AdV Standards July 3rd 2009
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Electronics for Advanced Virgo: Guidelines for a systems engineering approach

1. Introduction

The current effort aiming at identifying noise sources limiting the performance of Virgo and reducing their effect in order to move closer to the Design Sensitivity is necessarily coupled with the need of bringing the interferometer duty cycle as close as possible to 100%.

Reliability of all subsystems is therefore absolutely critical and an emergency plan in case of (unavoidable, in the long run) failure has to be ready. Electronics has a peculiar role from this point of view and it pays off to make an effort to improve its dependability.

In an environment like Virgo, or any other experimental field in which work is in progress most of the time, there is no such thing as a "definitive version" of a given subsystem electronics. The continuous strive for performance improvement requires upgrades and modifications.

In this perspective, it is tempting to avoid any commitment to a specific configuration, because in a short period of time the need to have, say, additional diagnostic features or frequency characteristics will likely arise.

Although this may be true, it is not acceptable to live permanently in a state of hold.
It is wise to allow room for flexibility when designing boards but some configuration freeze has to be established. If and when specifications change radically, in such a way that they can't be conveniently implemented on the design in use without affecting its reliability, a new revision should be taken into consideration (with the associated money and time investments).

A clear policy on how to manage the design, installation and maintenance process for the custom electronics would be beneficial.

2. Purpose

The intended audience for this document is represented by all groups in Virgo that have designed/installed electronic systems and subsystems in the past, and are likely to do so in the future.

The purpose is to help designer supplying electronic units to Advanced Virgo insure that the experiment can maintain those units over its entire life.

3. Overview

A handful of engineers belonging to an even smaller number of Groups have designed the custom electronics used in Virgo at first and in its evolution, Virgo+, later on.
These numbers are bound to grow for Advanced Virgo.

Before the design activity starts it is necessary that all parties playing a role in this process agree upon some ground rules that will facilitate the system integration phase and in general will improve the quality and reliability of Virgo electronics.

This document outlines a possible strategy to achieve this goal. If adopted, it would allow a leap towards a more professional management of the electronics over its entire life cycle.

The solution proposed is based on sound systems engineering practice, partly simplified to adapt it to Virgo environment in the attempt of minimizing the overhead costs we are not built to bear.

It adopts the well-known division of system design process in phases, identifies the design reviews that enable progression towards project completion, suggests the creation of a technical structure that can increase the probability of success of a design, lists a series of documents that should be produced (and maintained) and that would make the entire procedure effective.

4. Electronics Design Process

In the perpetual *make-or-buy* question every electronics engineer needs to address, the peculiar requirements of gravitational-wave antennas often force scientists to ask experts to develop custom solutions for their electronics. Past experience teaches that when this happens typically designers are more concerned with the behavior and performance of the specific board they are working on at any given moment than with documenting the modifications to the original project necessary to meet the "updated" specifications. To complicate the matter even more, every group has its own way to keep track of changes implemented (readme files, excel documents listing boards' peculiarities etc.).

A more systematic and shared way to proceed would help maintaining a known configuration of Virgo that scientists can rely on.

Systems engineering is a robust approach to the design, creation, and operation of systems (1) and adopting its methodologies would be advantageous.

The design process is typically divided in steps or phases. The names they are referenced with and the exact moments in which the project leaves one to enter the following take different names in literature (2) but the rationale behind the logic path is always the same.

As for Virgo electronics, it makes sense to mark clearly the distinction between the Computer Aided Design (CAD) phase, that goes from the design requirement collection to the technological files production, and an hardware one ("bend metal"), that covers fabrication, assembly, installation, and operation.

While the design process goes on, a series of documents should be prepared; they would allow a technical appraisal of its merits and oversights, to keep track of changes and modifications to any board and, in turn, to Virgo (see Configuration Management, par. 6).

In what follows the design process flow is detailed, the milestones characterizing each phase are described, the documentation to provide and a series of reviews are suggested.

A synthetic description that helps understanding what exactly every step of the process entails will be given shortly. For additional details on and definitions of specific points, please refer to 7.2 and 7.3.

