An EMC Design Approach for Integrating COTS Equipment into an Existing Military Aircraft

Edward L. Kirchner
Northrop Grumman Corporation
2000 W. NASA Boulevard
Melbourne, FL, USA

Bruce D. Salati
Northrop Grumman Corporation
2000 W. NASA Boulevard
Melbourne, FL, USA

Abstract: Using commercial off the shelf (COTS) computing equipment in military aircraft applications may cause harmful electromagnetic interference (EMI) to other on-board systems, including communication and navigation equipment. An electromagnetic compatibility (EMC) design approach to successfully integrate COTS equipment into an existing military aircraft is described. The following system design and development steps are outlined: (1) requirements definition, (2) preliminary EMC analysis, (3) EMC control measure design, (4) COTS equipment EMI characterization tests, and (5) system level EMC verification.

INTRODUCTION

Computer Replacement Program Philosophy

The E-8C Joint STARS battle management aircraft is operated by the United States Air Force in a joint program with the United States Army. The original Joint STARS primary mission equipment was specified to be composed of equipment compliant with the requirements of MIL-STD-461, an electromagnetic emission and susceptibility standard that is often applied to United States military procurements. The Joint STARS Program Office, through the Computer Replacement Program (CRP), is replacing some of the Joint STARS aircraft's original primary mission equipment with commercial off the shelf (COTS) computers and network equipment. The selected computers and network equipment are representative of the latest technology available in the commercial marketplace; they contain no features for the control of electromagnetic emissions or susceptibility beyond those control measures needed to comply with Title 47 of the United States Code of Federal Regulations (47 CFR) Part 15 rules, or the European Union's EMC Directive.

With a COTS procurement effort, the very latest computing and network equipment can be introduced into the Joint STARS aircraft to support and enhance the Joint STARS mission. An additional enhancement sought by the Program Office was the development of a system architecture that would allow COTS hardware items to be replaced with upgraded versions as computer and network hardware technology advances. For the Computer Replacement Program to be successful, ways had to be found to integrate COTS equipment into the Joint STARS aircraft using techniques to achieve compliance with the demanding environmental conditions associated with the aircraft's mission. Temperature, altitude, shock, vibration, crash loads, cooling - the list of requirements is long. This paper deals only with the techniques used to achieve system level requirements for electromagnetic compatibility (EMC).

With COTS equipment procurement, strict control of electromagnetic emissions and susceptibility is not viable at the equipment level; modification of equipment to add interference control measures negates the cost, schedule and logistics advantages of the procurement. Imposing additional interference control standards as part of the equipment procurement effort will yield similar negative results. COTS is COTS.

For the Computer Replacement Program, the original Joint STARS approach to EMC control (imposing MIL-STD-461 at the equipment level as one of the primary EMC control measures) would not adequately address the introduction of COTS equipment into the aircraft. To effectively integrate COTS equipment into the aircraft, a new approach to EMC design had to be developed for Joint STARS.

Investigation of Other Military Aircraft using COTS Equipment

Anecdotal stories persisted within the Joint STARS Program Office reporting that COTS equipment was already in use on other Air Force aircraft, referred to as Aircraft X and Aircraft Y for convenience, with no degradation of system level EMC observed in either aircraft. Investigations revealed that both aircraft are platforms for systems composed partially of COTS equipment. What was not originally reported to the Program Office was the fact that Aircraft X does not share the same complex mission requirements imposed on the Joint STARS aircraft. Aircraft X, operated by a flight test squadron, is partially used as a test platform for new equipment; some of the equipment in use on Aircraft X is COTS.

Aircraft Y is more interesting from an EMC perspective; Aircraft Y's mission systems must be able to detect incoming signals near the noise floor of it's receiving systems, and must accomplish this over a wide range of frequencies. Some of the COTS equipment supporting Aircraft Y's receiving systems is actually composed of COTS circuit cards repackaged within enclosures designed to control emissions, susceptibility, and other flight related environmental concerns. The circuit cards are procured as COTS hardware items, but the equipment containing the COTS circuit cards has the look and performance of equipment specifically hardened for a military application. Some equipment within Aircraft Y was observed to be installed within RF shielded enclosures.

