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EMC, Shielding and Grounding Retrofit Plan

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Distribution of this document:
LIGO detector commissioning team

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1 Introduction

Commissioning has highlighted inadequacies with the as-built LIGO interferometer electronics shielding, grounding and power architecture. We present a plan for addressing these through a phased reworking of rack, chassis, and interconnection protocols, in most cases maintaining current circuit boards and modules as-is or with minor modifications. Our plan is grounded in a few points of philosophy:

- EMI interactions are spatially distributed, typically nonstationary, and often nonlinear.
- At any given time, there will be one or a few "dominant" contributors of noise, and others will not cause measurable effects until these are reduced or until the environment varies.
- The volume of phase space to be examined for potential problems is a primary obstacle to troubleshooting unknown noise. Removing questionable elements and the associated opportunities for future suspicion is thus a worthy objective on its own, with measurable returns in saved commissioning time.
- Eliminating marginal or sloppy practices tangibly improves our confidence in asserting or refuting the reality of rare or weak putative signals. Compromising this degree of confidence threatens the core mission of LIGO.

Since EMI and grounding problems are intrinsically distributed, partial or local solutions rarely have dramatic impact. On the other hand, it's not practical to redesign all systems from scratch, nor can all fixes be implemented the same day. The following plan emphasizes the phasing of corrective measures in manageable stages, while maintaining a coherent vision of each interferometer as an integrated system.

The functional, operational and strategic requirements motivating this action plan are detailed in a separate document, LIGO-E020986, *LIGO Interferometer Electronics EMC Requirements*. Existing initial LIGO systems predate these requirements, and are not typically in compliance. We anticipate that execution of this plan, along with enforcement of the requirements for ongoing system improvements and upgrades, will bring the observatories substantially into compliance within about two years.

Document Revision History:

REV	*DATE*	*CHANGE*
00	*3/12/02*	*Initial draft*
04	*6/18/02*	*Incl. analog crate backplane isolation; implementation sequence*
05	*9/13/02*	*VME and digital noise containment, power supply replacement*
08	*10/10/02*	*Analog shielding concept heavily revised; board shielding& shielded substitute for open cross-connects proposed*

2 Plan overview

A sampling of selected problems is offered in the Appendix. From these and other observations we've distilled what appear to be the principal sources of interference energy, as well as the most likely receptors (although in many cases the precise physical reception mechanisms remain unclear). Apart from supporting assessment of the flaws in our current installation, these examples also suggest measures for effective mitigation.

Other sources of EMI energy are not specifically targeted, and may eventually need to be. We address digital equipment and power supplies directly operating and connected to the interferometer, but computer workstations, monitors, network equipment, communications devices, and their own internal power supplies are pervasive, share the same AC grid, and in some cases are positioned close to sensitive circuitry. A continued program of EMI audit and evaluation is an essential part of this plan.

2.1 Source Mitigation

The first priority is reduction or containment of interference generated by our own equipment, and thereby under our control. Our installations fall short in the following areas:

- Line & line harmonic frequency hum
- Fan and motor EMI
- DC power supply ripple & radiation
- Digital equipment clock and VME bus noise
- RF modulation leakage

The good news is that nearly all these source emission issues are common to a variety of "standard" industrial, commercial and defense applications (as well as some highly specialized research applications, such as radio astronomy). FCC, EC and MIL standards, intended, for example, to prevent TV interference from digital equipment or to preclude electronic eavesdropping, have led to standard off-the-shelf solutions for effectively containing stray emissions and currents. In most cases these solutions cost more, but are otherwise "pin compatible" with our normal system components.

In brief, we propose the following steps to contain self-generated interference:

- Eliminate switching power supplies in favor of low noise linear-regulated supplies
- Replace (or upgrade) VME crates to meet FCC and DoD EMC specifications
- Segregate VME crates and other digital electronics in separate "all digital" racks
- Make these racks EMI-shielded with conductive enclosure walls and conductive gasket closures for secondary containment
- Shield exterior cables carrying I/O signals between racks and crates within racks

- Introduce RFI blocking feedthroughs on all external conductors to disable conducted emission, slot radiation and antenna transmission.

2.2 Susceptibility reduction

The other factor in interference is the susceptibility of sensitive front- and back-end electronics (mainly analog). This factor is intrinsically more unique to our application.

One can calculate direct linear sensitivities for frequencies within the signal band (DC-10 kHz) and around each LIGO RF modulation frequency (25MHz +/- 10 kHz, etc.). Nonlinear susceptibilities are much less predictable. The following nonlinear processes have been caught mixing down or converting interference at HF through UHF frequencies into significant audio-band interference:

- Digital conversion sample aliasing
- Rectification by audio circuit front ends
- Fast spike saturation of analog circuits
- Slew rate limiting in audio circuit back ends
- Inadvertent diode action in deteriorated (corroded) shield and ground terminations

The definition of a “significant” interference level is anything that compromises LIGO sensitivity or might be confused with an astrophysical signal. What it means in voltage, current, or digital counts depends on which kind of signal and where the end product is measured.

LIGO detector requirements demand that many front-end sensing and back-end actuator drive circuits perform at or near the level of their intrinsic thermal noise (~nanovolts and ~picoamperes per root Hz voltage and current densities, respectively). As a result, significant interference may be just barely detectable in the full operating configuration, and undetectable in a test setup.

Some interference might not emerge at all except through a full astrophysical signal analysis. For example, narrowband periodic EMI lines can be invisible in normal diagnostics, but pop out prominently in long term signal integration; faint glitches may only become apparent after matched signal filtering. It may not be feasible to detect or estimate the margin for noise sources currently below detectable levels. This is compounded by the nonlinearity of many susceptibility patterns and the intrinsic variability in interference parameters. Lack of such concrete figures of merit obstructs qualifying an approach as “sufficient but not excessive” (i.e., cost effective).

In other fields of precision measurement, the accepted response is to follow certain minimal design standards that don’t necessarily guarantee immunity. Instead these measures are intended to

1) generally limit the probability and magnitude of interference as far as economically feasible,
2) stabilize remaining interference paths against variation or modulation, and
3) reinforce the diagnostic power of the experimenter to discern and fix specific interference problems.

In principle, such minimal EMI design rules should be considered through concept, schematic development and board layout stages as well as final packaging and cabling. LIGO has improved substantially in this regard, and current designs are significantly more robust. However, redesign of a even a substantial fraction of existing active circuits to minimize EMI susceptibility at the PC board level would be prohibitive.

We propose instead to institute the following relatively limited standards for analog signal electronics (including RF). These can likely be implemented without direct intervention in the core board-level circuitry designs, by retrofit of shielding, grounding and packaging details. Where specific internal susceptibility issues remain, e.g., crosstalk within a multichannel board, board modifications may still be required.

2.2.1 EMI defense measures for LIGO analog and RF circuits:

- All analog circuits will be fully Faraday shielded at the rack level, at the crate or chassis level, and wherever possible at the board level.
- All conductors leading to and from analog circuits (including power, digital control and monitoring, and signal lines) will be Faraday shielded.
- Cable shields will be contiguous with board and module shielding, to the extent compatible with breaking ground loops (below). Connector shells will be arranged for 360-degree shield contact without gaps or slots.
- Parallel signal, control and power lines running to remote sensors and actuators or between racks will be bundled and/or twisted to reduce loop area, and enclosed in a common Faraday shield (thus forming a minimum-cross-section umbilical for each device). Branching of lines terminating at a remote head will be eliminated (for example, by “pass through” of continuing connections via the parent board).
- Remote sensors and actuators (photodetectors, electrooptic devices, OSEMs, satellite modules, etc.) and their umbilicals will have shields and internal conductors isolated from the local environment and grounded at their parent board terminations.
- Analog board, chassis and rack mounting provisions, as well as cable shielding terminations, will be compatible with single-point or “star” grounding to a designated analog reference within each rack (typically, the common terminal of the relevant analog DC power supply). Typically this “star” ground will support sufficient current capacity to also serve as a safety ground for all affected systems (i.e., adequate to trip the AC mains circuit breakers in the event of a fault).
- Distributed shield grounding for RFI rejection (and RF signal distribution) will be enforced through use of capacitive EMI feedthroughs, transformer coupling of RF signals, and other methods that preserve high common-mode isolation impedance at line and audio frequencies.

