LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Specification	**LIGO-E960036-02 -**	**E**	06-07-96

LIGO EMI CONTROL PLAN AND PROCEDURES

Systems Engineering

Distribution of this draft:

This is an internal working note
of the LIGO Project.

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CHANGE RECORD				
Revision	*Date*	*Authority*	*Pages Affected*	*Item(s) Affected*
Initial Issue	4/10/96	Draft		
01	5/24/96	Draft	ALL	ALL
02	6/7/96	Draft	ALL	ALL

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1 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.

1.1. 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.

This plan concerns itself with the goal of eliminating, to the greatest extent possible, causes and effects of electromagnetic interference (EMI) which can limit the performance of the LIGO Detector System. EMI manifests itself by electromagnetic processes which may compromise the extraction of useful scientific information from the gravitational wave antenna either from the generation of events which can mimic a true GW signal (i.e., transients) or through an increase in the overall detector noise floor (stationary noise, either broadband or narrowband). EMI effects include both excess physical motion of suspended test masses through direct electromagnetic coupling with force actuators and electromagnetic pickup in electronic circuitry.

1.2. System Description

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. LIGO consists of two sites, one at Hanford, Washington, and one at Livingston, Louisiana. For effective detection, the two sites are to be operated as a unit, necessitating accurate time-tagging and coordination. Future collaboration with international sites is envisioned to enhance the effectiveness of gravitational wave detection.

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

1.3. Operational Environment

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

1.3.1. General 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 one distribution transformer 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.

1.3.2. LIGO Conducted Powerline Ambient Conditions

The 120 VAC, 60 Hertz, technical power will be reasonably protected from utility line noise by utility lightning protectors and isolation transformers. The distributed inductance and capacitance of the utility power lines will provide some degree of isolation from distant power system EMI sources. Facility power transients and steady state conducted emissions will be one transformer distant from technical power. With the possible exception of high energy transients, the incoming utility powerlines and facility power loads should present no operational threat to technical power loads.

Typical LIGO technical power loads and conditions include:

- + 24 VDC power supplies @ 30 amperes
- VME crates, with internal 1500 watt power supplies
- VME cards and processors, A/D converters, D/A converters, binary I/O, CPUs with clock frequencies exceeding 30 MHz
- Eurocard crates with 6U board analog electronics, with frequency responses from DC through tens of MHz
- RF amplifiers @ frequencies of tens of MHz, and power < 5 watts
- Rack area wire marshaling and crossconnect areas
- Long fiber optic cable runs
- No long conductor runs
- Local ground pads, bonded to safety ground, with all local equipment bonded to pad, to ensure low ground voltage differences between all local equipment

As installed, the technical power loads will have no power line isolation from each other. In most cases, this should present no problem. Problems might occur, if a "source" and "victim" are connected to the same AC power bus. If the "victim" is sensitive to the amplitude and bandwidth of conducted interference imposed on the powerline by the EMI source. An example could be a device causing transients on the powerline, upsetting a sensitive powerline neighboring device. Another could be voltage waveform harmonic distortion caused by current harmonics created by switching power supplies or simple rectifier output capacitor power supplies; this voltage waveform distortion could potentially cause problems with waveform-sensitive or zero crossing sensitive devices.

1.3.3. Radiated Ambient Conditions

Due to the rural nature of the LIGO sites, radiated interference sources will be limited. Likely sources include: distant transmitters, intentional on-site transmitters, and unintentional radiation from LIGO equipment. A 60 Hz magnetic field ambient of 10 mG, typical of industrial environments, is expected.

Distant licensed transmitters at the Hanford, Washington, site have been identified[1] by Mr. J.E. Curtis. Those transmitters are listed in Appendix B. As seen by the tables in Appendix B, the highest expected field intensity from distant licensed transmitters is 285 mV/m. This environment is considered benign, and represents no threat to normal electronic devices. The radiated ambient at Livingston, Louisiana still needs to be determined. To add to the radiated environment, radiated emissions from mobile transmitters, such as could be used by on-site personnel, need to be considered. Appendix B also presents representative transmitter and power combinations. The table was generated using the following equations:

$$E\left(\frac{V}{m}\right) = 5.5[P(Watt)]^{\frac{1}{2}}[R(meter)]^{-1} \quad [1]$$

$$R(meter) = 55\left[\frac{E(mV/m)}{100}\right]^{-1}[P(Watt)]^{-\frac{1}{2}} \quad [2]$$

From Table B-3, 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 more distant commercial transmitters.