Clearly, the definition of what constitutes "COTS" has some variability. For Aircraft X, operated by a flight test squadron, COTS equipment can be any commercial product that does not threaten the functionality of the aircraft. For Aircraft Y, COTS equipment appears to be limited to commercial equipment hardened for operation within a military aircraft, or commercial circuit cards or equipment installed within enclosures fitted with EMC and environmental control measures. The Joint STARS Program Office chose to define COTS in the literal sense; every effort would be made to utilize equipment in a "right out of the box" configuration. For CRP, all efforts to control COTS equipment emissions and susceptibility would be applied at the system level.

EMC DESIGN STEPS

CRP System Requirements Definition

A crucial step in the integration of a system incorporating COTS equipment is achieving Customer/Contractor agreement on EMC requirements. For the Joint STARS aircraft, it was necessary to amend the original system specification to remove the equipment level MIL-STD-461/462 requirements to allow for the incorporation of COTS equipment. The system level specification was changed to require electrical and electronic equipment to meet "EMI interface requirements suitable for ensuring that system operational performance requirements are met"(1). This statement provides the flexibility to choose from many types of equipment: military qualified, military hardened commercial equipment or COTS. The original Joint STARS system level MIL-E-6051 requirement for self compatibility (MIL-E-6051 is a United States military standard formerly used to invoke system level EMC requirements on military procurements) remained unchanged.

While the new approach to achieving EMC provides greater flexibility in choosing equipment, increased responsibility is placed on the system designers in two areas. First, the system designers must make wise decisions regarding where COTS equipment use is appropriate, and where military hardened commercial equipment and/or military qualified hardware must be used. For example, if equipment is to be placed in an area where system level EMC control is not feasible, then COTS equipment is probably not a good choice. Second, it is essential that the system integrator prepare subsystem level requirements documents (e.g. specifications, source control drawings) which clearly state the EMI interface requirements necessary for each hardware item. As an example, hardware intended as a COTS procurement item will have the proper commercial requirements specified in its requirements document, while a military hardware item will have the exact MIL-STD-461 requirements clearly specified in its requirements document.

It is important to note that the original MIL-STD-461 requirements for Joint STARS equipment were imposed at levels appropriate for equipment installed within Air Force aircraft. Therefore, the levels were not as demanding as they might be for other aircraft. As an example, the radiated susceptibility requirement is 20 volts per meter. This comparatively low radiated susceptibility requirement gave the system designers a high degree of confidence that COTS equipment could be installed on the Joint STARS aircraft using system level EMC techniques which would not have unacceptably burdened the existing airframe. The absence of a severe external environment also focused the system designers' attention on intra-platform EMC interactions as the most serious threat to compliance with the system level EMC requirements.

Preliminary EMC Analysis

Naturally, there was debate within the Program Office about the extent of the threat to aircraft EMC posed by the introduction of COTS equipment. Joint STARS test aircraft experiments conducted prior to the Computer Replacement Program demonstrated that COTS equipment had caused interference to existing aircraft UHF communications receivers. This demonstrated interference led the CRP system designers to perform a preliminary EMC analysis to predict the extent of the interference that could be expected from COTS equipment. Results of this analysis were used to define the performance levels of EMC control measures needed mitigate the effects of predicted interference.

The EMC analysis assumed that any COTS equipment procured for use within the aircraft must be minimally compliant with United States 47 CFR, Part 15, Subpart B rules for Class A digital devices. This established a reasonable worst case upper limit for emissions from COTS equipment. COTS equipment with emissions above the Class A limit, in theory, should not be available in the commercial marketplace. Had Class B digital devices been assumed (having reduced emissions levels compared to Class A equipment) the worst case upper limit for emissions would be at a reduced level. Unfortunately, that desirable Class B compliance assumption would have restricted the pool of COTS equipment available to the system designers. A similar argument was made against limiting the procurement to only CE marked (i.e. compliant with the European Union's EMC Directive) equipment. Having equipment with predictable immunity performance was very desirable for the program, but not at the cost of reducing the pool of COTS equipment available to the system designers.

