

EMI Fundamentals for Spacecraft Avionics & Satellite Applications

OEMs must ensure their avionics are electromagnetically clean and do not pollute other sub-systems with unwelcome radiative, conducted or coupled emissions. Similarly, integrators must ensure their space electronics are not susceptible to RFI from external sources as this could impact performance or even damage hardware. As a product provider, how do you ensure your sub-system can be integrated seamlessly ready for launch? As an operator, how does EMI affect your mission application and the quality-of-service you deliver to your customers?

Electromagnetic Interference (EMI) is unwanted electrical noise that interferes with the normal operation of spacecraft and satellite avionics, generated when fast switching signals with rapid changes in voltage and current interact with unintended capacitances and inductances, producing high-frequency noise that can radiate, conduct or couple unintended energy into nearby circuits or systems. No conduction exists without some radiation and vice versa!

Fast switching signals with rapidly changing currents and voltages energise parasitic inductances and capacitances, $V = L * di/dt$ and $I = C * dV/dt$ respectively, causing these to continuously store and release energy at high frequencies. These unintended interactions become stronger as the rate of change increases, generating transients, ringing, overshoot and undershoot, crosstalk, as well as power and signal-integrity problems that impact satellite applications.

Modern avionics use switching power supplies, e.g. isolated DC-DCs or point-of-load regulators, CPUs, FPGAs, clock oscillators and speedy digital interfaces, all of which switch at high frequencies with increasingly faster edge rates that contain RF harmonics. These functions have become more tightly coupled as OEMs integrate more of these into physically smaller satellites, exacerbating the potential to form and spread EMI. Furthermore, they typically share power or ground return rails, and a signal or noise in one circuit affects the others through common-impedance coupling via the shared impedance, contributing power-integrity issues such as ground bounce.

Similarly, satellites use motors, relays and mechanical switches to deploy and orient solar arrays, point antennae, control reaction wheels and gyroscopes, for robotics and to enable/disable redundant sub-systems. Rapid changes in current and voltage during their operation generates conductive and radiative EMI that impacts nearby circuits, caused by arcing, brush noise within motors, inductance kickback from coils and contact bounce from mechanical switches.

EMI can also enter spacecraft from the external space environment, *i.e.* high-energy radiation from solar flares and cosmic rays can induce noise resulting in discharges and transient spikes. Over time, charged particles from the Earth's magnetosphere, solar wind or from geomagnetic storms, such as electrons and ions, accumulate on satellite surfaces forming large potential differences. When the amassed electric-field strength exceeds the breakdown voltage of materials, ESD-induced EMI generates a fast, high-energy transient pulse that can couple into signal lines, disrupting or damaging space electronics. Conductive coatings and grounding networks are used to equalise surface potentials, as well as plasma contactors to remove built-up charge.

EMI can be generated, coupled and then conducted through physical wires, traces, connectors and cables. Conductors separated by a dielectric form a capacitor, even unintentionally, and

a fast signal on one trace switching at nanosecond speeds, *i.e.* a high dV/dt , energises a changing electric field that can capacitively couple noise onto an adjacent track, *e.g.* a sensitive analogue signal.

Similarly, any loop of wire or a PCB trace intrinsically contains inductance and a high dI/dt energises a changing magnetic field that can inductively couple (induces) noise onto an adjacent trace or circuit.

In both cases, inherent parasitic capacitance or inductance provides a lower impedance to current than the intended path. Since current must flow in a loop to its source, loop impedance is the key!

The faster the rate of change, the stronger the electromagnetic coupling and a changing electric field generates a corresponding magnetic field which will radiate as an antenna if its loop area is large, contains high-frequency harmonics or if there is not tight coupling between the forward and return paths. The radiated EM wave couples into nearby conductive structures such as cables, traces, metal enclosures and sensors, receiving the unwanted RFI.

Any conductor with a time-varying current creates an EM field and the signal wire and its return path form a loop which can become an antenna when carrying fast-switching currents. Similarly, a PCB trace can start radiating, even if the fundamental signal frequency is low, but contains fast edges, if its forward path is not referenced to an adjacent solid ground plane or if the track length approaches $1/10^{\text{th}}$ or more of the signal wavelength, when the EM fields no longer cancel, forming standing waves that radiate from the track. As a simple example, a 10 cm trace resonates around 350 MHz depending on the PCB dielectric and an edge rate of 1 ns contains harmonics up to this frequency that will radiate.