As a general guideline, radiated emissions levels greater than 1 V/m are of concern for the susceptibility of general electronic equipment (except for receivers, of course, which are much more sensitive). 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).

1.4. Applicable 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 50081-1	Electromagnetic compatibility generic emission standard for the residential, commercial and light industrial environments.
EN 50082-1	Electromagnetic compatibility generic immunity standard for the residential, commercial and light industrial environments.

1. 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.

EN 55022 Limits & Methods of Measurement of Radio Interference, Information Technology Equipment, 1995

2 APPROACH TO EMI CONTROL ON THE LIGO PROJECT

The essential electromagnetic compatibility requirement is that all components of the LIGO system perform properly at design sensitivity with no upset, disruption or operational degradation due to electromagnetic interference, whether due to the operational environment or neighboring components.

All EMI problems include three elemental components: interference source ("culprit"), interference energy transfer mechanism ("coupling path"), and an affected circuit ("victim"). The essence of an EMI problem is the inadequacy of electromagnetic isolation between culprit and victim. To complicate matters, each of these three problem components may not be singular. For example, a radio transmitter may interfere with more than one susceptible circuit or equipment simultaneously, with energy being coupled over more than one path. Fixing or preventing an EMI problem is accomplished by providing adequate electromagnetic isolation between all culprit-victim pairs. To achieve isolation at affordable cost, reasoned approximations must be made concerning culprit interference output, the efficiency of energy transfer over likely coupling paths, and the sensitivity of upset of likely victims.

For the EMI Control program to succeed, it needs an advocate with the commitment, responsibility and charter (i.e., project authority) to see the program to successful completion. Electromagnetic compatibility will be achieved by an organized management of potential electromagnetic disturbances, 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 Project resources.

The goals of the EMI Control program are not to impose an onerous burden on LIGO electrical designers, but rather to provide a reasonable set of guidelines representing accepted good engineering practices. It is likewise critical that the practices laid out in this plan and agreed upon by the Project be followed as consistently as possible throughout all phases of the project.

3 MANAGEMENT

LIGO is a relatively small Project and all critical electronic circuit components are the responsibility of the Detector-CDS Group (CDS). For these reasons, CDS will be requested to bear responsibility for the effective implementation of this plan. Oversight of its implementation at the Project level will be effected in the normal course within the context of the established design reviews. The role the EMI Control with regard to electrical component design will be analogous to the role of the QA with regard to process and fabrication.

Instances of non-compliance will be addressed individually as the circumstances may require.

Where necessary due to other constraints (such as funds or time), certain risks may be required: however any such risks will be identified, documented, and acknowledged by the Project.

In order to ensure program success and to minimize delays and upsets due to interference, a single individual within CDS will assume primary responsibility of EMC Engineer for the oversight of the implementation of the LIGO EMI Control Plan. The individual will be proposed by the Detector Group and approved by the Project Manager. When needed, the LIGO Systems Engineering Group will make additional resources available to the EMC Engineer to support him/her in fulfilling his/her responsibilities.

This document, when approved by the signatories, shall come under Configuration Control, and all revisions or modifications must be approved through the CCB process.

3.1. Responsibilities

The LIGO EMC Engineer shall have the responsibility to ensure proper and timely completion of the following actions:.

A Overall EMC program goals.

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

C Set EMC program milestones associated with design reviews (DRR, PDR, FDR).

D Establish a plan to identify and resolve EMI problems.

E Establish plans and procedures to implement identified EMI fixes.

3.2. Lines of Authority and Control

The oversight authority for EMI Control rests with the Detector CDS Group.

