AdV Standards
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Nov 25th 2009
VIR-0737A-09

Electronics for Advanced Virgo: Guidelines and Requirements for Electronics Installation
-a proposal-

1. Introduction

In the field of precision measurement, it is vital to eliminate or mitigate as far as possible unwanted causes and effects that can limit instrument performance.

In Virgo many different systems and their electronics live and operate in close proximity. A direct consequence of this situation is that electronic units need to perform to specifications not only in a controlled environment but also in presence of potentially aggressive electromagnetic surroundings.

In other words, systems and their components have to possess a high degree of *immunity* against external disrupting agents and a low level of *emission* of possible disturbing phenomena. These properties are compounded in a single system (or subsystem) quality, its ElectroMagnetic Compatibility (EMC).

A series of measures can be adopted, at premises' electrical infrastructure, system and unit tier, to increase the immunity of sensitive pieces of equipment to external signals or fields while maintaining the ability to perform at design level, i.e. their EMC, which should always be a major design objective.

This is the first of a series of three documents, each focusing on one of the levels mentioned, that aims at introducing technical solutions that should be adopted to improve electronic systems in Advanced Virgo. To simplify the references made to the table of content, a unique index will be used for the entire series. As a consequence, the second of the three documents, the one on electronic systems, will start with section 6 and the following one about electronic units with section 7.

2. Purpose

The intended audience for this document is represented by electronic engineers who are going to

- design custom electronics
- select commercial-off-the-shelf (COTS) equipment
- specify requirements for peculiar electronic units to be made by external companies

for Advanced Virgo.

3. Overview

The goal is to build a system that meets its requirements and grows as an organic whole as opposed to a compounded collection of parts assembled together at a later time.

To make this possible a series of guidelines and standards are suggested. If followed, they would allow to build the system methodically and increase its chances of success, easing integration and maintainability.

A top-down view of the electronics is adopted, starting from the infrastructure necessary to allow equipment to do its job and zooming in progressively to racks, crates, and finally units (seen as either single board or chassis). Only some general suggestions and basic indications about system and unit design and construction are given in this first document. For a much more detailed list of solid design practices and a set of technical standards, please refer to the following two documents of the series.

Along the way, pertinent design issues will be introduced when appropriate and technical rationale to support decisions and find solutions will be briefly presented.

4. Safety

Safety is crucial. In some situations a conflict between safety and performance could arise. The general rule is that all designs have to comply with safety codes and regulations and that safety always comes first. In some peculiar cases and when personnel life is not at stake, a compromise could be accepted but only if all following points are satisfied simultaneously:

1. the inherent risk can be accepted only if there is a well motivated technical argument that shows that there are no real alternatives in terms of performance
2. the violation and its implications are recognized, thoroughly understood, and the balance is shifted towards the safest solution possible.
3. accidental contact is prevented with barriers and obstacles
4. warning signs (stickers) are applied and clearly visible
5. only authorized personnel (list to be maintained by the Project Safety Officer) can access the area/operate the unit.

5. Infrastructure

In this paragraph electronic equipment are considered as black boxes over which, at this stage, there is no control. The EMC issues dealing with them will be discussed in due time.

For the time being then the attention will be focused on the Electro Magnetic Interference (EMI) containment through countermeasures such as location and layout of the modules and their connections. What can be kept under control is then coupling among units more than performance of single units.

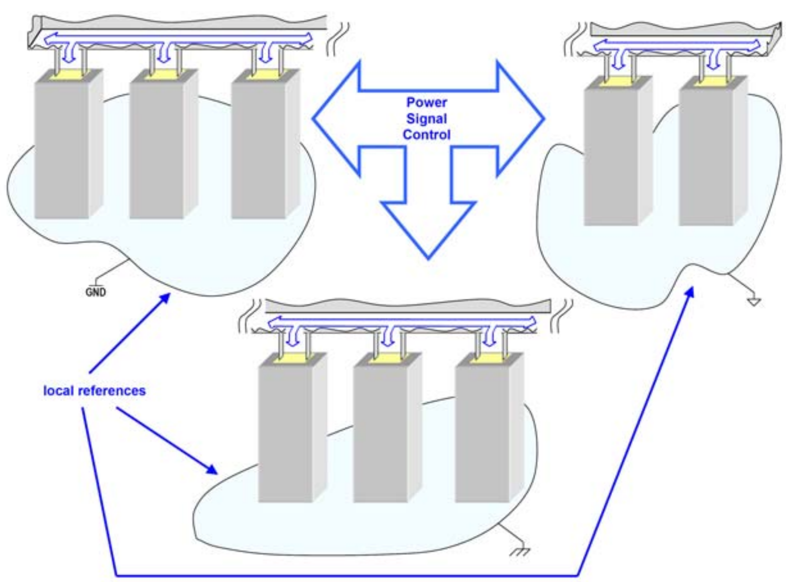

Fig 1: Multiple Distributed System.
Each area has its own local reference and they are, in general, different. Power, signal and control are shared among different subsystems and therefore avoiding interference is not trivial.

Virgo electronics can be seen as a Multiple Distributed System, as shown in Fig 1, defined as one where major systems are located away from each other (different areas) and they are powered through different phases and lines or even transformers of the power distribution system.

In situation such as this, multiple conductor paths (power, signal, and control) exist between system clusters and their elements.

A scrupulous application of sound engineering principles concerning grounding, shielding, and filtering is required to minimize interference and obtain the desired degree of protection.

5.1 Power

The continuity in Virgo data taking is only as reliable as its electric power distribution system.

A huge effort has been undertaken in the recent past to improve both reliability and quality of Virgo Power System. Describing in detail all possible measures that can be or have already been taken to improve this critical aspect is beyond the scope of this document.

In what follows it is assumed that the electrical network is fixed and that all possible measures (active harmonic correctors etc.) have been taken to insure both compliance with norms and correct functioning of the electronics units downstream.

It is worth mentioning that harmonic distortion on the mains caused by non-linear loads can cause EMC issues. A typical example is represented by AC-DC converters that frequently power commercial-off-the-shelf pieces of equipment.

A possible remedy to limit EMI effects due to AC power distribution is to add filters on the mains and that can help improving significantly the EMC performance of the system as a whole.

The past few years of Commissioning have shown that Virgo is strongly affected by power supply and distribution related issues. Recently evidence of couplings having different environmental origins with the Dark Fringe signal has been found: magnetic one due to cooling fans in close proximity of mirrors, and seismic and magnetic couplings caused by power supply transformers.

All this teaches us that a high degree of attention has to be paid to the generation and distribution of power to the electronic systems of Advanced Virgo.

This proposal aims at covering the largest by far number of possible cases. At this stage of the design process it is impossible to rule completely out documented exceptions to the standard solutions described here. They will be examined on a case-by-case basis.

5.1.1 AC Power Distribution

The baseline solution is to bring the UPS three-phase 4-wire 400 V power to a Service Entrance Panel (SEP) in every rack.

The receptacle (cable side) and the plug (panel side) used are going to be 3P+N+E 400V 16A compliant with IEC 60309 standard.

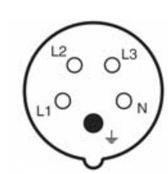

Fig 2: 3P+N+E 400V 16A plug (left) and socket pinout (right)

A panel-mount receptacle will allow to daisy chain these modules for adjacent racks.

This panel will feature a filter between the supply side and the equipment side on the mains to attenuate both common and differential coupling modes and a single emergency push button to switch the power off.

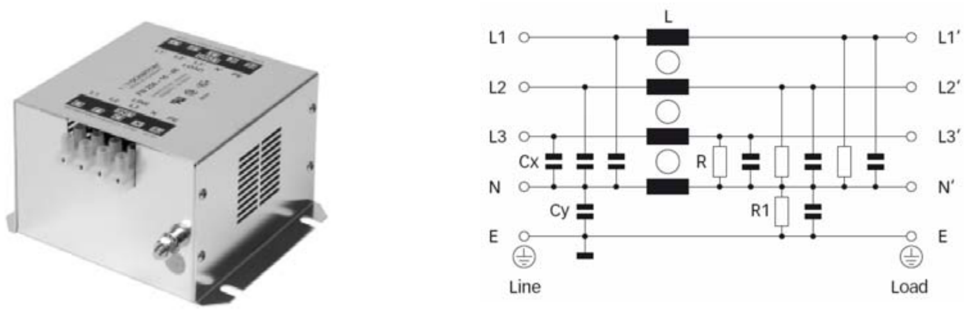

Fig 3: mains EMC filter and its simplified conceptual schematic

The filter is a three-phase and neutral line EMC filter (suggested type is Schaffner FN 256-16-46 or equivalent) having at least 40dB of attenuation from 100 kHz to 10 MHz (as per CISPR 17 A, B, C, D measurements)

Three single UPS 230 Vac 50 Hz (phase and neutral) lines will then leave the Panel and be available on rack-mount Power Strips (PSs) on the back of the racks where AC powered electronic devices can be plugged in. The 8 sockets on the power strip will be CEE 7/4 (also known as *Schuko*[⊗]), at a 45 degree angle.