- Audio-frequency signal conductors will pass through EMI/RFI filter feedthroughs at shield penetration points.
- Control, monitoring and ADC/DAC connections between crates will be galvanically isolated (no common or differential current path).
- Analog signals transmitted between racks will be sent and received differentially with high common-mode isolation.

2.3 Characterization and monitoring

Designing for low electromagnetic interference only guarantees the affected systems will be capable of good performance. Because of the spatially distributed nature of EMI problems and their sensitivity to details such as shield contacts, inadvertent loops, load balances and resonant gaps, it is also necessary to audit and test equipment, both under controlled laboratory conditions and *in situ.*

We will augment the LIGO observatory site electronic equipment pools with test equipment suitable for conducted and radiated EMC audit in the LVEA/VEA, mechanical equipment and OSB areas. We will also equip each site with portable instrumentation to enable open-field outdoor testing of emissions and susceptibility for isolated equipment racks, modules or assemblies under development or suspicion. Unless such testing reaches an unexpected volume, we do not currently feel investment in a large RF anechoic test chamber to be justified. However it may be indicated if personnel and logistics considerations force significant testing to occur on the Caltech or MIT campuses, since open-air RF backgrounds at these locations are incompatible with sensitive and repeatable measurements.

The site test facilities will be used in the initial phases of the retrofit to validate the effectiveness of specific equipment and methods before committing to full procurement or installation. After completion of the retrofit they will be used to verify the results, and then maintained for evaluation and screening of new or modified designs and commercial assemblies under consideration. Even in the absence of pending upgrades, a continuing program of EMC audit is required to detect new external sources of interference energy, monitor degradation in shielding effectiveness (through corrosion, for example), and police unauthorized configuration changes which compromise isolation.

3 EMC Retrofit Conceptual Design

3.1 Power supply replacement

Switching power supplies will be essentially eliminated[1]. Low-noise linear series-pass regulated supplies (such as Kepco JQE and ATE series or equivalent) are preferred. While these consume about a factor of three more rack volume per watt than switchers installed originally, a preliminary power load audit indicates we currently use less than

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[1] Some commercial digital devices, including powered VME crates, may incorporate internal switching supplies; these will be encapsulated and their emissions contained, generally by those measures that contain emissions from the associated digital circuits.

one fourth the switching supplies' capacity, such that no net increase in rack volume is required. Low-wattage linear modular supplies (such as Kepco PCX-MAT series or equivalent) will be used for photodiode and PZT bias and other miscellaneous small loads requiring unusual voltages.

Location of the new supplies is TBD pending an evaluation of their line harmonic magnetic fields. The three options under consideration are (in order of ascending cost and complexity):

- Housing in the lower third of "analog" racks (see below), possibly with ferromagnetic shielding or partitions
- Housing in magnetically-shielded separate racks near the analog circuits they supply
- Remote housing in physically separated racks, for example in the LVEA/VEA mechanical rooms.

The last option may be technically challenging (even if cost were no object), as the increase in lead inductance due to cable length may offset or negate the advantage of reduced magnetic coupling.

Grounding conventions for analog DC power will conform to a "star" or single-point convention within each analog rack. Depending on the location of the analog DC supplies and the number serving a given crate or rack, this may entail floating some supplies from their local 117VAC mains ground (using isolation transformers). In such cases the power supply output common terminal, which is typically bonded to facility ground at the star point, will be connected to the power supply chassis such that it can double as a safety ground for the supply itself.

A conceptual grounding arrangement for analog power supplies, card crates and racks is shown in Figure 2, and will be discussed further in the context of retrofits to the analog circuitry.

3.2 Separation of analog and digital functions by rack

High-speed level transitions (ns or less), even in nominally low clock rate digital applications, are typical of all modern digital systems and generate broadband emission from tens of kHz well into the GHz range and above. Although LIGO electronics are quintessentially "mixed signal", with a large number of interconnections between digital and analog circuit functions, we learned from NRAO engineers that it is both feasible and advisable to physically separate digital circuits from analog systems, and to interpose a minimum of two levels of Faraday shielding acting in series.

3.3 Containment of digital circuit EMI

Because of the high levels of radiated and conducted emissions from digital clock and bus activity, two levels of containment are specified.

3.3.1 Shielded VME crates

Original Knurr VME chassis are evidently not capable of effective RFI containment. New EMC-compliant VME crates will be procured. These are commercially available with shielding properties to meet CE, FCC and DoD (e.g., TEMPEST and MIL-STD-461E) EMI standards. Their main features include:

- Conductive blank panels filling all open slots (this is also required for effective cooling, so should improve reliability)
- Hinged, conductive overall front covers with edge gaskets to enclose a recessed front panel wiring zone
- Fingerstock contacts on module landing zones
- Enclosed rear wiring plenum behind the backplane
- EMI filters on line power and module I/O cables
- Shielding on all external I/O cables, with 360-degree backshell shield continuity
- Low-noise internal power supplies and fans

Module I/O cables will drop from their front panel connectors to a duct underneath the VME card cage and be dressed to the rear plenum of the crate. There they will terminate on RFI-suppression multipin or coaxial feedthrough connectors (e.g., Spectrum Control 700 series Pi-section filters). These filters will be mounted with conductive gaskets or soldered into knockout holes provided in the crate back panel. Optical fibers will pass through tubular waveguide vias similarly mounted in the back panel (length:diameter >10:1, with minimum diameter to pass the fiber end termination). A special bandpass feedthrough may be needed to pass the GPS clock antenna feed; similarly, clock distribution signals may require special filters to stabilize and maintain predictable edge delays.

Multiwire high-density I/O cables (e.g., IDC headers) incompatible with full shielding will be transitioned within the crate plenum section to a compatible standard connector type, e.g., D-subminiature (25, 37, 50 pin) or shielded parallel data (e.g., wide SCSI 64 pin).

From the outer side of the crate back panel, all cabling will be fully shielded. Cable shields will be terminated on conductive connector backshells with no open slots or gaps. Similarly, connector shells will make 360 degree contact with the mating bulkhead.

The VME crates will be electrically bonded to the rack at a minimum of four points. Redundant bolted connections with star washers and/or conductive gasketing will be used to minimize RF impedance of the ground path; wire pigtails of any practical length present excessive inductance, and should be avoided. Mating mounting surfaces will be provided with galvanically compatible conductive finishes (such as chromate, alodyne or conductive paint).

3.3.2 EMI-shielded racks

Existing Knurr racks are also incompatible with EMI containment or proper grounding. There are several commercial vendors providing appropriate off-the-shelf solutions. These range from 400-series welded magnetic stainless enclosures with beryllium-copper fingerstock gaskets on all openings, to low-cost standard enclosures adapted with conductive paint and carbon-filled elastomeric gaskets. The EMI isolation specs can be similar (typically 55-70 dB for plane waves up to 1 GHz). However we've been warned that the shielding integrity of elastomer gaskets can decay with time and access cycles, and racks also degrade due to galvanic incompatibility or corrosion. One attractive low-cost alternative, recommended to us by NRAO, is a carbon-steel modular rack system with cadmium-plated contact zones and field maintainable Monel gaskets marketed by AMCO.