3.3. Implementation Planning

The EMC Engineer will be responsible for determining resources and scheduling constraints to accomplish required tasks according to the LIGO EMC program schedule.

3.4. Milestones and Schedules

The EMC Engineer will develop the milestones and schedule. Starting from the scheduled "LIGO site ready" date, and working backwards, dates will be assigned for the individual milestones.

A tentative list of tasks to be accomplished by the EMC Engineer include:

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

Identification and measurement of any particularly suspect (as either culprit or victim) 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

3.5. Testing and Qualification

It is not intended that EMC/EMI testing will be accomplished with every electronic circuit boards or assembly. Rather it is anticipated that most subsystem tests will be conducted in similar EMI conditions to those expected in the LIGO facilities, e.g., the 40m laboratory. The LIGO EMC Engineer may propose to preform a radiated and/or magnetic susceptibility testing of selected assemblies or subsystems. The radiated and magnetic susceptibility tests are:

1) A maximum spectrum of RF that a testable assembly or subsystem is permitted to radiate. The limit allowed will be <1 V/m @ 1 m. The direct test will be preformed in a RF "free" area and acceptance of the unit under test will be signed off by the LIGO EMC Engineer.

2) A measurement of susceptibility of a testable assembly or subsystem to stimulation by a 60Hz line field of 10 mG amplitude at the device. Successful test will constitute a rise in the spectral amplitude density of noise by less than less than 2 dB at any frequency. Acceptance of the unit under test will be signed off by the LIGO EMC Engineer.

3.) A measurement of conducted emissions shall be made to assess the amount of mains (60Hz) line spikes present at the output of sensor/actuator systems. The mains spikes (and all harmonics) shall be at a level no greater than 6 dB above the broadband sensor/actuator noise floor.

An integrated EMC test will be performed at the LIGO facilities to measure instrumentation and incrementally operate individual equipment items while monitoring each other equipment item for effects in a normal LIGO operation. Part of this testing program will include Physics Environment Monitoring tests, such as:

- 3-axis magnetometer tests of ambient magnetic fields (10 Hz - 1 kHz) in the vicinity of test masses
- calibration of mirror displacements-to-magnetic field transfer functions
- discrete displacements caused by transients in switchable equipment

3.6. Procedures for Identifying and Resolving EMI Problems

When an EMI problem is identified, the following determinations will be made:

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.?

3.7. Procedures for Implementing EMI Fixes

After the EMC Engineer determines the path to be pursued, he/she will arrange the fix installation. He/she will determine the following:

Schedule

Cost

Necessary resources.

Verification/validation of the effectiveness of and implemented fix.

3.8. Conflict Resolution

Electromagnetic compatibility is a necessary concern for predictable, reliable, and economical LIGO system operation. It is, however, not the only LIGO system consideration. For example, an EMI fix could jeopardize personnel safety, such as the removal of a ground loop completing safety ground. In such an event, a fix technique would have to be developed to avoid the unsafe condition produced by disconnecting a ground conductor. To further address this example, the simple ground wire could be replaced with a ground inductor, which would maintain AC power frequency safety ground, while adding impedance to the ground path at higher frequencies. In this simple example, economy would be slightly impacted (increased cost of inductor over simple wire), as would reliability (the inductor could be damaged). Factors to balance in solving an EMI problem include, in the following general order:

Personnel safety

LIGO system successful operation, without EMI

Reliability

Economy

Convenience and maintainability

4 INTERFERENCE CONTROL

The intent of this paragraph is to provide EMC guidance to LIGO scientists, engineers, technicians, and other system integrators, to preclude the majority of interference problems which may arise. The requirements herein are presented without rationale. For supporting rationale, refer to the appendices in this document.

4.1. Design Requirements

The following paragraphs dictate specific installation design practices, which are intended to help establish an electromagnetically compatible system.

4.1.1. Grounding

All AC wiring and equipment safety grounding conductors shall be installed in compliance with the National Electrical Code ("Code"), as amended and/or modified by local laws and regulations. Nothing in this document shall be construed to conflict with those safety requirements.

