Modern Space Craft – Antique Specifications

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Abstract

Spacecraft now and of the future are being controlled by EMC requirements of the past. Little has been done by the launch vehicle/spacecraft manufacturers to abandon MIL-STD-461C which was released in 1986 because most of the electronics equipment being used aboard current launch vehicles is approved by similarity and heritage to MIL-STD-461C and its predecessors. Twenty years later these electronic equipment items are still not tested to today's MIL-STD-461E requirements because there is a risk that the items will fail to meet the requirements and thus the cost will increase if it becomes necessary to redesign the equipment. That cost is insignificant compared with the cost of losing an entire mission!

In the 20 years that have elapsed since MIL-STD-461C was released, the EMC environment has undergone major changes. High speed digital devices have been created that have fundamental clock and bus frequencies that span the entire LV/SC frequency range from the Flight Termination Systems through C and S-Band telemetry. Personnel involved in ground operations routinely carry and use hand held transceivers and cellular telephones close by sensitive electronics equipment. There are now many more orbiting receivers and emitters, plus range assets have increased dramatically since 2001. It's way past time to bring requirements up-to-date!

I. Introduction/Purpose

Early spacecraft EMC requirements were based on the RF environment and equipment sensitivities at the time of their creation.

Over the last 40 years, the RF environment has changed dramatically, but much of the LV avionics equipment is still being approved by similarity to the older equipment. Although the components that are used in the equipment design are markedly different their function remains the same and that is being used to justify that the equipment is similar to the previous equipment. The components and equipment really have under gone major changes but LV/SC EMC requirements have not kept pace with these changes. That has increased the risk of EMC problems.

This presentation compares the radiated heritage requirements with MIL-STD-461C and MIL-STD-461E; provide examples of the emission levels from the RF environment and addresses the needs to have modern spacecraft designed to meet modern systems level EMC requirements.

Many of the changes to MIL-STD-461 are in the conducted test requirements that measure power ripple and transient data. While these changes are important, the emphasis of this paper is on the radiated susceptibility limits.

II. 50 years of continuity and change

The RF environment is continuously changing. Although the first recorded incidents of an EMC problems were being reported in the late 1800's, it wasn't until the Federal Radio Commission began regulating AM Radio (the primary electronic device of the time) in 1927 that any controls were enacted on the commercial broadcast industry. These controls were upgraded in the Telecommunications Act of 1933 and in 1934 the US Army Signal Corps released SCL-49 entitled "Electrical Shielding and Radio Power Supply in Vehicles" New electronic devices continued to be developed driving changes in the RF environment accompanied by new standards and finally in January 1958 with the launch of Explorer I we have the beginnings of the space age.

The early launch vehicles have evolved into two major families – the Atlas and the Delta. As shown in **Figure 1** these are majestic vehicles. The EMC requirements for the hardware comprising the first launches of the predecessors to today's versions of the Atlas and Delta primary launch vehicles were based on MIL-I-6181 (1953) and MIL-STD-826 (1964). These were the foundation documents for MIL-STD-461(1967). Because of the changing RF environment this standard has continued to be developed and the MIL-STD-461C (1986) revision which is currently being used for today's

LV/SC looks nothing at all like today's MIL-STD-461E (1999) which is already 6 years old. A comparison of the radiated requirements of MIL-STD-461 along with the systems requirements from MIL-STD-464A and the newly proposed MIL-STD-1541B, are shown in **Figure 2**. The most significant change has been the radiated susceptibility requirement levels. Since the creation of MIL-STD-461 the radiated susceptibility levels have increased by 46 dB with an increase of 32 dB occurring since the MIL-STD-461C revision was released. Every revision to MIL-STD-461specification has increased the Radiated Susceptibility Levels while reducing the Radiated Emission Levels thus reflecting the real world situation of an increasingly noisier RF environment.