5. Project Life Cycle Overview

The time line for the design of any electronic system is reported in fig 1.

A system can consist of more than one unit and each unit (or module) can be made by one or more boards.

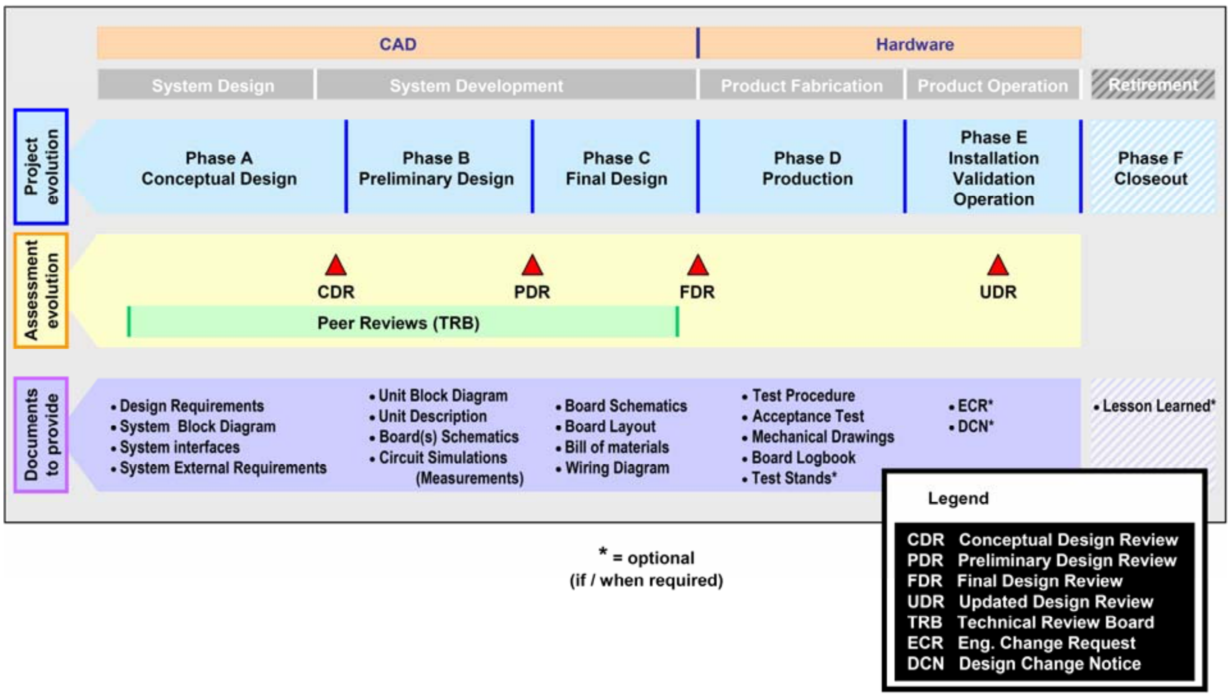

fig 1:Design life cycle. All phases, milestones, and documents are reported

The responsibility for every Project shall be shared between a Cognizant Scientist (CogS) and a Cognizant Engineer (CogE), who is going to take care of the actual design implementation. Their role includes the following duties: they will

- lead the design through its entire life cycle
  from conceptual design to disposal, through possible changes and modifications
- produce and maintain design related documents
  validating functionality, interfaces and ensuring system integrity
- be the design's point of reference for the Collaboration
  addressing concerns and technical questions and answering for schedule issues

5.1 Conceptual Design (Phase A)

This phase normally starts, in the context we are considering, when a science requirement is received and the functionality analysis and performance requirements have taken shape.
At this point, one or more suitable designs that fit the need can be considered and compared. A tradeoff analysis helps narrowing down the number of viable solutions.

This process, guided by a Technical Panel (more on this in par. 8), eventually converges on a choice (Reference Design). In any case, a formal Conceptual Design Review (CDR) shall be held at the end of this phase, to make sure the design complies with the requirements it needs to satisfy.