All technical load equipment enclosures shall be grounded to a local ground plate or ground grid, which shall in turn be connected to the AC safety ground. The grounding conductor shall meet Code requirements for impedance and ampacity. If a ground grid is used, the grid spacing shall be no greater than 1/20th of a wavelength at the highest intentionally generated frequency or anticipated EMI trouble frequency.

Ground low frequency (< 1 MHz) signal circuits at one end only, to prevent ground current contamination of the signal circuit. Ground the more critical end of the circuit (the receiving end for a potentially susceptible circuit; the transmitting end for a potential culprit circuit).

Figure 1 illustrates the difficulties potentially involved in simply "properly" grounding a simple signal circuit. At first glance, the circuit is already grounded, as drawn, and there should be no problem. There are, however, two sources of interference: the EMI ground current, and the radiated EMI field.

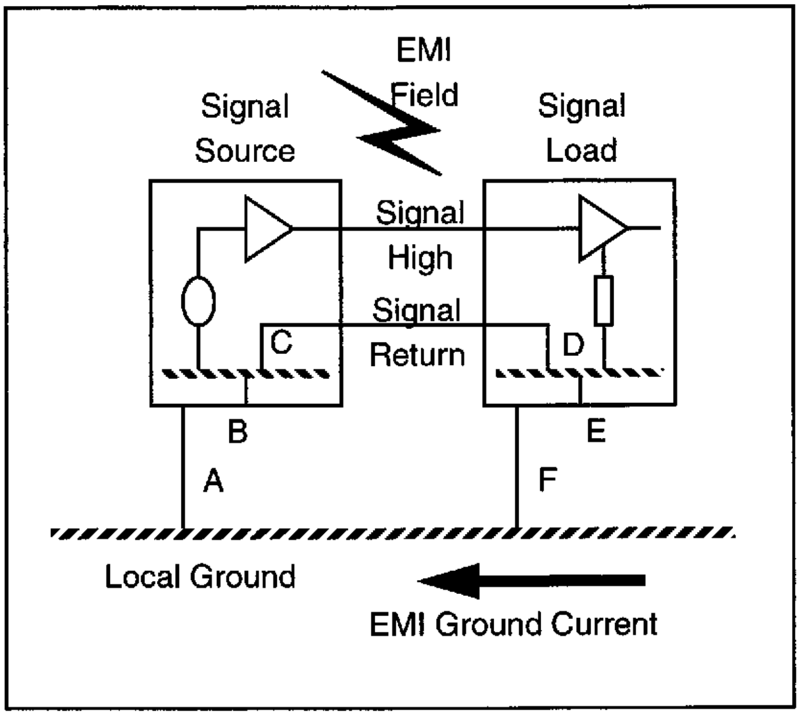

Figure 1: Depiction of Generic Signal Circuit Grounding Problem.

The EMI field generates differential mode voltage in the signal high/signal return loop, as well as common mode voltage in the box-cable-box-ground loop. At frequencies below which the maximum loop dimension is less than a half wavelength at the radiated interference frequency, the loop pickup is proportional to the loop area. To minimize both the common mode and differential mode loop areas, the two signal leads should be twisted together and routed right on top of ground, with the boxes as close together as possible.

If more isolation from the field is desired, the two signal wires can be shielded as a bundle, with the shield grounded at both ends. This works well for the differential mode case, as the two leads are constrained to experience the same field within the shield. For common mode, however, the resulting net shield current can cause coupling of common mode EMI to the wire pair. If on end of the shield is lifted from ground, the common mode current is interrupted, but at EMI frequencies where the cable shield represents a significant fraction of a wavelength, the ungrounded shield end acts as a monopole antenna, and rises to some RF noise potential. The resulting EMI voltage on the shield can be capacitively coupled to the wire pair, again resulting in common mode EMI contamination.

