Developing space instrumentation

Systems engineering from definition to verification

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Disclaimer

- Material presented is based on hands-on experience
- Biased towards ESA science missions
- Biased towards earlier phases

Developing space instrumentation: outline

- Space instrumentation
  - Definitions
  - Examples
  - Product tree
- Systems engineering (SE) basics
  - Lifecycle, TRL & model philosophy
  - The V model
  - Requirements
  - SE domains
  - Trade-off exercise
- Examples of
  - Definition phases activities
  - Implementation phases activities
- A few references to go more in-depth

Definitions: Systems

A **system** is an arrangement of parts or elements *(sub-system)* that together exhibit behaviour or meaning that the individual constituents do not

=> *emerging properties*

Systems Engineering is a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods.

Systems Engineering provides facilitation, guidance and leadership to integrate the relevant disciplines and specialty groups into a cohesive effort, forming an appropriately structured development process that proceeds from concept to production, operation, evolution and eventual disposal.

=> *life cycle*

More definitions and background at www.incose.org/about-systems-engineering/

Definitions: instrumentation

Instrument (oxford English dictionary)

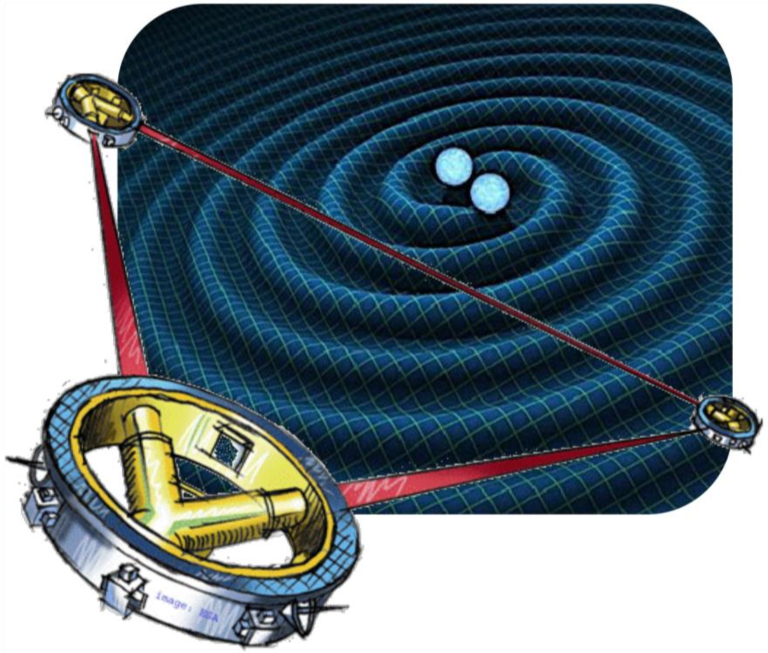
- An object, device, or apparatus designed or used for a particular purpose or task. A tool, implement, or utensil used to execute a piece of work.
- To equip or provide (a machine, laboratory, experiment, etc.) with instruments for observing, measuring.

Space instrumentation often referred to as Payload

- Instrument designed to operate from space: onboard satellites, probes, rockets, space stations etc.
- Application: earth observation, astronomy, planetology, solar physics, fundamental physics etc. etc.
- Specificities: shall survive launch & space environment, shall be operated remotely
- Requires a complete testing programme: "test as you fly, fly as you test"