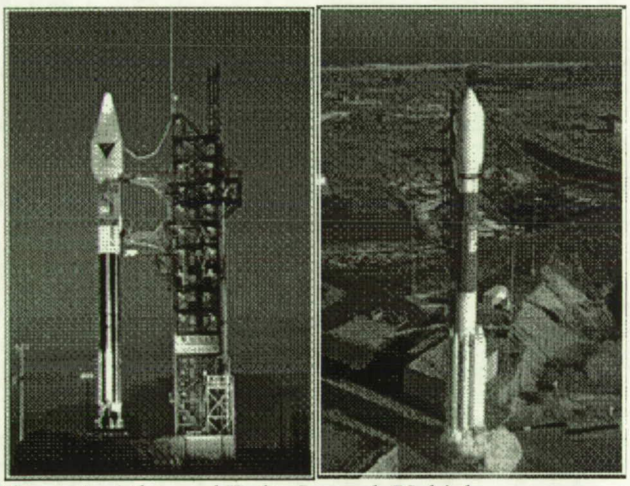

Figure 1. Atlas and Delta Launch Vehicles

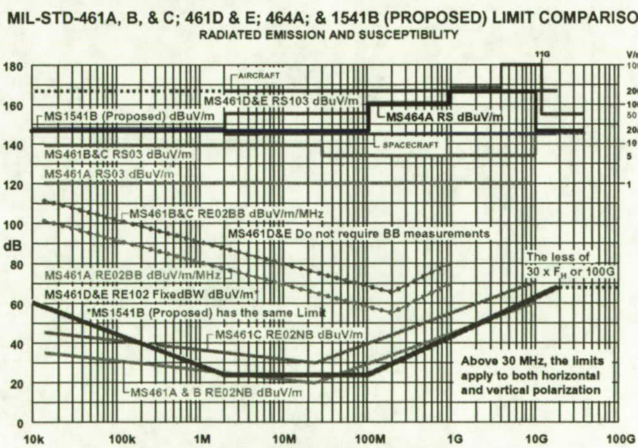

Figure 2. Mil Standard Radiated limit comparison

It is not true that a collection of hardware where each item meets the MIL-STD-461 requirements will result in a system that meets the same requirements. In addition, systems that are used in space applications have some peculiar requirements that ground based systems don't have. The system needs to work and perform its intended function no-matter-what. After all it is very difficult to implement a fix when the malfunctioning device is in low earth orbit or beyond. It is for that reason that EMC requirements are levied against the system. MIL-E-6051was used for early LV/SC and required subsystems to meet MIL-STD-461. Then in 1973, MIL-STD-1541 (1973) was released. This standard was specifically developed for LV/SC systems and written as a companion document for MIL-STD-461A. It did retain some of the characteristics of MIL-E-6051 in that the system had to be functional in an environment that was essentially defined by adding 6 dB (20 dB for ordnance) to the worst case emission profile.

The MIL-STD-1541A (1987) revision was released as a companion to MIL-STD-461C (1986) and added power system transient controls, design requirements for composite structure, and controls on interference that might result from spectral and orbital congestion. There were minor changes carried over from MIL-STD-1541 relative to the MIL-STD-461C (1986) radiated emission requirement and no changes to the radiated susceptibility requirement. That is where we are today. Stuck back in time 20 years with some items that have been previously approved by similarity still meeting 40 year old requirements.

It is in everyone's best interest to ***test like you fly*** but the players are not doing this because it costs money to prove that each major element of the lv/sc/launchpad is self compatible a-n-d also compatible with the environments that may be encountered during manufacture, transportation, and launch. What does not appear to be being considered is that the 3 year setback and loss of one $800,000,000.00 LV/SC system buys a lot of EMC engineering services . . . even at today's prices!

MIL-STD-461 continues to be revised to keep pace with both the ever changing environment and the advances in hardware with the MIL-STD-461F revision currently underway.

III. RF Environment

Although we take computers and other sophisticated electronic systems for granted these days, the integrated circuit was not invented until 1958 and Intel's first 4004 cpu arrived in 1971. Since then, a multitude of new devices and systems have been developed which either intentionally or unintentionally compete for space in the RF spectrum. The higher level unclassified RF emitters that we are most concerned with at the launch sites and in orbit are listed in Table 1.

SAMPLING OF THE RF ENVIRONMENT

- **Ambient**
- **AM/FM/TV Broadcast**
- **Amateur Radio**
  - Frequencies
    - 160m/1.875M
    - 80m/3.75M
    - 40m/7.5M
    - 20m/15M
    - 15m/20M
    - 10m/30M
    - 6m/50M
    - 2m/144M
    - 220MHz
    - 440MHz
    - Other bands to 300 GHz
  - Power output 1500w PEP
- **Bluetooth 2.4 GHz**
- **Cell Phones/Pagers**
- **Citizen's Band**
- **Commercial Radio**
  - Trunking Radios
- **Hybrid/Electric Powered Vehicles and Equipment**
- **Ignition systems**
- **Indirect Lightning**
  - HF and EF
- **Military Communications**
- **Notebook computers**
- **PDA's**
- **Range Radars**
- **Shipboard**
  - Radar, VHF, and SSB
- **Tools**
- **Wireless LAN**
  - 802.11

Table I - Chart of all the different RF emitters

The intentional frequencies used by LV are relatively narrow, consisting principally of the FTS UHF band around 420 MHz, and C-Band and S-Band microwave frequencies around 2.2 and 5.6 GHz. The SC on the other hand may have other types of RF devices and specialized low level sensors that may respond to RF energy at many different frequencies. These frequencies may be generated directly by the culprit RF sources or may result from non linear mixing of multiple sources.