For telecommunications applications, EMI can raise the noise floor masking low-power uplink carriers, impacting receiver sensitivity and dynamic range, lowering SNR and reducing channel capacity (*Shannon's Equation* : $C = B * \log_2(1 + SNR)$). Unintended, in-band spurs can distort modulation constellations, leading to bit/symbol errors, degrading EVM. Energy from unwanted spurs can completely mask narrowband carriers or leak into adjacent channels impacting performance and regulated RFI emissions levels.

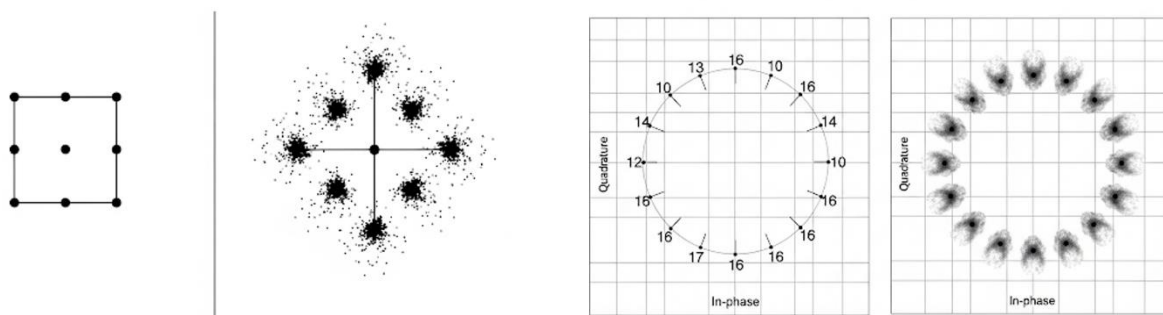


Figure 1 : Q-PSK and 16-PSK Constellations Before (left) and After (right) EMI.

Telecommunication satellites provide a continuous service with tight regulatory limits and even small EMI emissions can be problematic. Payloads typically process many channels and frequency bands, receiving low-level uplinks, so any unwanted noise impacts the overall link budget and operational integrity.

RFI coupling into the LNAs, frequency converters and filters can generate harmonic distortion, intermodulation products and cross-talk between channels.

Earth-Observation applications rely on high-precision optical, LiDAR, RADAR or hyperspectral sensors, and unwanted EMI can introduce noise or distortion into the receive electronics, degrading resolution, accuracy and calibration, misinterpreting the collected data:

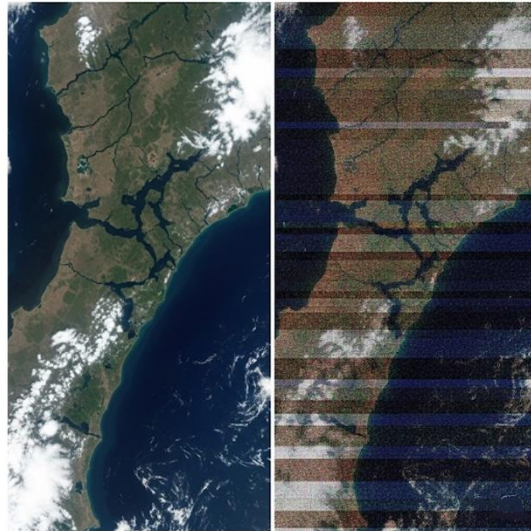


Figure 2 : Earth-Observation Imagery Before (left) and After (right) EMI.

SIGINT satellites rely on the accurate detection, reception and analysis of weak, distant and often low-power carriers, and unwanted EMI can severely degrade receiver performance, limit intelligence value or even render it ineffective. RFI can reduce sensitivity and dynamic range, or overload (jam) RF front-ends causing non-linear distortion. Internally generated noise can mimic the characteristics of actual intercepted signals, resulting in false-positive classifications or geolocation, misleading analysts or automated processing systems.

EMI from the on-board electronics or switching power supplies can raise the receiver's noise floor, making it harder or impossible to detect weak signals of interest.

