Camera System Plan	Document # **LCA-278-A**		Status LSST Camera APPROVED Effective Date: 30 Jan 2014
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Document Title **Camera Grounding and Shielding Plan**			

1. Change History Log

Revision	Effective Date	Description of Changes
A	30 Jan 2014	Baseline release of document. Reviewed under LCN-1047.

2. Contents

3. Acronyms

ADC	analog to digital converters
AlN	aluminum nitride
ASPIC	Analog Signal Processing Integrated Circuit
CCD	charge-coupled device
CCS	Camera Control System
CMRR	common mode rejection rate
DAQ	Data Acquisition
EMI	Electro-Magnetic Interference
GSP	Grounding and Shielding Plan
HCU	Hardware Control Unit
LVDS	low voltage differential signaling
MPM	Master Protection Module
PCM	Power Control & Monitoring
PLC	programmable logic controllers
PWM	pulse-width modulation
REB	Raft Electronics Board
REC	Raft Electonic Crate
RSA	Raft Sensor Assembly
RTD	resistive thermal device
RTM	Raft Tower Module
SCR	silicon-controlled rectifier

4. Applicable Documents

[1] LCA-48, “Camera System Specification”

[2] LCA-343, “Camera Block Diagrams”

5. Purpose and Scope

The LSST camera contains numerous electrical and electronic entities, all of which have the potential to electrically interfere with one another. Furthermore, the area immediately surrounding the Camera has additional electrical and electronic entities, including very large motors for the telescope and dome that could also cause interference with the operation of the Camera. It is the stated goal of this Grounding and Shielding Plan (GSP) to eliminate any such possibility. Specifically, this Plan establishes requirements and design principles to ensure that the various subsystems do not allow current flows or capacitive or inductive couplings that could cause such interference. Likewise, shielding is defined such that Camera subsystems do not couple into one another by way of electric (capacitive) or magnetic (mutual inductance) modes and so that on-telescope Camera subsystems are protected from external interference to the greatest extent possible. In addition, the plan extends somewhat beyond just "grounding and shielding" by defining "best practices" for device selection and device-to-device signaling to reduce the risk of internal interference from one device to another.

6. Overview

The control of unwanted currents, the shielding of sensitive components and the prevention of unwanted electrical interference in sensitive circuits such as the charge-coupled device (CCD) readouts is a well-developed but, paradoxically, not well understood science. Most textbooks consider the simple generic case of a single sensitive detector connected to some form of readout as shown in Figure 1. The rules developed from this simple case—single point grounds, isolation of detector and front end amplifier from other components, separately isolated power feeds for each element—work well. This case, however, breaks down in critical ways when the number of detector elements becomes "large" and where those elements are inextricably intertwined with each other and, even more problematically, intertwined with other mechanical or electrical parts of the system. In addition, the relative complexity of any CCD sensor, with multiple bias voltages and complex clocking and control requirements already places it at or beyond the edge of the simple model – even for a simple one- or-two output CCD. For LSST, with some three thousand low-noise channels in a circle scarcely larger than half a meter in diameter, we are well into the territory of the intertwined and need to consider a range of mechanical and thermal as well as electrical issues to arrive at an optimal solution.

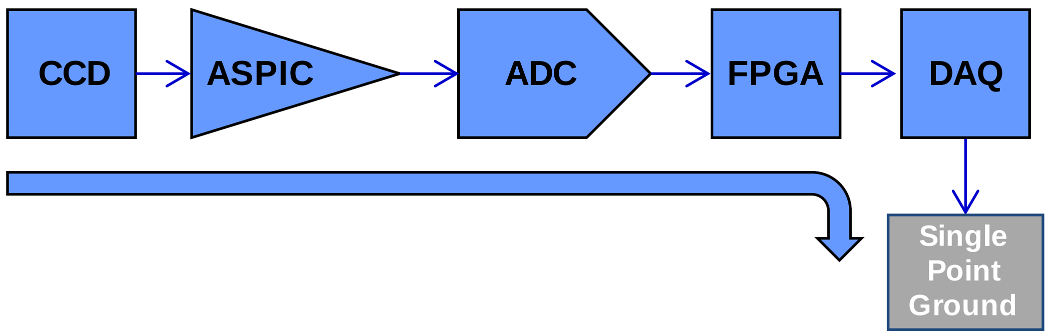


Figure 1: Simplified ideal signal chain and ground path.

The front end readout of the CCD sensors on the focal plane (both for science and corner rafts) is by far the most sensitive part of the Camera and of the Observatory as a whole, with noise specifications at the level of electrons. Therefore this document concentrates on aspects of grounding and shielding that are most critical for the front end electronics but also lays out rules for use in the other electronics where noise is less of an overriding issue but, nonetheless, as always, important.

To give some overall sense of the problem, interference from one electrical circuit (the "aggressor") to another (the "victim") can be caused by one or more simple effects:

Capacitive coupling between the circuits which allows a potential change in the aggressor to show up as a voltage change in the victim

Inductive (or radiated) coupling between an aggressor and victim that induces a current in the victim circuit

Conducted coupling along an electrical connection between aggressor and victim – for instance a "noisy" power supply feeding a sensitive amplifier

Unwanted offset voltages either constant or varying caused by voltage drops across a conductor

The simplest way to reduce capacitive interference is to reduce the capacitance between aggressor and victim, assuming the delta V is fixed for a fixed voltage differential with respect to time, so increasing distance, reducing coupled areas or reducing the dielectric constant between the coupled areas are effective strategies. The ultimate protection is to surround the victim with a Faraday Cage – a completely-enclosing perfect conductor (in the ideal case) that isolates the internal region from external electric field disturbances (Gauss's Law). In the real world, of course, circuits cannot be completely enclosed (power in and data out imply penetrations) and the conductor is never perfect (and generally only electric fields are considered although a magnetic equivalent is possible but, again, with imperfect conductors). Nevertheless, even an incomplete Faraday Cage can be very helpful in reducing interference and the "shields" discussed below are examples of partial Faraday Cages that are expected to be of value in protecting the integrity of the Camera electronics.

Inductive coupling can be understood in terms of Faraday's law of induction – where a changing current in some aggressor loop creates an electro-magnetic field intersecting some other (victim) loop and, thus, a changing current in the victim loop. So, in the extremely simple circuit shown in Figure 2, if the current around the loop varies in time, there is electro-magnetic energy radiated perpendicular to that loop and proportional to the current and the loop area.

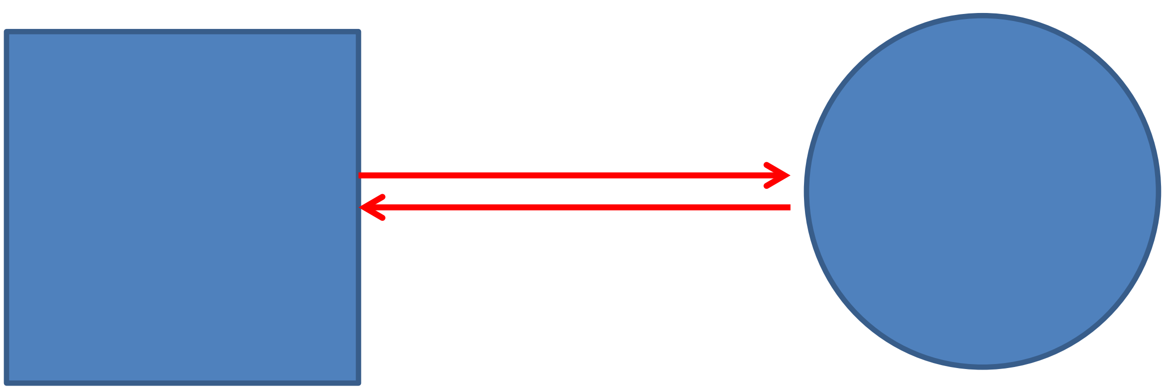


Figure 2 - A minimal circuit showing a current loop between a source and load (e.g. a battery and a motor). The radiated power from this circuit is proportional to the magnitude of the changing current and the area of the wire loop enclosed by the red lines

On the assumption that we have already minimized the currents involved, the only other variable available to us is to minimize the loop area. Note that as we minimize the loop area in circuits, we not only reduce the ability of an aggressor to radiate power, we also reduce the sensitivity of a victim circuit to any such radiated power. In later sections we will require signals to be carried differentially and on twisted pair conductors. The basis for that requirement is the minimization of loop area. For instance in Figure 3 we have the same circuit as above, but with the wire connections kept in close proximity, greatly reducing the loop area.

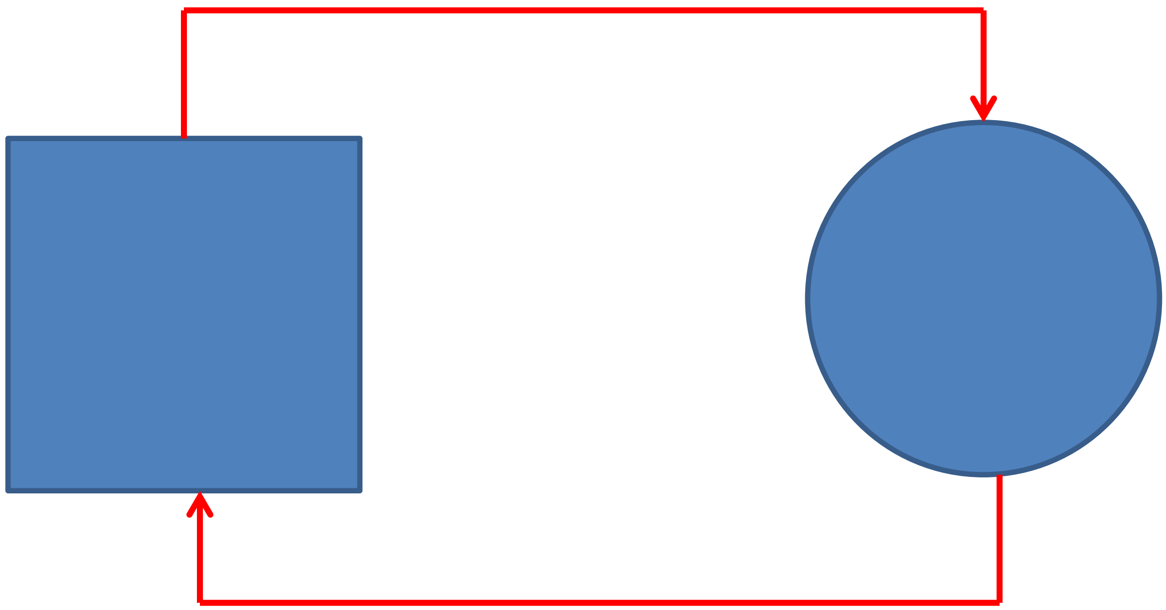


Figure 3- The same minimal circuit with greatly reduced loop area and thus a less aggressive disturber of neighboring circuits.