Fig 4: Multiple output Power Strip (left) and details of single *Schuko* socket and plug

These PSs will also have a safety switch with current limit capabilities and a direct visible indication of the presence of power.

5.1.2 DC Power

General-purpose, standard DC levels (± 24 Vdc and GND) will be available in every rack. This DC will be generated, in the most general case, elsewhere[⌖] but of course other possibilities can be contemplated when needed (local DC power supply).

5.1.2.1 DC Power Generation

The reference DC levels will be obtained with commercial dual (tracking) linear regulators capable of delivering 5 A of current per single line (i.e., 10 A per regulator).
In addition, these power supplies will feature OverVoltage Protection (OVP), OverLoad Protection (OLP) and Remote Sense (RS) capabilities.

OverVoltage protection can be accomplished in two ways: using clipping (clamping) devices (zener diodes, avalanche diodes...) or switching ones (mainly thyristors). Both exhibit non linear characteristics

[⊗] Schuko is short for *Schutzkontakt* which means "protection contact"
[⌖] the general idea is that these basic DC levels are generated way from any sensitive point of the antenna

and they both act diverting the extra current produced by the anomalous condition away from the electronic circuits they intend to protect.

Clamping circuits basically introduce a large attenuation of the voltage exceeding the threshold over which they have to spring into action. They work well provided they can tolerate the overcurrent and that the threshold is set high enough to avoid clipping the power continuously. Among their nicer characteristics is the seamless return to normal operation once the emergency disappears and that they do not represent an additional load (i.e. they do not draw "any" current) in standard conditions.

Crowbar circuits, on the other hand, "short" to ground the power supply source when a pathologic condition arises. This mode of operation has obvious advantages in terms of power dissipation and overheating of the electronics downstream. In addition, they can easily be used to flag the potentially risky event blowing a fuse (in series with the faulty current). The side effects are that this sort of solution does load the power supply even when it is in "sleep mode" and that, at least in its basic version, it does not allow to go back to normal operation without human intervention (for substitution of the blown fuse). The latter can be also seen as a diagnostic feature in some context and Virgo is one of them.

This second solution fits our needs best and we will adopt it. A crowbar circuit shall then protect all electronics downstream from over voltage conditions due to power supply failures.

Overload Protection (OLP) is meant to avoid that the equipment powered by the supply is exposed to currents above its rated capacity as a consequence of some damage occurred on the units downstream, with possible additional side effects like overheating that in turn can bring to other detriments and hazards.
A trip protection circuit that behaves as a current-controlled switch shall then be included in the power supply; once an over-current condition is detected on one of its output lines, the switch will disable this line and a human action will be necessary to go back to normal operation.

The implementation of this sort of characteristics requires the ability to monitor some meaningful variables that describe the conditions of the electronics powered by these units.

Remote Sense (RS) connections allow the Power Supply to regulate the voltage to the designed level not at the supply's output but right at the load, i.e., compensating for the voltage drop in the cables connecting them. The ability to accomplish the task depends obviously on the power supply voltage headroom and on the resistivity and length of cables used.

As a reference, consider that a 10 m run length of typical AWG #16 leads shows a resistivity of 0.132 Ohm; 10A of current flowing causes a voltage drop of 1.3V that the supply needs to be able to compensate for.

A general switch and a direct visible indication of the presence of power will be present in every rack on any of these DC lines.

5.1.2.2 DC Power Filtering

The Power Supply Rejection Ratio (PSRR) of any electronic units is finite and decreases rapidly as the complexity of the design and frequency grow. That is why the adoption of EMC filters on DC lines is suggested.

These filters must have both differential and common-mode filtering capabilities.

They shall be connected just after the general 24Vdc switch (suggested type is Schaffner FN 2002-25-33 or equivalent).

Fig 5: DC filter and its simplified conceptual schematic

5.1.2.3 DC Power Distribution

Every DC power line needs to have 5 connections to the load as a minimum (± 24 Vdc, GND, Sense+ and Sense-). Few additional lines can make possible to add extra diagnostic features (overload conditions etc.)

The distribution lines from the remote power supply to the racks will use the following kinds of mating circularly polarized, bayonet coupling connectors, belonging to the MIL-C26482 G Series 1

Receptacle 851 00 JC 14-12 S 50 Plug 851 06 JC 14-12 P 50

These connectors have two different contact sizes: the four central pins are AWG #16 and the remaining 8 are AWG #20. They belong to the environmental category (as opposed to the hermetic one), their shell (size 14) is plated with an aluminum alloy

pin	signal
B	SenseNeg+
A	SenseNeg-
H	SensePos-
G	SensePos+
C	Diag1+
D	Diag1-
E	Diag2-
F	Diag2+
K	-24 Vdc
J	GND
L	GND
M	+24 Vdc

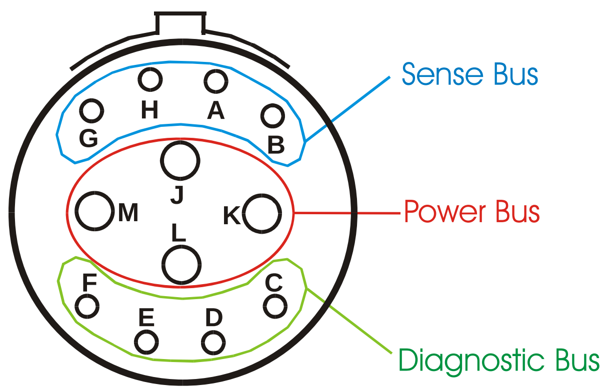

Fig 6: 851 00 JC 14-12 connector pinout (plug) and pin assignment

The cable used for this sort of connection will be custom made using the following cables as components: the two DC lines will be wired using Belden 3043A (AWG #16, two pairs, individually shielded) while both the Diagnostic and the Sense Bus will be wired using Belden 3016A (AWG #20, two pairs, individually shielded).

The DC Distribution Box will split every single 5 Amp Line in 4 separate lines (1.25 Amp each on average) inside racks. Every output power line will be available on connectors of the same military family but having 3 pins each

Receptacle 851 00 JC 8-33 S 50 Plug 851 06 JC 8-33 P 50

pin	signal
A	GND
B	+24 Vdc
C	-24 Vdc

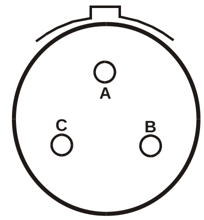

Fig 7: 851 00 JC 8-33 connector pinout (plug) and pin assignment

All custom designed electronics should then include this interface.
The cable used for the DC power distribution will be Belden 9364 (AWG #20, twisted triad, shielded)

Designers can either use this ± 24 Vdc directly or reduce it inside their enclosures to the desired values (typically ± 15 Vdc). In addition, if they want to use the diagnostic provision described earlier, a dedicated connector will be used (details in sec. 6.1)

For far-away generated DC voltage levels, although the reference solution presented is based on the use of COTS dual linear regulators, other possibilities, such as switching power supplies, can be taken into consideration. Although their use it is not recommended and should be considered as a last resort where everything else fails to meet the performance required, there are circumstances in which there are no alternatives, for example when the current required is well above 4-5 Amps.
In such cases extra care shall be taken in filtering the high frequency (100 kHz and above) noise produced by these kinds of converters.

In other instances it could be inevitable to have DC generated locally. In this context, exclusively linear power supply shall be used. In addition, the transformer should inevitably use toroidal cores, where the primary and secondary coils are wound concentrically to cover the entire surface of the core. Toroidal transformers are better than laminated E-I cores from many points of view for our applications: lower dispersed magnetic field and less mechanical hum in the audio band among them.