More background: en.wikipedia.org/wiki/Scientific_instrument

Space instrument examples



- SCM – RPWI search coil magnetometer
- RWI – RPWI Radio Wave Investigation

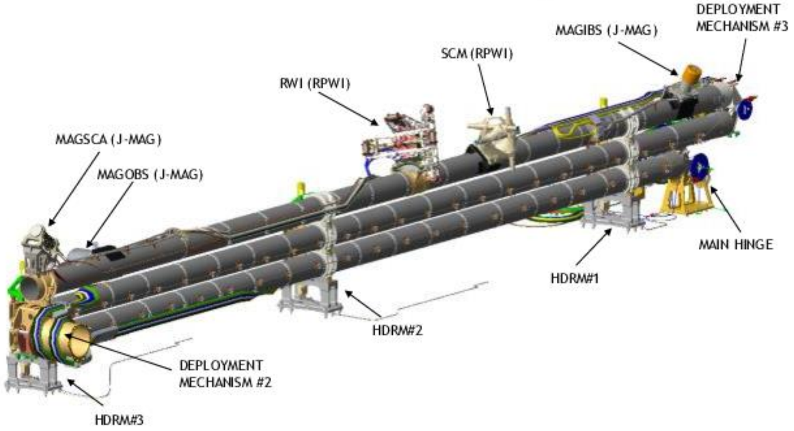


Figure 1. Stowed Mag boom

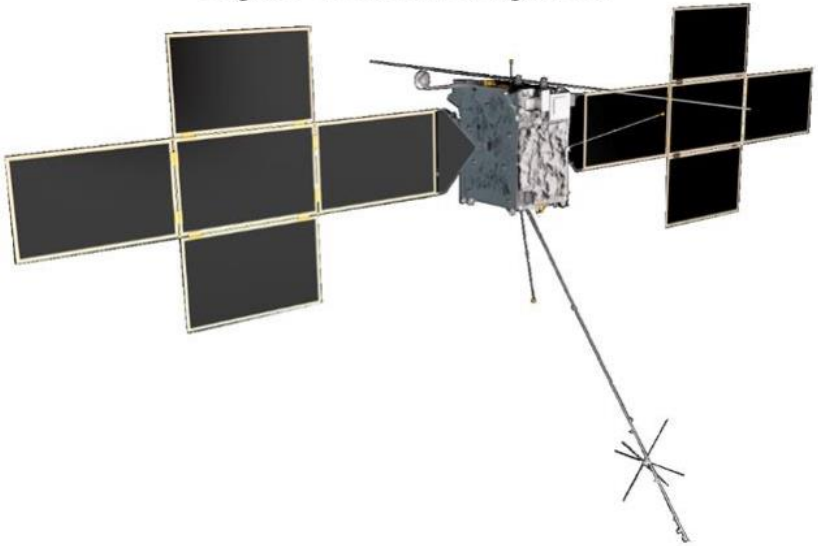
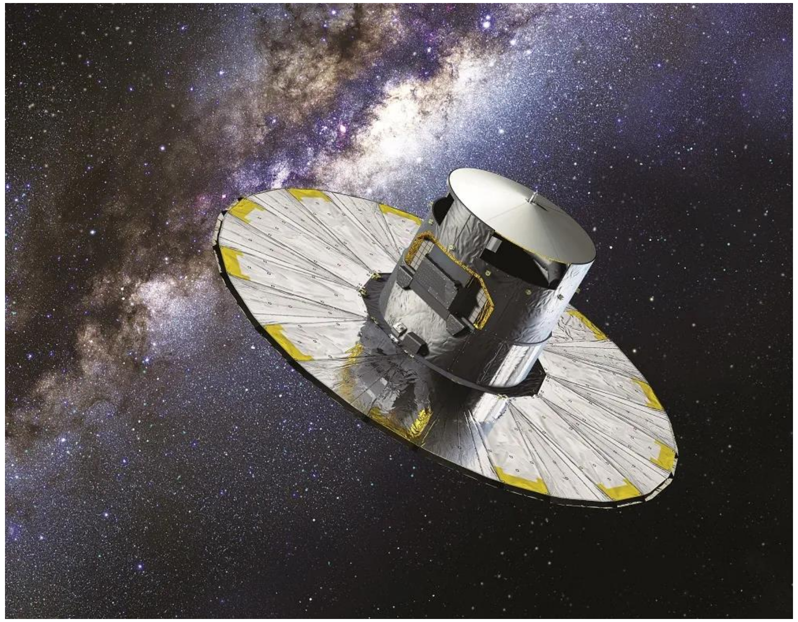
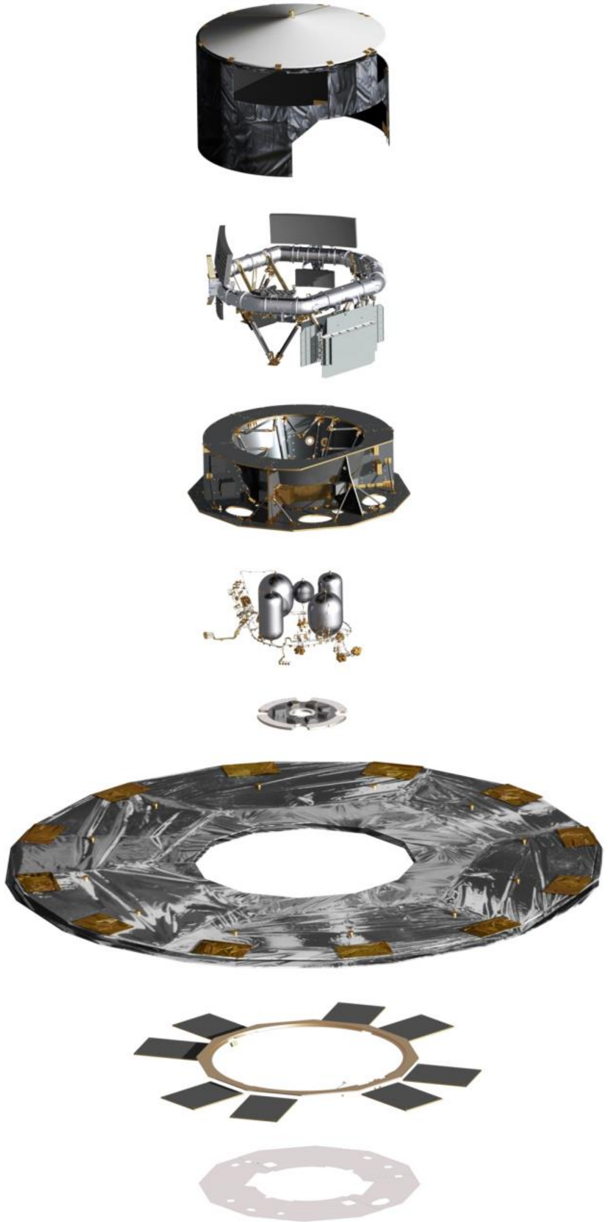
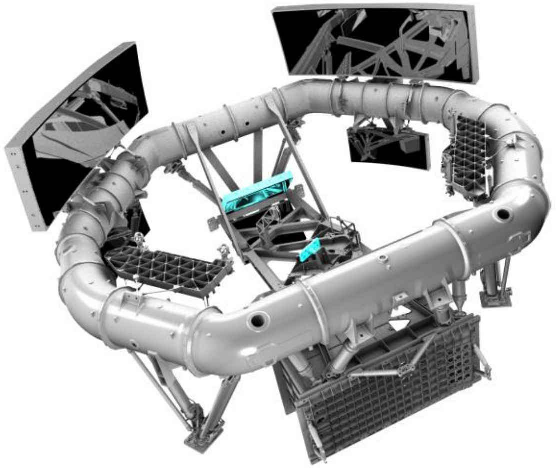


