LIGO E960036-00-E

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LIGO EMI CONTROL PLAN AND PROCEDURES

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1.0 Scope

This electromagnetic control plan with associated procedures addresses the LIGO electronic instrumentation, monitoring, and control systems, and the preventive and corrective procedures required to achieve electromagnetic compatibility of the Laser Interferometer Gravitational Wave Observatory. Self compatibility and compatibility within the intended operational environment are addressed.

2.0 Intent

The intent of this plan is to provide general and specific guidelines, and rationale for those guidelines, to help achieve and maintain self compatibility of LIGO electronic equipment, and the compatibility of that equipment within the operating environment. While all possible interference conditions can not be anticipated, the likelihood of bothersome interference can be greatly reduced by adhering to the practices and recommendations described herein.

3.0 Description of LIGO Installation

Each LIGO site consists of two orthogonal 4 kilometer long beam tube arms for laser interferometry. Each installation includes support buildings and equipment to provide power, facility support, and vacuum maintenance for the beam tubes. Present commitments are for a minimum of two sites, one at Hanford, Washington, and one at Livingston, Louisiana. For effective array dimension and noise cancellation purposes, the two sites are to be operated as a unit, necessitating intersite realtime communication and coordination. Future international sites are envisioned to enhance the effectiveness of the system.

The laser interferometry forming the basis for the LIGO system will monitor low level signal changes. To maximize observatory sensitivity and "uptime", it will be necessary to avoid electromagnetic and other interference with those low level signals. Equally critically, intra- and inter-site digital communications will need to be protected.

4.0 Operational Environment

The intended operational environments are rural areas. Electrical power is to be provided by dedicated utility substations.

4.1 Powerline Ambient Conditions

The electrical power provided to the LIGO installation is to be divided into general facility power and technical power, with a minimum of two distribution transformers separating the two categories. Two general sources of powerline conducted EMI are anticipated: utility line effects, and on-site, locally produced noise. Utility line noise will include lightning generated transients, utility switching transients, and interference induced on the utility powerlines by transmitters or other noise sources. Utility line noise will be somewhat attenuated by distribution transformers and facility lightning transient protection devices. Locally produced noise will include facility power transients and steady state EMI, such as produced by motors, heaters, and switching events. Technical power conducted EMI, which is of more direct and immediate concern, will also be produced by all previously listed sources, and will also be produced by rectifiers, switching power supplies, computer clocks, and intentional RF sources. Except for lightning induced transients and some facility power switching transients, the technical power loads themselves will probably present the most troublesome conglomerate source of most conducted EMI to other technical loads.

4.2 Radiated Ambient Conditions

Due to the rural nature of the LIGO site, radiated interference sources will be limited. Likely sources include: distant transmitters, intentional on-site transmitters, and unintentional radiation from LIGO equipment.

Distant licensed transmitters at the Hanford, Washington, site have been identified by Mr. J.E. Curtis of West Richland, Washington, in a January 3, 1996 letter to Mr. Fred Asiri of LIGO at the California Institute of Technology. Those transmitters have been identified below, with output power, frequency, and distance from the Hanford site. Predicted field intensities at the Hanford site have been computed and added to the information provided by Mr. Curtis.

TABLE 1. Anticipated Radiated Ambient at Hanford, Washington, LIGO Site Due to Nearest AM and FM Radio Stations.

Station	Frequency	Effective Radiated Power	Distance, Miles	Predicted Field Intensity
KALE AM	960 kHz	5 kW Day/ 1 kW Nt	18	13/6 mV/m
KARY AM	1310 kHz	5 kW	24	10 mV/m
KARY FM	100.9 MHz	6 kW	24	11 mV/m
KIOK FM	94.9 MHz	100 kW	26.75	40 mV/m
KEGX FM	106.5 MHz	100 kW	27.25	39 mV/m
KNLT FM	95.7 MHz	100 kW	57	19 mV/m
KTCR AM	1340 kHz	100 kW	19.5	55 mV/m
KUJ AM	1420 kHz	5 kW	57	4 mV/m
KFAE FM	98.1 MHz	100 kW	26.75	40 mV/m
KOLU FM	90.1 MHz	4.2 kW	28	8 mV/m
KONA FM	105.3 MHz	100 kW	26.75	40 mV/m
KONA AM	610 kHz	5 kW	36	7 mV/m
KORD FM	102.7 MHz	100 kW	27.25	39 mV/m
KXRX FM	97.1 MHz	50 kW	57	13 mV/m
KORD AM	870 kHz	10 kW	22.5	15 mV/m
KZXR FM	101.7 MHz	25 kW	25	22 mV/m

TABLE 2. Anticipated Radiated Ambient at Hanford, Washington, LIGO Site Due to Nearest TV Stations.

Station	Frequency	Effective Radiated Power	Distance, Miles	Predicted Field Intensity	
KEPR	501/506 MHz	5 MW	26.75	285	mV/m
KVEW	639/643 MHz	5 MW	27.25	279	mV/m
KNDU	536/542 MHz	5 MW	27.25	279	mV/m
KTNW	578/584 MHz	3 kW	27.25	7	mV/m
KEBB	680/685 MHz	1 kW	15	7	mV/m

As seen by the above tables, the highest expected field intensity from distant licensed transmitters, 285 millivolts per meter (i.e., 0.285 volt per meter), is less than one volt per meter. This environment is considered to be benign, and represents no threat to normal electronic devices. To add to this environment, radiated emissions from mobile transmitters, such as could be used by on-site personnel, need to be considered. The following table presents a sampling of possible transmitter and power combinations.

TABLE 3. Anticipated Radiated Ambient Due to On-Site Mobile Transmitters.