The documentation to provide the Panel with is the following:

- Design Requirements Document (DRD)
  complete list of all functional and performance requirements
- System Block Diagram
  top-level view of systems/subsystems concerned and their logical connections
- System interfaces
  nature and direction of all electrical (or other*) links
- System External Requirements
  any external constraint or dependency, hardware or software

The possibility to progress to the Preliminary Design phase is marked by the completion of a Reference Design in the form of feasibility, simulations, and analysis. An initial design budget is assigned to the project with the goal of building few prototypes.

5.2 Preliminary Design (Phase B)

Following a successful CDR, the detailed design work can start.

The electronic system at this point can be split in units and boards as seems fit and the creativity of the designer, supported as much as feasible by simulations, can have free rein.

As usual, tradeoffs are an essential part of engineering and the designer should never forget that, since the end user is going to be the Commissioning Crew, it is advisable to have a flexible, or even better reconfigurable, piece of equipment.
Other criteria to bear always in mind are testability and modularity, to the extent possible.

During this phase it would be productive to have regular “internal” meetings (peer reviews), with periodicity that depends on progress made and on the overall project schedule.

The deliverable of this phase is a fully working prototype that meets the possibly revised version of the specifications emerged at the very beginning of phase B.

A pre-release production of few units should be planned. Its performance shall be presented to a Technical Review Board for an official Preliminary Design Review (PDR).

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* for example, hydraulic (water pipes), mechanical (vacuum pipes), optical (windows) etc.

The additional documentation the Board will use to assess the maturity of the project at this point is

- Unit Block Diagram
  top-level view of subsections connections
- Unit Description
  overall description reporting general features, system of pertinence, and goal
- Board(s) Schematics
  as-built version that matches the final configuration
- Circuit Simulation and/or Measurements
  as it seem more appropriate

It would be wise to consider a set of preliminary tests *in situ* that should allow to spot and fix problems and issues before going on with the next step.

The outcome of the review depends on the proved design ability to meet specifications.

5.3 Final Design (Phase C)

With the solid evidence presented to the PDR and eventually the green light to go ahead, the project enter this phase with the goal of having a fully tested and working design ready to be produced (Baseline design). Explicit reference to single boards is made from now on.

In principle the number of functional modifications to the schematics should be kept to a minimum when compared with the one examined during the PDR. Nevertheless, the new version is one of the documents to deliver before the Technical Review Board can have a chance to meet for the Final Design Review (FDR). A complete list of the documentation follows:

- Board Schematics
  latest version of the schematic files, used for the board layout
- Board Layout[◊]
  pcb silkscreen printout for the top layer (and bottom, when it makes sense)
- Bill of materials
  specifies designators (part numbers) and values of every component used
- Wiring Diagram
  shows *exactly* where every electrical connection goes to or comes from

This final development step is the last that sees a formal review of the design. The goal of this review is to evaluate the completeness of the design and suitability to start manufacturing. At this point a production budget is assigned, commensurate with the number of units to be delivered.

[◊] If the same CAD package (Protel, OrCAD, Cadence...) could be used by every designer in Virgo, it would probably make sense to share the actual layout files. This not being the case, we can settle for something less, but useful anyway

5.4 Production (Phase D)

The project, after the approval granted by the FDR, leaves the design phase behind and moves in the hardware production one.

The initial part of phase D requires interactions with external companies for the production of Printed Circuit Boards (PCBs) and possibly their assembly as well. To accomplish this and managing to get back boards with reasonable chances of success, a (long) series of files and documents must be prepared (Drill files etc.). They are not relevant for the perspective at hand and will not be considered further.

The number of units to be assembled should take into consideration an appropriate number of spares, defined as exact functional copies of the ones that are going to be installed.
A typical rule of thumb to evaluate this number is that if the plan is to install *n* identical units then the number of corresponding spares could be $\sqrt{n}+1$.

Once the board is populated and the unit assembled, the tests to verify its compliance with specifications can start.