Rack ventilation will be provided by shielded AC blowers extracting air through aluminum honeycomb waveguide filter panels. Fresh air is admitted through similar honeycomb panels in the rack base or sides. Brush or brushless DC blowers typically produce excess HF noise; however AC induction fans can produce magnetic interference, so testing may be needed to select an appropriate type. It may prove necessary to remote some fans using flexible air ducting (this may also be motivated by acoustic or refrigeration needs).

Power for internal equipment will be routed through EMI filters in the rack base. Digital racks will be bonded to the AC technical ground at this point (analog racks may or may not be so bonded, depending on the power supply and grounding solution adopted).

Signal I/O will be routed to subpanels in the rack top, mounted on bump-out boxes to afford internal volume for wiring service loops and connector backshells. These boxes and subpanels will be landed on gaskets to afford continuous peripheral contact to the rack body. The rack I/O subpanels will contain an array of multiconductor and coaxial EMI feedthroughs, mirroring the crate-level feedthroughs. Again, each feedthrough will be seated on a gasket or soldered in place to insure peripheral shield integrity.

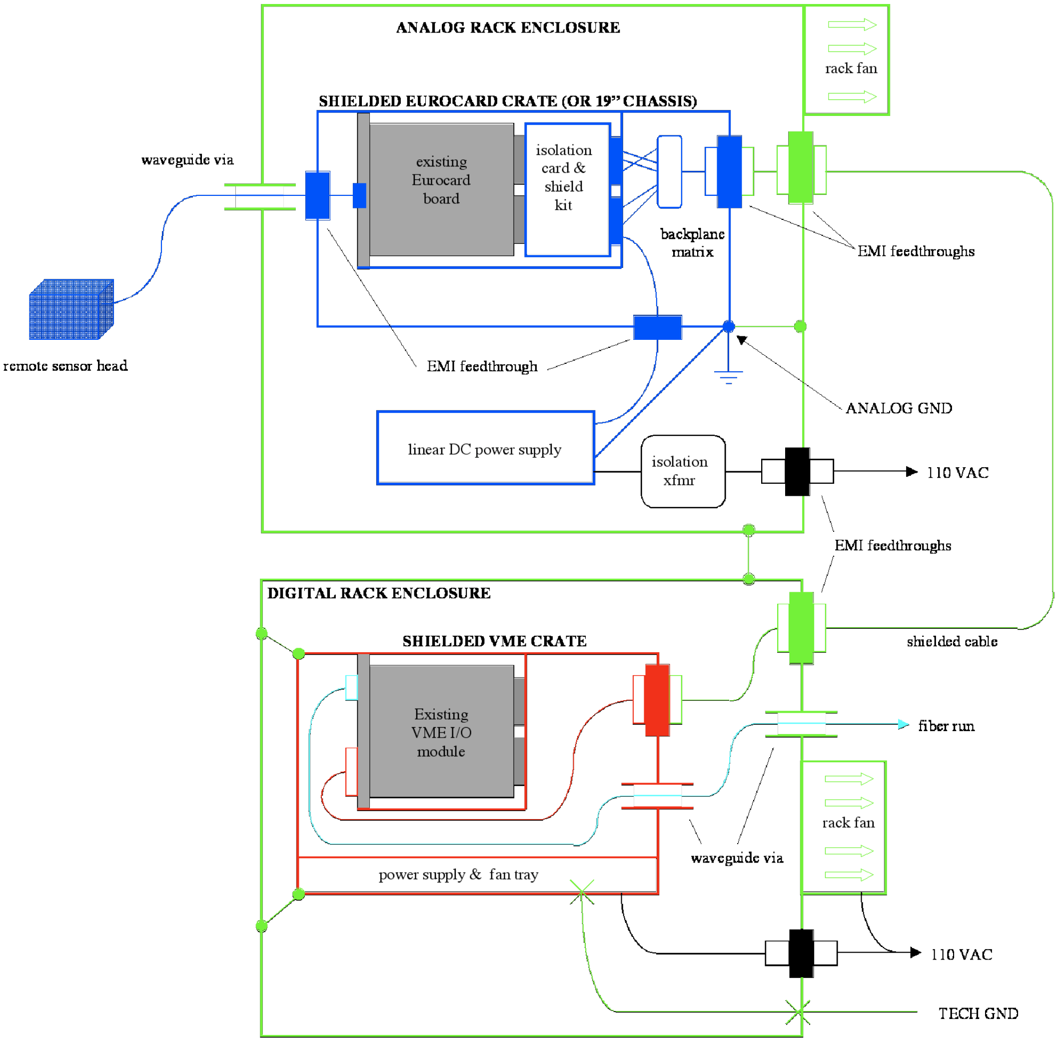

Figure 1. Schematic showing separation of analog and digital functions by rack and proposed interconnection methods.

3.4 Analog circuit isolation and shielding

Even with high containment of power supply and VME bus emissions, unshielded analog circuits are exceedingly susceptible to interference from motors, lighting, communications, and other digital equipment, as well as externally generated fields. The following measures are intended as a minimal response to the joint threats of magnetically coupled ground loops, radiated RFI, and conducted RFI.

3.4.1 Shielded analog racks

Analog crates and chassis will be housed in EMI-shielded racks similar to those chosen for containment of digital noise. Comparable protocols will be followed for EMI filtering at crate/chassis and rack shield penetrations, and for shielded cabling. However, the following significant differences will be observed;

- Chassis and crate grounds will be floated (at least have the option of floating) from the rack ground, to enable single-point grounding
- Cable shields may be broken between internal equipment and rack boundary EMI feedthroughs to break ground loops (see 3.6); alternatively, waveguide feedthroughs may be used to pass shielded cables intact.
- Power supplies may be run from isolation transformers, as required by grounding protocol (see 3.1).