Even if there is no EMI radiated field present, there is likely to be EMI current in the ground system. Whether the signal wire pair is grounded or not, the ground noise current will produce a voltage drop across the impedance of the ground system between points A and F in the drawing, and will apply that voltage to the signal circuit ground points. If we lift one end of the signal circuit from ground, we can remove the ground noise problem ("opening the ground loop"), but we set ourselves up for a monopole EMI reception problem again if an EMI radiated field arises.

Even with the above described difficulties, there are some generally applicable signal circuit grounding and related rules:

1. Do not use the ground system as a return conductor.
2. Twist signal conductors together and route them directly over ground, with minimum spacing from ground.
3. Ground a low frequency cable shield at one end only (usually the more critical, or receiving, end).
4. Ground high frequency cable shields at both ends, and at other points as practicable (such as at bulkhead feedthrough connector locations.
5. For cables with both low and high frequency potential problems, use a double shielded cable, with the two isolated shields grounded at opposite ends.

4.1.2. Electrical Bonding

Collocated technical load equipment enclosures shall be electrically bonded together, preferably by direct cabinet-to-cabinet, metal-to-metal contact secured by bolt and nut hardware, with no washers intervening between the joined surfaces. Flatwashers and lockwashers may be used for joint permanence, but not between the two joined metal surfaces. Each cabinet shall still be tied to AC safety ground through the normal safety grounding conductor.

4.1.3. Wire/Cable Treatment

Signal and power carrying conductors shall be arranged to minimize crosstalk.

4.1.3.1 Placement/Routing

Route dissimilar cables (classed by power or signal type) separately, where possible, with maximum separation between widely different types. Minimize common length of cable runs where separation is not feasible. As an example, consider the following typical signal types:Low level analog/dc power, High power RF/High Voltage High Frequency, Low Level RF, Optical Fiber/ Communications, High Voltage/Low Frequency, Switching/Motor Drive lines. Assuming that only four separate cable tray areas are available, these could be grouped as follows, to minimize crosstalk problems:

A. Low level analog/DC power, Low level RF, Fiber/Communications
B. High Power RF/High Voltage High Frequency
C. High Voltage/Low Frequency
D. Switching/Motor Drive

Route all cable runs as close as practicable to the best representation of local ground, to prevent loop area pickup and radiation.

Inside cabinets, avoid routing wires and cables across gaps or slots in the outer shielding material, as this tends to allow radiated energy coupling through the shield discontinuity.

4.1.3.2 Shielding

Shield low level, low frequency signal cables. Shield high level, low frequency signal and power cables. Use twisted shielded pair. Do not use the shield as an intentional signal or power conductor. Use coaxial cabling for signals much above 1 MHz. Where coaxial cabling is used for low frequency, low level signals, do not ground the outer conductor of the coax at more than one point, to prevent ground current flow in that conductor, and resultant signal contamination. For high frequency and high level coaxial cable usage, ground the outer conductor as often as possible, including both ends, and at grounded barrier feedthrough points.

4.1.3.3 Termination

Ground the more critical end of a low frequency cable shield. The receiver end of a sensitive low level circuit is considered the more critical end. The transmitting end of a high level circuit is the more critical end. If the cable is longer than 1/40th of a wavelength at the highest frequency of concern (emitted or received), ground the shield at both ends and every 1/40th of a wavelength. Terminate cable shields with proper 360 degree shield contact connectors. Do not extend cable shields into a twisted "pigtail" extension for termination at a ground screw.

4.1.4. Shielded Enclosures

House RF-sensitive components and potentially RF-radiating components within shielded cabinets, boxes, or compartments. Ensure that all compartment joints have tight metal-to-metal contact, with the maximum dimension of any areas of non-contact less than 1/40th of a wavelength long at the highest frequency of concern. Filter any penetrating wire leads with filters or feedthrough capacitors which will be effective over the frequency range of concern. Where nonconductors are used optical fiber or simple light paths, use waveguide below cutoff tubes to maintain compartment shielding.

4.1.4.1 Vacuum Feedthroughs

Vacuum chamber feedthrough filter connectors are commercially available. Optionally, standard nonfiltering feedthrough connectors can be used, and appropriate external filters can be used.