5.1.3 High Voltage generation

In specific cases there could be the need of "high" DC voltages (to bias piezo actuators, for example). These levels can be obtained either from the 230 Vac mains or, in principle, also from the ± 24 Vdc described above using switching regulators.
Great care must be exercised if the second choice is made to avoid introducing (or reintroducing) noise. In any case, the presence of High Voltage must be properly indicated (see sec. 4, points 3, 4, and 5).

In the remainder, it is assumed that only Low-Voltage systems♦ are addressed unless specified otherwise.

5.2 Grounding and Bonding

Grounding is an essential part of the infrastructure○. The origin of the widespread confusion about what ground and grounding actually mean can be ascribed to technical terminology differences.

♦ "Low voltage" is characterized by carrying a substantial risk of electric shock, but only a minor risk of electric arcs through air. The International Electro-technical Commission (IEC) defines low voltage as any voltage in the range 50–1000 Vac or 120–1500 Vdc

Since there are two main purposes of a “ground system”, it is important to clearly distinguish between them.

The first is Safety.

Specific regulations (IEC 60364 and, in Italy, CEI 64-8/4) prescribe the existence of electrical connection of ***all*** metal objects that can potentially be energized, to a protective conductor that in turn is in contact with (i.e., connected to) the mass of the planet we live on, the Earth.

This Protective Earthing Conductor (PEC), a metallic rod driven into the soil, is usually located at the site’s service entrance. It takes different names (like ‘safety earth’ or simply ‘earth’, among others) and, at least in Europe, the electrical connections to it are easy to identify because made with a green-yellow wire.

This practice is known as grounding or earthing, the latter being probably less prone to misinterpretation but not as popular as the former.

The second function of a ground system is to provide a Reference used to measure (relative) voltages in a system (typically assumed as “zero volt” point).
Although ideally this reference is represented by an equipotential plane, reality is more complicated and this assumption is misleading.

If a true zero-impedance reference plane (“real ground”) could be realized, it could be used for all currents (power, signal, control, RF) present in a system and as a perfect reference without side effects. Unfortunately this is not possible, especially on large scale such as an entire facility. That is why typically two distinct kinds of ground structures are present in scientific installations, with the goal of addressing both (i.e., safety and clean reference) needs.

Safety does not need a sophisticated solution but rather a systematic implementation, as detailed in section 5.2.1.

As for the Reference, the closest approximation to an ideal ground would be a very large plane of a conductor material, underlying the entire facility to which electronic equipment could be connected. Economic reasons suggest not to follow this approach. As far as sensitive equipment is concerned, the choice is normally to opt for a solution that, up to a certain frequency, constitutes a viable likeness: a grid. This is known also as Ufer ground system[•].
As a rule of thumb, when its characteristic pitch ranges in the order of the meter, it can represent a valid technical ground up to tens of MHz.

It is interesting to have a deeper look at the topic of grounding from an architectural point of view and to try to understand the relationships among the different kinds of grounds we can identify. Once again, they are referenced in literature in a non-consistent and, at times, even contradictory way (what Technical ground means for someone has a completely different meaning for someone else). A set of names will be defined and used consistently afterwards.

While the definitions and the classification of different kinds of grounds are given here, the details about the actual implementations are left for specific paragraphs that will follow.

[○] “think of “grounding” as part of electricity in the same way that “gravity” is part of architecture” [–IEEE Std 1100-2005]

[•] During World War II, a retired Vice President of Underwriters Laboratories, Herbert G. Ufer, developed it for the U.S. Army. check http://www.psihq.com/iread/ufergrnd.htm

5.2.1 Facility Ground

Possible alternative names for it could be Service or Safety Ground.
The main purpose of this ground is to protect personnel and equipment. The list of possible causes this system has to protect from includes major events like lightning, power system failures and so on. It provides a low-impedance path for fault currents, effectively bypassing (and thus protecting) devices it intends to preserve.
There is actually more to it than the electrical connection of non-scientific equipment to earth; wiring regulations require that ***all*** metalwork in the facility (gas and water pipes, structural steel etc.) is connected to earth.

The most appropriate way to define the intentional electrical connection between any metallic structure and the PEC with the specific goal of creating a safe path for fault currents is *bonding*. The structure resulting from bonding all these conductive materials together (and to earth) is defined as Common Bonding Network (CBN).

5.2.2 Technical Ground

The main goal of this ground, as briefly noted above, is to constitute the best, cleanest reference possible for scientific equipment. It is usually implemented burying a metal lattice with constitutive elements (rods) spaced a few meters apart (in Virgo's case, 2.7m).

In principle, the Technical ground should be (almost) electrically isolated from the Facility ground that, instead, should be the reference for *other*, noisy machines (air-conditioning, motors…) which require large currents that could negatively affect the most sensitive pieces of equipment spoiling measurements.

In reality, both legislation and literature dictate that an electrical connection shall exist between Facility and Technical grounds; from the point of view of regulations, if there were no electrical connections whatsoever, in principle an arbitrary (and potentially lethal) voltage difference could exist between the two thus creating a safety hazard.
Therefore they have to be connected.
The only choice is how and where, and here technical literature has its say.

The ideal solution□ consists in connecting the two grounds in ***only one*** point.
This way the two references would not share any current flow but at the same time the systems would not be allowed to drift away in time. This kind of connection is known as single-point, parallel (or star) connection.

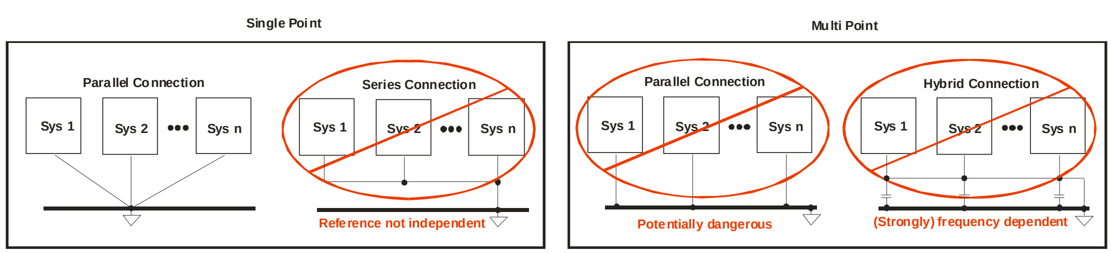

Fig 8: classic grounding schemes.
Single-point, series connection main drawback is the lack of independence among the systems' references (Sys n ground depends on Sys 1 current); in the Multipoint parallel connection, references drift away in time; as for the Hybrid connection, it represents a sort of compromise. The reactance used allows to select the frequency of the transition between the single-point series and the Multipoint connections.

This "special" point should be the already mentioned Protective Earth Conductor (see fig. 9).

□ Ott, Henry W. – Noise Reduction Techniques in Electronic Systems (Wiley-Interscience, 1988)

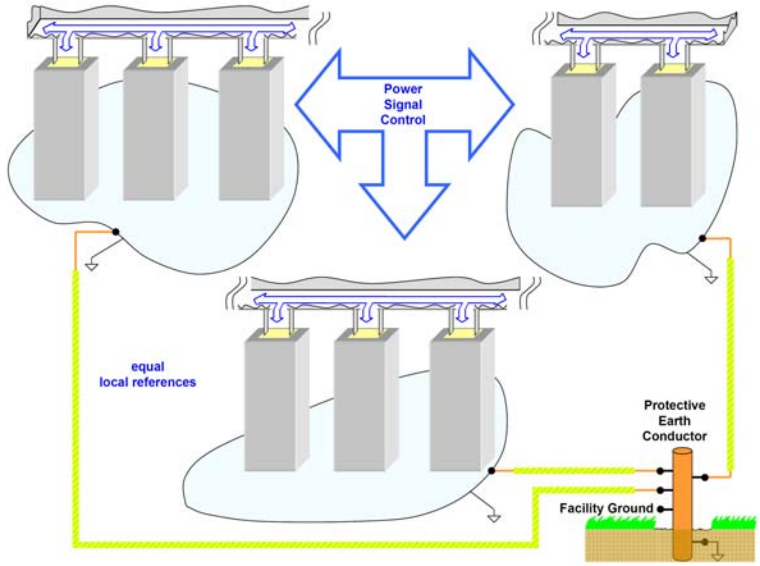

Fig 9: Safety and Technical Grounds.
The theoretical, universally prescribed way of connecting them is shown:
only in one point and that point is the PEC.