Remembering that the energy radiated from the loop in the previous examples had a direction perpendicular to the loop area, one can make one further simple but significant improvement by twisting the paired conductors in the cable. The effect of the twist is to take the unavoidable area of the loop caused by the presence of an insulator and point that area in a continuously varying direction and thus cancel, at least to first order, the field. This is shown, very crudely in Figure 4 with a single twist of the conductors.

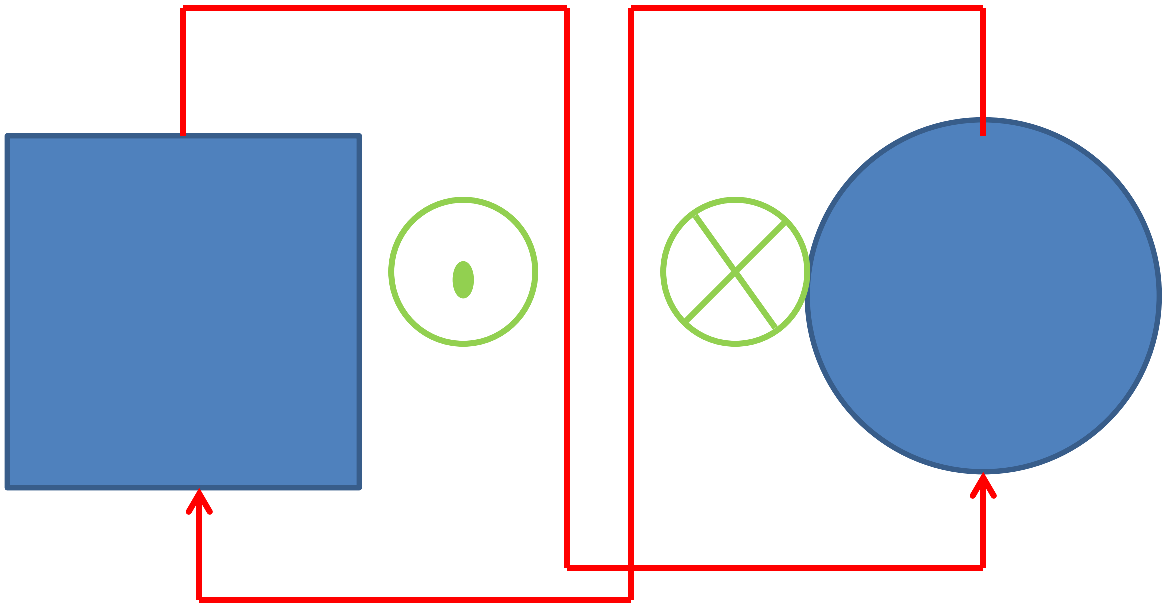


Figure 4- Very simple example of a single twist in the conductors showing the EM vector coming out of the page on the left and into the page on the right - effectively cancelling each other out.

The final additional step one can take is to cover our paired and twisted conductors with a shield which will further reduce the already small coupling to the outside. Note that shielded twisted pair works equally well on aggressor lines to reduce the energy escaping from the conductors and for victims, reducing the effect of any external fields. However, one should also remember that the shield around a twisted pair should not carry current or it ceases to be a shield in the sense of a Faraday Cage. Thus, in general, a true shield is connected at only one end although there are often reasons, noted below, to encourage a connection (either DC or AC) at both ends.

For conducted interference, of course, shielded twisted pair does no good. However, since one is, in general, concerned with relatively high frequencies of conducted interference (very low frequency disturbances imply either a design shortfall or a component failure) and so low pass filters can be effective in reducing the effects of interference. The simplest sort of filter is a capacitance across the lines (remembering that there are always two wires in any circuit) at either the source or destination. The capacitance acts like a low impedance at high frequencies ($Z_C=1/j\omega C$). Ideally such a capacitive shunt should be placed at the aggressor end of a cable to avoid adding additional radiative interference, but it is often wise, for low frequency lines like power or slow controls to place a capacitive shunt at each end of the line. In addition, it is possible to add a series inductor which has higher impedance with increased frequency (Z_L-$j\omega L$) to improve the attenuation of the low pass filter. An easy way to add inductance is to use ferrite beads around the paired conductors – this is most effective at frequencies in the tens of MHz and above but still useful in the LSST case.

The last case is, perhaps, the most subtle and least covered in introductory texts – unwanted offset voltages caused by the finite resistance of conductors. If one looks back at Figure 2 and imagines that the current between the square and the circle is 1 Amp and also imagine that the resistance of the source and sink wire happens to be 1 Ohm each, then it is clear that the delta V across the circle is 2 V less than the delta V across the square. If we make the case a bit more complex by having the circle report back some analog signals to the square then one sees that a 50% of full scale reading at the circle becomes a 40% of full scale reading at the square even with a high impedance input at the square (the situation is worse if the inputs at the square have relatively low impedance) unless one compensates in some way for the resistance of the wires.

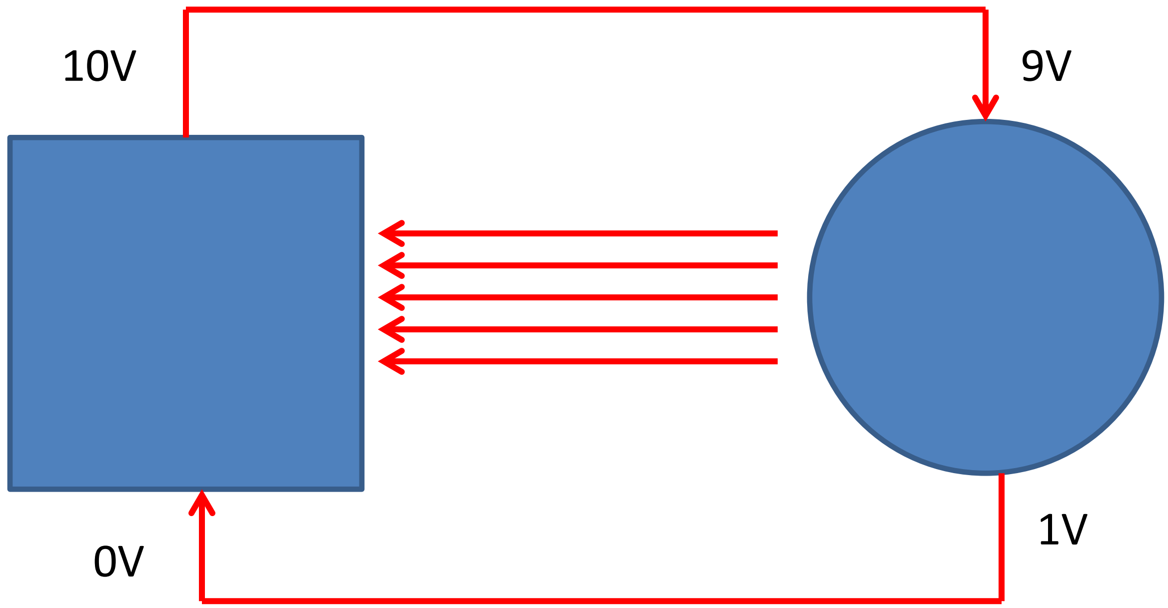
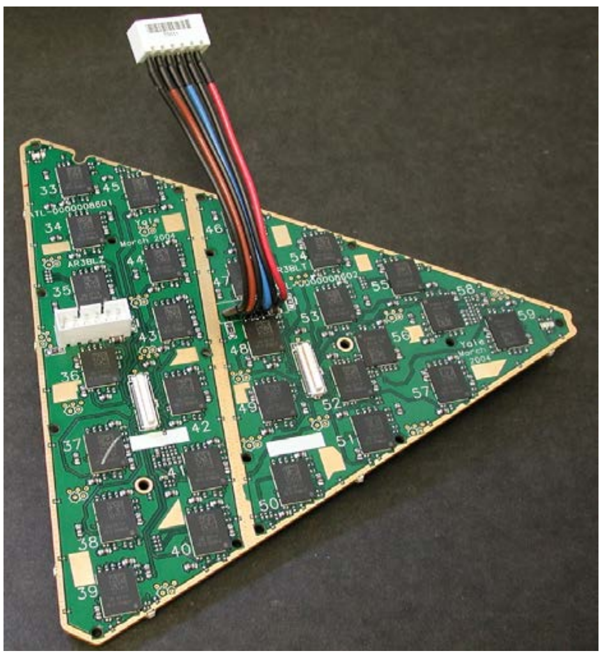


Figure 5- A more complex example with finite resistance in the power wiring.

This example shows why one does four wire resistance measurements (Kelvin connection) for precision work, but, more generally makes the case for differential measurements and floating power supplies.

If one goes from the example in Figure 5 to a more realistic two dimensional example of a real circuit board such as the one shown in Figure 6, one sees a rather more complex problem. The connections between circuits on the board are not wires but traces on a printed circuit board. The power is supplied to the active devices not through wires but via copper "planes" extending across the entire board area (although as one can see in the photo power is brought into the board via wires). Although "planes" do have an advantage over wires in terms of lower resistance (and, at higher frequencies, much lower inductance) they have a disadvantage in that current flows in two dimensions – one can no longer know for sure what path current takes from point A to point B. Knowing the path current takes, however, is important as even though the impedance of a plane is low, it is not zero and if an unwanted or stray current flows across some region of a plane it will change the relative potential across that region in the same way as the currents flowing through the wires in Figure 5 changed the potential. The defense here



is to design in the current flow one desires by putting small "cuts" in the otherwise smooth plane or some other scheme to encourage current to go where it will do no harm. In the board shown in Figure 6 there are very sensitive analog custom ICs on the bottom (hidden) side of the board and high speed custom digital chips visible on the top of the board. To separate the two domains, the printed circuit is fabricated with four layers on the bottom referenced to an analog "ground" plane and the four layers on the top referenced to a separate "digital" ground plane. In order to ensure that the two "grounds" are at a common potential they are electrically connected but, in this case, by a large number of 51 Ohm resistors around the periphery of the board (visible as little insets along the edges in the photograph) so that any currents from analog to digital "ground" flowed far away from the sensitive analog inputs. For LSST, the circuit boards will be designed using all reasonable good practice to avoid having unwanted currents disturb other circuitry. However, in addition to the circuit boards, other parts of the Camera may carry current (desired or unwanted) and an attempt is made below to catalog all places where we need to be careful to avoid problems and to suggest rules to enable a successful design.