Cursory calculations revealed that COTS equipment having radiated emissions at the Class A limit would likely cause harmful interference to collocated aircraft communications and navigation systems, even with some allowance for the limited shielding effect of the aircraft's fuselage. This conclusion was supported by previous aircraft experiments showing that a COTS equipment item caused interference to communications receivers operating in the 225 MHz to 400 MHz band.

Further analysis considered source to victim path loss, aperture coupling, receiver noise figure, bandwidth, and a threshold criteria for interference. This analysis was performed for several "victim" communications receiving systems already installed on the Joint STARS aircraft. Again, results showed that minimally compliant Class A digital devices would cause harmful interference to receiving systems operating in the HF through UHF frequency ranges. Results also suggested that a modest level of system level shielding, on the order of 40 dB of electric field shielding effectiveness, would mitigate the predicted interference from the assumed worst case "source". To give insight into the analysis methodology, a cursory example is given:

<u>A UHF AM Example, 225 MHz</u>

1. Assume you are using the AN/ARC-225 UHF radio at 225 MHz, AM mode, which is intended to have a -102 dBm input signal (into 50 ohms) for 10 dB (S+N)/N.
2. Assume that an interfering signal 6 dB below the intended signal, -108 dBm, is present at the receiver input.
3. Assume that the RF cable to the AN/ARC-225 has no loss.
4. Assume an electrically small antenna is installed.

The effective aperture, A_e, for a short element antenna can be approximated by:

$$A_e = \frac{\lambda^2 (g_d)}{4\pi} \qquad (1)$$

g_d = 1.5, maximum directive gain, current element [2]

$$\text{At 225 MHz, } \lambda = \frac{2.99 \times 10^8 \text{ (meter)(sec)}}{225 \times 10^6 \text{ (sec)}} = 1.33 \text{ meter}$$

$$A_e = \frac{(1.33 \text{ (meters)})^2 (1.5)}{4\pi} = 0.211 \text{ meter}^2$$

5. Assuming the current element antenna to be matched to a 50 ohm load, a -108 dBm signal across a 50 ohm load corresponds to a signal power in watts of:

$$P = -108 \text{ dBm} - 30 = -138 \text{ dBW}$$
$$P = 10^{(-138/10)} = 1.58 \times 10^{-14} \text{ watts}$$

6. Assuming that the power delivered to a matched current element antenna is equal to the product of the incident power density in watts per square meter and the antenna's effective aperture, A_e, the incident power density can be calculated:

$$\begin{aligned} P_{di} &= P / A_e \qquad (2) \\ &= 1.58 \times 10^{-14} \text{ watts} / 0.211 \text{ meter}^2 \\ &= 7.49 \times 10^{-14} \text{ watts / meter}^2 \end{aligned}$$

7. Assuming that the incident signal behaves like a plane wave, the incident electric field intensity can be estimated as the square root of the product of the incident field intensity and the free space impedance (377 ohms):

$$\begin{aligned} Ei &= [7.49 \times 10^{-14} \text{ (watts / meter}^2\text{) } 377 \text{ (ohms)}]^{1/2} \\ &= 5.3 \times 10^{-6} \text{ volt / meter} \end{aligned}$$

This is a small incident field intensity when compared to the 21.0×10^{-5} volt / meter emissions that are allowed at a distance of 10 meters from Class A COTS computing equipment that is marginally compliant with 47 CFR, Part 15, Subpart B at a frequency of 225 MHz. If this example were in free space, with the Class A COTS computing equipment 10 meters from the UHF antenna, interfering signals (S_{int}) from the computing equipment could be 32 dB more intense than the assumed minimum signal needed to degrade receiver performance:

$$S_{int} \text{ (dB)} = 20 \log \frac{21.0 \times 10^{-5} \text{ (volt / meter)}}{5.3 \times 10^{-6} \text{ (volt / meter)}}$$

$$S_{int} \text{ (dB)} = 32 \text{ dB}$$

This implies that an additional 32 dB of path loss (over that already included in the 10 meter path) is needed between the assumed worst case Class A COTS computing equipment and the UHF antenna at a frequency of 225 MHz, if interference free operation is to be achieved.