4.1.4.2 Active Electro-Optics

Optical fiber can penetrate shielded compartments without penalty, if waveguide below cutoff tubes are used if the fiber passage hole allows excessive RF leakage. Do not use metal-sheathed fiber to penetrate a shielded compartment.

4.2. Interference Design Analyses and Reviews

The LIGO system comprises a variety of electrical, electromechanical, and electronic equipment. Thorough analysis of all interference possibilities will require identification of interference parameters (emissions and susceptibility, frequency ranges and levels). Even without specific information on hardware, the following section lists a number of possible EMI problem areas, with associated solutions. In the event of an unanticipated EMI problem occurring during system integration, the following factors will be researched:

- EMI Receptor(s) - Victims

- EMI Coupling Path(s)
- EMI Source - Culprit
- Significant Bandwidth of EMI
- Effective Receiving Bandwidth of Receptors
- Ratio of Interference to Receptor Sensitivity (Noise Floor)
- Desired Margin of Noninterference (Number of dB below receptor noise floor of treatedinterference)
- Practicable, efficient, effective methods of EMI control
- Special factors (Cost, reliability, size, weight, complexity, temperature, maintenance requirements, installation difficulties, ease of inspection, permanence, etc.)

4.3. Possible Problem Areas and Methods of Solution

A. Problem: The technical loads themselves are identified as a general source of upset for other technical loads.

Solution: Each electronic device used as a load on technical power should meet minimal commercial conducted and radiated emissions requirements, such as FCC Part 15, Class A, for commercial ITE ("Information Technology Equipment"), or European Union EN 55 022, Class A, for commercial ITE. This is not an added cost factor, as most currently manufactured digital equipment meets these standards. Older digital equipment without emissions qualification, and non-digital equipment may be used, but will be front panel labeled, "EMI NONQUAL" or similar, to flag nontested status. Any problem-producing equipment will be modified (probably by filtering, shielding, or wire re-routing) for compliance or its usage will be discontinued.

B. Problem: Crosstalk.

Solution: Cable bundling will be on a strict by-function basis. Sample cable segregation categories are:

Low current DC

Low current AC

High current DC

High current AC

Low level analog

Digital and relay lines

Low power RF

Medium to high power RF

C. Problem: Ground voltage differential between racks.

Solution: Adjoining equipment racks and cable trays will be bolted or bonded together, producing a DC bond resistance ≤ 2.5 milliohms. Direct bolting together of clean, flat, bare metal surfaces are preferred over bond straps or wires. At the point of surface-to-surface contact, no starwashers, lockwashers, or other hardware will be placed between the surfaces. The mating surfaces will be kept dry and free of contaminants and corrosion.

D. Problem: Circuit upset/data contamination by locally produced RF fields.

Solution: Handheld radio transmitters will be banned from usage near any sensing or other low level analog circuitry, and from the immediate area of technical load equipment. Referring to the predicted radiated levels in Table B-3, assuming that 1 V/m is a marginally safe level, the following minimum separation distances are recommended:

Transmitter Power ≤ 2 watts:	10 meters
Transmitter Power > 2 watts:	30 meters

Transmitters greater than 20 watts should be excluded from the LIGO site entirely. If RF transmitters become necessary as a normal part of system operation, a comprehensive system check will be performed to detect any operational anomalies, if fields in excess of 0.5 volt per meter are produced.

E. Problem: Interference due to cable pickup from shield current caused by ground voltage differences or magnetic fields.

Solution: Low frequency ($\ll$ 1 MHz) and low level analog cable shields will be connected to ground using a full 360 degree peripheral shield contact termination method as the method of choice. The termination to ground will be at one end of the cable only, at the more critical end of the circuit (normally a "receiving" end). Single-ended shield termination will also be used for cables shown to be susceptible to low frequency magnetic fields.

F. Problem: Interference pickup by a cable from high frequency fields (> 1 MHz) or high frequency radiation from a cable.

Solution: High frequency cable shields (i.e., shields used to contain or exclude high frequency radiated energy) will be 360 degree terminated to local bulkhead ground at both ends, and at intermediate bulkhead penetrations.