Figure 6- ATLAS TRT front end board - 432 channels of wire chamber amplifier, shaping, discrimination, and time measurement on a 14 layer board about 15cm on a side.

The observant reader will have noticed that up to now in this section we have barely mentioned the word “ground” except in the initial comment about single point grounds. This was intentional as, to some extent, the whole idea of “ground” is a myth – useful but, as with any myth, important to understand the limits of the mythology. For instance, if you happen to look up and see some birds perched along a neighboring high tension power line you need to remember that you and the birds have very different ideas of what “ground” is – ideas that may differ by 10^5 Volts! “Ground” in normal parlance is simply the local reference voltage while in safety speak it is a common potential for all the local bits of conductor that humans might come in contact with. All “grounds” are defined locally although the extent of “local” can vary a good deal. The “ground” in one large building may be a common electrical connection extending across acres while in a suburban neighborhood the “ground” is defined house by house using connections actually embedded in the local soil (thus “ground”). In the following sections we will try to define what “ground” means for the LSST camera.

7. Camera Regions and Connections

From the point of view of grounding and shielding, the Camera (a three ton 1.65 m diameter by 3.73 m long device) is naturally divided into a number of separate electrical and mechanical regions, as shown in Figure 7.

Cryostat: containing the focal plane CCDs, support structures and the science and corner raft electronics, as well as heaters and temperature sensors on mechanical components

Camera Body: including the Shutter and Filter Exchange mechanisms, with multiple motors and solenoids as well as some moderately sensitive sensors and micro-controllers This includes the L1-L2 optics region which has no active electronic devices

Utility Trunk: containing ancillary support systems for refrigeration, vacuum, data acquisition (DAQ), control and power.

External mounting and connections: interconnections to the outside world at the top end of the telescope

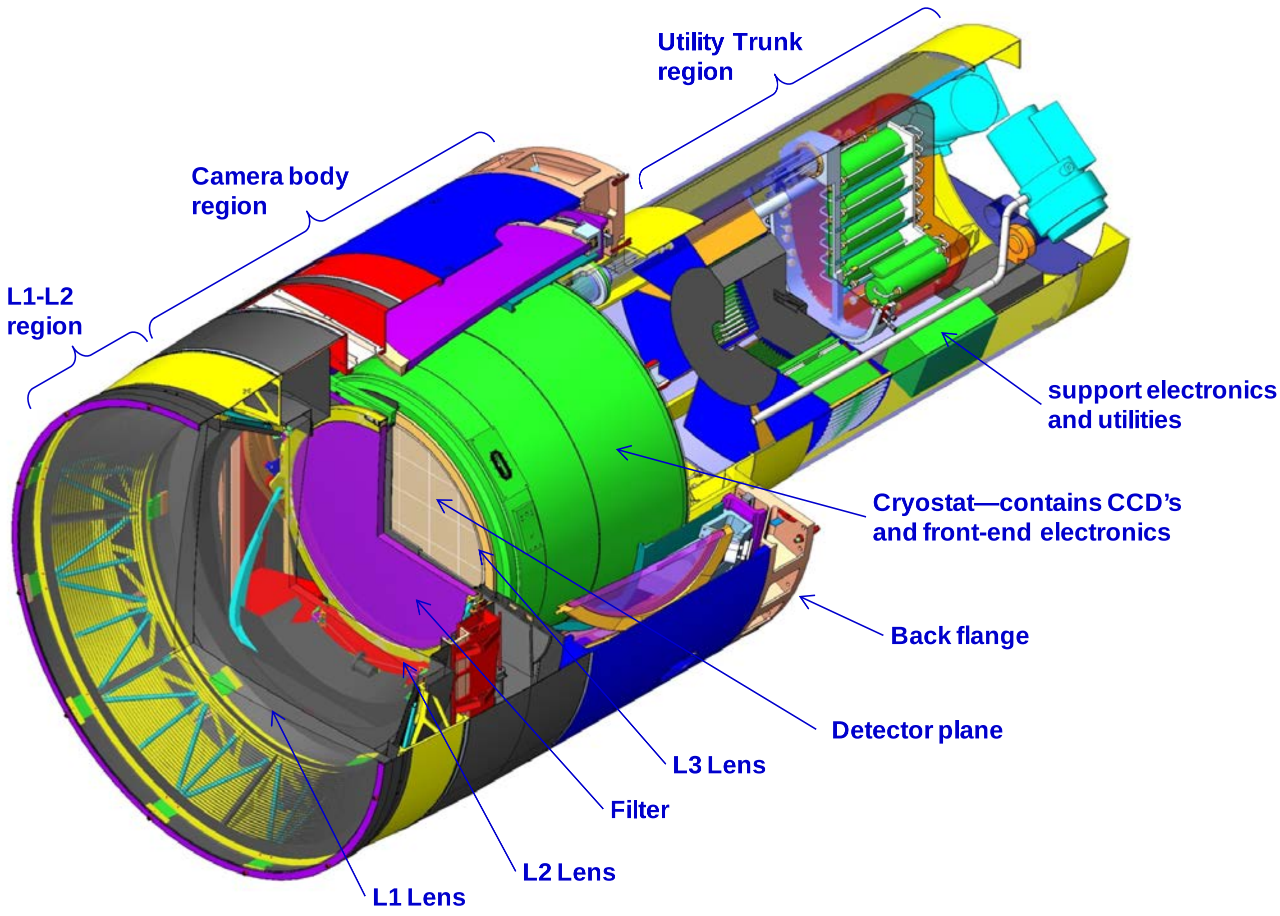


Figure 7: Cutaway view of the full camera with the L1-L2 optics region on the far left, the Camera Body region near the center, the Cryostat containing the cold electronics and CCD sensors, and the Utility Trunk at the right with heat exchangers, electronics crates and utilities

The Camera mounts to the Telescope at the back flange. This mount is a hard-bolted metallic interface and so is a natural electrical connection point between the Camera and the Telescope. All the power and communication connections to the Camera are located on the bulkhead on the end of the Utility Trunk (far right on Figure 7). In addition, the Camera is a large metallic structural object where nearly all structural elements connect electrically with each other because of their mechanical interconnection. This is important as, in general, it is necessary to hold all large conductors at a defined potential (where "large" is referenced to the frequency response of the electronics system). In the following section we outline a ground control scheme and shielding scheme that is compatible with the structural requirements of the Camera and that prevents differential voltages from generating unwanted circulating currents or capacitive or inductive pickup from interfering with the operation of the Camera. This is laid out schematically in the grounding block diagram shown in Ref. [2], LCA-343, "Camera Block Diagrams," and duplicated in Figure 8.

These four regions are described below, followed by a detailed breakdown of the problems and challenges in the major regions and outlines of the detailed requirements for components in the region to avoid potential problems.

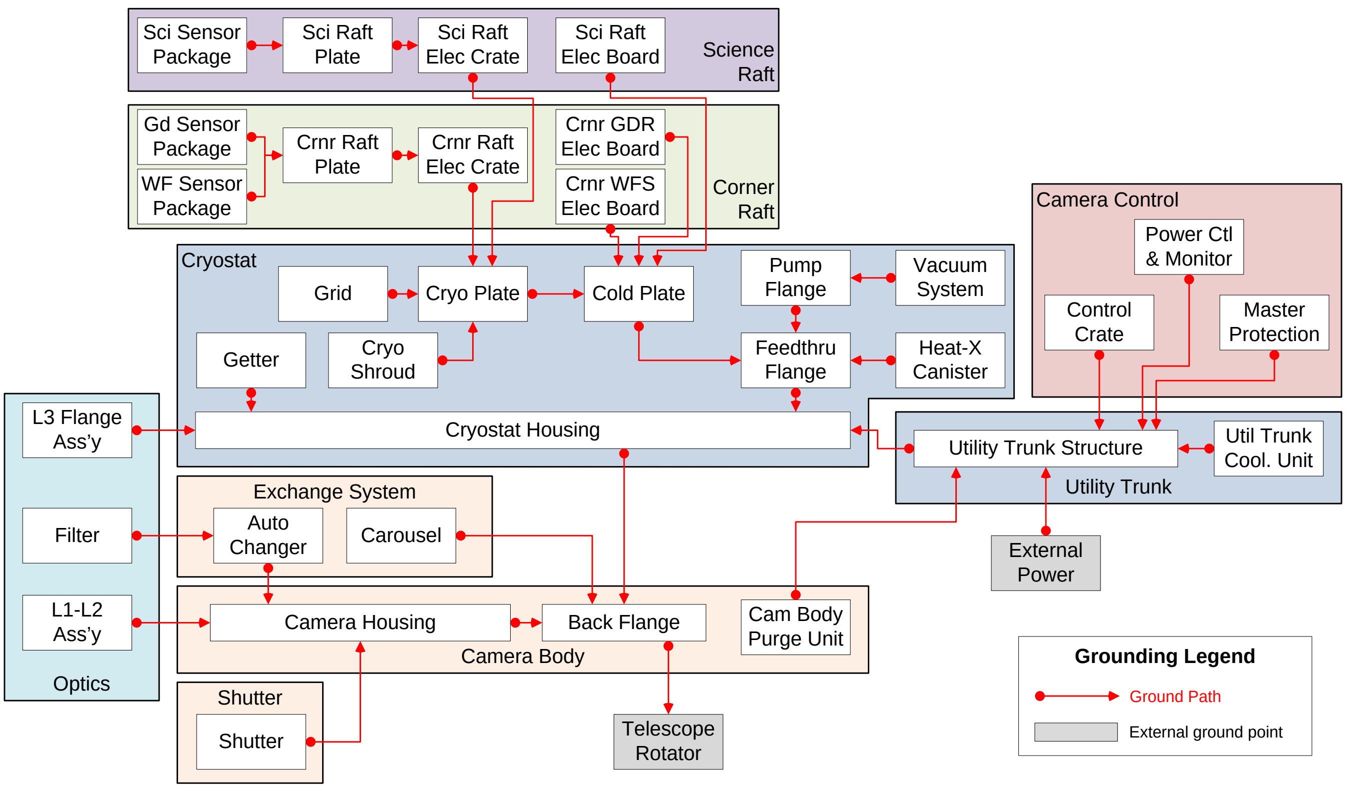


Figure 8: Grounding block diagram, showing ground connections between structures, neutrals, and shields

7.1. Cryostat

The Cryostat houses the "cold mass" of the very sensitive CCD sensors and electronics. It also provides the insulating vacuum and thermal environment for the detector plane, including a variety of vacuum pumps, vacuum gauges, heaters and temperature sensors. The detailed treatment of metal masses in the Cryostat is covered in Section 8, below, but the general plan is to treat the main body of the Cryostat, the

Grid and the Cryo Plate as a "shield" with the Cold Plate treated as the reference ground surface for the CCD detectors and electronics. This choice of "reference ground" is largely dictated by thermal considerations.