Transmitter Power	Distance	Predicted Field Intensity		Minimum Distances
100 mW				17 meters for 0.1 V/m 1.7 meters for 1 V/m
	1 meter	1.7	V/m	
	2 meters	0.87	V/m	
	5 meters	0.35	V/m	
200 mW				24.5 meters for 0.1 V/m 2.45 meters for 1 V/m
	1 meter	2.4	V/m	
	2 meter	1.2	V/m	
	5 meters	0.49	V/m	
1 watt				54.8 meters for 0.1 V/m 5.48 meters for 1 V/m
	1 meter	5.5	V/m	
	2 meters	2.7	V/m	
	5 meters	1.1	V/m	
2 watts				77.5 meters for 0.1 V/m 7.75 meters for 1 V/m
	1 meter	7.7	V/m	
	2 meters	3.9	V/m	
	5 meters	1.5	V/m	
5 watts				122 meters for 0.1 V/m 12.2 meters for 1 V/m
	1 meter	12	V/m	
	2 meters	6.1	V/m	
	5 meters	2.5	V/m	
10 watts				173 meters for 0.1 V/m 17.3 meters for 1 V/m
	1 meter	17	V/m	
	2 meters	8.7	V/m	
	5 meters	3.5	V/m	
20 watts				245 meters for 0.1 V/m 24.5 meters for 1 V/m
	1 meter	24	V/m	
	2 meters	12	V/m	
	5 meters	4.9	V/m	

From the above chart for radiated emissions due to handheld or mobile transmitters, it is clear that the level of radiated emissions from on-site handheld or vehicle mobile transmitters will tend to be much greater than the emissions from distant transmitters.

As a general guideline, radiated emissions levels greater than 1 volt/meter are of concern for the susceptibility of general electronic equipment (except for receivers, of course, which are much more sensitive). Of course, the susceptibility level for any specific piece of equipment depends upon bandwidth and level of emission from the culprit versus bandwidth and susceptibility level of the victim equipment, as installed (i.e., including any lead lengths which may enhance pickup efficiency)

5.0 Referenced Documents

MIL-STD-220A	Method of Insertion-Loss Measurement, 15 Dec. 1959
MIL-STD-461D	Requirements for the Control of Electromagnetic Interference Emissions and Susceptibility, 11 January 1993
EN 55022	Limits & Methods of Measurement of Radio Interference, Information Technology Equipment, 1995

6.0 Definitions of EMI/EMC Terms

Absorption Loss - A portion of shielding effectiveness, based upon conversion of impinging radiated electromagnetic fields to heat. Absorption loss in decibels is approximately given by $A = 1.31\, t\sqrt{f\mu\sigma}$ dB, where t = thickness of shield in centimeters, f = frequency in Hertz, μ = relative permeability of shield, and σ = relative conductivity of the shield material.

Barrier Impedance - The impedance of a shielding barrier to incoming radiated fields, approximately given by $Z_B = 3.68 \times 10^{-7} \sqrt{\frac{\mu f}{\sigma}}$ ohms per square, where μ is the relative permeability of the shield material, f is the frequency of interest in Hertz, and σ is the relative conductivity of the shield material.

Bonding - The low impedance electrical connection between two separate equipment enclosures, racks, or circuits, for EMI control purposes.

Common Mode - Current, usually unintentional, flowing in phase on two or more conductors in the same cable. In terms of voltage, a common voltage from each of several conductors to a common reference voltage point, such as a circuit ground.

Crosstalk - Cable-to-cable differential mode coupling by inductive or capacitive energy transfer from a culprit cable to a nearby victim cable. Best solution is generally avoiding the bundling or grouping of dissimilar function cables.

Differential Mode - Intentional or unintentional current flowing out-of-phase on two or more conductors in the same cable. In terms of voltage, the voltage between two or more conductors, ignoring ground.

E field - Electric field near a high impedance source circuit ($Z > 377$ ohms), or the electric field component of a far field radiated wave.

EMC - Electromagnetic compatibility. The lack of an interference problem.

EMI - Electromagnetic compatibility. The presence of an interference problem.

Emissions - The conducted or radiated interference output of a circuit or equipment.

ESD - Electrostatic discharge, resulting from excessive charge buildup, caused by friction between dissimilar materials in a low humidity environment. Especially damaging to modern solid state electronic components during assembly and handling. Discharges from charged personnel can exceed 10 - 15 kilovolts at several amperes. Can be both upsetting and damaging to inadequately protected electronic equipment.

EU - European Union (European common market organization). Responsible for far reaching electromagnetic compatibility requirements on electronic equipment. European Norm standards include both emission and immunity tests. Equipment passing relevant EN tests can be considered nominally resistant to upset and damage from common electromagnetic threats, and unlikely to cause upset to neighboring electronics.

Far Field - Electromagnetic radiation at a distance greater than $\lambda/2\pi$, where $\lambda = 1$ wavelength.

FCC - Federal Communications Commission, empowered by Federal Communications Act of 1934 to control quality of electronic communications in U.S., including EMI concerns. Empowered to regulate both emissions and immunity of communications-related electronics, but primarily addresses emissions. Attempts to coordinate many requirements with international standards, especially standards used by the European Union.

Filter - As used in EMI, usually a passive inductor-capacitor or resistor-capacitor frequency discriminating network, used to pass desired frequencies while rejecting unwanted frequencies.

Ground - A general term for a reference conductor, which may be a wire, a metal framework, or earth. Also a common source of EMI, due to the interconnection of equipment grounding conductors to a reference conductor system at different points. It must be recognized that ground systems are conductors, and have impedance. Any current flow through a ground conductor causes a voltage drop, which is then impressed between the interconnected equipments.