Figure 2. JUICE spacecraft general view with deployed

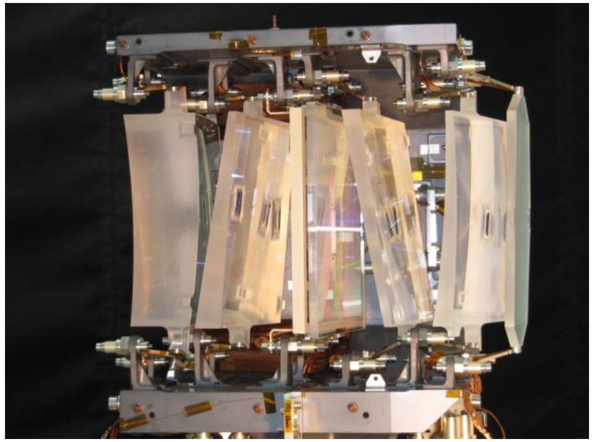
Zooming on ESA astronomy mission: Gaia (2013)

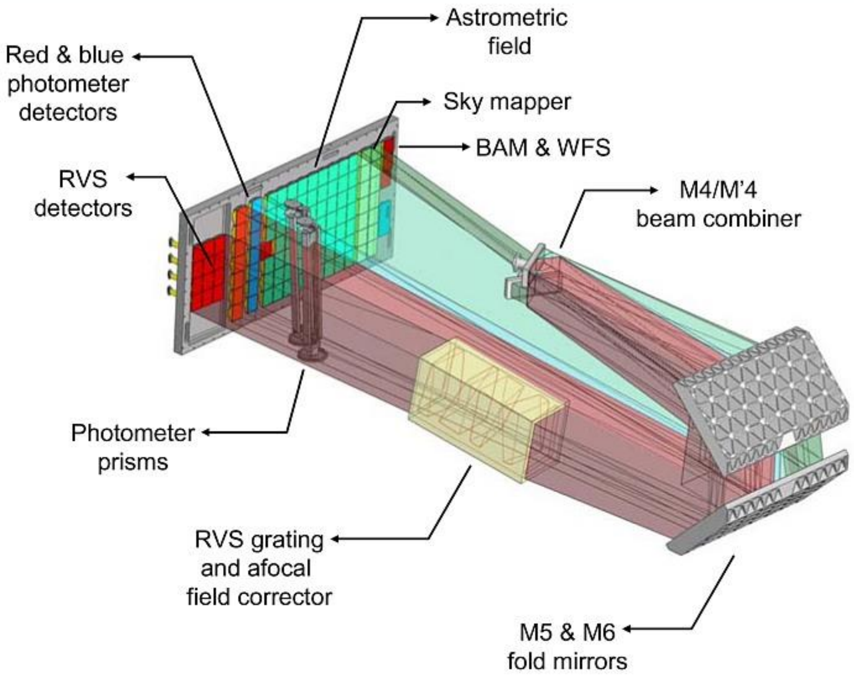


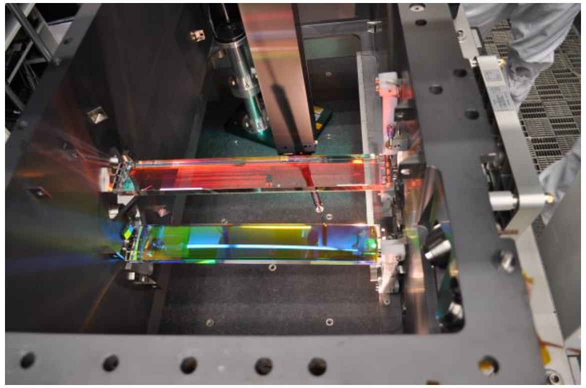


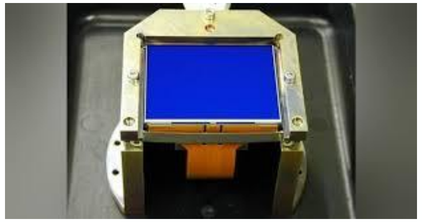


Gaia instruments: Imager, Photometers & Spectrometer

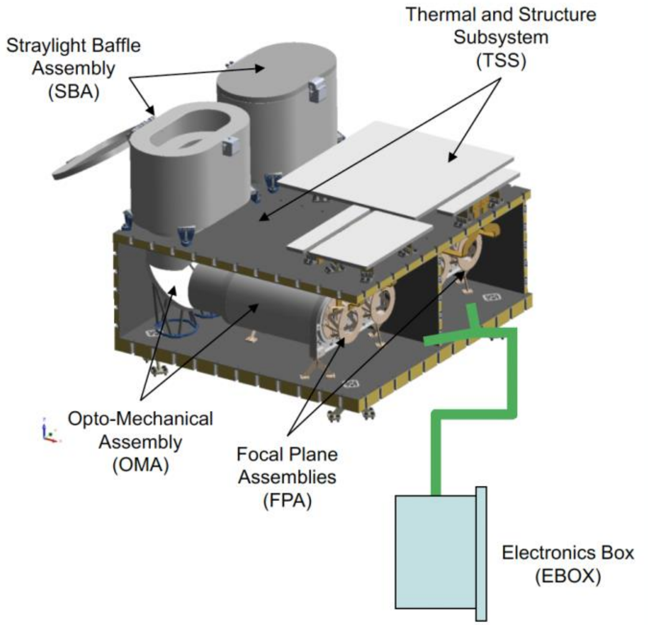




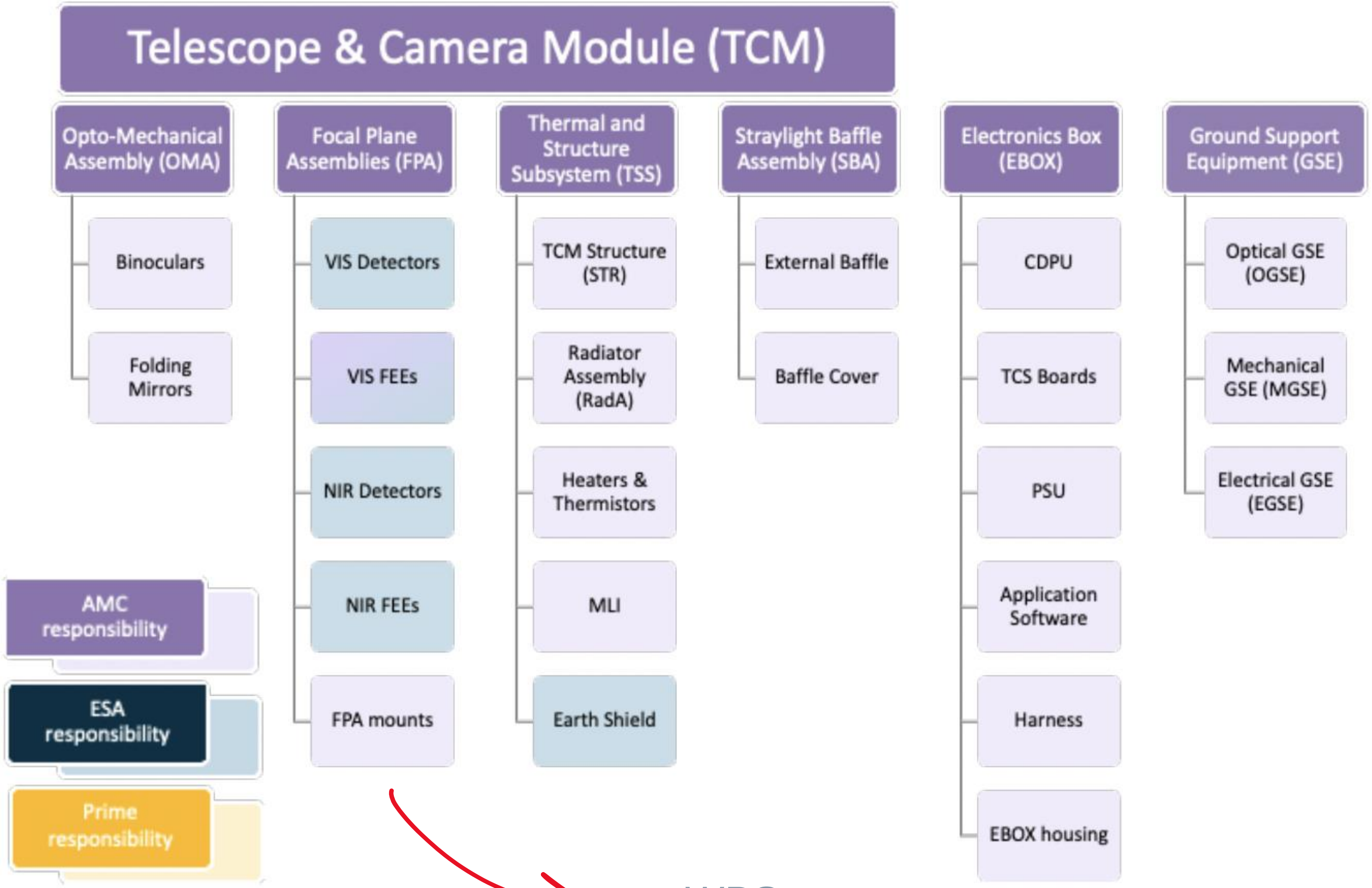




Product tree



ARRAKIHS payload (phase A)



=> WBS

System lifecycle overview = SE plan

esa

project phases > milestones > instrument models

Definition	Phase 0	**Mission analysis-need identification**	Mission Definition Review	
Definition	Phase A	**Feasibility**	Preliminary Requirement Review	
Definition	Phase B	**Preliminary definition**	System Requirement Review, Preliminary Design Review	**Breadboards**
Implementation	Phase C	**Detailed definition**	Critical Design Reviews	**EM, STM**
Implementation	Phase D	**Qualification and production**	Qualification and Flight aceptance Reviews	**QM, FM, PFM**
Operation	Phase E	**Operations / utilization**	In-orbit commissioning	
Operation	Phase F	**Disposal**	End-of-life review	