This is presented as "the" solution in many textbooks. Its main limit is that it is, in fact, outdated; nowadays the main source of EMI is not represented anymore by (low-frequency) ground loops, but by the always growing number of electronic units that work and exchange information at frequencies extending well into the MHz range. Stray couplings at these frequencies cannot be effectively controlled through star grounding schemes, not to mention the fact that, over time, it is practically impossible to avoid compromising the single-point-of-contact golden rule, for various reasons ("temporary" cabling, equipment relocation etc.)

The MHz-frequency-region, modern approach to grounding of buildings and facilities is exactly the opposite: connect everything together using the shortest path available and avoiding regular frame structures whenever possible. It amounts to build a three-dimensional (for multi-store buildings) metallic structure that takes the name of MESH-CBN.

This approach has of course its drawbacks (existence of ground loops, for example) but their effects can be contained and controlled with the application of other techniques (differential signal transmission, to name one) described later.

The composite structure obtained meets both requests mentioned at the beginning of this paragraph, being able to satisfy the safety requirements and, at the same time, to constitute a good reference point for measuring voltages. It actually does even more than that, since also the next kind of ground contributes to it.

5.2.3 Equipment Ground

This term refers to the grounding (or, more appropriately, bonding) of non-electrical, metallic elements of a system (mounting frames, enclosures, conduits etc.) to the MESH-CBN using bonding straps or wires.

The main purpose is, once again, personnel protection against shock hazard and system safety. This kind of grounding has an impact on electronics performance due to common-mode noise coupling.

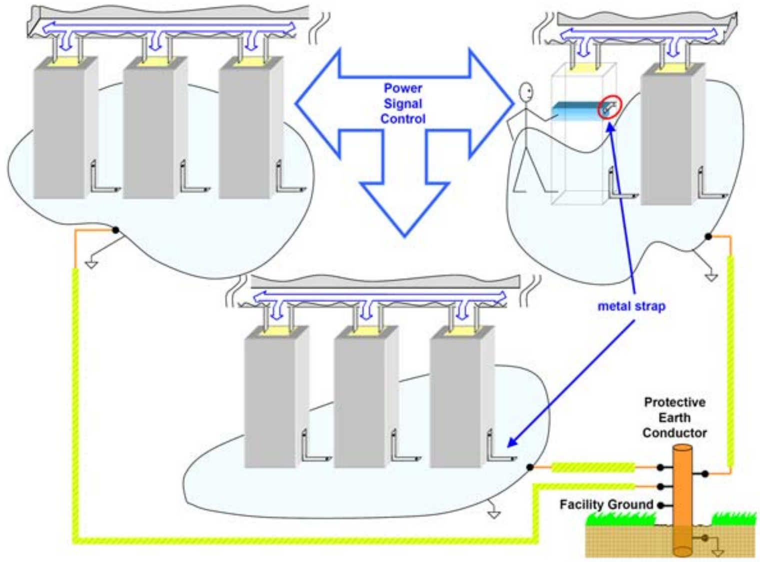

Fig 10: Equipment Ground.

Even if in Fig 10 both racks and a chassis are symbolically grounded using metal straps, what happens in reality is that while assembly structures (racks, cable trays…) are actually grounded this way, the typical method to ground AC powered equipment is via its mains receptacle: the “third wire” (i.e., the yellow-green one) is bonded it to the metallic case containing the electronics.

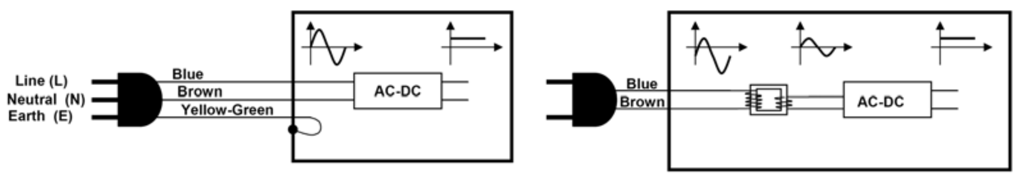

Fig 11: commercial AC powered electronic devices. The enclosure is assumed to be metallic.

It is possible to use two wire devices too, but only if they are (a) commercial and (b) they bear the “double insulated” CE mark (two concentric squares) or, equivalently, they are labeled as Class II devices.

Under no circumstances an AC powered, non-commercial piece of equipment having no ground connection can be installed in Virgo, not even temporarily.

5.2.4 Signal Ground

The signal ground is simply the return path to its source for the signal current.

This is the kind of ground electronics designers normally worry about and it is normally assumed to be represented by the intentional path the designer took care of introducing for that specific purpose, it being a ground plane of the board or the shield of a coaxial cable, to name some.

Reality tends to be more complex than schematics and often things do not go as drawn and, especially as frequency increases, alternative paths can allow to close the loop.
Specific techniques to fend off EMI at the unit level will be given in the third document of the series.

Next sections instead deal with applying EMC theory to hierarchical higher levels.

5.3 Shielding

This topic is usually discussed mostly at system or unit level. Its application to an entire installation finds obvious cost and logistic limits.

The addition of shielding consists in inserting an impedance discontinuity in the path of a radiating field causing, in the most general case, reflection, absorption, and transmission.

In principle, the set of tools that can be used to achieve proper shielding are limited to segregation, interface control and proper grounding. It specializes in a number of different techniques depending on the architectural level to which they are applied, but they all share the same physical principles summarized in the key points listed below:

1. use of metallic enclosures to passively limit different zones within which different levels of EMC protection or requirements apply.

When properly designed, this provides a significant improvement compared with the situation where source and receptor are not far enough for sufficient attenuation of free space radiation.

2. openings (or cable penetrations) in the shield decrease its effectiveness and need to be treated with care

Their size and shape plays a role in the overall shielding characteristics of the protection

3. attenuation properties of a shield depend, among other things, on its thickness

This very general rule needs to be examined further, since thickness may or may not play a role depending on which source the shield is protecting against.

4. thickness is inversely proportional to the frequency to block

Again, very generally speaking, the lower the frequency we want to "shunt" the thicker the shield has to be.

The typical figure of merit used to characterize the ability of a shield to do its job is known as Shielding Effectiveness (SE), defined as the ratio between the incident and transmitted electric field amplitudes and measured in dB

$$SE = 20 \log_{10} \frac{|\bar{E}_i|}{|\bar{E}_t|}$$

$$SE_{db} = R_{db} + A_{db} + M_{db}$$

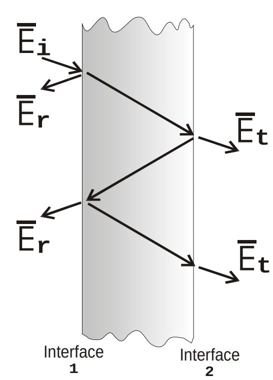

Fig 12: shield and its two interfaces

where A, R, and M represent the Absorption, Reflection and Multiple reflection and transmission losses, again expressed in dB

A thorough analysis of the phenomenon is beyond the scope of this document; only a brief summary of the conclusions (and perhaps not very well-known facts) that can be drawn is reported below✱ with reference to Fig. 12

- far-field sources
  - the attenuation the shield offers is exactly the same for both the electric field and the magnetic field
  - the interface that offers the largest reflection of the electric field is the left one, while the one on the right is almost transparent for $\overline{E}$
  - exactly the opposite happens for the magnetic field (highest reflection on 2^{nd} interface)

- near-field sources
  - the overall effectiveness of the shield depends on the type (electric or magnetic) of source examined
  - the reflection losses vary with strongly different behavior for the two kinds of possible sources when frequency and distance change
  - the contribution of absorption to shield effectiveness is not affected by the distance of the source (i.e., it is the same for both far-field and near-field cases)

As anticipated, the application of these principle to as large a scale as the one under examination here (architectural shielding) faces economic and physical constraints that are difficult to justify unless the goal is to build an anechoic chamber. Since this is not what we are dealing with here, a reasonable overall approach consists in going down one level and start applying the principles mentioned not to the entire rooms but to the selected, contained volumes that will either host electronics and electrical components or link them: racks, cables and cable trays to begin with.