Ground Loop - The circuit consisting of two or more cable-equipments connected to a common ground conductor at different potential points, resulting in net common mode current flow through the two equipments.

H field - Magnetic field near a low impedance source circuit ($Z < 377$ ohms), or the magnetic field component of a far field radiated wave.

Harmonic Distortion - For power quality or conducted powerline EMI purposes, the presence of multiples of the power frequency voltage or current. Utility power is often supplied with low harmonic distortion, but is contaminated by the nonlinear current drawn by common facility loads, including simple diode bridge/capacitor power supplies, switching power supplies, fluorescent lamp ballasts, and variable frequency drives. The nonlinear current causes nonlinear voltage drop across the power line source impedance, resulting in voltage harmonic distortion. Can cause equipment upset or interference due to voltage modulation, as well as neutral line and transformer heating due to harmonic current I^2R losses.

Immunity - Freedom from upset due to interference.

Interference - The undesired presence of any signal or electrical voltage or current.

Lambda, λ - Wavelength in meters, equal to $300/f_{MHz}$

Near Field - An electric field or magnetic field close to a radiating source.

Plane Wave - An electromagnetic field greater than $\lambda/2\pi$ meters from the radiating source, so named because the wavefront has little curvature, and is thus considered to be essentially flat, or plane-like.

Power Quality - Description of AC power, with respect to voltage amplitude, frequency, transients, and harmonic distortion.

Reflection Loss - A component part of shielding effectiveness, caused by mismatch between impinging wave impedance and shielding barrier impedance.

RFI - Radio frequency interference. An older frequency limited term, now generally deprecated and replaced by the newer, not frequency- restricted term, EMI.

Shielding Effectiveness - The shielding quality of an EMI shield, usually expressed in decibels of improvement at victim after shielding (reduction of field intensity). Approximated by $S.E._{dB} = R_{dB} + A_{dB}$, where R_{dB} is the reflection loss in decibels, and A_{dB} is the absorption loss in dB.

Site Survey - On-site measurement of radiated EMI, conducted EMI, and/or power quality.

Susceptibility - Description of EMI victim with respect to being upset by interference.

Wave Impedance - Ratio of electric field vector to magnetic field vector of a radiated electromagnetic wave. In the far field, $E_{V/m} / H_{A/m} = 120 \pi = 377$ ohms.

7.0 Management

As with any other program, an EMC program will not likely be successful without a champion, in the form of a manager with the drive, the commitment, and both the responsibility and necessary authority to manage the program to fruition. Electromagnetic compatibility is achieved on a program by an organized management of electromagnetic threats, attention to potential interference victims, a reasoned approximation of the operational environment, consideration of feasible protection measures, established procedures for conflict resolution, and utilization of available facility, hardware, and personnel assets. To enhance the probability of program success and minimum delay and upset due to interference, it is suggested that a single individual, with appointed alternate(s), assume EMC responsibility and authority, with designated technical staff to perform as an advisory staff.

Management appointments and contact addresses and numbers should be published to all appropriate parties. Available technical assets, including EMI test equipment and off-site consulting personnel, should be published to LIGO team members.

This document, including subsequent revisions, should be disseminated to the team.

7.1 Responsibilities

The LIGO EMC program manager has the responsibility to ensure proper and timely completion of the following actions:

A. Establish overall EMC program goals.

B. Establish an EMC program team.

C. Plan general and detailed action items to achieve EMC program goals

D. Set EMC program milestones and schedule

E. Establish plan to expeditiously identify and resolve EMI problems

F. Establish plans and procedures to install identified EMI fixes

7.2 Lines of Authority and Control

The EMC program manager should be a senior member of the LIGO technical team. He should be able to coordinate with LIGO team members at other locations than his own. Electrical, electronic, mechanical, safety, EMC, facilities, and other identified specialists should report directly to the EMC program manager as a support team. Each support team member should be used to provide technical advice from his specialty perspective to the program manager, who will be responsible for final program planning and incident resolution decisions.

7.3 Implementation Planning

The EMC program manager will be responsible for determining manpower, time, equipment, expendables, budget, site availability, and scheduling constraints to accomplish required tasks according to the final LIGO EMC program schedule.

7.4 Milestones and Schedules

To develop final milestones and schedules, the chosen EMC program manager and his selected EMC advisory team should read this EMC control document for familiarization with EMC requirements, conditions, and options. Starting from the scheduled "LIGO site ready" date, and working backwards, dates will be assigned for the individual milestones. It is envisioned that this document will be expanded and refined as a result of one to three meetings of the LIGO technical staff at California Institute of Technology. The attendees at those meetings should include the eventual EMC advisory team members.

A tentative list of tasks to be accomplished by the EMC program manager and the EMC advisory team, under the supervision of the EMC program manager, include:

Selection of EMC program manager and advisory team

Confirmation of LIGO site radiated ambient

Determination of, or approximation of LIGO site conducted ambient

Determination of level of prior EMC qualification of LIGO electronics by manufacturers, to FCC, European Union, or other commercial or military emissions limits

Measurement of any questionable electronics packages for conducted emissions, radiated emissions, conducted susceptibility, and/or radiated susceptibility

Preparation, review, and approval of system integration drawings

Research, review, and approval of system hardware

On-site inspection, preparation, or corrective assistance

Problem analysis, resolution, and fix installation

7.5 Plans and Procedures for Identifying and Resolving EMI Problems

The EMC program manager, detecting or being informed of a potential EMI problem, should assign relevant members of the EMC advisory team to research the problem. The team should make the following determinations:

Is there a repeatable, consistent problem?