Other contributors to the RF environment are range controlled assets and transmitters external to KSC. There is documentation available that provides the levels of these controlled sources and of other fixed known sources such as weather radars and TV stations. The range controlled sources are often masked or otherwise controlled to provide a defined RF environment at various launch sites. Known sources can be planned for and incorporated in test planning. It is important to note the daily KSC monitoring stations have detected levels from off site emitters that are theoretically beyond the horizon and at times detected levels higher than the theoretical free space maximum. This is possibly due to multipath and atmospheric ducting effects. That is one reason why margin is needed. An envelope of these sources is also more useful than using a lower baseline and testing to the individual sources as new range sources can be added late in the program and typically have to meet the standard range limit for the given launch site. 20 V/m is typical. Although radars can be controlled to these limits, there is sometimes the need to implement spacecraft limits bypass. In other words, if there is active tracking on a launch and an incident occurs, tracking the vehicle will be a priority over honoring the limits. Certain range tests can also be performed without radar limits in place. Coordination of these limit bypass periods is necessary.

Other RF transient sources are from shipboards near launch site ports and form air traffic. Notices are sent out to control these emitters on launch day. These notices are more effective for aircraft than for ship/boat emitters and there is no general protection from these emitters during launch site processing.

Other RF Sources External To KSC

KSC is a confined/controlled access location limited to individuals with permission to come on site. Uncontrolled individuals cannot get closer than the perimeter fence or the coast line. The closest separation distance is estimated to be at the coast line and is approximately 1000 meters. At this separation distance, it would require > 50kW to upset a non RF device that was sensitive at levels of ≥ 1 V/m. The current licensed transmitters capable of generating RF power levels of that magnitude are identified in range documentation. There are, however, ISM devices that can generate greater than 50kW, but these would likely be identified on local KSC RF monitoring stations if the items are used continuously for several minutes.

Other RF Source Internal To KSC (Handhelds and Land Mobiles)

Co-Site RF susceptibility for non RF equipment could be a problem if exposed to high power RF sources, if those sources were brought close to sensitive electronic devices. The most likely RF source candidates would be land mobile or hand held radios. These could be KSC Operations or Amateur Radio. Amateur radio stations can transmit with up to 1500 watts peak envelope power on frequencies in designated bands from 1.8 MHz to over 300 GHz. The FCC does not control antenna gain or placement at Amateur stations and some emission types such as phase or frequency shift keying have high duty cycles which results in higher average power levels. Thus is possible that an Amateur Radio station could have an ERP of 15 kW or more.

However, most Hams operating mobile at frequencies of 28.0 MHz and above restrict their operations to 50 to 80

Watts or less because of the limitations of commercially available equipment. Those operating mobile at frequencies of 28 MHz and below generally restrict their operations to 200 Watts or less because of FCC power restrictions in the Novice Bands and the limitations on primary battery power in their vehicles (full output power requires approximately 22 amps). A 200 watt transceiver will produce 1 V/m at 250 feet and 10 V/m at 25 feet. An 80 Watt transceiver will produce 1 V/m at 160 feet and 10 V/m at 16 feet. It is highly unlikely that an Amateur mobile station would/could be brought within 250 feet of sensitive electronics equipment installed on a LV.

The greatest risk comes from the 5 to 7 watt hand held transceivers. Although operational controls exist, these devices are easily carried and can be brought very close to the sensitive equipment where RF field strengths are high enough to cause equipment susceptibility (refer to chart for separation distance vs. power).