Similar analyses were performed at all frequencies relevant to the Joint STARS aircraft.

EMC Control Measure Design

With analysis results and experimental evidence indicating that COTS equipment could cause harmful interference to collocated communications and navigation systems, an approach to emissions and susceptibility control had to be developed to design for system level EMC. EMC control measures were selected for three general equipment installation scenarios, which are described in the following paragraphs.

Equipment Installed Within RF Shielded Rack Enclosures

Installing COTS equipment within RF shielded rack enclosures was chosen as a practical system level EMC control measure. The COTS equipment could be installed within the RF shielded rack enclosures without requiring any modifications that would negate the advantages of a COTS procurement. Analysis showed that 40 dB of electric field shielding effectiveness, easily achieved with lightweight shielding materials, was sufficient to address both radiated emissions and radiated susceptibility issues consistent with the worst case assumption of Class A compliance. Further, the application of EMC control measures at the RF shielded rack enclosure level provides the required capability to periodically upgrade the performance of the primary mission equipment by installing enhanced COTS equipment as it becomes available.

Equipment Installed Within Existing Non-Shielded Operator Workstation Consoles

The Joint STARS aircraft contains multiple Operator Workstation Consoles. The consoles are nearly identical from an internal equipment perspective; EMC control measures applied to one console would be appropriate for any other console. The existing consoles are non-shielded; to upgrade the consoles to include RF shielding would have imposed a difficult cost burden on the Program Office.

COTS equipment will be installed within the consoles, but only COTS equipment that has emissions and susceptibility performance appropriate for installation within the non-shielded structures. A characterization test program has been developed to determine the suitability of candidate COTS equipment items. This approach limits the pool of COTS equipment available to the system designers, but is viable as the number of hardware items to be installed within each console is small. Presently, two out of the four hardware items to be installed within the consoles are COTS equipment items. Their emissions and susceptibility profiles, demonstrated by characterization testing, are similar to what would be expected from MIL-STD-461D compliant equipment. The remaining equipment items, having other program specific requirements, are to be procured as military hardened commercial equipment.

Equipment Installed Within Existing Non-Shielded Rack Enclosures

Two Computer Replacement Program hardware items are to be installed within non-shielded rack enclosures. Both items are non-development hardware items (NDI) that are procured as MIL-STD-461 compliant.

Implementation of RF Shielded Rack Enclosure Design

The RF shielded rack enclosure design was a collaborative effort among all members of the system design team. Central to the design was the need to achieve the desired level of shielding effectiveness, while maintaining compliance with program requirements for: weight, cooling, shock, vibration, maintainability, ease of access and maximizing RF shielded rack enclosure interior volume.

The comparatively modest shielding effectiveness goal allowed readily available commercial shielding materials to be used in the design of a lightweight aluminum RF shielded rack enclosure. The availability of low compression force gasket materials supported the development of lightweight door panels and a low force door closure mechanism. RF shielded rack enclosure interface EMC control measures include: filtered connectors, power line filters, waveguide below cutoff optical fiber entry, and effective interface cable shield termination techniques. It should be noted that interface hardware treatment is a particularly critical element of an RF shielded rack enclosure design [3]. Poor EMC control measure selection for interface hardware can create fortuitous EMI conduction paths which will destroy the shielding effectiveness of an otherwise excellent design. The design of the CRP RF shielded rack enclosure allows interface EMC control measures to be modified or replaced to allow for future upgrades of COTS equipment. The CRP enclosure shielding design and selected shielding materials should provide 60 dB of shielding effectiveness for recently constructed enclosures; the shielding performance is expected to degrade to no less than 40 dB during the life cycle of the aircraft.