G. Problem: System noise due to lack of solid DC supply voltage reference, and interference due to electrostatic discharges.

Solution: DC power supply outputs will be referenced to ground.

H. Problem: Noise pickup in sensitive cabling due to radiated pickup in signal-carrying shield, or ground noise current flow in shield.

Solution: Cable shields will not be used as intentional signal conductors.

I. Problem: Cable pickup of radiated fields due to large loop area over local ground, and cable pickup or radiation through shielded compartment apertures.

Solution: Cables will be kept as short as practicable, and routed directly over continuous grounded conductors, or immediately adjacent to grounded metal members, avoiding runs over ground discontinuities.

J. Problem: System hardware upset or data contamination by steady state or transitory technical load equipment conducted interference, or by utility power transients or steady state interference.

Solution: If significant utility or facility power transients or steady state interference are detected at technical power loads, consideration will be given to installing additional power line filtering and/or transient suppression at each technical load location.

K. Problem: RF interference to the interferometer photodiodes and preamplifiers from Pockels cell modulators (RF voltages on the order of 10 to 100 volts, with RF power on the order of 10's of watts) and from the RF electric and magnetic fields due to the reference signals for the mixers that demodulate the photodetector signals.

Solutions:

a.) House the Pockels cells in continuous metallic enclosures, with tubular waveguide below cutoff light entry/exit paths.

b.) Use balanced leads within an overall cable shield to carry RF current, to avoid RF voltage drops across shields or enclosures. At higher frequencies (>> 1 MHz), low transfer impedance coaxial cable is adequate, assuming cable terminations are also low impedance, and circumferential, with proper RF fittings. Hard line coax is best for low cable transfer impedance.

c.) Use a waveguide below cutoff for the light entry path to the photodetector. Multistage filter all power leads to the photodetector preamplifier boxes. Such lowpass filters should have cutoff frequencies no higher than 10 MHz, and should provide at least 40 dB of attenuation through 1 GHz.

L. Problem: Excessive effective net neutral conductor RMS current, neutral line heating, transformer heating, powerline voltage distortion, due to technical load current distortion (nonsinusoidal load current waveform).

Solutions: Use of high power factor preregulators on power supplies to minimize current distortion. Oversizing of neutral and use of higher K factor distribution transformer to reduce neutral and transformer heating.

APPENDIX A: Definitions & Abbreviations

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 $Z_B = 3.68 \text{ x } 10\text{-}7 \sqrt{\frac{\mu f}{\sigma}}$ 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 interference. 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 λ = 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. This organization 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.

APPENDIX B: Tables of Emissions at Sites

Table B-1: Anticipated Radiated Ambient at Hanford, Washington, LIGO Site Due to Nearest AM, FM Radio Stations and TV 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
KEPR TV	501/506 MHz	5 MW	26.75	285 mV/m
KVEW TV	639/643 MHz	5 MW	27.25	279 mV/m
KNDU TV	536/542 MHz	5 MW	27.25	279 mV/m
KTNW TV	578/584 MHz	3 kW	27.25	7 mV/m
KEBB TV	680/685 MHz	1 kW	15	7 mV/m

Table B-2: Anticipated Radiated Ambient at Livingston, Louisiana, LIGO Site Due to Nearest AM, FM Radio Stations and TV Stations.

Station	Frequency	Effective Radiated Power	Distance, Miles	Predicted Field Intensity
TBD	TBD	TBD	TBD	TBD

Table B-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			24.5meters 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	

APPENDIX C: Types of EMI Coupling

Interference energy can be coupled from culprit to victim by conducted paths, radiated paths, or a combination of the two. Experience indicates that power line interference and ground system EMI occur much more often than radiated field coupling.

C.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.

C.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.

C.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.

C.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.

C.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.

C.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 capacitance's, 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 meter^2, and d = effective separation distance in meters between parasitic capacitance "plates".

Grounding conductor impedance's increase due to inductive reactance from stray conductor inductance, and unintentional cable resonance's 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.