Model philosophy impacts **cost & schedule** greatly
Option 1: Breadboard, EM, STM, PFM (refurbishment)
Option 2: Breadboard, EM, STM, QM, FM

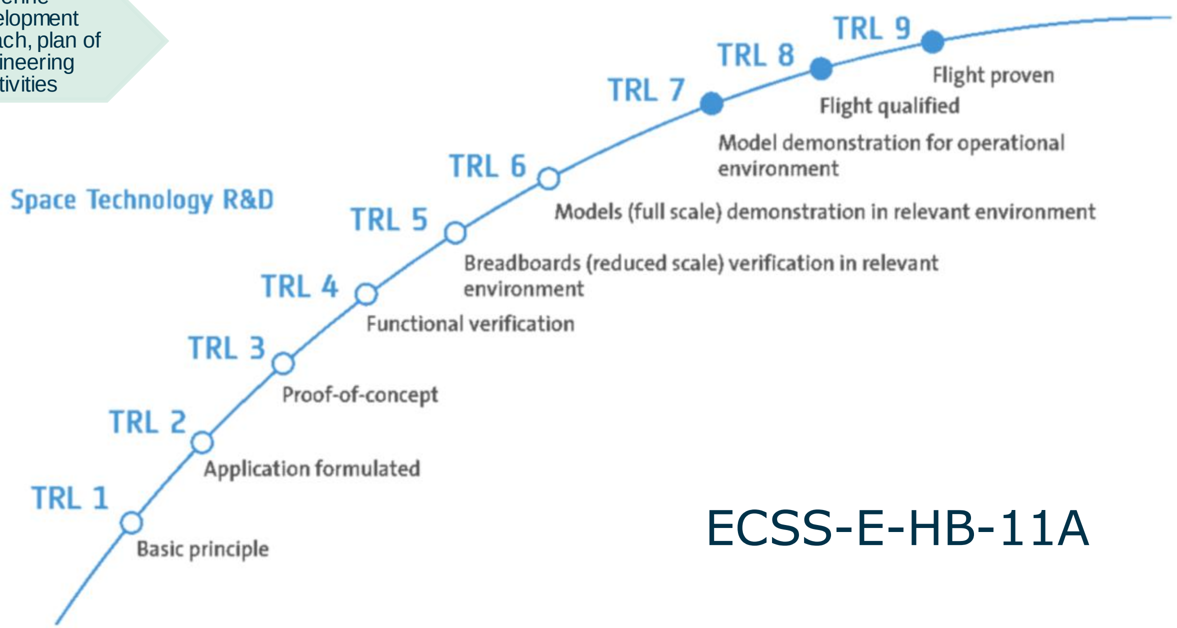
EM: Engineering Model
STM: Structural Thermal Model
QM: Qualification model
PFM: Protoflight model

Other models:
EFM, AVM, MTD etc.

System lifecycle: phases & TRL

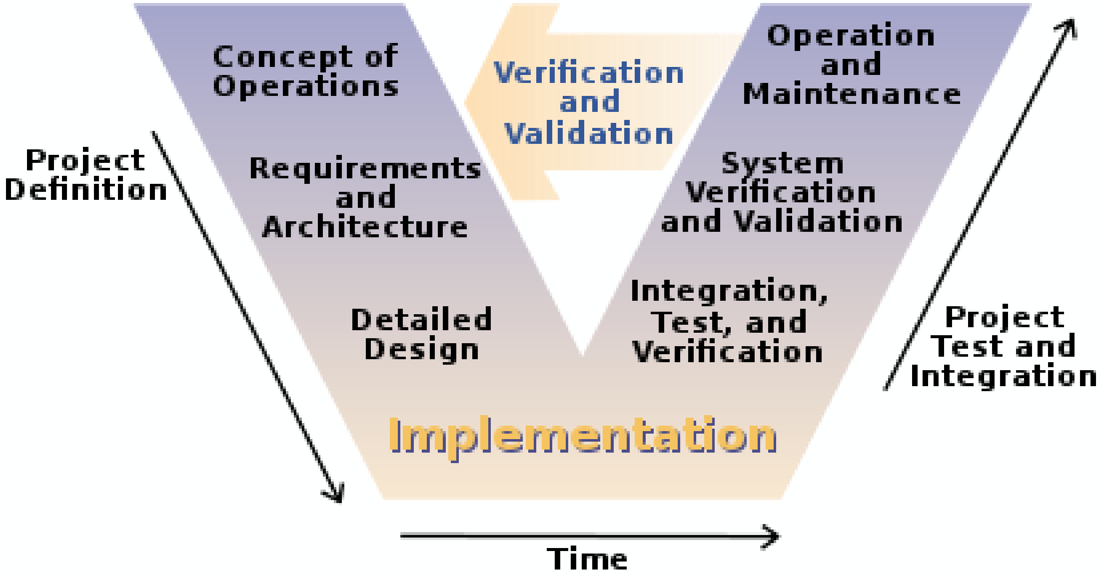
Phase 0	Identification of customer needs	Proposes possible system concepts		
Phase A	Finalise needs expression	Proposes system solutions	Identification of critical items and risks (TRL)	
Phase B	baseline system preliminary definition	technical requirements compliance demonstration	by tests for critical function breadboards	define development approach, plan of engineering activities
Phase C	system detailed definition	EM and STM production and test	technical requirements verification	
Phase D	QM and FM production and test	preparation for operations and utilization (calibration)		
Phase E	**Launch**	In-orbit verification of performance	Operations / utilization	
Phase F	Disposal			