5.4 Racks

Equipment cabinets or racks represent a first, obvious example of limited volume whose purpose is to conveniently hold and operate electronics. While they can be used simply as a set of bars forming a frame of shelves on which electronic chassis can be put, this would use only partially the potential that racks have.

The alternative is to use them as shields as well. To do that the internal bar frame must be wrapped in a metallic enclosure, which ideally should have no gaps or holes.

While generic electronic cabinets do not have specific performance in terms of EMI and they are in most cases well suited for use in Virgo, in peculiar others more stringent requirements exist and therefore the adoption of more sophisticated solutions could be necessary, as for example for racks located in close proximity of the towers and therefore of the mirrors, when it is really impossible to relocate them further away in dedicated EMI safer areas[×]. In any case, it is advisable to use racks correctly, i.e. with doors shut and interfaces treated properly, even when they do not have special EMI characteristics.

✱ for details about definitions and some basic formulas see Appendix A

[×] current trend seems to point towards a solution where all (i.e., both digital and analog) electronics will be co-located in the same chassis… if that is going to happen, the best thing to do would be to (a) move everything as far away as possible from sensitive sensors and (b) shield them

Their interface with the "outside world" should be through dedicated components, described in section 6 (Interface and Distribution Chassis and Service Entrance Panels)

The basic rack★ is a 220 cm (47 U) high, 60 cm wide, 60 cm deep cabinet dedicated to hosting 19" wide equipment. These general purpose racks consist of a steel welded, zinc-plated mounting frame with adjustable feet, side panels, top cover, and back and front doors. Ideally they should also have connecting plates at the very top and bottom, to facilitate the interface between the rack and the outside world.

For Advanced Virgo we could adopt a slightly larger version characterized by the presence of internal provisions for cable routing (cable management zone). This would represent our reference rack.

A survey of prices and availability of commercially available items has been completed. The reference selected is represented by the Schroff Varistar Zone 3 rack reproduced in Fig. 13, taken from the company's catalog.

Zone 3 indicates that the internal cabling is distributed on the sides of the rack "behind the 19" plane across the cabinet depth". This arrangement brings the cabinet width to 80 cm. Extra room on the back makes internal cabling even easier.

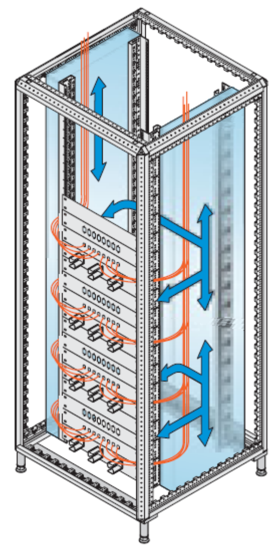

Fig 13: Zone 3 cabinet

Our standards rack is then going to be 220x80x80 cm.

In specific cases external constraint can suggest the adoption of a shorter version (say, 24") but the dimensions of the base should be the usual ones.

Experience gathered in Virgo has pointed out that solutions currently used for cooling electronics are not entirely appropriate and are turning a critical eye toward mechanical support systems (chillers, fans).
The mainstream emerged from all this is that future electronics should list among its requirements a high level of power consumption efficiency. This will be pursued in two ways: reducing power consumption as much as feasible and limiting (or avoiding altogether) as much as technically possible the use of forced air cooling, at the very least around the most critical and sensitive points of the antenna (i.e., mirrors), for standard operation (when the interferometer is locked with high sensitivity).

The commercial possibilities available cover a wide spectrum, from natural convection through thermal radiation of racks with solid steel doors to water cooled racks, with cooling capacity going from less than 500 W up to almost 20 kW per rack.

As it often happens, something in between the extremes seems appropriate for Virgo; free convection through small (1.5 mm) openings▲ in the front and back doors with the possible addition of classic forced cooling (fans at the top of the racks) that can be switched off on demand.

★ check some manufacturers' website: Schroff, Amco, Equipto, MFB, Knurr

▲ these openings are very small. Any aperture behaves like a slot antenna and the largest dimension L of the opening determines the frequency above which the antenna is an efficient radiator $L = \lambda_0/20 \Rightarrow f_0 = 1\ \mathrm{GHz}$

When racks are in their final position, it shall be possible to open both front and back door at least 90 degrees to allow access and repair.

5.4.1 EMC racks

The characteristics of an EMC rack differ from a standard one: the frame material is chosen in such a way that with its gasket they are galvanically compatible, and all openings have in turn fingerstock gasket. Special care is then taken for ventilation: typically, it is guaranteed through honeycomb waveguide filters.

The EMI rack category can be split in two: there are the standard ones and those for special (military) application, the main differences are the materials used and the care in the finishing.

In terms of performance the difference is not tremendous, at least below 1 GHz: typical values of attenuation go from as much as 120 dB at 10 kHz to 80 dB at 100 MHz for electric fields (and 20 dB or so worse for magnetic ones).

At the time of writing no quantitative measurement has proved that Virgo sensitivity is spoiled by Radio Frequency Interference (RFI). The only evident and reproducible interference-related effects seen so far are (a) at low frequency and (b) of magnetic origin. It would be therefore tempting to dismiss unconcernedly all other coupling mechanisms whose treatment would be potentially expensive and has no clear and immediate payoff, but that would be shortsighted; Virgo sensitivity is improving and what is not limiting our sensitivity today could easily limit it in the near future.

5.5 Cabling

Cables very often represent the weakest link as far as unwanted coupling between external world and the system, and there are many reasons for this susceptibility: among the most obvious one is their lengths, that in Multiple Distributed System installations spread over large areas like Virgo can easily reach tens of meters, but other causes contribute to it. An obvious initial remark is that the best way to reduce the level of interference due to cabling would be to avoid it altogether wherever possible, moving the support for communication to metal-free means like optical fibers.

The remainder of this paragraph is based on the implicit assumption that in some cases this is not possible and that appropriate techniques for limiting the impact of unwanted couplings need to be implemented.

Many kinds of cables exist and their performances differ significantly. They are characterized by lots of parameters (rigidity, ampacity, frequency behavior, presence or lack of a shield...) and selecting the right type for a given application is not trivial.
Not less important are the characteristics of the installation: terminations and routing (meaning by that both the selection of the path and the measures taken to protect this path).

As mentioned in the previous paragraph, in order not to compromise the performance of the enclosure as a shield, all interfaces should be treated carefully. This includes both non-functional openings such as doors and functional ones reached by cabling.

5.5.1 Cable Classes

Cable classes are defined, as it is often the case, in different standards and reports that do not necessarily agree 100% on some specific points (see, for example IEEE std 518-1982, EN 50174-2:2008, and IEC 61000-5-2); the latter is a very comprehensive technical report, that covers cabling of systems and installations with the goal of ensuring EMC among electronic systems. This classification is very general, including everything from load cell signals to high voltage power distribution.

Limiting our attention to the low-voltage classes alone, we find that what distinguishes them is the kind of signal they carry:

1. Very sensitive signals (Class 1)
This is further divided in Class 1A, to which belong very low-level (~ mV) analog signals such as sensor or antenna outputs, and Class 1B for high-rate digital communications (Ethernet).

2. Sensitive signals (Class 2)
Analog, relatively low-frequency (amplitude ± 10 V, frequency below ~ 1 MHz) and low-rate digital communication (RS-485) signals. Digital input/output signals as well.

3. Noisy signals (Class 3)
low-voltage (below ~ 1 kV), filtered AC or DC (below 48 Vdc) power distribution signals

4. Very noisy signals (Class 4)
AC power and return, motor drive, RF wideband signals

This arrangement suits us nicely, and we will adopt it.

5.5.2 Cable Segregation

Cables carrying signals belonging to different classes should not be grouped together; as a matter of fact IEC 61000-5-2 explicitly states that parallel runs of different classes of cables should be kept at an appropriate minimum distance (which depends on run length) and should be segregated, i.e., contained in a shield. It is worth noticing that this recommendation does not depend at all on the particular kind of cables chosen, but only on the characteristics of the signals they carry.