Is the problem due to EMI or some other cause?

Can EMI culprit(s), coupling path(s), and victim(s) be identified?

What are possible corrective actions?

Which of several EMI fixes is most desirable, from the standpoint of safety, reliability. effectiveness, cost, simplicity, etc.?

Do any special considerations affect this particular problem or its chosen fix?

Will this fix adversely affect other parties, other disciplines, schedule, etc.?

9.0 Types of EMI Coupling

Interference energy can be coupled from culprit to victim by conducted paths, radiated paths, or a combination of the two. This writer has observed a general tendency for many people to blame radiated field coupling as the preponderant EMI coupling path, whereas experience indicates that power line interference and ground system EMI occur much more often.

9.1 Conducted Coupling

Conducted coupling paths include power leads, signal/control leads, "ground" conductors, and shield conductors. The latter two coupling paths can be especially onerous, as those conductors are usually perceived to be part of an EMI fix, while they may aggravate, or even directly enable a problem. Shields and ground conductors are, first and foremost, conductors. If they are connected between points of differing electrical potential, interference current will flow, conceivably resulting in an adequate transfer of interference to related victim circuitry to cause upset, malfunction, or signal contamination.

9.1.1 Powerline Conducted Coupling

Electrical interference on input power lines tends to propagate through the associated power supplies, and appear in an attenuated form on output DC power leads and the circuits that use the DC power. The amount of attenuation of the interference by the power supply will vary with frequency.

9.1.1.1 Transient Conducted Interference

Powerline transients arise from switching actions, either by the power utility or within the power using facility. Peak transient amplitudes of five to ten kilovolts are seen, with quickest risetimes in the low nanosecond region. Inherent powerline parasitic capacitance and inductance can serve to somewhat filter these transients.

9.1.1.2 Audio Frequency Conducted Interference

Lower frequency conducted interference can arise from utility power quality shortcomings, locally generated powerline harmonics, switching activity, and noisy power supplies. The regulation of most power supplies will protect most potential powerline audio frequency interference victims from upset. Audio frequency conducted interference can be either common mode or differential mode, but is more often differential mode.

9.1.1.3 Radio Frequency Conducted Interference

Higher frequency conducted interference often arises from cable pickup of radiated fields, and, increasingly, switching powerline harmonics. Higher frequency conducted emissions, especially above 5 MHz, tend to be common mode.

9.1.2 Ground Conductor Conducted Interference

Equipment enclosures are commonly wired to ground to "prevent EMI problems". The thought seems to be, "Tie the box to ground to drain off the EMI". Much time is spent searching for the elusive "sweet spot" ground; connection to this point will presumably solve all EMI difficulties. In actuality, ground conductors or systems have inherent impedance, and often have interference current flow, resulting in an interference voltage between different points on the (hoped for) "zero voltage" or "clean" ground. Connecting a communication-by-wire two-box (or more) system at two different points on the ground system will result in potential interference current flow through the two-box system. In such a situation, the EMI condition can actually be radically improved by disconnecting the straps to ground, thereby isolating the two-box system from the ground noise. It should always be remembered that electrical current flows in circuits, and thus EMI current simply can not flow to ground and stop, in single-ended fashion; there must be a complete loop circuit for current to flow. Thinking of ground as just another conductor in a circuit is usually more productive than considering ground to be a cure-all voltage reference point. At frequencies above about 1 MHz, the intent of "single point" grounds can be violated by the completion of unintentional ground loops by parasitic capacitances, which can be derived from the capacitance formula, $C = \varepsilon\ A / d$ farads, with $\varepsilon = 8.84$ pF/m for air, A = effective parasitic capacitor plate area in meters^2, and d = effective separation distance in meters between parasitic capacitance "plates". Grounding conductor impedances increase due to inductive reactance from stray conductor inductance, and unintentional cable resonances abound, casting severe doubt on expected low impedance paths to ground. An approximation of round conductor inductance is 25 nanohenries per inch (10 nanohenries per cm, or 1 microhenry per meter). Confounding the matter even further are ground conductors which are at least a large fraction of a wavelength long at the interference frequency; the impedance to ground on a long grounding conductor depends upon precisely where along the conductor the impedance is measured, and having more to do with the number of quarter wavelengths than any physical characteristics of the grounding conductor itself.

9.2.4 Radiated Field Penetration into Enclosures

Common sheet metal equipment cabinets, racks, and enclosures are capable of providing significant shielding effectiveness against electric fields and plane waves. That shielding capability decreases with discontinuities in the metal housing, such as at doors, panels, joints, and apertures. As a worst case approximation, a shield is assumed to have 0 dB shielding effectiveness at and above any frequency at which the longest discontinuity in the shield is as long as one half wavelength. For example, with an aperture 15 centimeters long,

$$L = \lambda / 2 = 15 \text{ cm, and } \lambda = 2 \times 15 \text{ cm} = 30 \text{ cm} = 0.3 \text{ meter}$$

$$\text{Also, } \lambda = 300 / f_{MHz} = 0.3 \text{ meter, so } f_{MHz} = 300 / \lambda = 300 / 0.3 = 1000 \text{ MHz} = 1 \text{ GHz}$$

At frequencies below this 0 dB shielding frequency of 1 GHz, the shielding effectiveness of the shield will increase at a slope of 20 dB per frequency, up to the maximum shielding offered by the shield material. The material shielding effectiveness of the material can be computed from the shielding equation given in Paragraph 6.0 above, $S.E._{dB} = R_{dB} + A_{dB}$.