7.2. Camera Body

The Camera Body houses both the Shutter and Filter Exchange system mechanisms. Both of these systems include sensors and controllers as well as relatively high-powered motors and solenoids. The Shutter motor operates just before the beginning and immediately after the end of each readout cycle and so it is important that any induced current spikes decay very quickly and are shielded effectively. The Filter Exchange system operates motors and solenoids only when the Camera is not acquiring or actively reading images and so does not present as direct a threat to the sensitive CCD readout. However, the sensors, interfaces and controllers for the mechanisms themselves are also susceptible to interference from the large current draws and so the current switches involved must be carefully designed.

Beyond the mechanisms, the camera body also houses temperature and humidity monitors, as well as accelerometers and microphones. These sensors are likewise susceptible to interference from large current draws. Forward of these mechanisms, the only electronic devices in the volume between the L1 and L2 lenses are temperature and humidity monitors. These are read out by the camera purge system hardware control unit (HCU) in the Utility Trunk, so the long unamplified signal runs will need to be treated carefully and shielded appropriately.

7.3. Utility Trunk

The Utility Trunk houses a variety of support systems including vacuum pumping and instrumentation, refrigeration system heat exchangers, power supplies, network switches, and control and protection electronics. Some systems, such as the refrigeration system, have no motors or other high current operators but will have some sensors and, of course, are largely metallic and present possible current paths if not properly connected or isolated. Others, such as the vacuum system pumping and instrumentation, involve not only sensors but also motors for turbo and scroll pumps and so present a potential electro-magnetic interference (EMI) threat to the rest of the system. The power system must deal with the threat of conducted interference as well as limit radiated or induced interference from its own high speed switching supplies. Finally, the control computers and interfaces are sensitive enough to need protection from the assorted threats. All external, removable, connections to the camera (with the exception of the bolted mechanical mount at the Back Flange) exit from a patch panel at the rear of the Utility Trunk (the surface farthest from L1).

8. Cryostat Cold Mass Connections and Grounding

In the following sections we will address each of the major structures and entities inside the Cryostat and detail the electrical connections and isolations, finishing each discussion with an explicit list of derived requirements.

8.1. Cryostat Cold Mass and Cryo Mass Grounding Overview

A sectioned isometric view of the components inside the Cryostat is shown in Figure 9. There are two separate controlled temperature zones within the Cryostat – the Cryo system which maintains and controls the temperature of the CCD sensors on the focal plane and the Cold system which maintains the temperature of the in-Cryostat electronics. These two thermal zones are managed by two different refrigeration systems cooling two separate structures near the rear of the Cryostat – the Cryo plate and the Cold plate. The Cryo plate sits at about -130 degrees C and is thermally and electrically connected to the Grid, the cryo shield, the Raft Electronics Crate (REC) outer walls, the Rafts and the CCD sensor packages. The Cold plate sits at about -40 degrees C and is thermally and electrically connected to the Raft Electronics Boards (REB's) while being structurally supported by, but thermally isolated from the Cryo Plate. Both the cryo and cold masses are thermally and electrically isolated from the warm wall and flanges of the Cryostat, as well as the L3 lens and front flange.

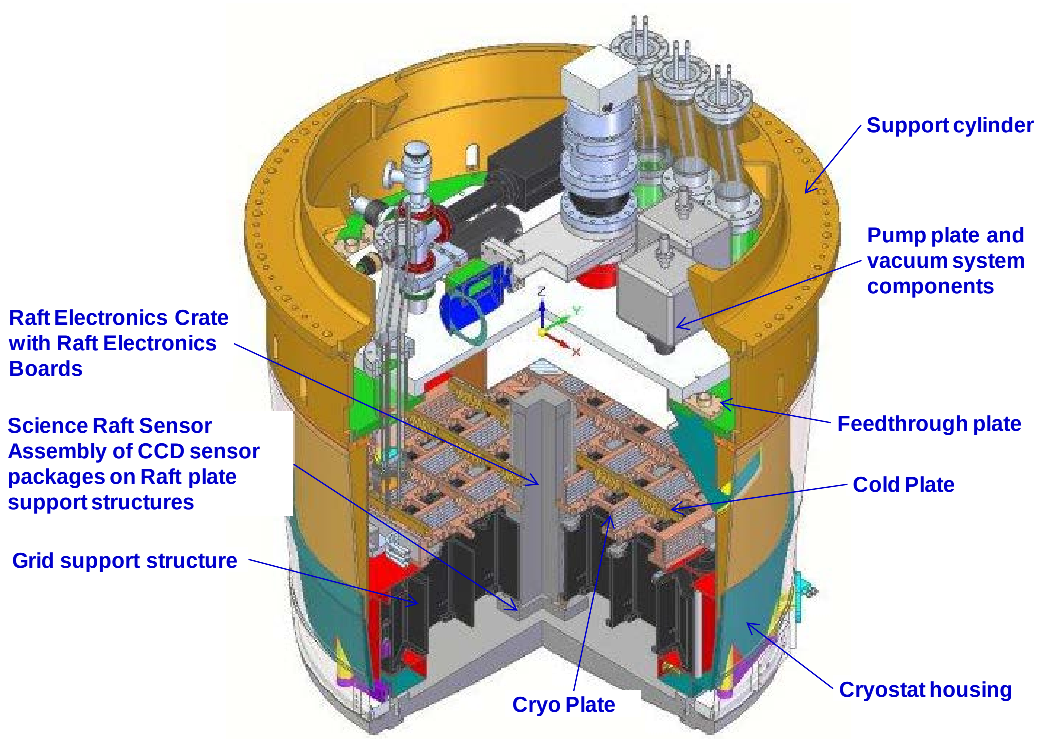


Figure 9: Isometric section of the Cryostat showing the location of the front end and back end detector electronics, as well as the Cryo and Cold Plates to which they are thermally and structurally attached

Given that the Cold plate is electrically connected to the REBs and their equivalents in the corner rafts – forming a very low impedance reference ground surface, any leakage currents between REB's will naturally flow through the Cold Plate. This makes the Cold Plate the preferred reference ground structure inside the Cryostat. The REC, Rafts, and CCD package structures are electrically connected to the Cryo Plate which is then electrically connected by a ground strap to the reference potential of the

Cold Plate. Other metallic and conducting structures in the Cryostat and the walls and flanges of the Cryostat are also held at the same potential as the Cold Plate but only by way of single-point connections so that no current can flow through or across those elements. For instance, the Grid structure, is thermally and electrically connected to the Cryo Plate but is not electrically connected to other elements of the Cryostat.

The electronics in the science and corner rafts are cooled by mixed refrigerant flowing in the Cold Plate, so the thermal connections between the REB's and the Cold Plate need to have a very low thermal impedance. If one were to try to electrically isolate each REB from the Cold Plate that electrical isolation would necessarily increase the thermal impedance and, because of the relatively large area of the mating metallic surfaces and the inherent capacitance across any electrical isolation, the electrical isolation would only be at relatively low frequencies. Thus the simplest plan is to make the Cold Plate copper the reference "ground" surface for the raft electronics – this guarantees a low-impedance thermal and electrical path but implies some mild requirements for the mechanics.

As the Cold Plate provides the reference potential for the REB's, it is important to not allow stray currents to flow through or across it, so the Cold Plate must be electrically isolated from the cryostat and any other mechanical structures. This is accomplished by mounting the Cold Plate to the Cryo Plate and introducing electrical breaks in the piping carrying the refrigerant in and out of the cryostat. However, once those isolating components are in place we have a nearly ideal multi-channel electrical environment. The REBs in each raft tower are powered by floating power supplies (independent current returns for each supply) and the communication to and from the FPGA on the back of the REB uses low voltage differential signaling (LVDS) with its very relaxed common mode voltage requirement. Each raft tower is then a 144 channel (or 48 channel for the corner raft tower) readout system which is only electrically connected to the other raft towers by the ground reference at the Cold Plate. This is shown schematically in Figure 10.

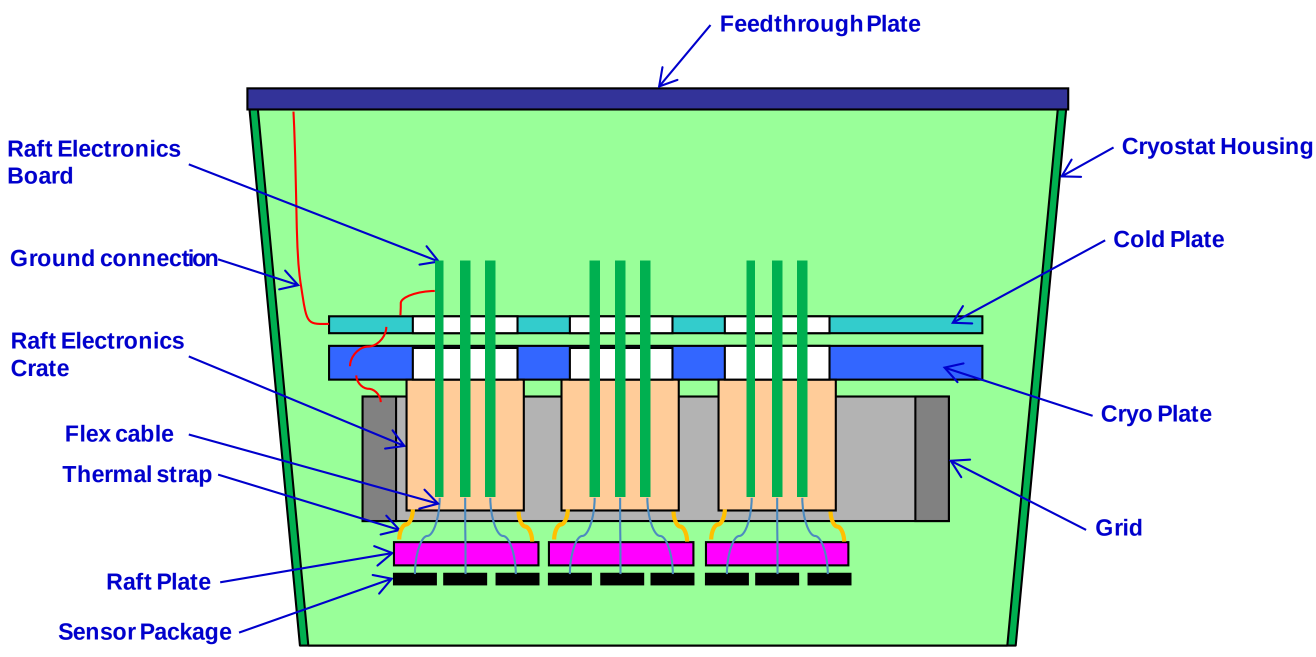


Figure 10: Schematic representation of the Cold and Cryo Plate connections to rafts, to each other and to the Cryostat.