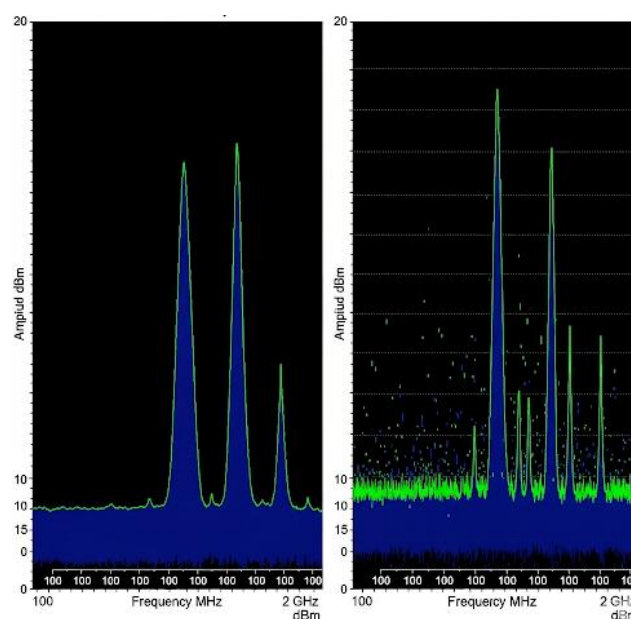


Figure 3 : SIGINT Spectra Before (left) and After (right) EMI.

For ISAM applications, unwanted EMI from motors, actuators and robotics can impact LiDAR, RADAR, cameras and proximity sensors, resulting in loss of situational awareness, errors in docking and alignment, and reduced control accuracy.

For space exploration, EMI can affect sensitive instruments corrupting measurements resulting in the misinterpretation of scientific data. For example, magnetometers are used to detect weak, planetary magnetic fields and their variation, and artificial emissions from the avionics or spacecraft motors can mask or distort real science. Magnetometers are often mounted on long booms away from the satellite to reduce the impact of EMI from the on-board electronics:

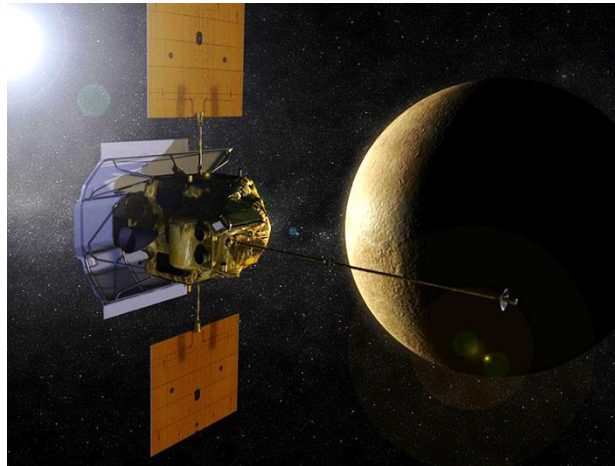


Figure 4 : NASA's MESSENGER Spacecraft with Magnetometer Boom.

For all applications, unintended and uncontrolled EMI on power, ground and signal cables/traces affects on-board circuits and overall system performance. If not managed, RFI can pose a greater threat to avionics than the radioactive environment of space, damaging sub-systems, impacting mission reliability and satellite lifetime.

For decades, many OEMs have built avionics with little regard to EMI to discover emissions are too high or their sub-systems are susceptible to external RFI. Considerable time is then spent identifying the source of the interference, retrofitting fixes to patch the problem and pass the mission's EMC requirements. Often the root cause is never found or fully understood, and this 'sticking-plaster' approach increases product cost, both non-recurrent and recurring, as well as delaying time-to-market.

What should you do if you discover EMI with your latest hardware? For all applications, unwanted noise could result in RFI emissions that violate spectral regulations and interfere with other satellites or terrestrial systems. The UN's ITU defines how the radio spectrum is allocated between different services and sets maximum allowable levels for out-of-band emissions, spurs, EIRP and the received power flux density on Earth. National regulators such as the FCC, Ofcom, CEPT and ETSI enforce these limits before granting operating licences. Agencies provide EMC standards to guide OEMs developing avionics hardware, e.g. MIL-STD-461, AIAA S-121A and ECSS-E-ST-20C.

The first step in determining the origin of unwanted EMI is to understand whether this is being radiated, conducted, coupled or a combination of these. EM hardware is often tested as a proof-of-concept PCB in a lab. without a case using unshielded cables and connectors, making system validation more susceptible to external pick-up and common-mode noise. This interference needs to be initially characterised (probe ground to understand the measurement

noise floor) and managed using ferrite-bead clamps for example, to avoid false positives. The following images shows EM testing with significant common-mode noise picked-up by the set-up that appears on all the power rails and the ground plane. Both the supply and return cables are around eighteen inches in length, mostly untwisted and unprotected from EMI:



Figure 5 : Typical EM Testing in a Lab. Using Exposed Hardware.

