate solution. The standards bodies for both civil and military aeronautics have also reacted to these issues. The current version of the military standard MIL-STD-461F has defined actions to mitigate the resonance effect. The bonding strap between the rod antenna counterpoise and the test bench ground plane has been removed. The counterpoise is now bonded vertically directly to the floor through the shield of the antenna cable and the cable is wrapped around a ferrite bead (20-30 Ohms @ 20 MHz) in order to reduce the inductance of the shielded cable. The height of the antenna counterpoise is also lowered such that the centre point is 120 cm above the chamber floor.

In order to test the effectiveness of these changes, radiated emissions of the PLC EUT were again measured up to 25 MHz using the test setup according to MIL-STD-461F (see Fig. 7). Comparing this measurement to the ED-14E measurement shown in Fig. 5, it can be seen that the strong resonance at 12 MHz has been reduced by approximately 15 dB. For higher frequencies (above 18 MHz), the reduction is more around 5 dB. However, the strong discontinuity at 25 MHz compared to the measurement with the biconical antenna (Fig. 6) still exists. This result appears to be in line with the conclusions drawn in [9] in which the absorber characteristics of the chamber are the major contributing factor to such resonances.

The most recent version of the civil EMC standard (ED-14F) has diverged from the military standard in its approach. ED-14F has removed altogether the use of the rod antenna only requiring radiated emissions measurements for frequencies above 100 MHz. Conducted emissions measurements are furthermore extended from 30 MHz to 152 MHz and replace radiated measurements in characterizing the EMC emissions below 100 MHz. Taking into consideration the obvious discrepancies in the measurements with the rod antenna below 30 MHz, this appears to be a valid approach. In-band measurements with the biconical antenna clearly show the radiated PLC signal to be below the required limits as would be expected when considering the observed conducted emissions measurements.

6. CONCLUSION

PLC has historically received a bad reputation as a poor performer regarding EMC emissions. Achieving EMC compliance has, therefore, also presented a potential roadblock for the use of PLC in aeronautics applications. The TAUPE project has thoroughly investigated its use in commercial aircraft with positive results. Results of EMC conducted and radiated emissions have been presented in this paper. In-band conducted emissions have been found to be significantly below the designated equipment category for interconnecting bundles (> 20 dB) and even below that of the more restrictive power line designation. This is true even for a relatively high transmission PSD of -50 dBm/Hz. Radiated emissions measurements made according to ED-14E have produced anomalies in measurements made with the rod antenna below 25 MHz which were made apparent due to the nature of the OFDM PLC signal. An argument has been made that these anomalies result from chamber resonances due to deficiencies in the ED-14E test setup. These deficiencies highlight the inherent difficulty in performing reproducible and characteristic measurements of EMC emissions below 30 MHz. The currently applicable version of both the military (MIL-STD-461F) and civil (ED-14F) standards bodies have already reacted to this problem. The developed PLC-enabled aeronautics prototypes have been found to be fully compliant according to ED-14F. This can be considered as a significant result opening the door for the further development of PLC aeronautical solutions. The combined transmission of data and power on a single network may become a key factor in reducing the ever increasing wiring complexity and weight in future aircraft.

7. REFERENCES

1. O. Elgezabal and A. Sanz, “Modeling & simulating power line communications on civil aircraft: First steps,” in *Digital Avionics Systems Conference (DASC), 2010 IEEE/AIAA 29th*, 2010, p. 5–B.

2. F. Grassi, S. A. Pignari, and J. Wolf, “Channel Characterization and EMC Assessment of a PLC System for Spacecraft DC Differential Power Buses,” *Electromagnetic Compatibility, IEEE Transactions on*, vol. 53, no. 3, pp. 664-675, 2011.

3. V. Dégardin et al., “On the possibility of using PLC in aircraft,” in *Power Line Communications and Its Applications (ISPLC), 2010 IEEE International Symposium on*, 2010, pp. 337-340.

4. C. H. Jones, “Communications over aircraft power lines,” in *2006 IEEE International Symposium on Power Line Communications and Its Applications*, 2006, vol. 0, pp. 149–154.

5. S. Dominiak, H. Widmer, M. Bittner, and U. Dersch, “A bifilar approach to power and data transmission over common wires in aircraft,” in *Digital Avionics Systems Conference (DASC), 2011 IEEE/AIAA 30th*, p. 7.

6. D. Warkentin and A. Wang, “Shielded enclosure accuracy improvements for MIL-STD-461E radiated emissions measurements,” *Electromagnetic Compatibility, 2005. EMC 2005. 2005 International Symposium on*, vol. 2, pp. 404–409, 2005.

7. S. Jensen, “Measurement Anomalies Associated with the ‘41 Inch Rod’ antenna when used in Shielded Enclosures,” 2000.

8. C. W. Fanning, “Improving monopole radiated emission measurement accuracy; RF chamber influences, antenna height and counterpoise grounding (CISPR 25 & MIL-STD-461E vs MIL-STD-461F),” in *Electromagnetic Compatibility, 2009. EMC 2009. IEEE International Symposium on*, 2009, pp. 103–118.