10.0 Methods of EMI Protection, Exclusion, and Suppression

This paragraph presents general methods of EMI protection of victim circuits against externally generated EMI, exclusion of that EMI, and suppression of EMI at the source. Paragraphs 12.0 and 13.0 below describe specific LIGO conditions and specific recommendations for LIGO equipment.

10.1 Powerline Protection

The 60 Hertz AC powerline is intended to provide electrical power at a set voltage level, to load equipment. Ideally, only 60 Hertz energy is present on powerlines. Practically, however, the power system is contaminated by radiated and conducted sources, over a wide frequency range, with interference signal amplitudes ranging from the submicrovolt level through the low kilovolt range. Powerline cleanup devices operate by discriminating against signals outside the allowable amplitude and frequency ranges. *All powerline cleanup devices have inherent* limitations, dependent upon the particular technology used. Powerline improvement depends upon actual device performance parameters, and not the given nomenclature of the type of device. For example, the term, "power line conditioner" sounds positive, but is used to describe a wide range of devices, including uninterruptible power sources, powerline EMI filters, transformers of various types (ordinary isolation transformers, Faraday shielded isolation transformers, constant voltage transformers), and combinations of these devices.

10.1.1 Filtering

Powerline EMI filters are passive, inductor-capacitor, lowpass networks. The inductors are in series with each power lead, and the capacitors are installed in shunt, either line-to-line (for differential mode noise), or line-to-case ground for common mode noise. Inductors may be designed to emphasize either common mode or differential mode suppression. To effectively design or procure a powerline EMI filter, the frequency range and degree of both common mode and differential mode interference on the target powerline need to be identified. Excessive values of differential mode inductance and capacitance cause voltage drop or power frequency waveform distortion. Improperly designed inductors can cause the generation of power frequency harmonics. Excessive values of line-to-ground capacitors cause higher than desired values of power frequency current to ground due to excessively low capacitive reactance at the power frequency. Electrical safety regulations concerning shock hazards, and military specifications such as MIL-STD-461D, concerning ground corruption, limit the values of line-to-ground capacitance.

Filter manufacturers typically rate filter performance in a fifty ohm source and load test circuit per MIL-STD-220A. As powerline source and load impedances are generally not fifty ohms, actual in-situ filter performance bears little performance to the fifty ohm test circuit curves. Filters cannot be effectively purchased by reference to manufacturers' performance curves.

10.1.2 Transient Protection

LIGO facility power will be protected at the service entrance by primary protection utility grade transient protection devices. These devices, such as metal oxide varistors (MOVs), are primarily intended to prevent entry into the facility power system by lightning-induced transients and utility switching transients. These devices do little to protect facility equipment from facility-generated transients. Secondary level (lower clamping voltage, quicker response) MOVs are usually installed inside the protected facility, at secondary distribution transformers. For further protection, additional MOVs can be placed directly on the power leads of potential victim electronic equipment.

Other voltage-limiting transient protection devices are available, such as ionizable spark gaps, back-to-back zener diodes, and Transzorbs (TM, General Semiconductor Corporation).

Factors affecting the choice of transient suppressor device are response speed, power dissipation rating, terminal-to-terminal capacitance, impedance when activated, cost, size, and reliability.

10.1.3 Powerline Isolation Transformers

"Ground loops" are unintentional common mode circuits involving an interference current contaminated common ground system, two items of cable-interconnected equipment, and the interconnecting cabling, which can be power or signal cabling, cable shields, or some combination thereof. The problem with a ground loop is that the two pieces of equipment are connected to the common ground at different points; the interference current flow causes an interference voltage drop across the ground system. Any cabling between the two pieces of equipment will carry common mode interference current caused by this interference voltage. If a set of power leads is included between the two locations, that common mode current will be carried on the power leads. One way to reduce common mode current flow on power leads is to insert a break in the power lines for the common mode current, while not interrupting the differential mode power flow path. The obvious answer is a simple 1:1 power transformer, called an isolation transformer because it isolates the two sides of the power circuit, but only in a common mode sense. The power frequency energy is differential mode, and is coupled through the transformer by transformer action.

The common mode isolation offered by a simple 1:1 transformer can exceed 100 dB. At higher frequencies, however, the stray interwinding capacitance effectively recloses the common mode loop. To reduce the high frequency common mode coupling, it is necessary to reduce the interwinding capacitance. This reduction is accomplished by including a thin aluminum shield between the primary and secondary windings at the time of transformer manufacture. This electric field, or "Faraday" shield is connected to circuit ground. Common mode EMI that would have been capacitively coupled from the primary winding to the secondary winding is, instead, capacitively coupled from the primary to the shield, then shunted to ground, and back to the common mode source. The effective level of common mode reduction at the secondary is increased to much higher levels with the shield than would be possible without.

The grounded Faraday shield described for common mode isolation offers little differential mode isolation. First of all, at or near power line frequencies, the intended inductive coupling mechanism of the transformer prevents any capacitive mechanism isolation at those lower frequencies. At frequencies much above the power frequency, the magnetic coupling is reduced automatically, by the decreasing effectiveness of the transformer laminated core material. As frequency increases and the transformer core loses differential mode coupling efficiency, the differential mode capacitive coupling mechanism begins to predominate over the inductive coupling mechanism. To reduce differential mode coupling at these higher frequencies, a second aluminum foil shield is added to the transformer, but is connected to the lower voltage side of the primary instead of to local ground. The effect of this connection is to force the shield, as capacitively "seen" by the secondary, to be unipotential. With one potential seen by the secondary, the transfer of differential mode (line-to-line) interference voltage to the secondary is interrupted.

Signal isolation transformers work similarly. Power isolation transformers with one shield can be hooked up as described above for either common mode or differential mode performance. For transformers with multiple shields, it is usually best to include shield hookups for both common mode (shield to ground) and differential mode (shield to low side of primary) isolation.