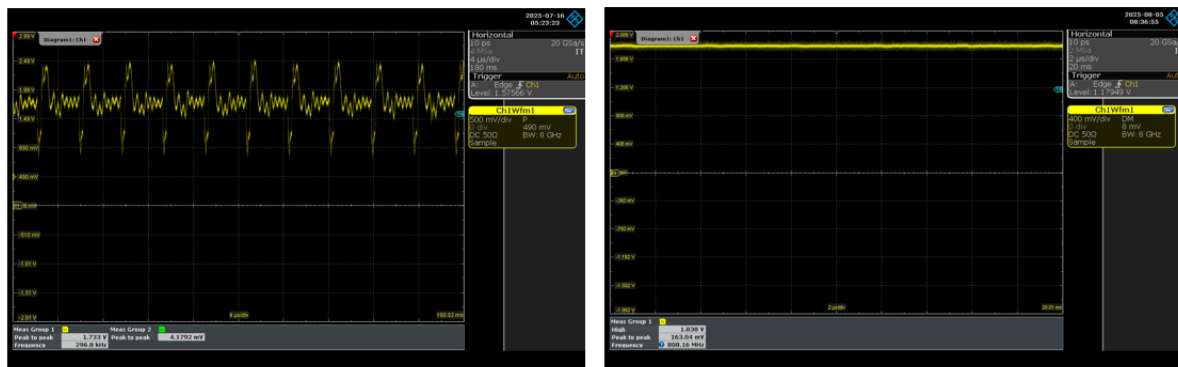


Figure 6 : Common and Differential-Mode Scope Measurements of 1V8 Power Rail.

Testing in an anechoic chamber isolates the DUT from external interference as well as internal reflections, simulating open-space conditions, allowing you to measure the actual emissions from your avionics to understand their origin and mitigate their impact.

EQM and FM hardware are typically verified in a sealed metal box with gaskets, shielded cables and connectors, providing a protective Faraday cage for the device under test. This makes the system less susceptible to external EMI and minimizes RFI emissions from the avionics.

To reduce EMI in existing avionics, filters, chokes and ferrite beads (lossy as opposed to energy-storing inductors) are added to lower conducted noise on power, signal and data cables. The most obvious way to decrease EM coupling is to increase the physical separation between conductors, but this may not always be possible. The use of twisted pairs equalises field coupling between two wires resulting in common-mode interference that can subsequently be removed. Similarly, differential signalling cancels EM fields.

Clamp-on-ferrites choke high-frequency common-mode noise on conductors, passing low-speed signals while dissipating RF interference as heat. If the same EMI could have generated radiated emissions from long cables, then the ferrites will indirectly reduce this antenna-effect. Chip-bead ferrites can suppress both differential and common-mode noise depending on where they are placed.

Shielding reduces radiated EMI by creating a physical barrier that reflects or absorbs EM fields before they can escape, as well as preventing external noise entering avionics. Gaskets maintain an electrically conductive seal preventing external EMI radiation entering through openings or internal RFI escaping through gaps or seams in a metal enclosure. Gaskets ensure a continuous Faraday cage, maintaining a low-impedance electrical path to ground, reducing potential differences that could allow common-mode currents and radiation. The gasket redirects EM fields along the enclosure or to ground, instead of allowing them to radiate into or out of the avionics.

I've seen absorbing foam added to many avionics products to soak-up unwanted radiated emissions, both internal reflections to prevent these bouncing around within enclosures coupling and inducing further EMI, as well as reducing the strength of RF energy before it escapes through gaps or seams, or conducts onto cables and traces. The foam contains carbon or ferrite particles that create resistive losses when RF fields interact with them. An electronic case can act as a cavity that resonates at a certain frequency and the use of foam can reduce such standing waves.

While the addition of EMI filters, RF absorbing foam and ferrites are very helpful, they should be the last line of defence, not the first solution. If you design it right, you won't need to fix it later! Sometimes there will be exceptions to the rule and I have used a high-speed semiconductor in a large ceramic package whose intrinsic parasitic inductance generated an EMI spur. Initially this was an issue for both the OEM and the telecommunications operator, who cleverly positioned the problematic channel over a low-traffic region of the Indian Ocean.

Likewise, when observing and measuring signals, you must ensure your test equipment does not pick-up un-wanted interference, confuse decision making and delay time-to-market by incorrectly diagnosing a working sub-system as a faulty, noisy one. A scope probe and its ground lead form a loop creating a closed-circuit path that can pick-up signals or interference due to electromagnetic induction. Faraday's Law states, '**a changing magnetic field through a closed loop induces an EMF in the loop**'. The larger the loop area or faster the rate-of-change change in the magnetic field, greater the induced voltage.