It is essential that during these tests some standard documents are prepared. Although no formal review needs to conclude this step, all documentation represents an essential piece of information that will be integral part of any project.

- Test Procedure
  explains how to certify that the unit is functioning properly
- Acceptance Test
  short check-list of tests to perform and range of acceptability of parameters
- Mechanical drawings
  reports all mechanical details useful for the assembly of the unit
- Board Logbook
  registers changes on every unit (identified with *code*, *version* and *revision*, see 6.1)
- Test Stands (optional)
  description of additional hardware or software for calibration and testing, if any

5.5 Installation, Validation, Operation (Phase E)

Units that move into this phase are ready to be installed in Virgo.
All necessary information to proceed with this step is available and traceable.

During normal operation changes in the interferometer can and will require modifications to one or more electronic units. The question is not whether or not changes will become necessary, but rather when, and how to respond quickly to that need.

These actions are originated by Commissioning Crew requests, and they should be addressed promptly. Understanding the implications of the changes and translating these changes in a set of actions is responsibility of the project's Cognizant Engineer and Scientist.

Unfortunately, while the practical aspects are usually taken care of swiftly, the documentation effort that should follow often falls short of expectations and amounts to not more than a somewhat exhaustive entry in the Logbook, at best. This is absolutely insufficient.

In an environment like Virgo it is of the outmost importance that electronics behavior is very well known and dependable. To achieve this goal, electronics performance must be certified, verifiable, and meticulously documented.

When a need for modification arises, there are two possible scenarios:

(a) planned modification
Interferometer studies show that a change on one or more boards would increase its performance.

(b) immediate modification
A given interferometer configuration at a specific point in time indicates that one or more modifications are absolutely essential and cannot be postponed.

Details on how to handle appropriately these situations are given in par. 6.2

5.6 Retirement (Phase F)

The details of the decommissioning phase are not of particular interest in this context.
A possible interesting aspect could be the production of a document detailing the lessons learned that can be taken into consideration for future upgrades.

Once described the design phases with some accuracy, it is possible to have a look on how to implement this course of action. The right tool is known as Configuration Management.

6. Configuration Management

As for the System Engineering case, also here various definitions of Configuration Management exist in literature as set forth in (many) standards (3, 4, 5, 6).
Adopting the definition given in (6), we can see it as "the functional and physical characteristics of a product as defined in technical documents and achieved in the product".

Although its original scope is much broader than the one we are suggesting to use here, through this discipline it is possible to implement two main goals, Configuration Identification (CI) and Configuration (Change) Control (CC).
The first is more related to the product release phase, while the second one deals with the change request and the actual design change processes.

With Configuration Identification, in the context at hand, it is possible to identify and document functional and physical characteristics of electronics system constitutive elements (units, modules, boards), both hardware and software, and document them.
With Configuration Change Control instead it is possible to first of all to establish a configuration reference solution (baseline), thoroughly document it, and then record functional and physical changes in the characteristics of all items of interest.

6.1. Configuration Identification

The main goal of Configuration Identification is to make possible a taxonomy of any subsystem part (breakdown structure), distinguishing among them and, where necessary, between different flavors of any specific item belonging to the structure. In addition, it allows documenting performance, interfaces and other attributes of a product.

To achieve this goal, a design/system structure has to be identified and unique identifiers assigned to each element of the structure. In addition, for each item a suitable set of documents describing properties and characteristics must be defined.

It will be necessary to assign not only a full name (*code*) to each item but also, in general, *version* and *revision* identifiers, as for the case of the more characteristic element of the electronics world, a board, that will be detailed in par. 7.1

6.2. Configuration Change Control

Applying Configuration Control's prescriptions it is possible to follow and monitor changes to any constitutive element of the system and/or its associated descriptive documentation. This allows to control continuously the evolution of the design providing traceability.

It is through Configuration Control that proposed changes are documented, evaluated and (in case) implemented. Its application involves evaluating the scope of a possible change and the most cost-effective way to implement it, whether a new version is required or a revision could suffice, which documents are affected and, finally, establishing an action plan detailing release process and authorizing its use.