In Fig 14 the reference distances mentioned in the report are reproduced

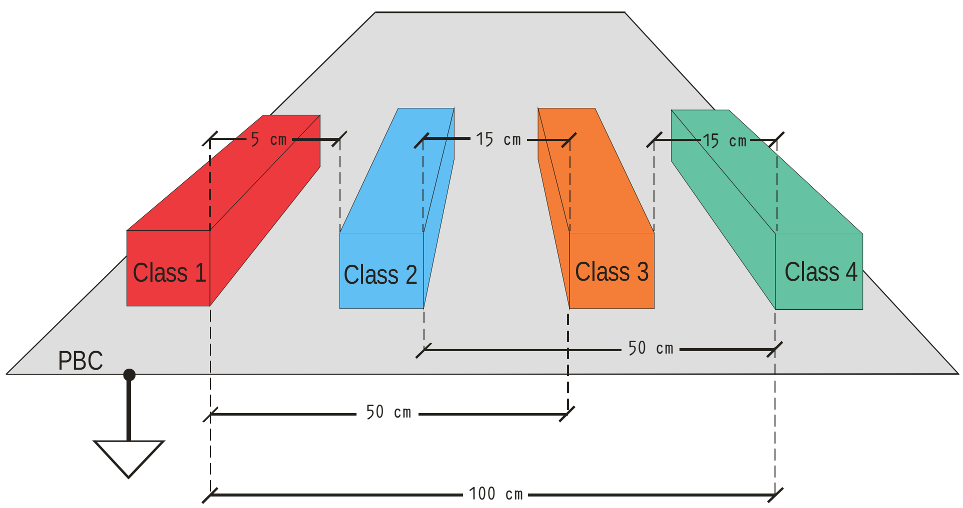

Fig. 14: minimum distances between cables belonging to different classes. They refer to cable parallel runs up to 30 m length. As a rule of thumb, they vary linearly with total cable run length.

As visible in the figure above, these distances assume the existence of a Parallel Earth Conductor. Once again, the choice of this name is unfortunate and in addition its acronym is too common. A better one would have been Parallel Bonding Conductor, given the job function it performs: this is a conductor that follows in close proximity the cable runs, that is uninterrupted, and grounded (i.e., connected to the plant's earth) at both ends. We will adopt this alternative version and the acronym that follows it (PBC).

Its presence and use do not rely on any specific kind of cable used (i.e., shielded or not), but in case shielded cables are used they have to be connected in parallel to the associated PBC.

The practical implementation of PBCs goes, in increasing level of performance, from a simple heavy gauge wire to open metallic trays, closed (perforated or not) conductive containments all the way to solid metallic conduits[†].

Since, as explained in sec 5.3, the shielding properties of a barrier (and that is exactly what PBCs are) depend crucially on its continuity, it should be obvious that PBCs should ideally have no interruption between source and destination and that they should be bonded to the cabinets they connect. Using cable trays "everywhere", segregating cables belonging to different classes separately wherever it is possible and in any case maintaining the separating gaps among them at the prescribed levels is therefore more than a simple option.

The application of this principle will have an impact on Virgo infrastructure since in some cases no provision at all exists to allow the implementation of this policy while where it exists there is need to upgrade them to make them as compliant as possible with the minimum distance specifications listed before. If external bounds or pre-existent conditions prevent to act in accordance with the rules specified, they should be interpreted as a reference towards which strive for.

If at some point parallel cable trays part for different destinations and they need to cross each other paths, the proper way to do this is through 90 degree crossing.

5.5.3 Cable Routing

After examination of necessary infrastructures for cabling, it is time to have a look on the proper way to route the cables from source to load. Specific details on their termination (i.e., the proper choice of connector) will be given in par 6.4; the minimum requirement for correct termination (of screened cables, that present obvious advantages compared with unscreened ones) is that the cable shield is bonded to the grounded metallic enclosure of its destination unit. This in turn means that (please refer to fig 15 for a clarification of terms used)

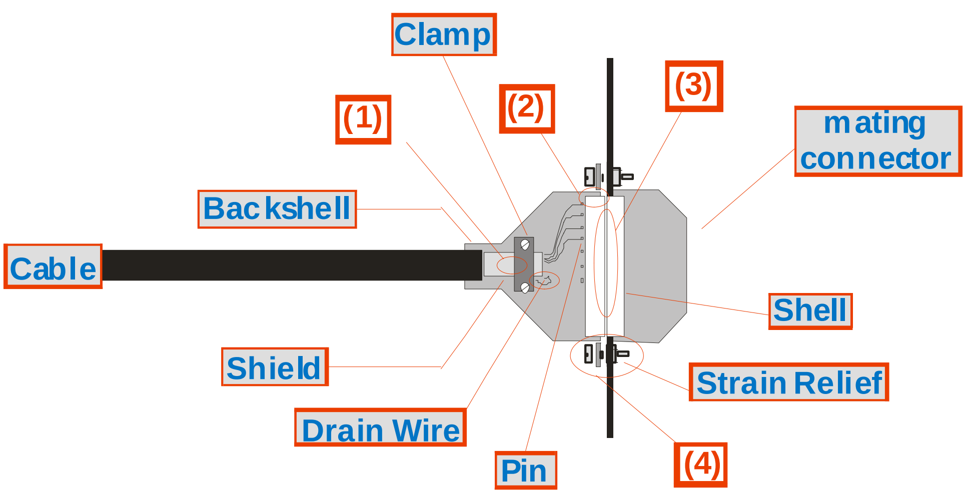

Fig 15: correct termination of a multi conductor cable

[†] IEC 61000-5-2 recommends to increase distances among different cable classes by a factor 10 when there is no PBC

- the cable shield makes a circumferential contact through a clamp (or iris) with the (metallic) connector's backshell used to terminate it. No pigtail allowed. (1)
- the backshell is bonded to the connector shell (2)
- this shell and the corresponding one on bulkhead mating connector are in electrical contact along their entire perimeter. (3)
- the stability of the contact is ensured through a strain relief mechanism (4)

When all recommendation listed so far in this section have been scrupulously followed, routing amounts to simply use the cable trays installed and reach the communication panels installed on either ends. It is important to avoid breaking this rule, even if only for short paths (adjacent racks). This allows maintaining reliability over time and easies troubleshooting, if required.

A proper cabling routing management policy should prevent the use of cable trays as storing facility for extra cable length: all cables should be dressed to suitable length. In addition, if operative conditions change (electronics relocation etc.) old cables should be all removed, unless this would potentially cause side effects on the other cables sharing the same cable trays. To facilitate this, mechanical fastening of cables or cable bundles to the tray structure should be kept to a minimum.

5.5.4 Cable Families

It is difficult to provide guidelines for every conceivable type of signal across distances that, in principle, could go up to several tens of meters. For the time being, we'll limit our discussion to the infrastructure point of view and therefore to the most general level possible.

As already said, very often in Virgo shielded cables presentl advantages over unscreened ones. The only exception can be represented by the power distribution cables (which should be filtered, though, as explained in par. 5.1.2.3).

As for the other kind of signals (control etc., basically class 1 and class 2), the standard solution for communications either between racks or racks and rack-like structures (tower flanges, for example) is to use a multi-pair snake cable with overall shield (foil plus drain wire). Each pair is individually twisted, foil-shielded, and jacketed. Exceptions to this rule are contemplated but they have to be examined on a case-by-case basis.

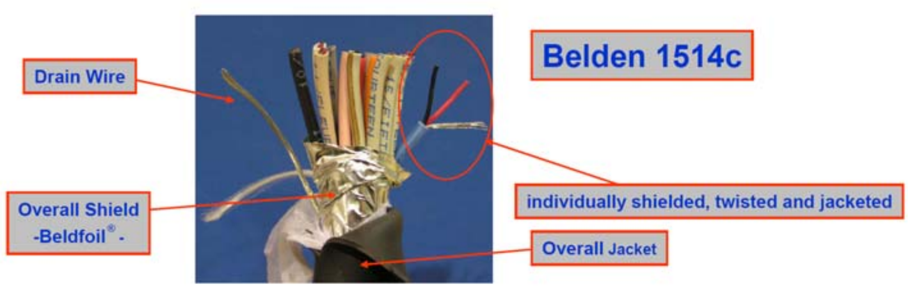

Fig. 16: Belden 1514c Analog Multi-pair Snake Cable

Every single pair is made with 2 stranded tinned copper wires (each AWG #24). The pair impedance is 50 Ω (while the nominal conductor resistance @ DC 76.4 Ohm/km and the nominal shield resistance @ DC 52.2 Ohm/km). The nominal capacitance between conductors is 102 pF/m.