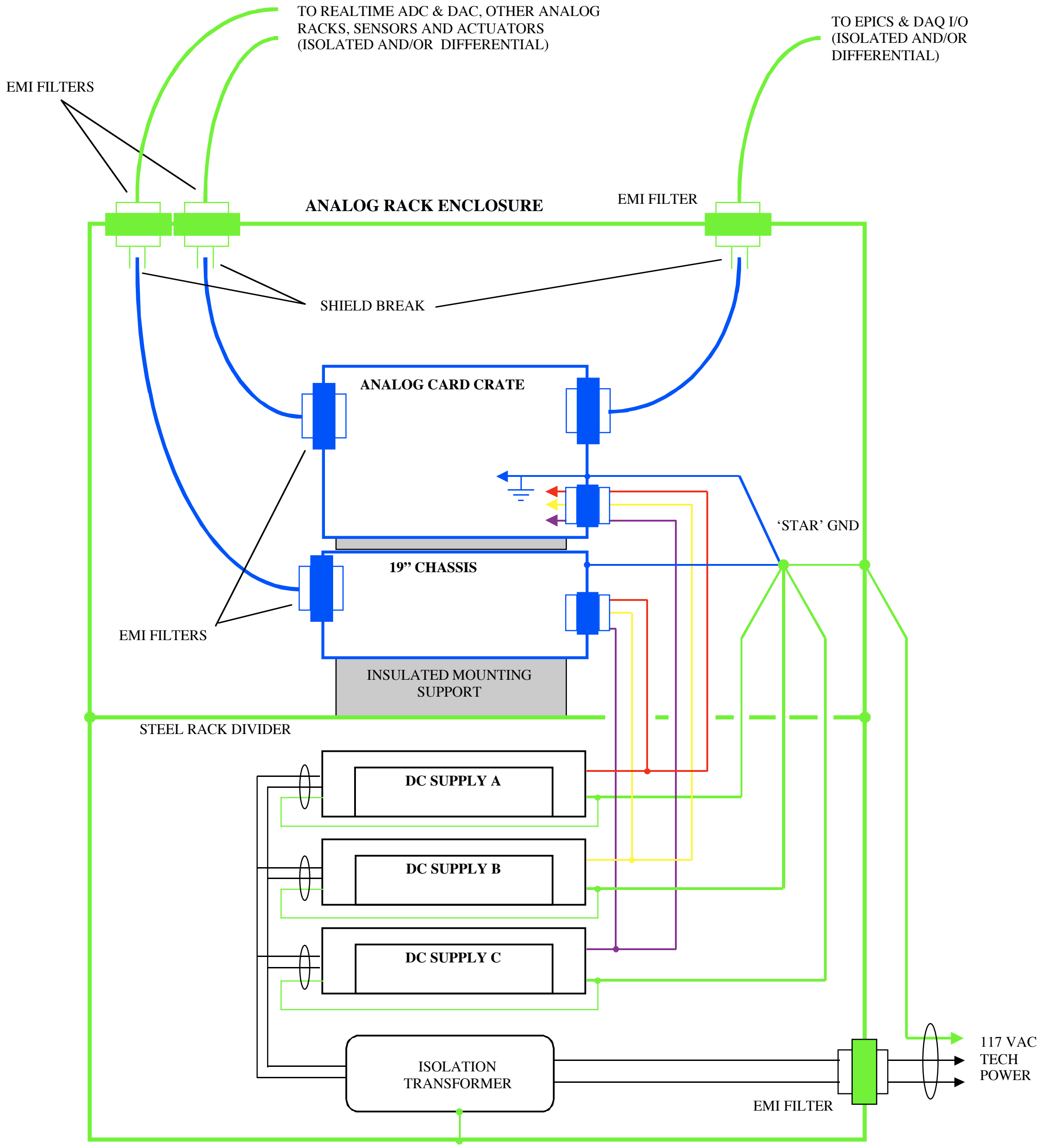

Figure 2. Schematic analog rack grounding and power. Here DC supplies are incorporated in the lower third of the rack. A steel divider reduces their magnetic coupling to the upper portion of the rack. Ground connections all pass through the "STAR" grounding point; control and signal lines terminating outside the rack are galvanically isolated and/or differentially driven and received with high common-mode impedance, such that all line and audio-frequency return current passes through this point. Uniform RF grounding is ensured by use of EMI filter feedthroughs at crate and rack shield penetrations.

3.4.2 Remote sensor/actuator grounding and umbilicals

All power supply, coaxial RF, control and high voltage leads for each remote sensor head (WFS, SPOB, LSC, etc.) and actuator (EO shutter, PZT steering mirror, OSEM) will be routed through an interface module, located in the analog rack (typically, in the crate housing its corresponding, whitening filter board or other support functions). Power and EPICS controls and readbacks should approach through this crate's backplane as described below. No connection to any remote ground or other conductor will be permitted; all supply and signal currents going to/from the remote sensor must balance back at the crate interface.

Coax signals and individually twisted/shielded pair power and control lines will be bundled together in a common flexible braid, externally insulated. This external braid is bonded to the interface module front panel and also to the sensor head body, such that an uninterrupted ground envelope (at crate analog ground potential) is formed around all lines and the remote sensor head.

A custom mixed D-sub, similar to, e.g., common Sun RGB monitor cables (three 50-ohm mini coaxes plus 10 twisted pairs in a common DB-50 shell) may be an attractive alternative to such bundled/shielded cabling.

High-voltage bias for silicon detector heads and PZT's will also be routed via the corresponding interface modules and power conditioning facilities.

Similar treatment will be given to all remote actuator cabling, such as that serving satellite modules and OSEMs.

3.4.3 ADC and DAC signal isolation

Eventually we anticipate second-generation ADC and DAC converters will be split into a remote sampling and conversion head, located with the analog circuitry, and a VME bus and clock interface located in the digital VME crate. These will be connected by galvanically isolated optical or RF transmission lines. Until these custom modules are developed, the task of isolating analog circuits from digital noise is complicated. We have designed and started to implement a system of floating differential drivers and receivers to minimize conduction and radiation of VME hash into the analog circuits and back into the converter ports themselves.

Single-ended voltages processed by anti-aliasing filters in the analog crate will be converted to balanced differential signals and sent on balanced twisted-pair transmission lines from the analog crate to the digital crate. RFI feedthrough filters interposed in these lines at shield penetrations will be augmented by common-mode cores to enforce high collective CM impedance. Additional lines within the same shield will transmit DC power and common returns sourced at the analog rack end.

On arrival at the VME crate housing the converter, a differential receiver powered by this remote DC feed will buffer the signals, apply a final passive anti-aliasing filter, and send them to the differential ADC inputs. This buffer module will be housed in the VME card cage, but its internal groundplane and common-mode reference will be defined at the analog source. A minimum-length ribbon cable (~ 4 cm) will join each such module to its ADC input connector. An additional capacitive RFI blocking feedthrough and/or common-mode choke may be added just at the ADC input pins.

Similarly, DAC outputs will be sensed by adjacent differential amplifiers, again powered from the Eurocard end but physically located in the VME crate. Variation in absolute potential of the DAC output "analog ground" reference (which bounces due to VME bus activity) will thus be subtracted out; the voltage transmitted downstream should then more nearly represent the true output of the DAC with respect to its own reference pin. The RF and common-mode rejection will be augmented by placing RFI feedthroughs on the DAC output pins, and by passing each pair through a common-mode bifilar core choke upstream of the differential amplifier. Signals will be sent back out to the analog crate along differential twisted pairs, where they will be received differentially and converted to single-ended inputs for the analog anti-image filters.

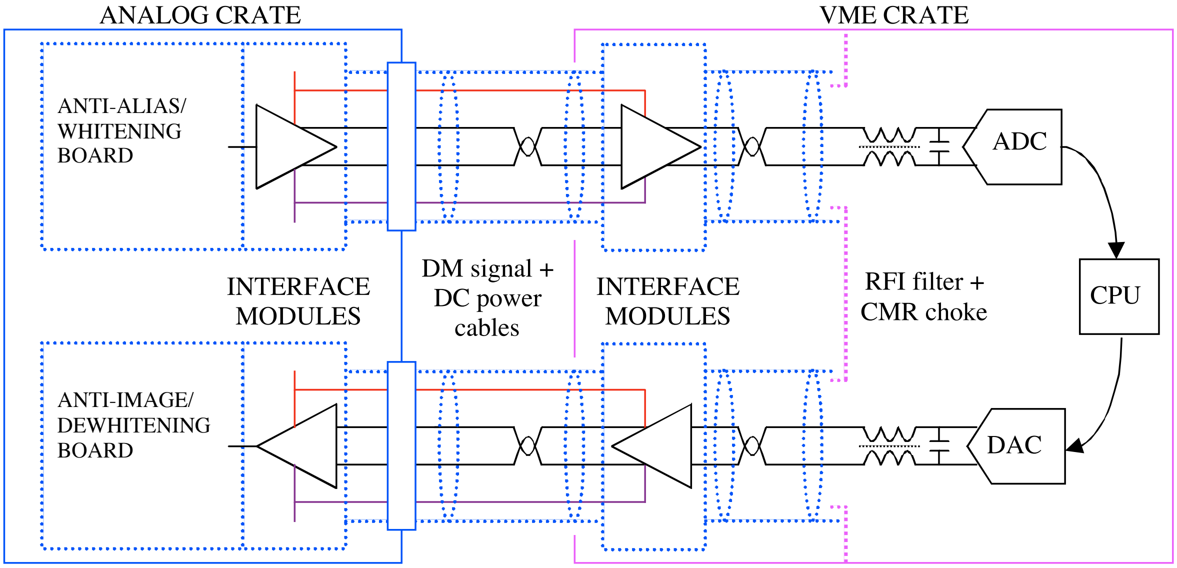

Figure 3. Schematic for common-mode isolation of ADC and DAC converter modules using differential driver and transmitter interface modules. A single channel is shown for clarity. Signals are transmitted from analog to digital rack and back over differential-mode balanced shielded twisted pair wires. DC power is also provided on these cables to operate the receiver/transmitter located remotely in the VME crate.