Of course within an REB, it is essentially impossible and would be unwise to attempt to treat each channel separately. Already at the CCD sensor level the channels are intertwined with common substrates and bias structures. On the REB eight channels share a single Analog Signal Processing Integrated Circuit (ASPIC) and a given sensor is handled by two ASPICs on opposite sides of the board. In this intertwined situation the general rule changes to one of keeping a common very low impedance reference for all channels so that even if there were to be (more plausibly, when there are) circulating currents from one area to another across that reference surface, the potential differences are, perforce, insignificant. For instance, if one can maintain micro-Ohm impedances, even milli-Amp stray currents cause only nano-Volt level shifts. Given that the least-significant bit for the analog to digital converters (ADC's) is a few micro-Volts, this shows that a low-impedance reference can render potential differences insignificant. In this case we are helped significantly by the simultaneous requirement for low thermal impedances. The additional copper mass required for good heat transfer serves to lower the electrical impedance even more.

The Cryostat housing forms the primary—albeit leaky—Faraday shield for all cold mass electronics and is held at the same potential as the cold mass by way of a single point ground as indicated schematically in Figure 10. It should be noted that this single point connection may be location sensitive and so multiple possible connection points will be identified but only one such connection will be implemented. All long distance (i.e. not local on a single printed circuit board) signals within the Cryostat, both on and off the cold mass, are isolated differential signals. The use of analog differential signals significantly improves rejection to pick-up of common mode signals, referred to as common mode rejection rate (CMRR). Likewise the use of LVDS for digital signals significantly reduces radiated EMI, which can couple to the high-gain front end electronics. The CCD sensors are inherently single-ended, and thus require the most care in grounding. Note that there will be some number of two wire sensors, such as resistive thermal devices (RTD's), located throughout the Cryostat. The wiring for such sensors is isolated from the local structure (and twisted where possible) and the external sensing electronics will maintain the isolation of the lines from Camera "ground."

8.2. CCD Sensors

N-channel CCD's are used for all three sets of sensors for the Camera: science imaging sensors, wavefront sensors, and guide sensors. There are multiple single-ended outputs from each sensor and it is imperative to provide separate low impedance paths for their return currents and adequate shielding to prevent crosstalk between the outputs. The prototype CCDs are connected by cables with paired OS and OD lines and interleaved isolating lines as well as an overall "ground" shield for the cable. These cables need to be measured and characterized to verify that they provide sufficient isolation. In general, the bulk of the silicon substrate is connected through a large bypass capacitance to the signal reference analog ground for each sensor, which will in turn be assigned to multiple conductors on the ribbon cable which connects the sensors to the FEB's. Note that, except for leakage current and current due to light injection, no DC current flows in these analog ground conductors, as the CCD's do not have a complete current path to the substrate (source follower current sources are off-chip). AC currents due to induced signals from the CCD clocks largely return through neighboring clock lines due to the high coupling capacitance between the long polysilicon lines on the CCD but about one third of the clock current does return by way of the substrate. Bias voltages which can couple to the sensor outputs are driven from low impedance sources to prevent undesired crosstalk between outputs.

CCD Requirements:

Single-ended outputs from sensors shall have separate, shielded, low-impedance return paths

8.3. Sensor Package and Raft Sensor Assembly

The CCD sensor is bonded to an aluminum nitride (AlN) ceramic circuit board which guides signals from the CCD edges to cables that go to the REB's. This AlN circuit is bonded to a conducting metallic or silicon carbide mechanical structure which is then physically and thermally attached to the silicon carbide Raft baseplate.. The set of nine sensors bolted to one Raft make up the Raft Sensor Assembly (RSA). Thermal control of the RSA is through copper conduction from the Cryo Plate and so, without heroic measures, the RSA is naturally connected electrically as well as thermally to the Cryo Plate. In addition, the RSA is structurally and electrically connected to the Grid at the kinematic mounts and the hold-downs. Thus the thermal connection establishes the reference potential for the RSA but, as the CCD signals and voltages are electrically isolated from the RSA, does not set up any ground loops. Furthermore, there is no electrical connection from one RSA to another except by way of the Grid or Cryo Plate. The moderate conductance of the Raft baseplate material makes the raft, in combination with the Grid and the copper sides of the Front End Cage something of a shield for the electrically isolated REBs. The shield cannot be perfect but it is likely to be helpful. This expectation puts an upper bound on the resistivity of the raft and sensor packaging.

Sensor Package and RSA Requirements:

Raft plate material maximum bulk resistance: 1 Ohm

Maximum electrical resistance from sensor package to interface with thermal strap off back of raft plate: TBD Ohms (for one sensor)

8.4. Raft Electronic Crates

The Raft Electronic Crate (REC) is the mechanical/thermal structure that conducts heat from the RSA to the Cryo Plate, that provides the hold down mechanism for the RSA and that stabilizes and locates the three Raft Electronics Boards that serve the RSA. The heavy copper sides of the REC not only serve to conduct heat from the RSA but also, incidentally, serve as an electrical shield albeit a leaky one with a hole at the top and bottom. The upper "hole" is partially closed by both the RSA itself and by the conductance barrier. The lower hole is not closed but since the most sensitive parts of the electronics (the current sources and the ASPICs) are "far" away in terms of REC dimensions there is still some shielding effect. As noted above, the REC is bolted directly to the Cryo Plate and so is electrically connected to the Cryo Plate. The REC is also electrically connected to the RSA by the thermal straps and, through the RSA to the grid via the kinematic mounts – although those connections are relatively high resistance. As noted, the REC outer chassis is bolted directly to the Cryo Plate, which provides a very low impedance uniform-potential connection for all 25 REC's. . However, the dominant mechanical factor in the joint is the thermal impedance and so some enhancements for decreasing and ensuring the thermal impedance may be necessary. Were it to be necessary to improve the thermal connection by using some electrically insulating material, then an explicit ground strap or other conduction path will be added between each REC and the Cryo Plate

8.5. Raft Electronic Boards

Each REB provides all the electronic functions to drive, readout and support three CCDs. Three REBs support all nine CCDs on an RSA and are contained within a single REC as shown in Figure 11.

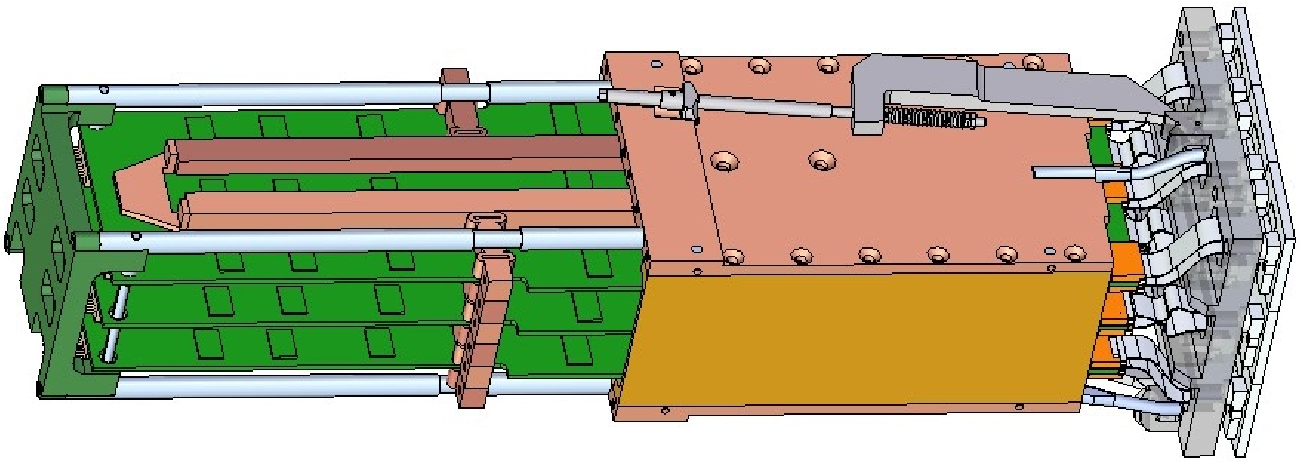


Figure 11- Raft Electronics Cage (Cu colored) with RSA to the right and three REBs shown in place. The REC copper is connected to the Cryo Plate, the Cu cooling bars shown on the REBs are connected to the Cold Plate at the attachment flexures shown in the left center.

From a purely electronics point of view, the REB must be a multilayer structure with multiple ground planes. In order to satisfy the thermal conduction requirements, the thickness and total number of ground planes is increased to 2 oz. with four such planes minimum. The REB includes heavy Cu conduction bars top and bottom running most of the length of the board. The bars reduce the thermal impedance from the various heat sources to the Cold Plate attachment points near the midpoint of the REB. Because these bars need to be thermally connected to the internal ground planes of the REB they are unavoidably electrically connected to the ground planes and form part of the current return path for the board. However, in order to prevent currents from one board flowing through a different board, it is important that there be no electrical connection from REB to another except at the Cold Plate attachment points. The conduction bars of one REB must be electrically isolated from the other REBs except at the Cold Plate.