TRL: technology readiness level



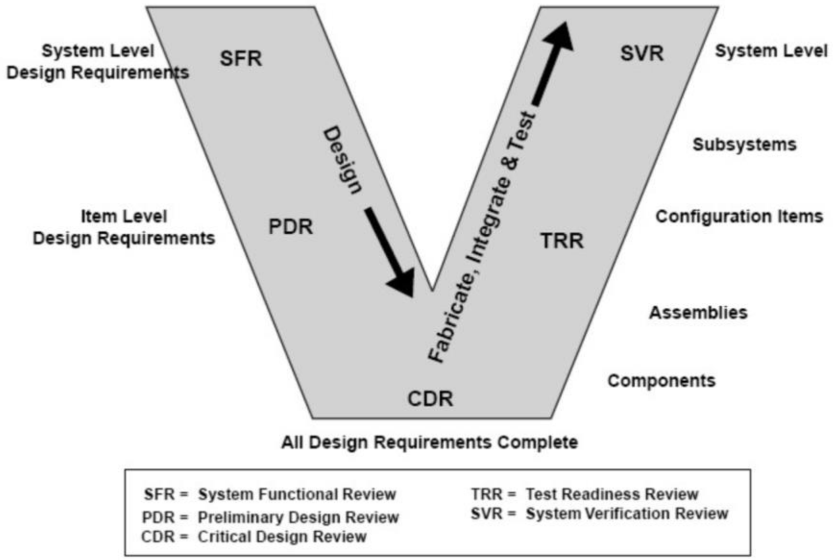
V model in theory

V stands for Verification and Validation

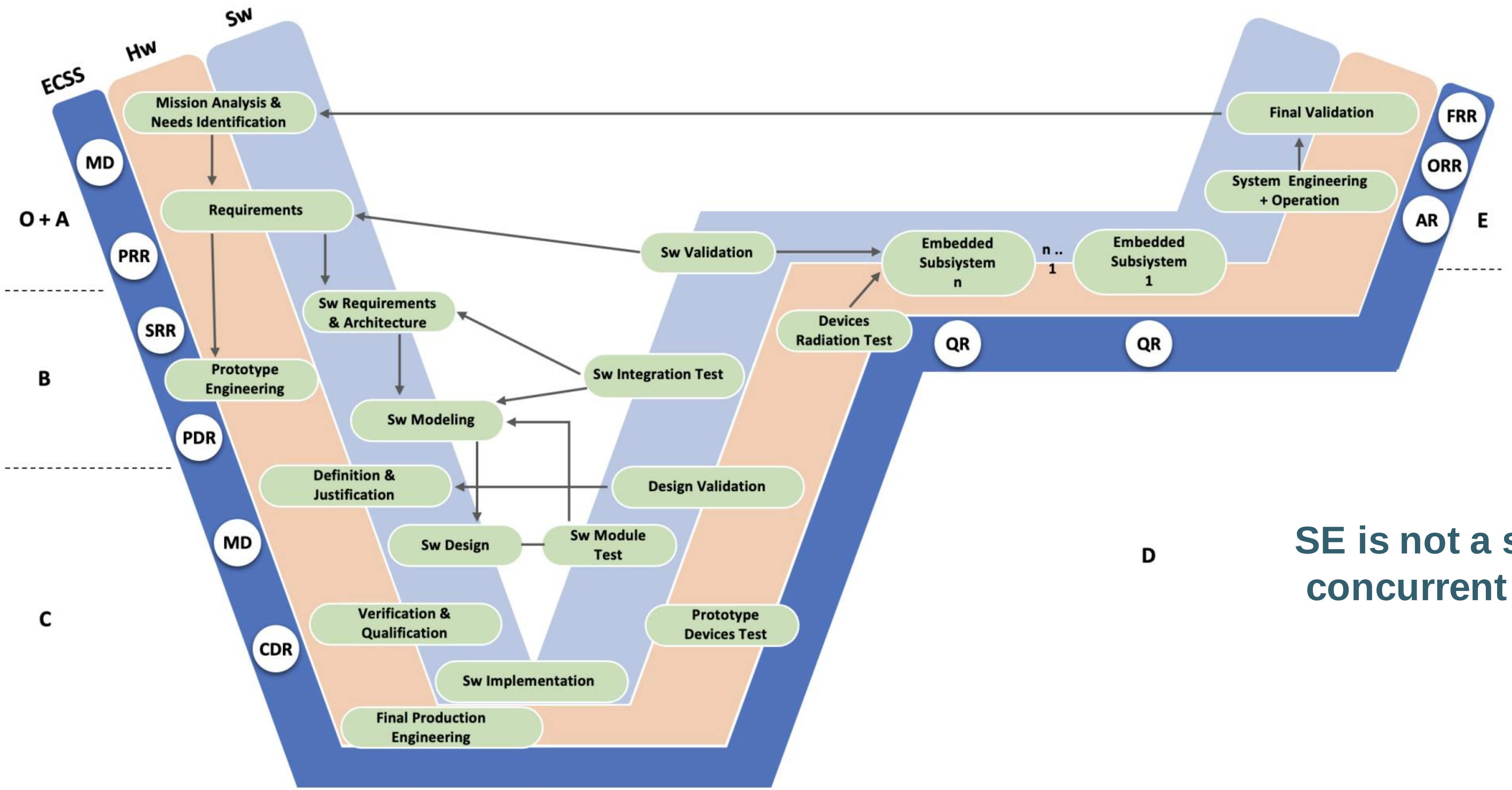


https://en.wikipedia.org/wiki/V-model

- validation "Are you building the right thing?”
- verification by "Are you building it right?"