Transformers usually offer little common or differential mode isolation above 10 MHz, due to nonzero effective interwinding capacitance, even with Faraday shields, and direct input wiring to output wiring stray capacitance. The high frequency performance of isolation transformers can be enhanced by minimizing the input-to-output capacitance. This is accomplished by maximizing the separation distance between input and output leads, which translates to running the leads 180 degrees apart in all orientations. This maximum lead separation performance enhancement is valid for any type of high frequency suppression component.

10.2 Grounding and Bonding

Grounding is the act of forcing a piece of equipment to be at a specific reference ("ground") potential by direct electrical connection. Bonding is the act of forcing two pieces of equipment to be at the same (but not necessarily ground or reference) potential by tying them together.

10.2.1 Rationale and Intent for Grounding and Bonding

The intent of grounding and bonding is to prevent interference by forcing two or more pieces of equipment to be at the same voltage, which may not be the local ground voltage. Thinking of EMI control in only this voltage control sense, however, is inadequate, in that noise current paths are deemphasized, and high frequency effects are ignored.

To modify the above "forced equal voltage by bonding or grounding" concept, it may be constructive for lower frequency circuits ($<<$ 1 MHz) to think in terms of "forced equal voltage by bonding or grounding, without providing a complete path for interference current flow". This "complete path for interference current flow" is the well known "ground loop". This low frequency "no ground loop" policy explains the single point ground concept practiced by audio and low frequency analog engineers.

At much higher frequencies (>> 1 MHz), ground loops are unavoidable, because parasitic capacitance will "close" any open circuit near a ground plane or any other conductive surface or object. Also, the essentially zero assumed impedance of simple connections to ground or bond connections between equipments that is an adequate true model at low frequencies is no longer accurate at higher frequencies.

10.2.2 Rack Grounding

An equipment rack is commonly connected to ground for two reasons: for personnel safety and to avoid the generation and transmission or buildup of stray circuit voltages by induction or electrostatic discharge. From an EMI-only standpoint, it would often be desirable to break all ground connections, to reduce common mode current (by increasing ground loop impedance). The AC electrical safety issue prevails, of course, so racks are grounded with controlled impedances. Usually this "controlled impedance" is the lowest impedance we can manage, which is accomplished by directly bolting an equipment rack to an adjacent ground plane, with no intervening wires or straps (Of course, this connection is in addition to the safety-mandated grounding wire). Somewhat less desirable than direct rack bolting to ground would tying the rack to ground with a minimum length/maximum width bonding strap. Flat braid or flat copper straps are acceptable. A maximum length to width ratio of 5:1 is recommended, to control strap inductance. As strap self-inductance is likely to be on the order of 3 -10 nanohenries per inch, the inductive reactance at high frequencies can be considerable, and is usually much higher than the strap's DC resistance. Ground strap acceptability should be based upon total impedance at the targeted EMI frequency range rather than adherence to some arbitrary construction technique or strap composition. Still, the 5:1 length to width ratio, together with very low DC resistance (< 2.5 milliohms), is a practical and reasonable rule of thumb for many applications.

In an installation for which an EMI ground loop has been detected, the common mode ground loop can often be effectively "opened" in the nominal 100 kHz to 10 MHz frequency range by intentionally inserting an inductance of 50 - 200 microhenries in the safety grounding conductor, and removing any other grounding connections. This is a special case, however, and should not be performed at the time of original equipment installation.

10.2.3 Circuit Grounding

The first intent of circuit grounding is to provide a solid signal and power voltage reference for interconnected circuits, unaffected by nearby inductively, capacitively, or static discharge induced voltage changes. Of course, safety is always a consideration, and one side of higher voltage supplies is usually tied to local safety ground to support high fault current and breaker action in the event of the shorting of the higher voltage side of the supply to ground. To avoid common mode ground loop interference in sensitive signal circuits, they should be tied to local ground at only one point, to prevent circuit voltage drops due to stray ground currents being accidentally routed through the circuit by way of the multiple ground connections. This is another example of the single point ground concept. With a multiplicity of circuit types in a given system, such as digital, low frequency analog, high power high frequency RF, and DC power, grounding considerations may become confusing. The simplest approach is to simply avoid alien current flow in a particular subtier ground system. This, again, is accomplished by single point grounding; the whole grounding hierarchy will resemble a tree, with each type of circuitry representing a branch, leading to the trunk, which is ultimately tied to ground.

10.2.4 Bonding

Bonding is simply the electrical connection of two equipment housings or circuits, to force them to be at the same voltage (not necessarily ground). Bonding is best accomplished by direct, high pressure contact over an adequate surface area between clean, flat metal surfaces. In general, simple nut-flat washer-bolt hardware should be used, with any lockwashers or starwashers <u>not</u> placed between the two joined metal surfaces. Although starwashers can enhance DC contact resistance, the point contact of starwashers causes bond impedance to increase at high frequencies. The mounting hardware should be considered to provide joint pressure only, and conductivity through the nut-washer-bolt hardware should not be assumed.

10.2.5 Ground/Bond Impedance versus Frequency Concerns

At high frequencies, the AC resistance of a ground conductor or bond strap or wire increases due to skin effect (lower effective conductor cross-section), the inherent self- inductance of wires (nominally 25 nanohenries per inch for round wires, somewhat less for flat cross-section conductors), and wavelength-related effects complicate the effective impedance. By wavelength effects is meant that the impedance of a conductor in question is dependent upon the precise multiple of quarter wavelengths represented by the conductor length. The impedance of a conductor may seem minimal at even multiples of a quarter wavelength, and maximum at odd multiples of a wavelength. To avoid this wavelength trap, all grounding or bonding conductors should be no greater in length than a fifth or a tenth of a quarter wavelength (i.e., $\lambda/20$ or $\lambda/40$) at the highest EMI frequency of concern. Of course, in actual practice, bonding or grounding conductors often exceed these lengths. That means, in turn, that in actual practice, the impedance of these conductors is unknown and uncontrolled.