REC Requirements:

REB ground plane minimum configuration: 2 oz. thickness; Four ground planes

Maximum total resistance from any point on a REB board to interface to Cold Plate: TBD Ohms

Maximum total resistance across REB—Cold Plate joint: 1 Ohm

Electrical isolation REB to REB (excepting Cold Plate joint) > 100 kOhms

8.6. Grid

The Grid is thermally linked to the Cryo Plate by multiple flexible copper cold straps that keep the Grid at the Cryo Plate temperature. The Grid is made of silicon carbide and is somewhat conductive, so these copper thermal straps also define the Grid potential as being identical to the Cryo Plate. The Grid support flexures include ceramic electrical isolation, so the Grid is electrically isolated from the Cryostat housing. This ensures that there are no currents flowing through the Grid or its supports.

Grid Requirements:

Grid material maximum bulk resistivity: TBD

Grid flexure minimum resistivity for electrical isolation: TBD Ohms per flexure x 3 flexures

Grid—Cryo Plate cold strap maximum resistivity: TBD Ohms, per strap (including bolted connections at each end) x 16 minimum number of straps

8.7. Cryo Plate and Shroud

The Cryo Plate is the reference surface for the RSA and Grid. The Cryo Plate is isolated from the outer shell of the Cryostat with ceramic insulators mounted in-line with the titanium flexures that structurally support it. The Cryo Plate is cooled by refrigerant flowing through embedded lines that are connected to external heat exchangers. To maintain electrical isolation of the Cryo Plate, the refrigerant feedthrough lines include electrical breaks as they pass through the Cryostat housing and before they reach the Cryo Plate.

The Cryo shroud is mounted to the perimeter of the Cryo Plate and surrounds the Grid to provide a uniform thermal radiation environment. It, too, is electrically and thermally connected to the Cryo Plate, and does not physically touch either the Grid or the Cryostat housing.

The Cryo Plate also includes heaters and temperature sensors. All sensors and heaters must be electrically isolated from the Cryo Plate.

The Cryo Plate potential is defined by a single electrical connection between the Cryo Plate and the Cold Plate that defines the ground potential for the cold mass inside the Cryostat. Multiple possible connection points will be provided in case there is some position sensitivity.

Cryo Plate Requirements:

Cryo Plate flexure minimum resistivity to outer housing: TBD Ohms per flexure x TBD flexures

Cryo Plate minimum total impedance to outer housing: TBD

Cryo Plate includes a single-point ground wire to the Cold Plate, of TBD gauge braided OFE copper with minimum current rating of TBD Amps and a minimum width to thickness ratio of 5 (TBD?)

Heater requirements:

Power wiring is shielded twisted pair, isolated from the Cryo Plate with cable shield attached to the Cryostat at the feedthrough

Heater power supply electronics (in Utility Trunk) to be full proportional linear controllers only, with no silicon-controlled rectifier (SCR) or other pulse width modulation (PWM) control

Sensor requirements:

Sensor wiring is shielded twisted pair, isolated from the Cryo Plate with shield attached to the Cryostat at the feedthrough

8.8. Cold Plate

The Cold Plate is the reference ground surface for the REB and corner raft electronics. It also is isolated from the outer shell of the Cryostat with ceramic insulators built into the structural support flexures. The Cold Plate, as in the case of the Cryo Plate is cooled with refrigerant, so its feedthrough lines also include electrical breaks. The Cold Plate incorporates sensors to measure the Plate temperature and heaters to provide fine control of that temperature.

The Cold Plate potential is defined by a single electrical connection between the Cold Plate and the Cryostat housing. Multiple possible connection points will be provided in case there is some position sensitivity.

Cold Plate requirements:

Cold Plate flexure minimum resistivity: TBD Ohms per flexure x TBD flexures

Cold Plate includes a single-point ground wire to the Cryostat housing, of TBD gauge braided OFE copper with minimum current rating of TBD Amps and a minimum width to thickness ratio of 5 (TBD?)

Heater requirements:

Power wiring is shielded twisted pair, isolated from the Cold Plate with shield attached to the Cryostat at the feedthrough.

Heater power supply electronics (in Utility Trunk) to be full proportional linear controllers only, with no silicon-controlled rectifier (SCR or other PWM control

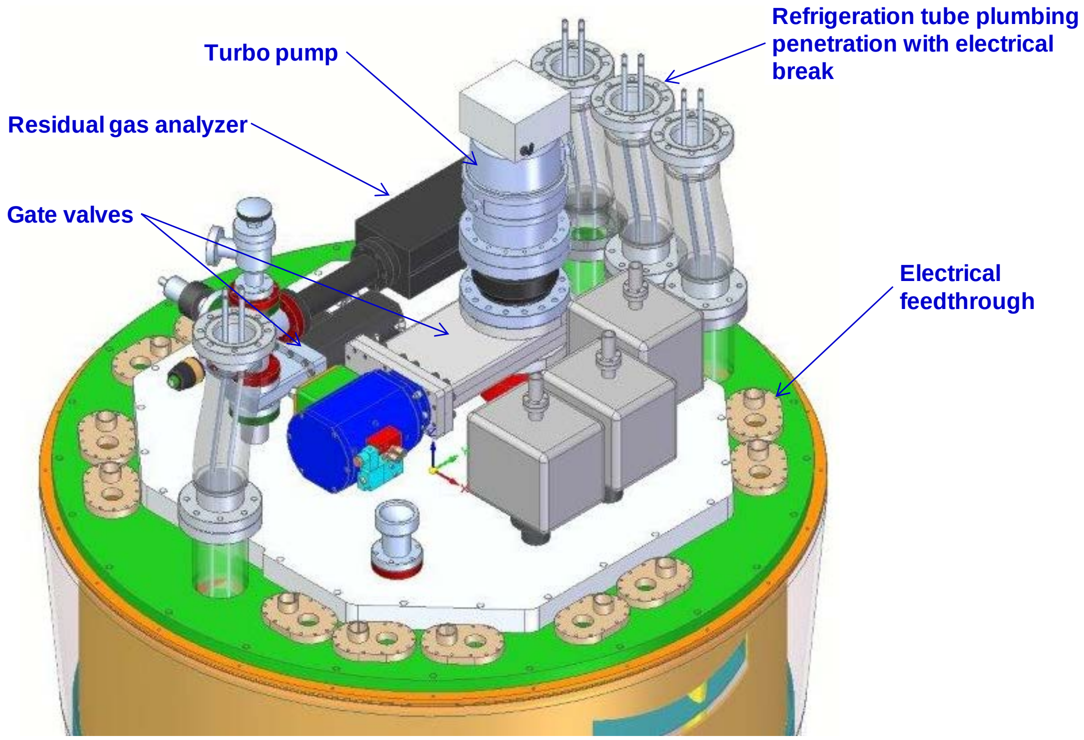
Sensor requirements:

Sensor wiring is shielded twisted pair, isolated from the Cold Plate with shield attached to the Cryostat at the feedthrough.

8.9. Cryostat Vacuum Enclosure

The Cryostat vacuum enclosure—the outer housing of the Cryostat—is isolated electrically and thermally from the cold and cryo masses. Electrically, the Cryostat vacuum enclosure acts as a very leaky Faraday cage (leaky because of the opening of the L3 lens). Nevertheless, the metal enclosure should provide a useful shield, especially against aggressor devices in the Utility Trunk area, away from L3. There are also a pair of passive molecular sieve getter pumps at the front of the Cryostat near the focal plane. The large metal parts of these getters will be at the same potential as the vacuum enclosure because of metal to metal contact. In addition, there are a number of electrical items directly mounted on the back of the Cryostat, including vacuum pumps and gauges on the Pump Plate and feedthroughs and cables on the Feedthrough Plate.

The Pump Plate, shown in Figure 12, provides mounting for a relatively high powered turbo pump, a residual gas analyzer, several vacuum gauges of various types and remotely operated gate valves. All of these devices are mounted to the Pump Plate on high vacuum flanges with multiple bolts. These bolt circles create a low impedance electrical connection between the device housings and the Pump Plate. The Pump Plate itself is bolted onto the Feedthrough Plate which is, in turn, bolted to the Cryostat housing. These multiple bolt circles create a low impedance electrical path between all the various metal parts. This assumes that no paint or insulating passivation is used on any of the mating surfaces. If such insulating layers exist then either lockwashers are used to bite through the layers or insulation free zones in the contact area must be created. Power to the electrically operated devices is isolated from the



housings of the devices. As usual, no current can flow in the structural parts of the Camera.

Figure 12: Cryostat Pump Plate with valves, turbo pumps, gauges and residual gas analyzer

Similarly for the Feedthrough Flange shown in Figure 12, the plumbing feedthroughs on the left and right of the figure are welded and bolted structures in direct electrical contact with the flange and the individual dual electrical feedthroughs which carry signals and power to and from the REB's and the small number of miscellaneous sensors and heaters inside the Cryostat are hard bolted to the flange and their cable shields are electrically at the potential of the Cryostat.

The Cryostat housing is bolted directly to its support cylinder, which in turn is bolted to the Camera back flange. These bolted connections ensure that no potential differences, either DC or transient, exist between the Cryostat and back flange.

Cryostat Vacuum Enclosure requirements:

Getter pumps at front of Cryostat to be electrically connected to the Cryostat outer housing, with resistance of any connections to the cold mass greater than TBD Ohms (DC to 10MHz)

Pumps, valves, and instrumentation mounted on the Pump Flange shall have their housing grounded to the Pump Flange with maximum resistance across the mount of TBD Ohms (DC to 10 MHz)

Neutral/ground lines from all pumps, valves, and instrumentation shall return to their respective power supplies and not be attached to the Pump Flange

Maximum resistance of the Pump Flange—Feedthrough Flange bolted connection and Feedthrough Flange—Housing bolted connection shall be no more than TBD Ohms (DC-10MHz) for each connection

Cryostat bolted connection to its support cylinder and support cylinder to the Camera back flange shall each have a maximum total resistance of TBD Ohms

Vacuum ducting mounted to the cold mass shall be electrically isolated from the Pump and Feedthrough Flanges, with the minimum resistance of TBD Ohms

9. Penetrations Through the Cryostat Vacuum Enclosure

A variety of electrical and plumbing connections are made between the inside of the Cryostat and the outside world. The treatment appropriate for each class of connection is detailed below.