Closer to reality*



SE is not a sequential but an concurrent and iterative process

V-Model Adaptation for Space Systems in Light of the ECSS Standard Regina Moraes et al. IEEE 2021

Requirement basics

Requirements correspond to an identified critical system or subsystem need.

They are mandatory, must be complied with, and shall be verified.

Some basic rules

- Short/Synthetic
- Definite/Unambiguous
- Verifiable: input to the verification plan and model philosophy => cost, schedule, complexity driver
- Traceable: flow down from system to subsystem => one parent requirement max (see document tree)
- Formulated using terms that have been properly defined earlier

Requirement types

- Function: what shall this element do?
- Performance: how well shall it do it?
- Interface: how does it interface with another element?

Example of a performance requirement

Image quality requirement example for an optical system

MIS-0410 The Full Width at Half Maximum (FWHM) of the single-exposure polychromatic Point Spread Function (PSF) at any point within the Field of View over the exposure integration time shall be not greater than:

- 1.3 (TBC) arcsec in each of the visible bands (VIS-1 and VIS-2).
- 2.5 (TBC) arcsec in each of the near-infrared bands (NIR-1 and NIR-2).

What's not great? What is missing?

Example of a performance requirement

Image quality requirement example for an optical system

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What's not great?

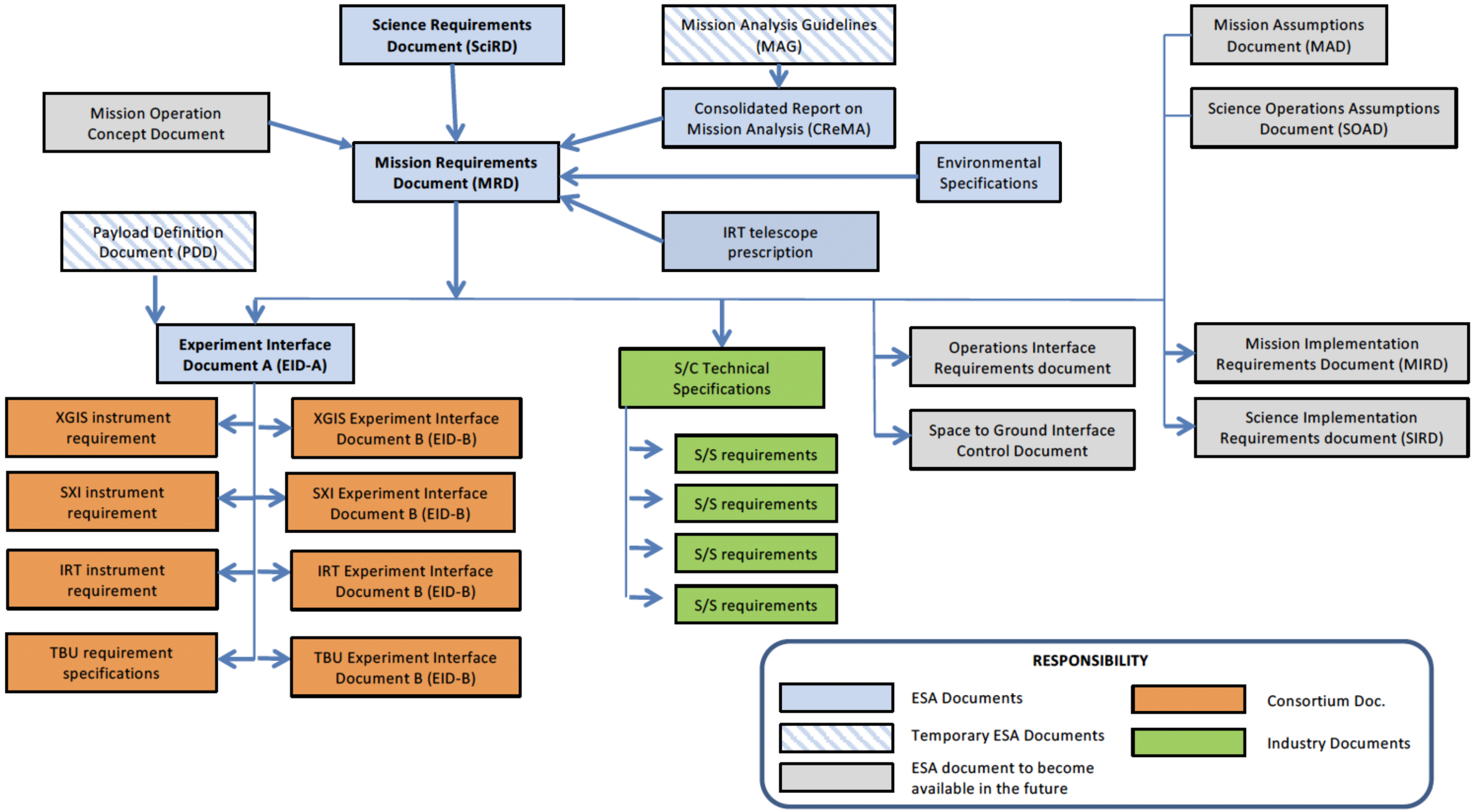
- Two requirements in one (VIS and NIR channels)
- Negative statement
- TBC values

What is missing?