An example of how these principles can be applied to a typical situation in which there is need to make modifications on electronics (hardware or software) follows.

As anticipated, the modification can be either carefully planned or unexpected, triggered by changed operation condition. In the former case, a Standard Procedure should be followed while in the latter an "emergency" one allows a rapid reaction.

6.2.1 Electronics Modifications - Standard Procedure

(1) An Engineering Change Request (ECR)[×], at least partially filled out, is presented to the CogS and CogE.

This document is made of four parts: part A should be filled out, part B is optional. Parts C and D should be left blank

Anybody working with the system the unit belongs to can in principle file the request.

The essential information to provide to allow a careful evaluation of the proposed modification is

[×] A possible draft of this form can be found in appendix A

Part A

- ECR serial number and date
- Originator
- Description of Problem/Reason for Request
- Symptoms/Nature of the change

Part B

- Proposed Solution (only if known)
- Product/Document affected by the change (only if known)
- Serial number of the unit(s) affected (only if known)

Part C

- Decision: change accepted/rejected
- Motivations for the choice

Part D

- following step (if any)

(2) Part C of the ECR should have a check field where the CogE and the CogS, after consulting with the design team if they think it is appropriate, suggest to accept/reject the change proposed in part B (that it is their duty to describe if this was not done by the Originator) and a field to motivate the decision.

(3) The form should then be made available to a Technical Review Board (TRB). This organism shall evaluate the suggested changes, scrutinize them to the depth it feels it is appropriate and communicate timely its decision to the CogE and CogS.

(4) If the modifications presented are agreed upon, part D of the ECR should be filled out and then the last steps that precedes the implementation is the issue of an Design Change Notice (DCN)[*] form prepared by the CogE.
The essential information on this document is

- Background facts
- DCN serial number and date
- Level of the change (system/unit/board)
- Detailed changes
- Scope (all units/only Serial Numbers X and Y and...)
- Notes

(5) At this point the modifications can be implemented by the design team

(6) As a result of the DCN, *all* affected system/unit/board documentation has to be revised (schematic, layout, test procedure etc.). It is responsibility of the CogE and CogS to make sure this is done.

[*] A possible draft of this form can be found in appendix A

6.2.2 Electronics Modifications - Extraordinary Procedure

(1) The ECR part A and B are entirely filled out and the serial number of the units on which modifications need to be implemented scrupulously indicated.

(2) The modifications are made on the units specified and reported on the board's Logbook (see 7.3.8).

(3) The process goes on with the CogS and CogE crossing out the ECR part C, filling out part D and following the routine procedure described previously starting with point (4), i.e., with filling out the DCN *a posteriori*.

In the next paragraph a description of the documents required during the different phases of the design life cycle (that need to be under configuration management control) will be given.

7. Documentation

At this point, we can take a step back and add some details to define with greater accuracy what the names mentioned before, sometimes very briefly, really mean.

This documentation will potentially let someone other than the original designer construct additional units at a later date. This information can be critical, since people do not necessarily stay at an experiment for its whole duration.

7.1. Board Names and serial numbers

Every board shall have a full name (*code*), associated to its functionality but also its *version* and *revision*. Whenever possible, there should be provision on the PCB to note explicitly the latter, in the form of two editable fields. This would allow to notice this information at first glance.

Board version shall be indicated with a capital letter (A, B, C...); in case further versions are needed beyond the one identified with Z (unlikely), they shall use two letters (AA, BB, CC...) and so on.

Board revision shall be indicated with a two-digit progressive number, starting from 01 (01, 02, 03...).

If deemed useful, this solution can be adopted for both the printed circuit board and its enclosure/panel independently.

Adopting this code would result in having a newly designed board with the following name:

boardname A-01

Every time a minor change is needed (a value of a component, for example) a new *revision* follows accordingly.

However, a new *version* for the board would be necessary if the required change entails a major modification (interconnections among chips, addition of components, extra paths...).