9.1. Refrigeration System Lines

Vacuum-jacketed Refrigeration System lines penetrate the Feedthrough Flange of the Cryostat and the internal cold lines run to the Cryo Plate and Cold Plate, which are part of the cold mass of the Cryostat. These metallic lines and their vacuum jackets must be broken by insertion of an insulating material, placed sufficiently close to the Feedthrough Flange so that no electrical contact between the floating portions of the lines and the outer housing or other components is possible.

Furthermore, the length of the insulating break must be long enough to ensure that the column of refrigerant in the lines does not provide a ground path.

Refrigeration Feedthrough requirements

The electrical break must provide a minimum of TBD Ohms, DC resistance per line

The break must be at least TBD mm long, to ensure that there is no leakage current through the refrigerant

The refrigerant mixture and all constituent elements must have a minimum bulk resistivity of TBD

Refrigerant lines on the cold/isolated side of the electrical break must not be supported by or come in contact with the vacuum housing or flange on the inside of the Cryostat

9.2. Electrical Power

Electronics in the cold mass require a number of different voltages and power sources. Cables for each of these voltages and sources must be individually shielded outside of the Cryostat, with their shields electrically connected to its feedthrough shell at the point of penetration as shown in Figure 14. Each power conductor must have a corresponding power return cable which will not be connected to the cold mass or feedthrough shell. The corresponding power supplies must have both terminals floating, with the only connection to “ground” at the point of use of the supply (e.g. on the REB).

Within the Cryostat, power lines may or may not require shielding and will be treated accordingly. This is shown generically in Figure 14. Note that the circuit board and all other components in the cold mass are referenced to the Cold Plate as described above.

Loads or devices that do not need a ground reference, such as the raft heaters or Cryo Plate heaters or raft or Cold Plate thermal sensors, are floating with respect to the cold mass reference ground and must remain floating. During integration and test it may be required that a "ground alert" system be implemented to catch any accidental connection between the isolated cold mass structures and the Cryostat wall and other shielding structures.

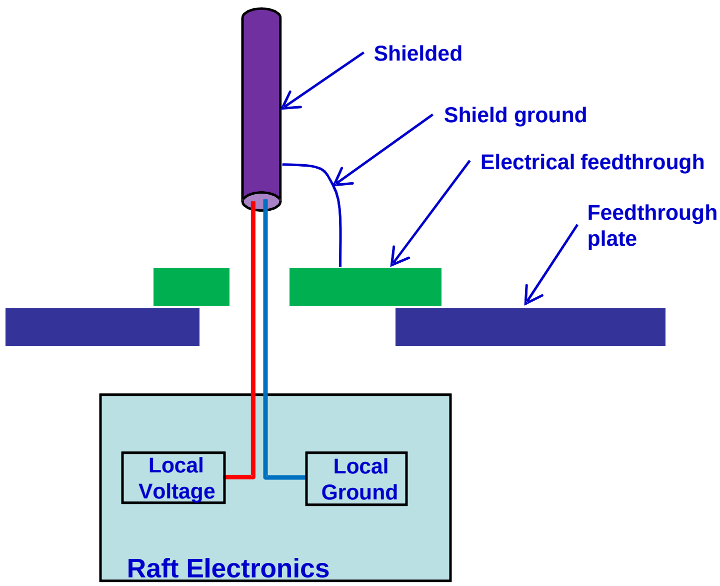


Figure 13: Cable shield attachment at the Cryostat flange

Power Feedthrough requirements:

Power cable runs outside the cryostat shall be shielded

Cable shields shall terminate at the flange feedthrough shell at the point of penetration

All power brought into the Cryostat is "floating" and current is returned on a power return line and never on metalwork or to the feedthrough shell

9.3. Digital Signals

There are multiple digital lines coming from the Control Crate into the Cryostat to control and monitor the Science and Corner electronics. For these connections, the following rules apply.

Digital Feedthrough requirements:

All digital lines must be LVDS or similar low voltage differential (e.g. CML).

Digital lines and busses must be shielded external to the Cryostat wall and may (TBD) be shielded within the Cryostat

All cable shields must be grounded to the vacuum feedthrough shell at the point of penetration

9.4. Analog Signals

There are no analog signals planned to or from the Science or Corner Rafts, but there are expected to be a number of temperature sensors (e.g. RTDs), heaters and, perhaps, other sensors attached to the Cryo Plate, Cold Plate and other areas of both the cold mass and the interior of the Cryostat. The wiring for such sensors is isolated from the local structure (and twisted where possible) and the external sensing electronics will maintain the isolation of the lines from Camera "ground."

All electrical connections to or from such sensors or heaters are electrically isolated from the structure and are sensed or driven by fully differential electronics outside of the Cryostat. All such connections must be shielded external to the Cryostat, as shown in Figure 14, and should be carried on twisted pair cable unless otherwise approved.

Analog Signal Feedthrough requirements:

All lines shall be electrically isolated from the cold mass

Signals are sensed or driven by fully differential electronics

All signal and power cabling shall be shielded external to the Cryostat

All cable shields must be grounded to the vacuum feedthrough shell at the point of penetration

All signal and power cabling shall be carried on twisted-pair cabling unless otherwise approved

10. Camera Body Component Grounding

10.1. Shutter

The Shutter includes motors with local controllers, sensors, solenoids and a Hardware Control Unit with specialized interface hardware. The Shutter and its associated hardware fits just in front of the L3 lens, with the controller and interfaces located near the periphery of the Camera Body. The motion of the shutter takes place just before or just after CCD readout and so the high current draw of the motors is not coincident with the low noise operations of the sensor electronics. Nevertheless, the Shutter's own sensors and the sensors of the nearby Filter Exchange System are potentially vulnerable and should be protected.

As with all other parts of the Camera, the shutter electronic and electrical devices treat the Shutter support structure as a ground reference at a potential of Camera "ground," but not as electrical conductors. All power to the Shutter is returned to the Power Control and Monitoring (PCM) system by way of independent return lines. All sensor signals are differential and are brought back to the Shutter HCU as differential signals. The motor controllers are housed in a metallic cage that is connected to the Camera housing. Power to and from the controllers is always feed and return and is always carried in shielded cable with the shield attached at one end to the local reference "ground" with the option of connecting both ends of the shield to the reference either directly or through an impedance element. In any event, no current is to be carried in the structure. In addition, for the motor controller it may be necessary to install additional snubbing and limiting devices to reduce the potential for radiated noise. These additional devices may include (but are not limited to) varistors, HV capacitors, ferrite cores and additional metal enclosures.

The Shutter is a replaceable modular unit and so provision will be made to ensure that the Shutter is firmly connected to the Camera reference "ground," either by the mounting design (e.g. bolts) or an explicit ground strap.

Shutter requirements:

- Shutter motor controllers must be in a metal cage our housing that is electrically connected (bonded) to the Shutter frame
- The Shutter frame shall provide an electrical connection point for the Camera common ground
- The frame shall be electrically connected to the camera body by way of structural support screws or a dedicated ground strap, with a minimum overall resistance of TBD Ohms
- Sensor signals shall be differential
- Sensor cables shall be fully shielded twisted pair cables
- Power cables shall be fully shielded twisted pair cables with dedicated safety ground if required by code or Camera system-level schematic

10.2. Exchange System Components

The Filter Exchange System includes motors and local controllers, sensors, solenoids and an HCU, so many of the same challenges as the Shutter. However, the Filter Exchange System is never run while the

Camera is observing and so the risk of interfering with science data is greatly reduced. Nevertheless, all of the same precautions mentioned in Section 10.1 apply.

Exchange System requirements:

Exchange system motor controllers must be in a metal cage or housing that is electrically connected (bonded) to the frame of the sub-assembly (Auto Changer, Carousel, or Filter Loader)

The Exchange system frame shall provide an electrical connection point for the Camera common ground

The frame shall be electrically connected to the camera body by way of structural support screws or a dedicated ground strap, with a maximum overall resistance of TBD Ohms for each sub-assembly

Sensor signals shall be differential

Sensor cables shall be fully shielded twisted pair cables

Power cables shall be fully shielded twisted pair cables with dedicated safety ground if required by code or Camera system-level schematic

Filter Loader power and signal lines shall connect to supplies and control systems on-board the camera only, with no other lines or power sources off the camera

10.3. Camera Body and Purge System

The Camera Body is comprised of a metal housing and back flange, along with a temperature-controlled purge system with blower units, re-heaters, local controllers, sensors, solenoids and a HCU, all located in the Utility Trunk. A limited number of pressure, temperature, and flow sensors, as well as accelerometers and tiltmeters, are distributed throughout the volume of the camera and are physically connected to the housing..

Camera Body requirements:

All mechanical structures shall be electrically connected together and to a common ground point

The common ground shall be connected to the back flange with a maximum resistance of TBD Ohms

Signals are sensed or driven by fully differential electronics

All signal cabling shall be shielded external to the Cryostat

All signal and power cabling shall be carried on twisted-pair cabling unless otherwise approved

Purge system blowers and controllers shall be in a metal cage or housing that is electrically connected to the Utility Trunk structure.

Purge system outlets shall include TBD ion discharge system to neutralize flow and minimize charge build-up.

10.4. L1-L2 Assembly

The L1-L2 Assembly has no electrical operators and few sensors. The major challenge here is to ensure that all large metallic elements are connected to the Camera potential and are not floating. Direct mechanical connection by way of bolting is likely to be sufficient unless metal parts have insulating coatings, in which case explicit electrical bonding points will be required.

The one ongoing concern is the large amount of dielectric material represented by the lenses. As we plan to blow dry nitrogen or dry air purge flow over and between the lenses there is a distinct possibility of creating a buildup of static charge that would result in occasional discharges to the structure. This may dictate the need for either a radioactive or ion discharge system near the purge outlet points to neutralize the flow. This is to be determined as part of the ongoing design effort.

L1-L2 Requirements:

- All mechanical structures shall be electrically connected to a common ground
- The common ground shall be connected to the camera body with a maximum resistance of TBD Ohms
- Signals are sensed or driven by fully differential electronics
- All signal cabling shall be shielded external to the Cryostat
- All signal and power cabling shall be carried on twisted-pair cabling unless otherwise approved
- Purge system outlets shall include TBD ion discharge system to neutralize flow and minimize charge build-up.

11. Utility Trunk Component Grounding

Grounding, shielding and "best practices" for the Utility Trunk components are covered in this section. The Utility Trunk contains a number of electrically active or partially active objects:

- Power Control and Monitoring System
- Camera Control Crate
- Master Protection Module
- Vacuum pumps, instrumentation, and valves
- Camera Body Purge system blower units and re-heaters
- Utility Trunk ventilation system blower units and fans
- Refrigeration system heat exchangers

As with all of the other systems, all "large" metal pieces are electrically connected either by the mechanical structure of the Utility Trunk or through explicit ground straps.