The characteristics and performances as a shield of a metallic foil differ from the ones of the other commercially available solutions (braids, spiral); among its good ones it is possible to list the 100% coverage of the internal cables, its light weight, and its high flexibility. A side effect of its excellent mechanical qualities is that it is most effective at high frequency (RF).

This choice suits well all typical Virgo signals but the Mains distribution, the RF signals, and the field cabling. For them a different solution must be adopted.

The first case is common to all racks which, and it was has been exhaustively examined in sec. 5.1.1.

The RF distribution, although not as widespread as the AC Power supply, retains some of the characteristics that allow it to pertain to the level under scrutiny, such as the central generation and the later allocation over the entire site.
In this case, the default solution is to use coaxial cables "locally" (up to 40 meters) and go to optical fibers for superior lengths (terminal buildings).
Given its nature, it will be treated in additional details (cable and connector selections etc.) in the second article of the series.

Field cables represent more a typical point-to-point link (sensors, actuators...) instead of a generic connection among rack-like electronic infrastructures. For them, the adoption of single cables as opposed to multi-pair ones could be more appropriate, but again it will be examined extensively at system level.

Patch panels will not be used anymore.

Remote metallic connections will go through the screening walls of racks where they will be correctly terminated on the separating shielded enclosure.
In some specific cases, and for the mains, the "dirty box approach" can be effective: a small box, with less demanding performance in terms of EMI, is used as interface between the outside world and the sensitive electronics inside Virgo racks: all potentially interfering signals go through this "dirty" box, are filtered if necessary, and then can enter the cleaner volume of the rack. No untreated cables can go through this second interface.

The proposed solution consists in going with patch cables from the conductive walls of the racks either directly to the processing (could be front-end or back-end) electronics in a crate (or chassis) or to a dedicated unit used for signal interface and distribution, that shall be as modular as possible in terms of its interfaces. Each cable will be terminated at both ends.

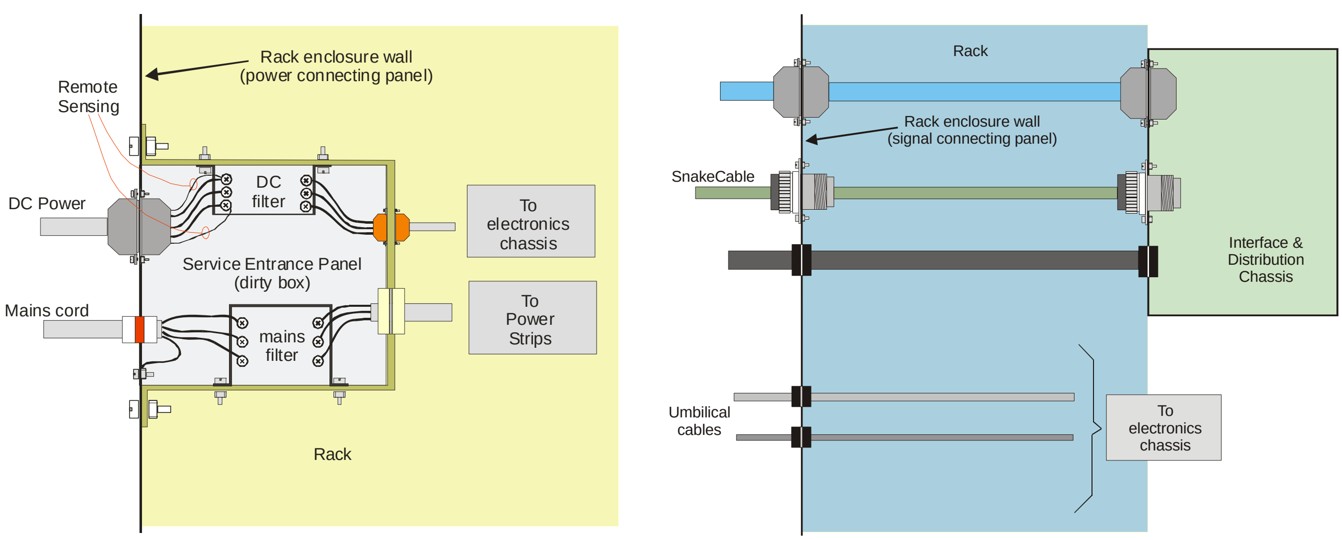

Fig 17: rack-world interface. Some typical cases are reproduced.
The AC mains is filtered, the main DC is measured with the Remote Sensing to ensure conformity to required levels. While some specific signals go straight to the electronics they are supposed to reach, all "rack-to-rack" connections are going through the Interface and Distribution Chassis.

5.5.5 Cable Numbering and Markings – an introduction

So far in Virgo different subsystems adopt different protocols when labelling cables. A higer degree of uniformity is desirable. The use of the Hardware Inventory and Integration Database requires an identifier. The logic used there can be adopted to prevent duplication. In addition to the identifier, other useful information should be associated to cables, such as

- system to which the cable belongs[⊕]
- cable length
- number of signals and their type (class)
- signal name
- cable routing

There are pros and cons about displaying at least part of this information on the cable tag. This issue is eamined with additional details and remarks in sec. 6.4 where they are more pertinent. For the time being it is sufficient to say that, based on the naming convention suggested there, information about the system of pertinence could be helpful at this "infrastructure" level.
Please refer to section mentioned for a thorough discussion of this point.

All cables should be labeled at both ends, an the two labels should be exactly the same. A violation to this rule is admissible only for short cables, when both ends are visible at the same time and the connection is easily traceable. This should happen only for intra-rack cables though and never for inter-rack ones; all cables should follow the designed path that shall never contemplate the possibility of "laundry rope" cabling. In addition, for long cable run length (above 20 m or so), extra labels should be placed every few meters, to simplify cable identification after installation and possibly their removal.

These general principles apply always and particularly to remote connections, whatever kind of cables has been selected as support.

[⊕] with reference to Advanced Virgo Work Breakdown Structure: PAY-BS, VAC-CRY-DET etc.

Appendix A: EM propagation and shielding: basic formulas

A (very) brief summary of the essential points about field propagation, with no ambition of explaining let alone deriving the formulas reproduced is reported below:

B.1 Far Field

At large distance from the source, the field propagates as a uniform plane wave having the following properties.

- $\overline{E}$ and $\overline{H}$ are orthogonal
- both are perpendicular to direction of propagation
- $\overline{E}$ and $\overline{H}$ are both $\propto 1/r$
- their ratio is constant and represents the impedance of the medium (in vacuum, $\zeta_0 = \overline{E}/\overline{H}$)

It is possible to obtain an exact solution for the shield effectiveness placed in the far field of this source. If the shield is made with a "good conductor" ($\zeta_{shield} << \zeta_0 = \sqrt{\mu_0/\varepsilon_0}$) and has a thickness t much larger than the skin depth δ of the shield material at the frequency of the incident wave, a simplified expression of the solution can be found

$$|\overline{E}_i/\overline{E}_t| \cong |\zeta_0/4\zeta_{shield}| e^{t/\delta}$$

$$R_{db} = 20\log_{10}|\zeta_0/4\zeta_{shield}| \qquad A_{db} = 20\log_{10} e^{t/\delta} \qquad M_{db} = 0$$

A deeper analysis would point out that

- $|\overline{E}_i/\overline{E}_t| = |\overline{H}_i/\overline{H}_t|$ but
- the primary transmission of the magnetic field occurs at the first interface
- the primary transmission of the electric field occurs at the second interface

The attenuation of the magnetic field as it goes through the shield is therefore more important than the one of the electric field. The thickness of shields then plays a role only for magnetic fields.