Proper EMC design and mitigation is essential to ensure data integrity, mission reliability and satellite longevity. As avionics sub-systems become faster and more integrated, a more proactive approach is required to deliver right-first-time, EMC-compliant hardware and satellite applications:

1. EMC compliance must be a key part of early product design.
2. Understand the sources of emissions and how to control them - 90% of all EMI originates from unintentional signal flow, e.g. crosstalk or return currents flowing where they were never intended to be, such as too close to the edge of a PCB. All unwanted EMI originates from intentional signals!
3. Simulate before building hardware: current radiates, not voltage, check its spectrum before building hardware. The radiated electric field, in V/m, from a current loop in free space can be simplified as, $E_{\theta} = kIA$, where I is the current amplitude, A the loop area and k a constant for a given frequency and observation point. The corresponding magnetic near field in, A/m, can be approximated as: $H_{\theta} = 0.16kI(S/D^2)$, where S is the loop separation and D the measurement distance.
4. The most common cause of EMI from products is unintentional common-mode currents on external cables and shields as a result of voltage differences relative to the chassis.

5. Manage the layout of your return currents by providing dedicated ground planes, their spread (path of least impedance dominated by inductance) on these reference planes to avoid them coupling, minimise loop area and provide adjacent ground layers for signals. The following Hyperlynx simulation predicts current-flow density from a SIGINT SDR:

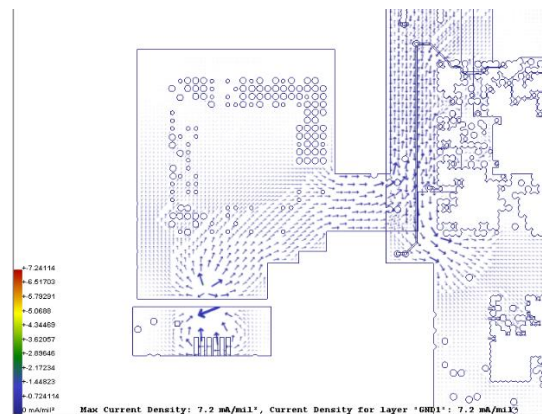


Figure 7 : Siemens' Hyperlynx Post-Layout Prediction of Return-Current Flow.

6. Minimise loop area by keep PCB trace lengths and cables $< \lambda/10$ of the highest harmonic frequency within a signal, and not just the fundamental component.
7. When probing signals using an oscilloscope, use the smallest ground lead possible to minimise loop area to reduce the amount of induced magnetic flux and hence EMI. A shorter ground connection also has less inductance, which means less distortion and a more accurate representation of the signal under test. Probing in differential mode cancels common-mode noise at the measurement point and the use of a ferrite-bead clamp around the cable reduces the amount of external noise picked-up (induced) by the lead entering the scope. Null probing of ground baselines the noise floor and future measurements!
8. When testing EM hardware in the lab., exposed circuit boards and/or unshielded power and ground cables pick-up EMI interference. These can pollute measurements and obfuscate decisions validating the system design.
9. Test in an anechoic chamber to isolate the avionics from external interference as well as internal reflections to measure the actual emissions from your hardware to understand their origin and mitigate their impact.
10. Design your PCB stack, floorplan and layout to prevent the generation of EMI: assign routing layers between neighbouring ground planes to contain the spread of return currents and maintain good Z0. Never route across a power or ground-plane split!

There's so much more to say and if you would like to learn more, Spacechips teaches courses on ***Right-First-Time PCB Design for Spacecraft Avionics*** as well as, ***EMI Fundamentals for Spacecraft Avionics and Satellite Applications***.

Spacechips' Avionics-Testing Services help OEMs and satellite integrators solve EMI issues that are preventing them from meeting regulatory targets and deliver hardware on-time.

Dr. Rajan Bedi is the CEO and founder of Spacechips, which designs and builds a range of advanced, AI-enabled, re-configurable, L to K-band, ultra high-throughput transponders, SDRs, Edge-based on-board processors and Mass-Memory Units for telecommunication, Earth-Observation, ISAM, SIGINT, navigation, 5G, internet and M2M/IoT satellites. The company also offers Space-Electronics Design-Consultancy, Avionics Testing, Technical-Marketing, Business-Intelligence and Training Services. (www.spacechips.co.uk).