11.1. Power Control and Monitoring

All power for Camera-mounted entities is provided by the PCM system. In general, the power is supplied at the lowest possible level (i.e. the smallest reasonably sub-dividable load) in order to allow detailed monitoring of the Camera status and to limit the energy available to cause damage. In all cases the power feed to an entity is matched with a power return line from the entity with the PCM supply acting as an independent floating supply for each device and voltage and no current is allowed to flow in the Camera mechanical structure which functions only as an electrical shield, and never as a conductor. The PCM itself is composed of a number of custom printed circuit boards plus some commercial AC-DC converters and whatever AC distribution system is ultimately required by on-Camera loads (TBD). The card cage carrying the custom boards and the metallic enclosures containing the AC-DC converters and AC distribution equipment is kept at Camera "ground" with either mechanical attachment or explicit connection. The parts of the PCM handling AC mains power will satisfy all the relevant electrical codes.

In general, power is distributed to remote loads with shielded (twisted) pair cables, with the shield hard connected to Camera "ground" (i.e. the local structure) at the load and with an optional connection through an impedance (resistance, capacitance or inductance) at the PCM end to either the PCM local "ground" or the PCM return line for that supply.

Power Supply and Power Crate requirements:

- Power supply in the PCM shall float with respect to ground potential
- All power supplies (AC or DC) shall include dedicated power return lines from the powered device
- Common return/neutral lines from different loads shall not be used, but each circuit shall have its own return line
- AC-DC converters in the PCM shall be safety-grounded to the PCM cage structure with a maximum resistance to ground of TBD ohms
- The PCM cage shall be electrically connected to the Utility Trunk structure with a maximum resistance of TBD ohm

11.2. Control Crate

The Control Crate contains both custom-built control boards, such as the Optical Transition Modules, and commercial units such as HCU boards and their associated interface boards, which provide subsystem instrumentation and control. The crate contains both digital and analog electronics and is powered by a set of dedicated PCM supplies.

As above, the crate and mechanical structure is directly connected to Camera reference "ground" through mechanical interconnections (or dedicated ground straps) and so the mechanical structure serves, to some extent, as a shield for the devices contained therein. However, each control board is electrically isolated from the crate mechanics and all communication between control boards and controlled objects is with a full loop signal/return pair. In so far as possible, all digital communications between controllers and other entities will be differential (e.g. LVDS or Ethernet) and all single ended signals will return current through a dedicated return line from the sensor or operator back to the controller. In no case will current be returned through structural elements or a chassis connection. If, in any instance, a controller or device has no defining connection to a ground potential through any other means, a single point direct ground connection to the Crate structure may be used to provide a reference.

Control Crate Requirements:

- Digital communication between controllers and other entities shall be by way of differential signals
- The Control Crate shall be electrically connected to the Utility Trunk structure with a maximum resistance of TBD ohms
- Controllers in the Control Crate shall be electrically isolated from the crate cage structure, with a minimum resistance of TBD ohms
- Single-ended signals shall return current through dedicated return lines from the sensor

11.3. Protection System PLC's and DIN Rail

The Master Protection Module (MPM) and, if needed, other Local Protection Module programmable logic controllers (PLC's) will reside on a DIN rail near the Control Crate and PCM Crate. The power for the MPM (and other PLC's if used) is supplied by a dedicated supply which is part of the PCM system but independent of other supplies in the PCM system. The power to the DIN rail is, as usual, fully floating, with a dedicated return, and independent for each entity on the DIN rail. In addition all sensor and control inputs and outputs to the PLC(s) are either isolated or differential.

Protection System PLC Requirements:

- Rail power shall float with respect to ground potential
- Sensor and control inputs and outputs to/from the MPM and any LPM's shall be electrically isolated from the cold mass
- Sensor and power cables to/from the MPM and other protection modules shall be fully shielded twisted pair cables

11.4. Grounding of Other Components

Other electronic or electrical loads in the Utility Trunk are handled in a similar fashion. For instance the scroll pumps are mechanically and electrically connected to the structure of the Utility Trunk and are powered by an independent two-wire feed (with a separate breaker if AC).

Component Grounding requirements:

Each component is individually powered by a dedicated feed

The component chassis shall be electrically connected to the Utility Trunk structure

12. External Connections to the Camera

Input power to the camera is by way of a three phase feed from a dedicated electrostatically isolated transformer on the Observatory floor. This feed also carries a "neutral" and "safety" ground and is shielded. This is the ONLY power feed to the Camera. The safety ground line and the power line shield provide the electrical safety connection to the Observatory ground reference. There should be no current carried in this line and it will be monitored to catch ground faults. This "safety ground" connection will be at the same potential as the Telescope structure.

The optical fibers for the Camera DAQ and Camera Control System (CCS) are non-conducting and have high-resistance jackets.

Compressed air or nitrogen used for purge and environmental control may be carried up to the Camera in conductive lines, but there will be an electrical break at or just before the patch panel at the back of the Utility Trunk in order to avoid another ground current path.

There may be a small number of direct copper connections to carry safety related signals or backup control connections. All of these conductors will be electrically isolated from the Camera structure and drive to or be driven from electrically or optically isolated interfaces. If a shield is used on this collection of signals, that shield will be hard connected only at the Observatory end and unconnected on the Camera end, but there will be provision to allow capacitive or resistive coupling at the Utility Trunk.

Camera External Connections requirements:

Shielded cables from the Observatory to the Camera will have their shield hard connected at the Observatory end to local Observatory "ground" and be isolated at the Camera side but allowance will be made for coupling the shield to the Camera "ground" by way of a discrete impedance element

One and only one "ground" (green wire) cable connection will be used from the Observatory to the Camera

The current in the ground connection shall be monitored for ground-loops or faults

All external conductive plumbing and gas lines shall be electrically isolated with an electrical break at or near their entrance to the Camera so as not to conduct currents between the Telescope structure and the Camera

All fiber connections to the camera shall have non-conductive shields and wraps or include an electrical break for any conductive elements at their entrance into the Utility Trunk.

13. General Rules for Aggressors and Victims

While it is relatively easy to prescribe "good practice" for cabling plants, the design space for active (powered) devices is much broader and so there are fewer clear cut prescriptions that can be used to provide definitive assurance of proper operation of the fully assembled Camera. Nevertheless, it is possible to enumerate a number of important points for designers to keep in mind during device selection and housing design. For this section we propose a set of rules for possible "aggressors" and for possible "victims" – i.e. those devices that may broadcast electrical interference and those devices that are especially sensitive to electromagnetic interference. In many cases these are obvious or even almost trivial, but since people with varied levels of experience in electromagnetic interference issues will be making initial design decisions it may be useful to set out some basic definitions and rules of thumb applicable to our case.

Aggressors – devices that switch currents in excess of 0.1A or voltages in excess of 5V – typical examples include:

- Motors of any size (but more power is worse)
- Electromagnetic relays except for reed relays used for low level signals
- Electromagnetic solenoids
- Power control systems (e.g. heaters) that are digital – either PWM or FM
- High voltage gauges such as ion gauges

Victims – devices that sense currents below 1mA or voltages below 10mV – typical examples include:

- Thermocouples
- RTDs
- Bridge based pressure or load sensors
- CCDs

13.1. General Rules for Potential Aggressors:

The following design and implementation rules should be used for any component or system including components that are potential aggressors

- All cabling to be shielded twisted pair to reduce radiation from cable plant, consider adding ferrite beads to the source and sink ends of the cable to further increase the high frequency impedance of the cable
- Choose linear over digital devices if possible – e.g. a synchro over a stepper motor
- Avoid SCR based controllers, if not possible all SCR switching must be zero crossing
- High power controllers to be fully encased in a metal shell (Faraday Cage) with the shell firmly bonded to the Camera structure or metalwork
- High power controllers to have snubbers (i.e. diodes) and capacitive filters at the controller power input and control output
- High power loads to have snubbers (i.e. diodes) and capacitive filters at the load

13.2. General Rules for Potential Victims:

The following design and implementation rules should be used for any component or system including components that are potential victims

Faraday Cages – continued through the cabling plant via shielded cable

Capacitive shunts across slow signals to kill high frequency interference

Resistive stoppers in-line with signal path if possible

13.3. Other Considerations:

Aggressors that only operate when victims are quiescent and vice versa present less of a problem and so careful scheduling of operations is an additional possible prophylactic measure. However, to retain as much operational flexibility as possible, this possibility should only be exercised when no other reasonable options exist.

$1/R^2$ is an important consideration – distant aggressor and victim device pairs are less likely to show problems than neighboring devices so most of the design effort on EMI/EMC should concentrate on local volumes of the Camera. However, the cable plant is part of the system and so adjacent or nearby cables can be a cause for concern (shielding is never 100%)

The goal is smooth operation of a highly reliable precision instrument

14. General Rules for Integration and Plan for Design Verification

The Camera will be assembled over an extended period of time from subsystems and devices supplied by the collaborating institutions and by commercial sources. As each new stage of integration is reached it will be useful (and is therefore mandatory) that a verification test of electromagnetic non-interference be performed. The Integration Plan will detail the exact stages at which such verification tests will be carried out, but, in general, each new piece added to the assembly will be exercised relative to all the other pieces already in place in as realistic a way as possible to verify reliable operation of all pieces – including possible electromagnetic interference.

While the integration tests (and later commissioning tests on the mountain) will be the final arbiters of suitability, it would be wise to carefully examine all conceptual and preliminary designs and identify all possible or probable Aggressors and Victims in order to identify any problem areas well in advance of integration. Any Aggressors and Victims identified by the subsystem design team should be forwarded to the Camera System Engineering team, along with appropriate data sheets or calculations that demonstrate the concern as well as any suggestions for mitigation (e.g. time or spatial separation). The System Engineering team will then be in a position to consult with relevant experts not only in other subsystems but also outside the Camera or LSST communities to concur in the suggested mitigation strategies or suggest others. In addition, it may be necessary or useful to conduct physical tests and measurements of prototype systems or devices to partially quantify the degree of aggression or susceptibility. Clearly, the sooner any issues are identified, the longer the Project will have to identify and verify mitigation strategies, so this EMI/EMC identification process should be part of each conceptual and preliminary review cycle.