The remote (converter end) interface modules will be encapsulated in Faraday shields, contiguous with the twisted pair cable shield and *floated from the VME chassis*. (This means the interface modules, while physically sitting in the VME crate, will effectively be electrical "outposts" of the analog Eurocard crate at line and audio frequencies). All reasonable precautions will be taken to prepare these modules for life in a harsh RFI environment. Such measures may include, for example, secondary shielding, multilayer sandwich ground planes, etc. It's worth noting, however, that these portions of the signal chain are at characteristic noise levels equivalent to the DAC and ADC noise, of order

0.1 to 10 microvolts per root Hz, and are thus comparatively about a factor of 100 more RFI-tolerant than the ultimate front- and back-end signal electronics.

3.4.4 Analog card (Eurocard) crate shielding & backplane isolation

Open analog/mixed signal Eurocard crates will be replaced by shielded crates. Two options are under consideration:

a) Unpowered 6U Eurocard crates similar to the EMI-hardened VME crates discussed above, but with customized LIGO backplanes and extra depth for board extender filter/interface adapters (see below). These are form-compatible with existing analog cards. However, they do not provide additional width for added card-level shielding (board pitch is fixed at approximately 0.7” horizontally or multiples).

b) Unpowered VXI-type crates designed mechanically for B-size VXI cards, but with custom LIGO backplanes. These crates are intrinsically designed to afford shielding and isolation for sensitive analog modules, but with guides, backplane connectors and front panel attachments compatible with 6U Eurocards. The VXI format provides additional depth to include board extender filter/interface adapters. It also provides a larger minimum board pitch (about 1.1” horizontally) to allow for inter-card shielding and wider front panel connector bodies. The downside is that existing subsystems with more than 12 cards (e.g., the corner station DSC and ASC) may then overflow single crates and have to be split up.

In either case, the upgraded crates will conform to the following requirements:

- Analog crates will have recessed fronts with provision for hinged, conductive front cover panels, and options for remote ducted cooling and/or integrated fans.
- Chassis will be provided with optional means to isolate them electrically from the EIA mounting rack, or alternatively, to electrically bond to the rack at a minimum of four corner mounting points.
- Contiguous Faraday shielding will be provided on all sides of each crate. Conductive surface finishes, finger stock gaskets, seam welding and/or multiple fasteners will be used on panel seams and joints.
- Front panel wiring will be guided to ducts above and/or below each 6U cage and then right or left to vertical risers on either side of the panel area.
- Conductive filler panels will be installed in all unused slots.
- An enclosed rear volume will be provided for backplane wiring, connectors and signal conditioning; this volume will itself constitute a separate shielded enclosure.
- External wiring to and from the cage backplane will be fully shielded and will enter the rear volume via bulkhead connectors. These will be mounted in rear shield panel knockouts and may be RFI feedthrough type, depending on other filtering protocols.

- A custom backplane will be provided consistent with existing and planned module functions. Customization of the backplane to new module additions or changes will be made as convenient as possible consistent with maintaining EMC compliance.
- The backplane will incorporate a copper groundplane to separate the rear volume and wiring plenum from the card cage volume.
- All backplane I/O signal and control conductors will incorporate series RFI feedthrough traps referenced to this groundplane, as close as practical to active P1 and P2 pins.
- These filters may be located on the backplane proper, or on module-specific extender boards which replicate the applied P1 and P2 pin assignments.
- The module-specific extenders may also house optoisolators, isolation amplifiers, differential driver/receivers, local voltage regulators, or power supply filters as required to adapt or augment existing modules lacking these functions.
- The backplane will provide a single, star-connected analog ground point for the entire analog crate. If the crate is floated with respect to the rack, this star point will also connect to the crate Faraday shield; alternatively if the crate is bonded the analog ground will be disconnected from the crate body.
- All DC power forms will route their commons through the crate analog ground star point.
- All DC power commons and bus connections will be sized such that they can be relied upon for safety ground in the event of a ground fault (e.g., sufficient to support sustained AC mains current that would trip the mains supply breakers, typically 20A).
- All DC power forms will enter the rear volume through RFI suppression feedthrough traps mounted to chassis knockouts.
- Internal distribution of power forms will emanate from these feedthroughs via point-to-point wiring or printed backplane circuit traces.
- Additional DC power form filtering may be placed on the backplane and/or module-specific extender cards to isolate pickup and crosstalk within the rear volume from each P1 and P2 connector pin, as for signal I/O lines.
- Power forms for analog Eurocard functions will no longer be distributed via a cross-connect; DC lines for each power form within a rack will be hard wired directly back to a dedicated supply.
- Generally, crates within a given rack will share a supply for each form. To minimize potential drops between crates, the common connection between their backplane grounding points will be of minimum length and inductance (e.g., flat bar or ribbon) and common connections back to all supply forms will emanate from a single central star point.

3.4.5 Analog card shielding

Several options are under consideration for individually shielding analog cards. On recent LIGO designs, multilayer "sandwich" ground planes have been combined with soldered-on flat cans to protect sensitive circuitry; however, it is difficult to extend coverage to the backplane and front panel connectors with these methods, and service access can be impeded.

One attractive alternative is to repack existing (or slightly modified) 6U boards in a VXI module kit, marketed for short run or prototype VXI boards. One such kit, marketed by ICS Inc., provides aluminum clamshell halves that bolt through the board. Contact fingers along their edges land on copper foil strips wrapped around the board periphery. The extra depth of the kit will simultaneously accommodate an extender card with filtering or isolation circuitry.

3.4.6 Analog 19" chassis enclosure adaptations

Most analog full-width chassis boxes will require some physical and circuit modifications to become RFI-tight and to break ground loops. These measures may include the following:

- Replacing front- and back-panel I/O connectors with RFI blocking capacitive feedthrough types
- Repowering through RFI blocking feedthroughs
- Floating chassis from the rack enclosure and providing for single-point grounding
- Modifying the box to provide continuous Faraday shielding (e.g., abrading paint and anodization from contact surfaces, adding gaskets, etc.)
- Altering analog in/out stages to provide differential or galvanically isolated signal paths, or building add-on boards to convert these signals
- Introducing opto-isolators in TTL control lines

3.5 Elimination of exposed cross-connects

As installed, the rack cross-connects suffer from some seemingly insurmountable problems. They present an enormous geometric cross-section for magnetic and electrostatic pickup; they inevitably mix digital and analog signals on nearby conductors for extended cable runs, and force them to share ground returns with high common impedances; and they are impossible to shield effectively.

One possible solution is to eliminate them. In this scenario, point-to-point shielded cables will bring each VME I/O function directly to a connector on the corresponding analog crate or chassis back panel. For an auxiliary I/O device to support functions in multiple analog units, this cable would be daisy-chained to each of the crates in turn. End-use distribution would be done within the backplane plenum of the analog card crate, using custom wiring to address the appropriate individual P1 and P2 pins.

To see if this is feasible one needs to analyze the mapping of VME-to-analog crate control and monitoring connections and evaluate the comparative labor and material for an initial installation as well as future system additions or changes. This analysis has not been done yet. However, it is clear that an efficient and general means for mapping I/O cable pins to P1 and P2 analog backplane assignments without excessive technician involvement could easily render such a system even less labor-intensive than the existing cross connect.

In one scenario, we can envision making the analog crate backplane, or sections of it, "disposable." Auxiliary I/O cables of each type (DIN, DOUT, AIN, AOUT, etc.) as well as power forms would be brought to the edges of multilayer printed-circuit backplanes or backplane segments, using mass termination headers. These terminated I/O pins would be interconnected to appropriate P1 and P2 pins on each card slot by printed traces. Analog, power and digital lines could in principle be separated on distinct layers with groundplanes interposed between them. The pin mapping would be routed in a CAD layout generated on the designer's workstation, which would be outsourced to a PC card vendor. The vendor could in principle generate, stuff and solder the backplane board by machine and ship it back ready for installation in the crate.