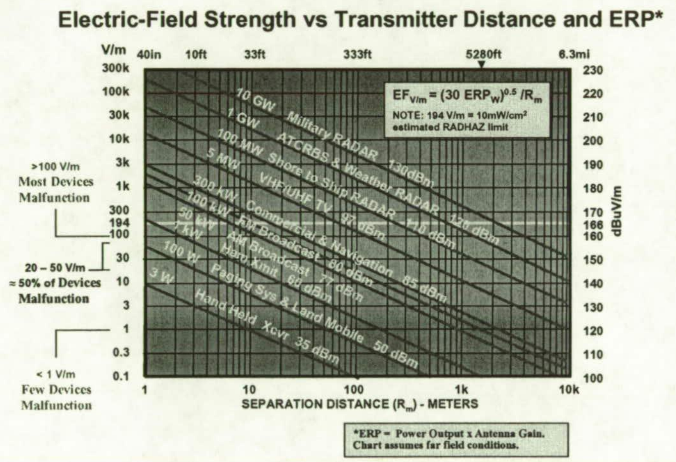

Figure 3. Electric-Field Strength vs Transmitter Distance and ERP*

Although operational controls exist for these handheld type emitters, the number of people who carry these devices is great so relying completely on operational constraints in the handheld frequency range is a risk.

It is important to note that the risk from these sources is not generally destructive but only causes operational malfunctions/disruptions during the time the interfering source is present. If an upset occurs from an intermittent source, having an unverified failure can cause large schedule costs. If testing is performed at reasonably expected levels, it can be shown whether or not equipment is sensitive at certain frequencies. In this case, additional operational constraints can be put in place and a starting point to check for potential interferers is known.

Although the power output from handheld RF devices is generally limited to a maximum of 7 watts because of RADHAZ safety constraints, their portability makes them particularly troublesome. As is illustrated in the following table, the higher power hand held devices can easily create EF levels over 20 V/m. Tests performed by Oak Ridge National Laboratories (ORNL) shown in Table 2 indicated that approximately 50 % of electronics devices are susceptible to EF levels in the amplitude range from 20 to 50 V/m. Devices tested were predominately non-RF solid state analog control systems used in Nuclear Power Plants.

PARAMETER	HANDHELD HT	CELL PHONE	MICRO-CELLULAR
PWR OUT	5 Watts	600mW	1 mW
ANT GAIN	1.64	1.64	1.64
ERP	8.2 W	972 mW	1.64 mW
DISTANCE cm	V/m	V/m	V/m
2000	0.78	0.27	0.01
1000	1.57	0.54	0.02
500	3.14	1.1	0.05
300	5.2	1.8	0.07
200	7.7	2.7	0.11
100	15	5.4	0.22
50	31	11	0.49
30	52	18	0.73
20	77	27	1.1
10	155	54	2.2
5	310	107	4.4

TABLE 3. Susceptibility to Handheld Emitters

RF Susceptibility of RF equipment

The focus of this paper is susceptibility of non-RF equipment. RF equipment is designed to process RF signals. In the case of an RF receiver, its passband sensitivity make it extremely susceptible to low level RF signals that fall within the passband. These signals can be generated directly at the receiver frequency or as a result of intermodulation. For example the LV/SC FTS system and radio amateurs share the 420 MHz band. It is very important for launch vehicles and spacecraft to specify interference and damage levels for their receivers and to protect this equipment from equipment and RF environment interference.

RF Environment During Launch and on-orbit

The vehicle may fly closer to an emitter during launch than it is on the pad. There are also downrange emitters that can cause strong fields at the vehicle. In this case the trajectory of the vehicle must be considered. Data bases that are developed by the Joint Spectrum Center are used to determine these levels. We have recently started predicting ascent field levels for each mission based on the flight trajectory. In addition, once the spacecraft separates from the vehicle the on-orbit fields must be considered if it will be in a near earth orbit. It is common for tracking radars to use spacecraft as targets of opportunity and field levels from both US and other emitters can be as high as 100's of volts/meter. Additionally there are other extremely high level emitters (over the horizon back scatter RADAR, etc.) that produce levels in the 1000's of V/m that SC trajectories may inadvertently cross. Table 3 shows the worst case ascent and on-orbit field levels. Some of the emitters reflected in this table such as C-Band tracking radars are mitigated, however some can not be, especially foreign emitters.