7.2. Technical Documentation

7.2.1 Design Requirements Document
This document should describe in details technical requirements and specifications the design wants to satisfy. It should also include a demonstrative conceptual design that meets the design requirements.

7.2.2 Unit Block Diagram
It describes the functional blocks implemented in the units detailing the families of connections among them (power, interface etc.).

7.2.3 Unit Description
Overall description of the Module, specifying modes of operation and technical characteristics (inputs and outputs with their voltage levels; connectors used; diagnostic features and the information they provide etc.)

7.2.4 Board Schematics
Schematic drawings are an obvious example of Design document.
They should always be up to date and represent correctly the version installed at any given time. In many instances, a certain design has slightly different implementations depending on where it is installed. It would then be advisable if not only a given design, but every single board had a specific schematic that matched its actual status “attached” to it.

7.2.5 Circuit Simulations (Measurements)
Whenever possible, it would be highly desirable to simulate at least critical portions of the design and compare the results obtained with the measured data of the prototypes. A document reporting them side by side would simplify the assessment of the performance.

7.2.6 Board Layout
The PCB silkscreen printout for the top layer (and bottom, when it makes sense).

It helps identifying board’s components and modifications, if any, when diligently maintained.

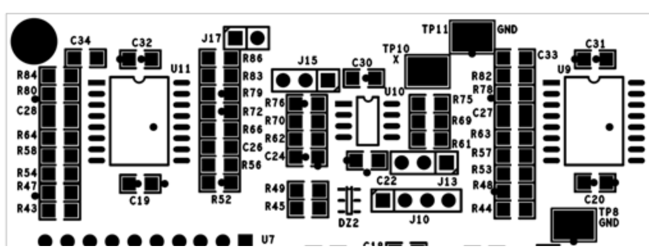

fig 2: detail of a top layer layout.
Part number and location of components on the printed circuit board are visible

7.2.7 Wiring Diagram
Every cable reaching/leaving the board in question should be labeled at both ends –especially true for long cables– and the Wiring Diagram should specify where each of them goes or where it comes from *exactly*. Every board location (position in a rack or else) should be specified as well.
This document should specify or represent in some form as many useful details as possible, like all the information to buy the cables used (brand, part number, if possible physical characteristics), the

specific kind of connectors chosen for terminating them, including pin-to-pin correspondence and if applicable even sex.

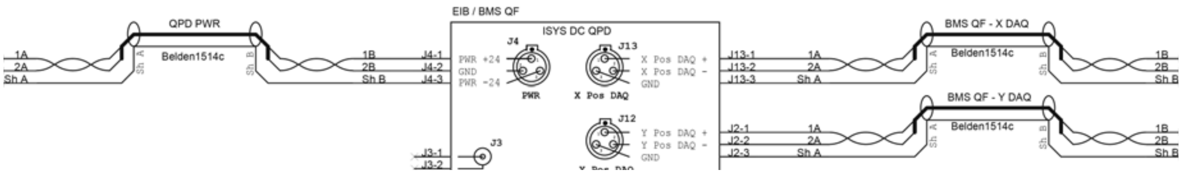

fig. 3: detail of a wiring diagram.
Cable name, brand, part number and characteristics (twisted pairs, overall shield) are visible

7.3 Manufacturing/Assembly/Support Documents

This set of documents helps making the long term maintenance and support (and, if necessary, duplication) of all modules installed.

7.3.1 Mechanical Drawings

It is either the real mechanical drawing of the machined panel/box when available or a simpler drawing specifying shape and location of connectors (and signals names too).

In this case, especially for stand alone chassis, could make sense to have the same kind of information mentioned for the electronics (version and revision) applied to the mechanics as well. In alternative, the two fields mentioned could be used to identify the whole package (electronics+ mechanics).