This method could be significantly less expensive than building and hand wiring a new cross-connect[2]. For rework or updating a new layout, it might still be competitive, depending on the extent of required alterations; clearly, moving an isolated wire or two is much easier on a system of exposed terminal blocks. More importantly, however, an automated outsourced method would typically place fewer demands on in-house labor. Updating I/O assignments would be a matter of swapping backplane cards and testing. Naturally, the designer has to properly define the pin mappings and test protocols in either case.

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[2] Based on a small-quantity quote of ~ $2k for complete custom-routed Eurocard backplanes.

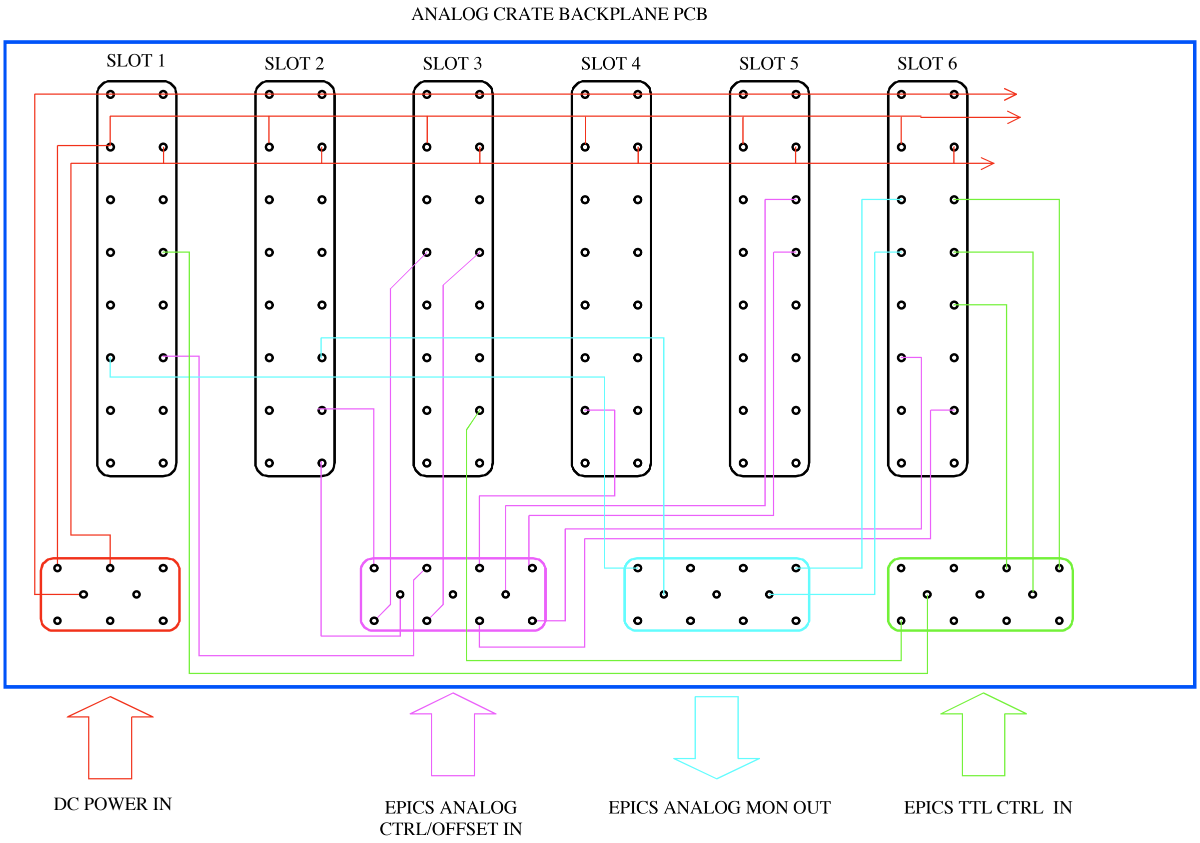

Figure 4. Printed circuit backplane cross-connect concept. Distribution traces for each form of power or I/O type are printed on a unique PCB layer; alternating ground planes are specified between types for shielding. Analog modules loaded in each slot extend into the paper. Headers on the board edge are connected to bulkhead EMI feedthroughs mounted through the crate chassis. Shielded external cables connect these to I/O boards in other (principally digital) racks.

3.6 Hybrid grounding

The shielding and mounting protocols discussed above and in connection with Figure 2 etc. concentrate on breaking loop receptors for line-frequency magnetic fields, and preventing electrostatically induced common-mode line voltages from appearing differentially on signals. At frequencies above about 100 kHz, however, practical cable inductances effectively open-circuit ground leads of any appreciable length, while parasitic capacitance reconnects floated assemblies with their local environments.

To control this transition we will deliberately recouple floated assemblies capacitively at RF frequencies. The precise transition frequency and common-mode impedance values will be determined as part of the design. The general goal is to achieve a reasonable approximation to a uniform ground potential on all cable, rack and module shields at the interferometer modulation frequency (25 MHz) and at higher frequencies.

Where shield breaks are required to maintain line-frequency isolation, for example, just inside a rack boundary, one possible method is to route the discontinued "floating" shield to one or more unused pins on the associated EMI feedthrough. This method is shown schematically in Figure 5.

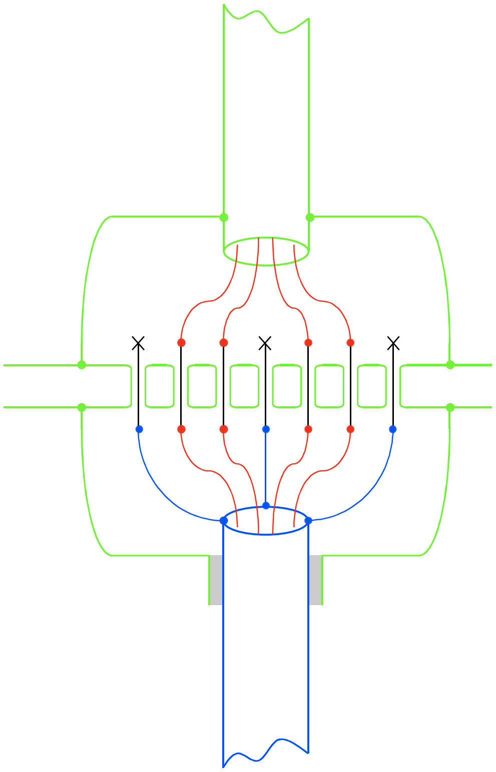

Figure 5. Capacitive RF shield termination using spare pins on a capacitive EMI feedthrough connector. The lower cable's shield is insulated from its connector backshell and bulkhead.

3.7 EMC Test Equipment

We will equip each site with a test suite suitable for carrying out isolated product testing and in situ EMC auditing. This equipment will support verification of compliance with LIGO-E020986 and the portions of MIL-STD-461E and FCC protocols cited therein. The following major components are expected to form the core of this system. Many of these components are already on hand in each location and may be shared with commissioning activities.