The detailed design effort for the RF shielded rack enclosures was a process that involved extensive communication between all members of the system design team. The design process required an assessment and discussion of alternative design techniques and materials appropriate for airborne systems. Achieving the desired level of RF shielded rack enclosure shielding effectiveness could not be viewed as an isolated requirement; the enclosure would have to meet all of the other cost, schedule, manufacturing, and environmental requirements established for the program. The result was a coordinated design for compliance with all program requirements.

COTS Equipment EMI Characterization Tests

Characterization testing was performed on selected COTS equipment to validate the overall EMC design approach. Characterization methods were extracted from MIL-STD-462D and RTCA/DO-160D; these test methods are accepted by military and civilian aviation interests and are appropriate for equipment that will be installed on or near metallic ground plane structures. Tests were selected to provide a practical and economical characterization methodology. The conducted emissions, radiated emissions, conducted susceptibility, and radiated susceptibility performance of COTS equipment was examined. Slight tailoring of measurement system bandwidth was chosen to approximate detection of signals by primary mission equipment receivers. Testing was performed in a Northrop Grumman shielded facility configured to simulate the test conditions of MIL-STD-462D and RTCA/DO-160D.

Emissions Testing Results

As noted, for the Joint STARS CRP program the system designers are predominantly concerned with potential EMI resulting from interaction of COTS equipment emissions with other aircraft equipment. At the time of this writing, test results showed better than expected performance from many COTS equipment items; some comparing favorably to the MIL-STD-461D radiated emission limits for Air Force, Aircraft Internal Equipment. Selected results for six candidate COTS equipment items are summarized in Figure 1.

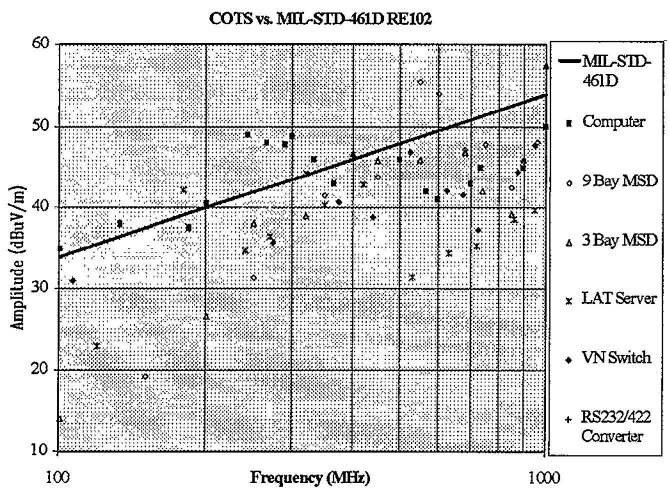

Figure 1. Radiated Emissions Test Results

General Characterization Results

All candidate COTS equipment items examined to date will operate within the RF shielded rack enclosures with no interference to aircraft systems predicted. Additionally, the RF shielded rack enclosures attenuate the aircraft's internal electromagnetic environment sufficiently such that candidate COTS equipment items are predicted to function within the RF shielded rack enclosures without concern for electromagnetic susceptibility. Characterization testing results also revealed that two candidate COTS equipment items could be integrated within the non-shielded operator workstation consoles without degrading system level EMC.

Reasons for Better Than Expected Characterization Results

Some candidate COTS equipment items were marked as compliant with Part 15 rules for Class B digital devices. This was unexpected; the candidate equipment, intended for advanced computational capability and high rate data transfer, was not typical of equipment expected for use within a residential environment. Apparently, some COTS equipment vendors are more aggressive with their compliance programs than had been anticipated.

Some of the candidate COTS equipment items were CE marked. These COTS equipment items are compliant with emission and immunity standards offering the user additional value over equipment that is compliant with 47 CFR Part 15 rules only. The desire to reach export markets may explain the aggressive compliance approach taken by several COTS equipment vendors.