Frequency Hz	Factory/Transport Launch Proc/Pad	Ascent	On-Orbit 100 nmi	On-orbit 500 km	On-Orbit 1000 nmi
10k – 1.99M	25[1], 20[2,3]	20[2,3]	20[2,3]	20[2,3]	20[2,3]
2 – 99M	50[1], 20[2,3]	20[2,3]	20[2,3]	20[2,3]	20[2,3]
100 – 999M	100[2], 1500[1]	100[2], 1500[1]	50[4], 40[5], 100[2]	20[3,4], 100[2]	20[3,4], 100[2]
1 – 3.99G	250[6], 200[2], 2500[1]	200[2], 2500[1]	190[4], 100[5], 200[2]	70[4], 40[5], 200[2]	20[3,4], 200[2]
4 – 10.99G	1000[7], 2500[1], 44000[8]	1000[7], 2500[1]	500[4], 120[5], 200[2]	200[4], 50[5], 200[2]	50[4], 20[3,5], 200[2]
11 – 40G	50[9], 1500[1]	20[2,3], 1500[1]	70[4]	30[4]	20[2,3]

Table 3. RFI Susceptibility Verification Levels for Worst Case (Polar) Orbit, Any Launch Area

IV. The need to change (Need to increase test levels – Equipment changes)

The problem continues to worsen. In the quest to process data faster and cheaper, large scale integrated circuits are being designed with

- Smaller geometry to reduce self inductance,
- Greater packaging density
- Shorter substrate conductors
- Lower 0/1 state change voltage swings,
- Lower power requirements
- No internal protection diodes
- Limited shunt protection capacitance
- Plastic packages
- Higher device speed (directly related to bandwidth)

Just as Moore predicted 30 years ago, component density doubles about every two years and data processing is increasing at an exponential rate! What he failed to mention was that these advances would be accompanied by a corresponding increase in EMC problems.

Since the differential mode radiated electric field is proportional to the square of the freuqency, reducing the drive current and the radiating loop area has resulted in a reduction of the emission levels of individual substrate components while at the same time enabling systems to process data faster. Unfortunately the increase in the number of components changing state simultaneously (synchronously with a clock) at these increased switching speeds has increased the emission levels faster than the lower power and smaller loop areas have reduced it. The net result is an overall increase in RF emission from systems, especially at the higher frequencies where the wiring and PCB traces acting as antennas have greater efficiency.

The wider bandwidth and lower power requirements have increased the susceptibility of the system across the RF spectrum to any culprit signals that fall within the passband of the system. The problem is compounded by new RF/wireless communication devices that continue to be developed that operate or produce harmonics in the same general frequency range as the LV/SC tracking and telemetry equipment. Since it may take years from the time a LV/SC system is conceived until it's delivered, any future EMC problems cannot be solved by tailoring because tailoring presumes that the environment is known when in fact it is not. There will always be unknown and uncontrolled emitters with a new one born ever day. Shielding once worked because fairings used to be made from formed aluminum with 100's of dB attenuation but now they are made from composite materials with 10 – 15 dB attenuation or less.

V. Recommendations

The most conservative approach is to test to the most severe environment the launch vehicle/spacecraft is likely to see. Using a recognized military standard that defines system level requirements such as MIL-STD-464 or the new MIL-STD-1541 is a good approach. EMC tests are performed with a single source slowly swept through the frequency range where as during actually operation the LV/SC system is immersed in a complex RF environment made up of an ever changing combination of signals occurring simultaneously. Interfacing with range and other launch site personnel to keep informed of the latest emitter environment for the specific launch processing facility and launch pad is also essential. This approach is recommended for all launch vehicles since they are likely at some point to incur a space craft limits bypass scenario and the hardware should be designed to be durable. Many launch vehicles will run a systems test with range emitters intentionally pointed at the launch vehicle at their maximum power levels.

For spacecraft, the most risk free approach should be considered. Since many spacecraft are designed to make sensitive measurements, testing to full radar levels could pose a risk to the S/C. However, not testing to an environment they are likely to see is also a risk. We recommend (as a minimum) spacecraft test to the agreed to range emitter control levels for the launch site. These levels are typically at least 20 V/m for each site. Although, these levels are not guaranteed, the range will take particular effort to control their emitters when a sensitive spacecraft is on the pad. Blanking and elevation angle constraints can be used to protect processing facilities. There are also normally operational constraints for handheld emitters, but since multiple people have to be relied on to follow these constraints, it is not recommended that field levels be lowered below 20 V/m. As previously shown this level is more of a sensitivity level than a damage level and if particular sensitivities are found during testing, it only aids in the convincing personnel that added precautions are needed to protect the spacecraft. If a spacecraft is in a series, such as weather and communication satellites, the risks of eventually having and EMC problem increases and test requirements should be increased accordingly.

This is not your father's space craft. Thermal levels may remain the same, but the RF levels do not.

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