To complicate conductor impedance matters even more, there is the matter of parasitic capacitance to nearby conductors, and the resulting series and parallel resonances. Ground strap and bond strap impedances at higher frequencies are nonelementary quantities.

10.3 Signal/Control Conductor Protection

Signal and control conductors are intended to pass specific types of signals (with respect to signal level, bandwidth, modulation) within specified loss requirements. Unintended signals, which may interfere with reception at the receiving end of the circuit of the intended signal, may need to be excluded. The method of exclusion depends upon the parameters of the offending invading signal, and its method of original coupling into the signal/control line.

10.3.1 Circuit Location and Layout

Proper choice of circuit location , or circuit orientation, can remove the requirement for more extensive (and more expensive) EMI corrective measures. This is especially true for the proximity of sensitive circuits in the presence of hostile circuits, cables, or fields (such as low level, wide bandwidth analog circuits near digital circuits or strong magnetic field sources, or very high impedance circuits near strong electric field sources).

10.3.2 Conductor Placement/Separation

Simply put, all active conductors have associated electric and magnetic fields surrounding them. If other conductors are brought into the close near field "cylinder of influence" of these fields, then significant energy transfer may result from the active wires to the approaching wires. This "crosstalk" at close distances is on the order of -10 to -20 dB (i.e., the accidentally transferred signal level on the "receiving" wires is 10 to 20 dB below the level on the "transmitting" wires). This potential energy transfer should be considered when laying out cables and wire bundles. Because the received level is lower in amplitude than the original level, it is usually permissible to group similar wires together (i.e., a low level analog group, an AC power group, a DC power group, relay switching lines, high power RF coaxial cables, etc.). Many, if not most, cable EMI problems can be avoided, not by expensive or exotic shields, but by simple separation of bundled wires into functional types. Adequate separation depends upon cable length, respective signal levels, and degree of coupling. If dissimilar wire bundle types must cross at close distance, a perpendicular crossing is best, as the crosstalk is proportional to the cosine of the angle between the source and affected wire bundles.

10.3.3 Wire Twisting

Wire-to-wire crosstalk is differential mode coupling. Crosstalk can be reduced by wire twisting (either culprit or victim wires), as can be the unintentional pickup of energy from a radiated field by a wire loop area. Reduction of coupling by wire twisting can be approximated from the following formula:

$$\text{Twist Rejection} = 20\log_{10}\left\{\left(\frac{1}{2nL+1}\right)\left[1 + 2\,nL\,\sin\left(\frac{\pi}{n\lambda}\right)\right]\right\}\ \text{dB},$$

where n = number of twists per meter,

L = cable length in meters,

λ = wavelength at EMI frequency in meters = $300/f_{MHz}$ meters,

the sine function is performed using radians,

and rejection is assumed to be between 0 and 60 dB.

To maintain the effectiveness of wiretwisting, the twists must be reasonably uniform and tight. A good number of twists for many applications is 40 - 120 twists per meter. The twisting must be continued over the entire length of exposed wire pair; the twisting reduction is only as good as the ratio between adjacent twist areas. If a tightly twisted wire pair is terminated with the two wires inches apart, then loop pickup or radiation will occur at that end instead of over the length, but the net effect will still be excessive pickup or radiation.

10.3.4 Filtering

In contrast to power line filters, which are usually lowpass LC filters, signal line filters may be lowpass, highpass, band reject (also called notch filters), or highpass. Signal filters may also be RC circuits, or active filters, such as constructed from operational amplifiers with selective feedback. The general thrust of signal line filtering is the same as for power line filtering: pass the intended signal while blocking signals out of the intended frequency range. Note that there must be a frequency difference present to be able to use filters productively. If there is no frequency difference between the interfering signal and the intended signal, signal line filters are useless. On some occasions, digital circuits radiate excessively, and must be filtered. On the other hand, digital signals require significant bandwidth; if we filter out the offending higher frequency harmonics, we may end up with timing anomalies or "transition level timing confusion". A common compromise between maintaining fast digital logic transition times and minimizing unnecessary "noise" content is to use a low pass filter on digital signal lines, with the 3 dB point at the fifth harmonic of the computer clock frequency.

10.3.5 Transient Protection

As with powerlines, signal lines may require transient voltage protection. This is especially true for long run signal lines, lines running through an electromagnetically noisy area, and lines going outside a facility. As with powerlines, MOVs, Transzorbs (TM, General Semiconductor Corp.), ionizable spark gaps, or back-to-back zener or avalanche diodes may be used. Signal line transient protection devices are rated at lower power dissipation levels than powerline devices.

Device capacitance is more critical for signal line devices, due to the loading effect high capacitance devices have on high frequency digital or analog circuits.

10.3.6 Balancing

As a simple statement of fact, ground conductors in electrically busy environments carry potentially bothersome EMI currents, producing potentially bothersome EMI voltages in the ground system. As we would not want to use such a noisy ground system as an intentional signal conductor, so we should want to keep our signal conductors isolated from that ground system noise. We should keep the two signal conductors in a transmission line equally isolated from ground, so the ground noise will have a simultaneous and equal effect on both conductors, so there will be no net EMI voltage difference between the two conductors. This arrangement involves ensuring equal impedances from each line to ground and is called circuit balancing. Balancing signal circuits can be an economical circuit protection choice at lower frequencies, although higher frequency (> 1 MHz) impedance is difficult to maintain, due to differing stray capacitances from each wire to ground, based upon wire positioning.