Ground plane proximity may play a role in the better than expected characterization test results. COTS equipment is normally tested to simulate operation on a non-metallic structure. Characterization testing was performed with the COTS equipment installed on a MIL-STD-462D and RTCA/DO-160D compliant metallic ground plane to simulate aircraft installation conditions.

High speed digital equipment performed well from an emissions and susceptibility perspective. Fears that this equipment would have exceptionally high emissions in the VHF and UHF frequency range were unfounded. Our belief is that the printed wiring board interconnections for high speed digital circuits are designed as controlled impedance transmission lines. Without transmission line interconnection schemes, most high speed digital circuits would not work at all. A desirable benefit of well designed transmission line interconnection schemes is reduced board level electromagnetic emissions and susceptibility. A similar argument can be made for the printed wiring board decoupling needed to support high speed digital circuit operation; again, there is a board level emissions and susceptibility control benefit.

Reasons for Worse Than Expected Characterization Results

COTS equipment without CE marking was not expected to fare well during susceptibility testing. Our general assumption was that domestic COTS equipment would fail radiated susceptibility testing at the 1 volt per meter exposure level. Testing was conducted at the 20 volt per meter level; a surprising number of equipment items withstood the challenge. Most performed well above the 10 volt per meter level. A few failed at less than 1 volt per meter.

The equipment items that failed at less than 1 volt per meter often failed because incident electromagnetic energy coupled into low and moderate data rate interface ports. The addition of external filtered adapters at these ports was observed to improve the performance of these devices. Filtered adapters are a system interface control measure; the addition of these low pass filtered adapters to equipment connectors does not alter the "COTS" status of an equipment item.

Completely Unexpected Characterization Results

One of the non-COTS equipment items, designed for MIL-STD-461D compliance, was subjected to characterization testing. Emissions performance was worse than some candidate COTS items, susceptibility performance was below specified levels. The item had the look and feel of an equipment item hardened to military specifications, but the EMC control measures were not well implemented. Metallic enclosure sections were joined with non-conductive gaskets, interface ports had no protective control measures and were susceptible to incident energy. The item was returned to the vendor with advisement.

One of the COTS equipment items intended for use in the Operator Workstation Consoles performed well during characterization testing, but would probably have been a marginal radiated emissions performer for installation within the non-shielded console. Emissions leakage was traced to a cabinet slot opening that could be sealed with two small segments of conductive spring fingerstock. Opening each equipment item to add the fingerstock would alter the "COTS" status of the device. The equipment vendor, on learning that a simple corrective measure would reduce emissions in the COTS product (already a Class B digital device), chose to include the corrective measure in his production product.

System Level EMC Verification

As in the case of the CRP system requirements definition, it is also essential to achieve Customer/Contractor agreement on the CRP EMC Test Plan/Procedure. The system level electromagnetic compatibility demonstration approach successfully used for the original Joint STARS aircraft remains valid for CRP.

Requirements compliance verification for the installed equipment will be demonstrated by performing a system level EMC test on the aircraft, as specified by the system level EMC requirement, MIL-E-6051. This demonstration is intended to show that there are no unacceptable interactions between equipment integrated into the Joint STARS aircraft under the CRP contract and existing aircraft systems. During the test, aircraft electrical and electronic equipment will be operated normally; these will be monitored as potential interference "victims". Then, the new CRP equipment will be exercised as interference "sources" in order to assess their effect on system EMC.

CONCLUSION

The challenge of integrating COTS equipment is a reality facing all designers of military systems: the United States Department of Defense has directed the defense industry to exploit the significant cost and performance advantages gained by using COTS equipment. This paper has described how commercial electronic products can cause harmful interference to communication and navigation receivers used within a military aircraft, unless an EMC methodology for COTS equipment selection and integration is developed. While the use of COTS equipment imposes unique EMC challenges in the design of airborne systems, many of these challenges can be met with relative ease if a sound EMC design approach is adopted at the early stages of a COTS equipment integration program.

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