A further elaboration of the equation reported above allows to express losses in a more insightful way:

writing the shield impedance as $\zeta_{shield} \cong \sqrt{j\omega\mu/\sigma}$ (good conductor), it is possible to show that

$$R_{db} = 20\log_{10}(1/4\sqrt{\sigma_{Cu}\sigma_r/\omega\mu_0\mu_r\varepsilon_0\varepsilon_r}) = \ldots = 168 + 10\log_{10}(\sigma_r/f\mu_r)$$

where σ_r is the conductivity relative to copper ($\sigma_{Cu} = 5.8\times10^7$ [S/m])

while using this expression $\delta = 1/\sqrt{\mu\sigma\pi f}$ for the skin depth brings to the following one for the absorption losses

$$A_{db} = 8.686\, t/\delta = \ldots = 3.338\, t\sqrt{\mu_r\sigma_r f} \quad \text{[t in inches]}$$

Summing things up for the case of far-field propagation

- frequency dependence
  - R_{db} is proportional to $1/f$
  - A_{db} is proportional to $\sqrt{f}$

- shield material dependence
  - R_{db} depends on σ_r/μ_r
  - A_{db} depends on $\sigma_r\mu_r$

A table of typical materials used as screens and the characteristic values of their properties is reported below to ease comparison. Copper is assumed as a reference.

material	σ_r	μ_r	σ_r/μ_r	$\sigma_r\mu_r$
stainless steel (430)	0.02	500	10	4×10^{-5}
mumetal (@ 1 kHz)	0.03	30,000	900	1×10^{-6}
tin	0.15	1	0.15	0.15
aluminum	0.61	1	0.61	0.61
copper	1	1	1	1

Fig. A1 shows the behavior of a 20-mil-thick copper continuous shield. The shielding properties at low frequency depend on reflection losses while the absorption ones start to prevail above 2 MHz.

The shield effectiveness increases at high frequency thanks to the absorption mechanism that therefore plays an important role in protecting from interference due to magnetic fields.

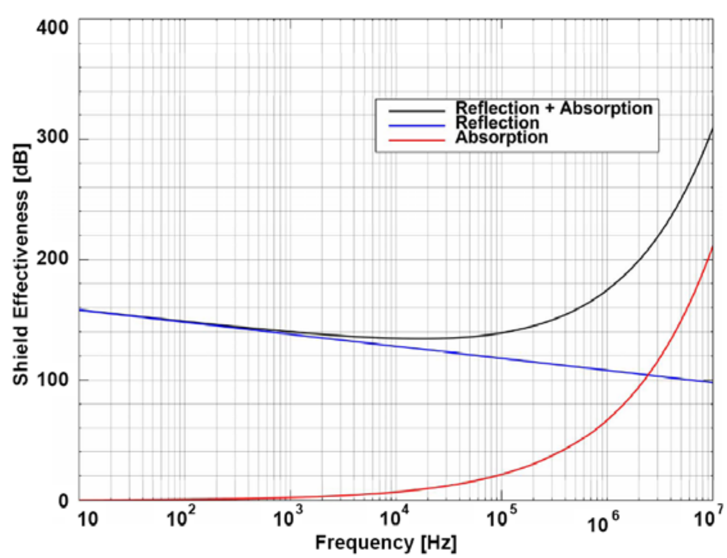

Fig A1: Shield Effectiveness of a 20-mil-thick Copper Shield

In conclusion, for far-field sources, the most effective tool available for shielding is reflection at low frequency and absorption at high frequency.

B.2 Near Field

The results reported here are approximations based on the replacement of the intrinsic impedance of free space with the concept of wave impedance $\zeta_{wave} = |\overline{E}_p / \overline{H}_q|$ with $p,q = \theta,\varphi$

Close to the source the properties of uniform plane wave do not hold: $\overline{E}_p$ and $\overline{H}_q$ are not orthogonal and their ratio $\overline{E}_p / \overline{H}_q$ is not equal to the intrinsic impedance of the medium. Moving away from the source, starting at a distance $d = 3\lambda_0$ the two impedances are equal.

In addition, for $r \leq d$ the fields do not go simply as $\propto 1/r$ but have additional components proportional to the inverse of the second and third power of the distance that in this region are larger than the former.
The distance at which the $1/r$ term equals the other two and then starts to prevail is conventionally assumed as the boundary between far and near field; it can be shown that this condition is reached for $r = \lambda_0 / 2\pi$

The same principles valid for shielding from far-field sources apply also in the near-field case, but the nature of the source plays an important role in evaluating the most appropriate techniques. As already done previously, we'll express the Shield Effectiveness in terms of losses for the two types of possible sources. It is worth noticing that actually the Absorption loss do not depend neither on the kind of sources nor on the distance between source and shield.

B.2.1 Elementary electric source: dipole antenna

For an electric field source, in the region of space where the reactive components are larger than the radiative one, the wave impedance $\zeta_{wave}|_E$ is higher than ζ_0; that is why this kind of source is referred to as a high-impedance source.

- wave impedance $\zeta_{wave}|_E = \overline{E}_\theta / \overline{H}_\varphi > \zeta_0$
- $\overline{E}_\theta \propto 1/r^3$
- $\overline{H}_\varphi \propto 1/r^2$

The Reflection losses can be obtained using $\zeta_{wave}|_E$ instead of ζ_0 in the expression seen before for the far-field case

$$R_{db} = 20\log_{10}|\zeta_{wave}|_E / 4\zeta_{shield}| = \ldots \cong 322 + 10\log_{10}(\sigma_r / \mu_r f^3 r^2)$$

In conclusion, for near-field electric sources, the most effective means available for shielding are the same already seen in the far-field case: reflection at low frequency and absorption at high frequency.

B.2.2 Elementary magnetic source: loop antenna

Magnetic field sources are low-impedance sources since in this case $\zeta_{wave}|_H$ is smaller than ζ_0

- wave impedance $\zeta_{wave}|_H = \overline{E}_\varphi / \overline{H}_\theta < \zeta_0$
- $\overline{E}_\varphi \propto 1/r^2$
- $\overline{H}_\theta \propto 1/r^3$

As for the reflection loss, using the same procedure reported above

$$R_{db} = 20\log_{10}|\zeta_{wave}|_H / 4\zeta_{shield}| = \ldots \cong 14.57 + 10\log_{10}(\sigma_r f\, r^2 / \mu_r)$$

This formula shows that shielding near-field magnetic sources presents some distinctive characteristics that make this case very different from the ones examined before: both Absorption and Reflection losses increase with frequency and although the former tends to be the dominant effect at low frequency, both are (very) small.

This makes shielding at low frequency very challenging.

To conclude this appendix, in Fig. A2 the Reflection Losses of copper shield as a function of frequency for all cases described above are reported.

It is worth noticing that

1. At very low frequencies the shield does not offer any protection effect from magnetic sources
2. the frequency at which far field and near field (for both kinds of sources) become equal, for a given distance r from the source, is $f = 3\times10^8 / 2\pi r$ [Hz]

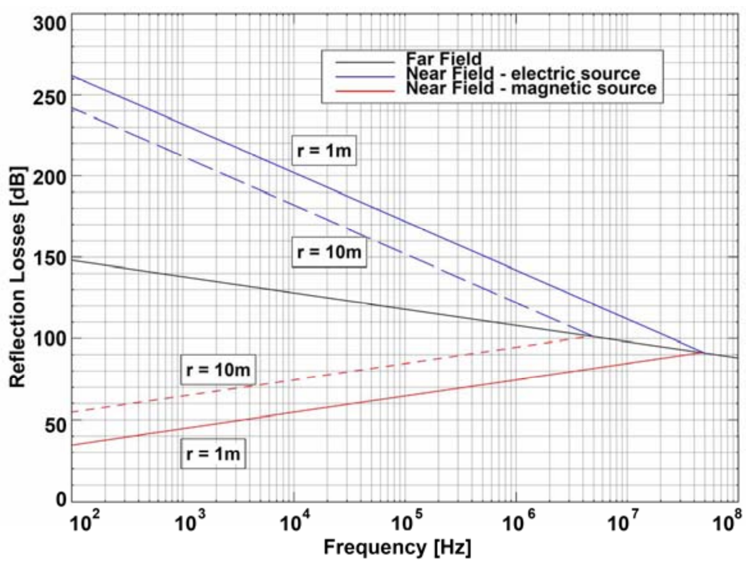

Fig. A2: Reflection Losses for copper shield

Part I Acronyms

EMC	Electromagnetic Compatibility
EMI	Electro Magnetic Interference
COTS	Commercial Off The Shelf
SEP	Service Entrance Panel
PS	Power Strip
PEC	Protective Earthing Conductor
CBN	Common Bonding Network
SE	Shielding Effectiveness
RFI	Radio Frequency Interference
OVP	OverVoltage Protection
OLP	OverLoad Protection
RS	Remote Sense
PSRR	Power Supply Rejection Ratio
PBC	Parallel Bonding Conductor