10.3.7 Optical Isolation

As was discussed for power lines acting as a portion of common mode ground loops, so can signal lines complete ground loop circuits. All ground loop fixes entail modifying (increasing) common mode loop impedance, or providing a shunt path for the common mode current. Signal line optical isolators function by inserting an optical path in the metallic signal line, breaking the common mode signal path. Based purely on the physical size of conductive elements in a typical optoisolator, the stray input-to-output capacitance is on the order of 3 to 10 picofarads. This small stray capacitance limits high frequency common mode isolation. As long as input and output leads are routed directly away from each other, the degree of isolation is inversely proportional to the separation between input and output conductor circuit elements. Recall the capacitor equation discussed in Paragraph 9.1.2 above.

Fiber optic cables maximize the light path common mode isolation by minimizing the input-to-output capacitance, through the mechanism of maximizing the length of the light path. If fiber optic cables are metal armored or sheathed to protect them from hazards, the metal sheath must be cut back at each end, to preclude common mode current coupling around the light path, on the metallic envelope. One foot of separation distance between the equipment cabinet or enclosure on each end and the fiber cable sheath should be adequate.

10.3.8 Signal Transformer Isolation

Signal transformers are an available method to help break common mode current loops. In procuring such a transformer for a given application, the effective primary to secondary capacitance is as important a parameter as differential mode intentional signal coupling performance. The parasitic capacitance on typical unshielded isolation transformers is on the order of 3,000 to 10,000 picofarads. A well made shielded transformer, installed properly, may have an effective interwinding capacitance much less than one picofarad.

10.4 Cable Protection

Cable to cable crosstalk has been discussed in Paragraph 10.3.2 above. In addition to "choosing cable neighbors" when laying out cables, cable positioning and shielding affect cable performance with regard to unintentional pickup of radiated energy, or unintentional generation of a radiated field.

10.4.1 Cable Placement/Routing

In general, all cables should be routed adjacent to grounded sheet metal. This placement presents a minimum cable loop area to the environment, and spoils the potential "loop antenna effect". For either radiation or reception, the efficiency of coupling of a loop antenna (intentional or not) is proportional to the loop area, until loop dimensions approach one half wavelength. By collapsing loop areas (common mode: laying entire cable close to ground, and differential mode: keeping circuit high and return conductors adjacent to each other), the need for cable shielding can often be eliminated.

In the event that a cable is routed close to a local representation of ground, such as a metal cabinet bolted to ground, it is usually best to avoid running the cable across a hole, aperture, joint, or slot in the cabinet, if there is any chance of radiated susceptibility (strong radiated field source <u>outside</u> the cabinet) or radiated emissions (strong radiated field source <u>inside</u> the cabinet); the cable running past a slot effectively negates the shielding effectiveness of the housing material, due to interactions between the cable and current patterns in the metal adjacent to the slot.

10.4.2 Cable Shielding

Cable shielding is similar to grounding, in the sense that many engineers continually search for the ideal hardware and the ideal installation method. As a simple fact, most cable shielding is fairly effective to excellent for providing differential mode shielding (i.e., prevention of the radiation from wire pairs inside a shield, or the pickup of an external by wire pairs protected inside a shield), and only poor to mediocre for providing common mode shielding. A cable shield is, first and foremost, a conductor, on which current will be generated by external fields or by shield connection to two differing ground potentials. Net cable shield current will induce common mode current onto the supposedly shielded conductors inside the shield. Only thick shields, such as solid wall conduit, will solve this problem.

10.4.3 Cable Shield Termination

By personal observation, many engineers know that grounding audio cable shields, such as speaker wires at both ends will cause 60 Hertz hum in the audio system. This is due to the cable shield acting as a simple parallel conductor in the presence of a 60 Hertz field; power frequency current is induced in the shield, common mode current is induced by the shield into the speaker wires inside the shield, and some fraction of that common mode current, by unbalanced wire impedances to ground, produces a differential mode noise voltage received by the speakers. Result: 60 Hertz hum. Solution: unground one end of the shield, to break the common mode current path.

Alternatively, RF engineers are familiar with stray capacitance, the inductance of long conductors, wavelength related impedances, and standing waves, and know that an RF shield ground at only one of a cable is often inadequate. The single end grounded shield will act like a grounded monopole antenna, with the ungrounded end of the shield rising to some RF potential with respect to the ground. That end voltage will be capacitively coupled to the conductors inside the shield, again producing common mode voltage contamination of those conductors. The ungrounded end of the shield can be grounded to avoid this capacitive coupling problem, but then the above described inductive coupling problem returns.

The shield grounding decision is thus based upon whether we are primarily concerned with the audio frequency range (wavelengths are exceedingly long, grounding at one end is acceptable, and preferred), or the radio frequency range (wavelengths are medium to short, ground shields at least every one tenth wavelength, or as often as possible). If problems in both audio frequency and radio frequency ranges exist, more specialized shield and shield termination techniques may be necessary, such as double, isolated shields, grounded at opposite ends, heavy conduit shielding, or reactor grounded shields.

Whether the cable shield is grounded at one or both ends, all ends that are terminated by mechanically clamping the shield to the terminating bulkhead, either with a manufactured cable backshell, or perhaps with a cable hose clamp around a pipe stub through the bulkhead. Although twisted shield braid or drainwire "pigtails" are acceptable for very low frequency applications, the high self inductance and current concentrating effects of nonperipheral terminations are to be avoided.