1) Outdoor test range platform with groundplane and DC power provisions
2) AC power conditioning and isolation transformers
3) Portable RF spectrum analyzer
4) Low-noise broadband RF preamplifier
5) Portable audio and RF signal generators
6) RF power amplifier and matching network

7) Audio power amplifier
8) Radiated emission receiving antenna set (magnetic and electric fields)
9) Radiated emission local probe set (magnetic and electric fields)
10) Radiated emission handheld “sniffer” probe
11) Conducted emission current probe set
12) Radiated susceptibility transmitting antenna set (magnetic and electric)
13) Conducted susceptibility injection transformer and current readback set

4 Implementation

The retrofit must be integrated without causing unacceptable loss of observing or commissioning time. We will adhere to the following general rules:

- No upgrade step will be undertaken without prototype qualification and extensive bench testing of the underlying methods, as well as “dry run” installation practice.
- All upgrade steps will be integrated in a reversible way wherever feasible, to permit backtracking.
- For each category of improvement (crate, cable, module) there will be a limited trial integration of one or a few instantiations, made on *one* interferometer. Expanding integration to other instances and to other interferometers will only be approved after this trial integration has proven successful[3].
- Upon qualification of an upgrade step, production and completion of the retrofit to each interferometer will be scheduled in accord with commissioning and observing timetables. In some cases it may be desirable to repeat the trial installation step for each subsystem on each interferometer, depending on initial experience.

We will use the Detector Revision Technical Review Board and associated procedures (specified in LIGO-M020382-A, *Detector subsystem (re)design review process*) for review of intermediate results, pre-installation readiness, and major procurements conforming to approved scope. Substantial changes in scope or technical approach will be brought to the LIGO TRB and CCB as necessary.

4.1 Design development & prototyping tasks

The following tasks will require ongoing laboratory research and development in the course of executing this upgrade plan.

4.1.1 EMI testing protocol and test facility development

Equipment will be specified and procured and/or developed in-house for detecting emissions from commercial or custom candidate devices and systems, and for subjecting

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[3] Note: in this context, “success” does not necessarily require a measurable improvement in performance. Some measures are not expected to realize measurable benefits until several complementary tasks are also complete. However, restoration of reliable operation is generally a necessary criterion for proceeding.

systems to simulated EMI environments to establish their susceptibilities. Commercial, scientific and military test methods and criteria will be evaluated for applicability and adapted to LIGO concerns as required. Test ranges will be established at both observatory sites, and surveys will be performed initially and at stages through the retrofit.

4.1.2 Galvanic isolation and hybrid analog/RF grounding

We will evaluate methods for achieving single-point current balance at line and audio frequencies while assuring a controlled transition to distributed ground at radiative frequencies. Tests of capacitive blocks, RFI feedthrough filters, isolation transformers and common-mode chokes will support a uniform design for analog rack and crate grounding.

4.1.3 Analog board shielding & backplane isolation

Shield kits and backplane isolation adapter boards will be developed to retrofit existing analog cards to comply with EMC requirements. Performance will be evaluated. In some cases where adaptation is found not to be feasible, board redesigns will be initiated to incorporate EMC features.

4.1.4 Cross-connect shielding or substitution

Alternative methods will be researched and prototyped for establishing the matrix connecting power, control and readback services to the analog and RF module backplanes. The investigation will concentrate on EMC performance and on life cycle engineering and maintenance costs, given anticipated field update and modification patterns.

4.2 Resource commitments and plan phasing

4.2.1 Staffing for plan execution

We estimate that executing this plan will require a continuous level of effort over the period of performance comprising about 2 dedicated FTE's, distributed as follows:

- 1 FTE experienced EE (probably divided between 2 individuals, at least one preferably resident at a LIGO observatory site)
- 1/2 FTE experienced interferometer instrumentation scientist
- 1/2 FTE junior engineer and/or experienced technical assistants.

The staffing will be approximately doubled during episodes of actual installation, wiring and field testing by addition of commissioning and site staff.

4.2.2 Steady-state support after completion

After completion of this plan we expect each observatory site will need to commit approximately 0.25 FTE of resident engineering and science staff to maintaining site test capability, auditing operating interferometer installations and local environments, and screening incoming equipment prior to installation or upgrade. We recommend full integration of EMC considerations in the design, fabrication and test cycle for LIGO electronics, such that no explicit staff assignment is required on the design or fabrication side. However, EMC consultants will be engaged as needed for training, review of major upgrade initiatives, and possibly for specialized testing or design tasks exceeding in-house capabilities.

4.2.3 Proposed sequence

The following tentative sequence differs slightly from the current revision of M020135-02-D, *Initial LIGO Detector Upgrade, Commission and Science Run Plan* (D. Coyne, 9/16/02). On reflection we determined that rushing a major procurement (order of $0.3M) in a time frame suitable to support a pre-S2 installation of power supplies appeared risky. As a result we now propose deferring the first major installation stage (linear power supplies) to after S2.

In general we have tried to stage procurement and offline test activities to run concurrently with science running, when the machine configurations are frozen and installation or in situ testing is not feasible. A further level of detail must be incorporated to interleave these upgrade tasks with other planned commissioning activities without interference.

4.2.3.1 Pre-S2 tasks

- Complete testing of linear power supplies installed at LLO end station.
- Spec and procure initial EMC test equipment for lab and observatory trial.
- Conduct baseline EMC surveys of existing equipment & installations
- Procure linear supplies & support hardware for remaining installations
- Prepare wiring diagrams and equipment layouts for digital/analog rack division
- Build up shielded VME crate/digital rack prototype in lab; test & iterate offline.

4.2.3.2 Between S2 and S3

- Install linear power supplies on all interferometers (one station at a time)
- Integrate single instance of shielded digital rack & associated new wiring; test
- Procure shielded crates, racks, feedthroughs and cabling for remaining instances.
- Install digital electronics shielded crate/rack/feedthrough packaging systems (one station at a time)
- Swap analog racks for shielded versions (reinstall existing analog systems unmodified)
- Conduct update EMC surveys of revised equipment & installations
- Design and build offline prototype for analog shielding and isolation solution

4.2.3.3 Post-S3 Tasks

- Install prototype analog shielding and isolation system & test in situ
- Review and procure hardware for remaining instances

- Install all interferometers/all stations (one station at a time)
- Revisit EMC survey and address remaining issues

5 Appendix: Selected As-Built Problems & Diagnostics

The following indications are directly observed in the electronics operating at the interferometer sites as of early 2002. These are the more definitive RFI/EMI diseases; many more are suspected, but (due to nonstationarity, limited diagnostics or insufficient time) most have not been studied sufficiently.

5.1 Clock and bus noise on ASC and LSC Pentek inputs and outputs:

We see several hundred millivolts p-p of RF hash on the input pins of the Pentek 6102 ADC's, with frequency components up to a few hundred MHz and burst rates synchronized with 4.2 MHz sample clocks. It is not stationary and depends on movement of ribbon cables, people and equipment nearby the racks. Remarkably, this has not yet caused documented "excess" noise, even though signals of this magnitude and frequency are deemed likely to be rectified by audio-frequency semiconductor devices within the analog front ends and ADC, and the burst rep rates are semi-synchronous with the acquisition sample rate. Sniffing with a probe coil points to many potential radiative/inductive sources for this energy within the VME crate, including the unused multi-pin bus connector on the Pentek front panel itself and (somewhat remarkably) the reflective memory modules. Some of the hash is also conducted or capacitively coupled directly to the Pentek input pins within the module, however. It is hard to concieve of a way to address this without redesigning the 6102 (internal inspection indicates insufficient attention was paid to proper EMC/EMI practices by its designers).

We also see excess nonstationary noise on the Pentek DAC outputs. Large periodic pulses appear to be "ground bounce" associated with polling of the VME backplane, causing deflection of the DAC "analog" ground (obviously derived from the VME backplane) with respect to the ground potential of subsequent analog modules. (Note: this is distinct from the excess and variable noise associated with high-speed DAC clocking, which is believed to be a defect of the DAC itself).

In principle we should see no out-of-band noise beyond the intrinsic Johnson noise associated with the respective characteristic impedances. Best practice would insure that the ADC input pins be protected from any interfering signal comparable to 1 LSB at any frequency (above or below the Nyquist rate). Since we rely on squeezing the full dynamic reserve out of the DAC, this principle in our case applies equally to the outputs within the signal band. Nonlinearity of the audio filter electronics at high frequencies would argue for comparable protection of the downstream anti-image and dewhitening filters at RF as well.