9. D. Swanson, “Analysis of MIL-STD-461E and MIL-STD-461F RE102 Test setup configurations below 100 MHz,” in *Electromagnetic Compatibility, 2008. EMC 2008. IEEE International Symposium on*, 2008, pp. 1–11.

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APPENDIX: MEASUREMENT RESULTS

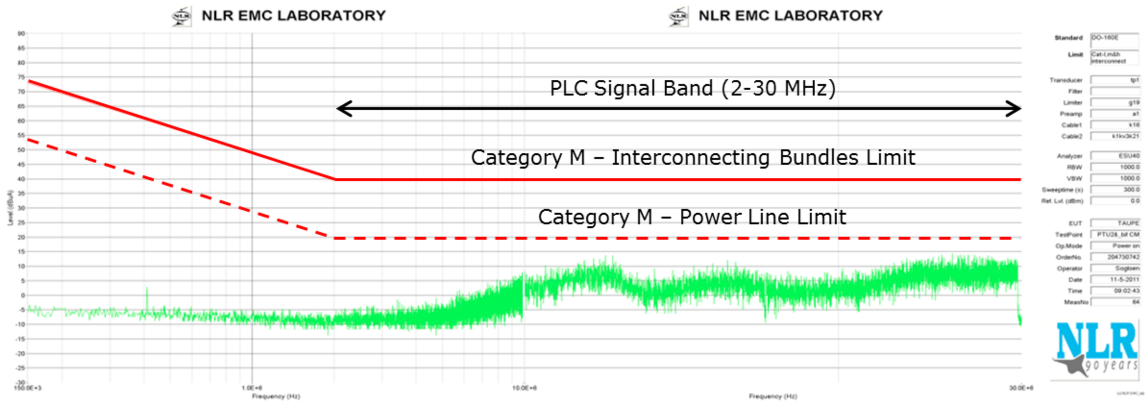

Figure 4. ED-14E conducted emissions measurement 150 kHz – 30 MHz

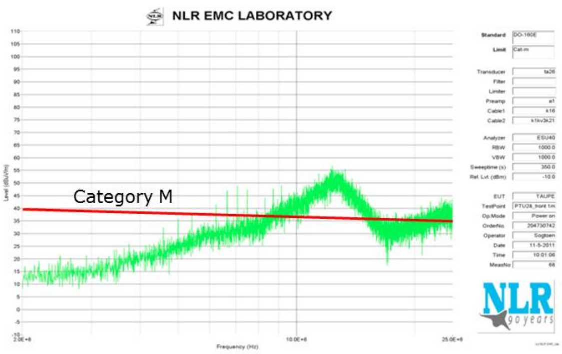

Figure 5. ED-14E radiated emission measurement 2 MHz – 25 MHz with rod antenna

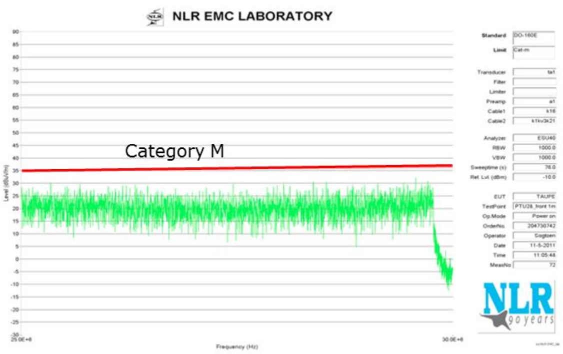

Figure 6. ED-14E radiated emissions measurement 25 MHz – 30 MHz with biconical antenna in vertical polarization

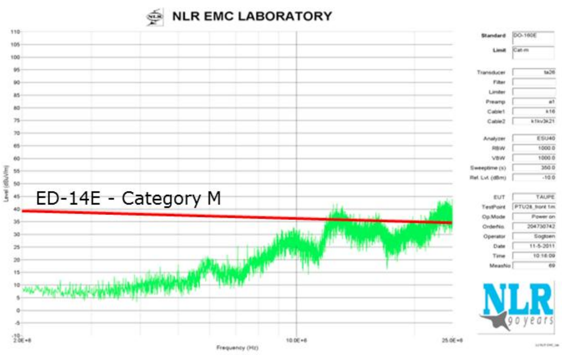

Figure 7. MIL-STD-461F radiated emissions measurement 2 MHz – 25 MHz with monopole antenna (ED-14E limit highlighted for comparison purposes)

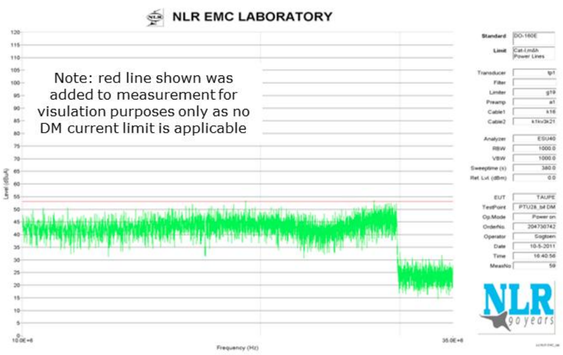

Figure 8. Differential mode current measurement 10 MHz – 35 MHz (current meter clamped around single wire of the bifilar pair)