C.2 Radiated Coupling

Electromagnetic radiation is often considered to properly be the study of only far field radiation effects. For EMI control purposes, radiated coupling is considered to be all coupling that is not purely conducted coupling, including crosstalk, near field magnetic and electric field coupling, radiated field coupling to cables, and radiated field coupling into enclosures.

C.2.1 Crosstalk to Signal/Control Conductors

Loosely included in radiated field coupling is *cable-to-cable differential* mode coupling , or "crosstalk". Crosstalk interference generally results when incompatible wires/cables are collocated too closely or over too great a common length. Cable-to-cable EMI transfer can be predominantly inductive or capacitive in nature, depending upon circuit impedances. The degree of coupling depends upon the interference frequency, the size of the cables, the length of the common cable run, the distance of separation between the source and victim cables, whether the cables are parallel or cross at an angle, and the distance to local ground.

C.2.2 Near Field Coupling

Near field coupling can also affect victim circuits. For EMI control purposes, near field sources with circuit impedance < 377 ohms are classified as magnetic field sources, while circuit impedances > 377 ohms are classified as electric field sources. Whether a strong near field is magnetic or electric, the field falls off rapidly with distance.

C.2.2.1 Electric Field Coupling

Near field electric field coupling can occur when a sensitive, high impedance circuit is placed near a high voltage circuit.

C.2.2.2 Magnetic Field Coupling

Near field magnetic field coupling can occur when a device sensitive to magnetic fields, such as computer monitors, magnetic field sensors, or low impedance circuits, are placed near magnetic field sources. Typical magnetic field sources are high current cables, current loops, and gapped magnetic devices, such as transformers, motors, and high current inductors. Power supplies can have a number of these sources.

C.2.3 Radiated Field Coupling to Cables

Radiated coupling paths include far field radiation impinging directly upon affected equipment enclosures, or, more commonly, such radiation impinging upon system wires and cables, which are usually of greater dimensions than equipment enclosures and act as more effective (accidental) receiving antennas. Cable shields immersed in a radiated field are, of course, conductors, and will conduct a resulting interference current. This current can contaminate the conductors within the shield. Similar contamination can also occur with coaxial cables in a hostile radiated field, due to induced interference current flow on the outer conductor. The degree of coupling to the victim circuit depends upon the transfer impedance of the outer conductor (transfer impedance, $Z_{Transfer} = E_{Outer\ Conductor} / I_{Outer\ Conductor}$), which is affected by conductor material, thickness, degree of coverage, and method of termination.

C.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 Appendix A above, $S.E._{dB} = R_{dB} + A_{dB}$.

APPENDIX D: 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.

D.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.

D.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 resemblance to the fifty ohm test circuit curves. Filters cannot be effectively purchased by reference to manufacturers' performance curves.

D.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.

D.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. his 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.

D.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.

D.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.

D.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.

D.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.

D.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.

D.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.

D.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.

D.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).

D.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.

D.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:

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

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.

D.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.

D.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.

D.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.

D.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 Appendix C.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.

D.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.

D.4 Cable Protection

Cable to cable crosstalk has been discussed 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.

D.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 outside the cabinet) or radiated emissions (strong radiated field source inside 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.

D.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.

D.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.

D.5 Summary of EMI Protection Methods

The overall goal of all electromagnetic interference suppression, exclusion, prevention, and protection measures is to prevent excessive unwanted energy transfer between the equipment of concern and its operational environment. The generalized treatment method is to address the EMI source, the coupling path(s), or the EMI victim, taking into account cost, reliability, maintainability, and feasibility.

This plan concerns itself with the goal of eliminating to the greatest extent possible causes and effects of electromagnetic interference (EMI) which can limit the performance of the LIGO Detector System. EMI manifests itself by electromagnetic processes which may compromise the extraction of useful scientific information from the gravitational wave antenna either from the generation of events which can mimic a true GW signal (i.e., transients) or through an increase in the overall detector noise floor (stationary noise, either broadband or narrowband).