Some of the observed hash results from some known and relatively obvious errors:

- the default ADC and DAC clock inputs for the Pentek 6102 are derived from pins on the analog input/output connectors, and the TTL clock signals must thus be passed through the analog whitening and dewhitening modules and travel alongside the sensitive signal lines through the long analog I/O ribbon cable. A retrofit to the

Penteks which brings the clocks in on separate, shielded LEMO connectors on the front panels is in progress and partially implemented.

- Because of the peculiar multipin analog I/O connector on the 6102, unshielded flat ribbon cables were initially used to connect to/from the analog interface boards. In some cases, because of indefinite module placement and rearrangement, these cables were also made excessively long. They are gradually being replaced by rolled/shielded twisted pair ribbon cables of minimum service length, with shields grounded at the analog interface end. These corrective measures helped significantly with induced RF potentials, but have limitations. There is no provision for eliminating the bus-induced fluctuations in the VME ground potential, and a shunt current path is still provided between the VME crate and analog Eurocard crate grounds (this is bound to increase susceptibility to external RFI, line interference and switcher noise induction as well, by affording a "loop return").
- There is no way to separate the Pentek physically from the hash inherent in a VME crate environment. However, the 6102 does have crude differential ADC inputs, and its DAC is expected to be reasonably accurate with respect to its own "signal ground". What is really needed to isolate the connection between the ADC and DAC and their analog interface cards, essentially treating the ADC and DAC as "hostile" sinks and sources by rejecting all common-mode potentials and RF. We can then do best by referencing input and output signals to the Pentek reference voltages, however crappy they may be.

5.2 Loop & whip antennas with ASC and LSC remote front end wiring:

The LSC and ASC use remote sensor devices located on the ISC tables. Each sensor typically uses separate power, DC output, HV bias, RF output and test input cables, which run separately from the head to different locations within the mother rack (or even several racks). These long runs form significant loop areas which intersect magnetic flux, causing ground currents to flow through the sensor head and rack at each end.

The sensors are all designed to float from the optical table and vacuum system ground; however, many lines have been extended or otherwise modified such that an exposed connector body or shield braid can randomly touch the metallic table surface or cable tray, providing a current path from the front end to VE/facility ground. In some cases this has been patched by disconnecting the cable shield, defeating its screening effect.

LSC and ASC front ends also receive local oscillator RF from distribution systems, whose oscillators are located in the PSL/IO racks. This provides an additional group of paths for unintentional ground current.

Many current LSC and ASC boards do not have independent, contiguous Faraday shielding and/or use unshielded cables and connectors to join modules within a crate.

5.3 MC and PSL analog control line ground loops/antennas:

These signals travel from rack to rack and thus form loops with safety and powerline grounds. Currently most (though not all) these signals travel via shielded differential twisted-pairs with buffered transmitters and differential receivers. However both driver and receiver circuits are referenced to local rack cross-connect power supplies and grounds, and for RFI immunity the shields may need to be contiguous (again, actual installation practice varies here).

5.4 Back-end dewhitening, coil driver, satellite and coil wiring:

Somewhat counterintuitively, the "back end" dewhitening and coil drive circuitry is arguably our most sensitive point for induced voltages and currents. These signals demand interference levels well below the thermal noise in the driving circuits (nanovolts and picoamperes, respectively) as thermodynamics has afforded us no operating margin. The following problems with our current treatment of these signals have been observed:

- The dewhitening filters suffer from the same problems associated with other analog Eurocard implementations (above)
- For both analog and digital suspension systems, analog coil drivers are generally located in a different rack that the dewhitening filter which serves them. Although we are now usually using differential driver/receivers to transmit these signals these sets are not fully isolated (power and signal are locally referenced) so they provide some CMR but still permit current flow.
- There is anecdotal evidence that the failure of LOS controllers to meet noise specifications in the field is related to internal ground plane and layout practices within the chassis, coupled to the intense EMI/RFI environment found in the racks. It is hoped that the redesigned coil drivers (associated with the DSC) will not suffer from this problem.
- The satellite modules (which are maintained with the DSC) are subject to accidental grounding to cable trays or vacuum equipment
- Multiconductor cables from coil drivers to the satellite modules and from the modules to the VE feedthroughs are not shielded or shields are not correctly terminated

5.5 Rack cross-connect radiation & reception:

The rack cross-connects present a large cross section for magnetic and electrostatic pickup. They are optimally positioned to intersect magnetic flux from power supplies in the rack proper and bus hash from the VME crates. Wiring from supplies to cross-connect blocks and from cross-connects to devices is several meters in length, and has appreciable self-inductance, permitting end-to-end HF potential drops of a volt or more in some cases. Wires also have high capacitive cross-coupling to each other. Within a single analog Eurocard crate there are typically several independent power supply and ground connections back to cross-connect fuse blocks; beyond its redundancy, this introduces multiple closed loop antennas.

Unshielded ribbon cables serving the EPICS ADC, DAC and DIO modules conduct VME backplane and device clock hash directly into the cross-connect area, inducing interfering broadband signals up to 0.5 Vpp in some “ground” and “DC power” lines. Direct conductive paths also join these VME devices to control and readout points within the low-level analog control cards, which generally sense and drive single-ended and may have little or no on-board isolation or filtering. TTL control points are also brought into modules without isolation, conjoining analog signal, analog power, and digital (VME) grounds. Analog grounds are also connected to the rack via mounting points, compounding stray current opportunities.

5.5.1 RF distribution:

The system as-built radiates relatively little RF (at least by comparison with campus lab experience). Unfortunately the susceptibility of certain sensitive boards (e.g., WFS demodulators; see below) is very high due to their own design problems. This leads to an unacceptable and highly variable DC offset problem in the ASC system.

The RF distribution also provides inadvisable current paths between widely separated racks. There’s no reason to maintain DC continuity for RF distribution, so DC blocks should be installed on one end of any inter-rack run. Balancing certain runs may also be helpful.

5.5.2 Unshielded boards & crates:

Many Eurocard boards have essentially no shielding other than their own ground plane (where it exists). Our analog Eurocard crates have open tops, backs and sides and no provision for closing off unused front panel space or interconnection areas. Their backplane wiring is fully exposed. Voltage fluctuations can be induced on critical signals by walking nearby, brushing cables, opening and closing doors, and so on.

5.5.3 Switching power supply radiation, induction and conduction

The Sorenson switching supplies radiate and conduct magnetic field pulses at their switch rates (typically 60-80 kHz). These pulses are envelope-modulated at the 60 Hz line rate and harmonics. The supplies are located directly above the sensitive electronics and cables and adjacent to the cross-connect, coupling this flux efficiently into circuits. Partial shielding and loop area variation makes the interference highly variable and unpredictable.

RF “tails” have been seen in the radiation from these supplies extending into to the main LIGO RF modulation bands (25 and 29 MHz), and picked up on ASC or LSC front-end RF signal lines. Directly demodulated, these signals will appear in our signal band with variable and unpredictable frequencies and amplitudes. In addition, there is evidence that emissions at all frequencies are rectified by analog circuits. In particular there is a conjecture that this phenomenon is responsible for the anomalous increase in suspension coil driver noise when the drivers are moved from the electronics lab out to the LVEA floor.

Although some tests have been made with the supplies removed to a separate rack, radiated emissions were not adequately attenuated by this step alone. Substitution of linear-regulated supplies would reduce the radiated emission but might simultaneously increase direct magnetic induction due to the introduction of large 60 Hz power transformers. If this secondary problem becomes the dominant issue it is possible magnetic shielding or remote location of the supplies will be warranted.

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