7.3.2 System Interfaces

It describes the nature of all physical interfaces towards the rest of the world, specifying all details useful for the integration.
Simple interfaces are preferred.[⌖]

7.3.3 System External Requirements

The designer should describe any external requirements for the Module. These can include cooling, power, safety interlocks needed, etc. which require hardware external to the Module. These requirements can have impact on the infrastructure and need to be known as soon as possible

7.3.4 Bill of Materials

Whenever a netlist is imported in a layout package, it is possible to generate also a useful document that specifies designators (part number) and value of any given component. An expanded version of this document, including additional information such as the actual manufacturer part number or the supplier code (to simplify procurement) would prove very useful.

[⌖] from ref (2): "According to Morris, NASA's former Acting Administrator George Low, in a 1971 paper titled "What Made *Apollo* a Success," noted that only 100 wires were needed to link the *Apollo* spacecraft to the Saturn launch vehicle. He emphasized the point that a single person could fully understand the interface and cope with all the effects of a change on either side of the interface"

7.3.5 System Block Diagram

It is a schematic representation of the system's architecture, a "top-level" picture which helps identifying the main components of the subsystem (typically, sensors, actuators –and their locations– etc.). No technical details need to be specified.

7.3.6 Test Procedure

Every single board should have a Test Procedure that allows to verify whether its behavior is in agreement with specifications. This document will be used as a reference to verify noted or suspected malfunctions and repair the unit accordingly if necessary.
It should report –for example– measured Transfer Functions gains and phases with acceptable tolerances, power absorption etc.

7.3.7 Acceptance Test

The Acceptance Test, should stem from the Test Procedure. It should reproduce briefly (in a Pass/Fail sort of way) the outcome of the tests made to characterize the board and allow to check immediately whether or not the board has a clean bill of health.

7.3.8 Board Logbook

Each and every board should have its own Logbook on which modifications, discrepancies etc. should be registered. The two should live together and, eventually, die together.
Whoever makes changes on a given board for whatever reason is responsible for updating this particular document.

7.3.9 Test Stand

Test Equipment needed and Test Setup should be thoroughly described. Any special equipment or software required should be included.

8. Technical Review Boards

The role of Technical Panels is paramount in steering designs in the right direction. Often designers are looking at their project too closely and end up not seeing the forest for the trees. The purpose of this body is to simplify the designer's work, not to make it more difficult.

Members of the board shall be selected by Virgo Detector Coordinator based on their specific area of expertise and experience among groups (occasionally even outside Virgo) not responsible for the design.

The review board determines whether the design in question is ready to go to the following phase or not. Its findings are made available to the Detector Coordinator that will have the final word on the matter.

To make the review process effective, the Panel should receive the pertinent documentation at least one week prior to the review.

At the review the Panel will:
a) provide the designer with immediate feedback on any problems with the design
b) work with the designer in resolving any issues which may arise, and
c) aid the designer with any potential problems which could cause the design to fail to pass the review.

Bibliography

(1) SP-610S, NASA Systems Engineering Handbook, Jun 1995

(2) INCOSE-TP-2003-016-02 version 2a, International Council of System Engineering: Systems Engineering Handbook, Jun 2004

(3) US Department of Defense, Systems Engineering Fundamentals, Jan 2001

(4) ECSS-M-ST-40C Configuration and information Management, Jul 2008

(5) ANSI/EIA 649-A-2004, National Consensus Standard for Configuration Management, Apr 2004

(6) ISO 10007:2003, Quality Management Systems– Guidelines for Configuration Management, Jul 2003

Appendix A

Engineering Change Request	ECR #
Originator	Date

part A			
Reason for change	☐ malfunctioning	☐ performance	☐ other
Description of symptoms / requested modification			

part B (only if known)	
	Date
Proposed Solution	
Product / Document affected by the change	
Serial number of the unit(s) affected	

part C		
		Date
Proposed solution is	☐ accepted	☐ rejected
Motivation		
Cognizant Scientist		
Cognizant Engineer		

part D	
	Date
The approved modifications will be detailed in DCN #	

Design Change Notice	DCN #
Cognizant Engineer	Date

Background facts
The changes detailed were originated in ECR #
Brief Description
Detailed description of change implementation
Scope (units/boards affected)
Affected Documents
Notes