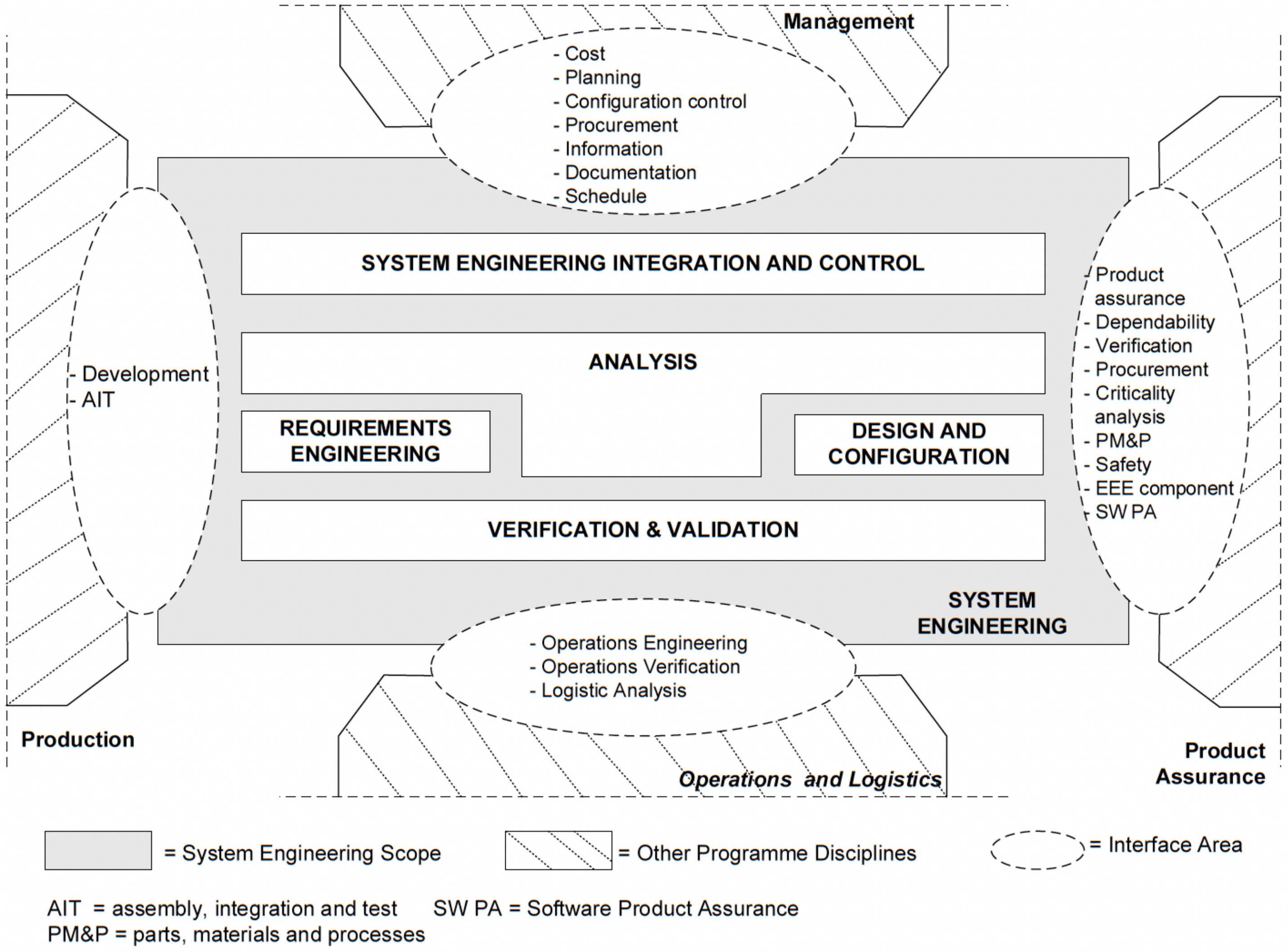
- No parent requirement
- No verification method

Example of document tree

THESEUS Phase A Requirement Documents (2019-2021)



System engineering, sub-functions and boundaries



European Cooperation for Space Standardization ECSS

ECSS-E-ST-10C: System engineering general requirements

Space instrumentation SE domains

- Thermal
- Mechanics & structure
- Electrical and electronics
- Optics
- Detection
- And Mechanism, Radiation assurance, Contamination and cleanliness, EMC etc.
- Pointing (AOCS) & Power (more platform/satellite responsibility)
- Product Assurance & Quality Assurance (some times considered outside of SE activities)

Roles and responsibilities

Lead systems engineer or Systems lead

- coordinates all SE activities
- has the project full overview and arbitrate between domains
- can assume more responsibilities depending on project size e.g. project manager, performance, domain lead

Architects

- SE lead for a given domain e.g. thermal lead
- leads the overall SE domain activities:
    - manage requirements, design, analysis, verification planning and implementation for their own domain
    - a liaise with other disciplines in coordination with systems lead

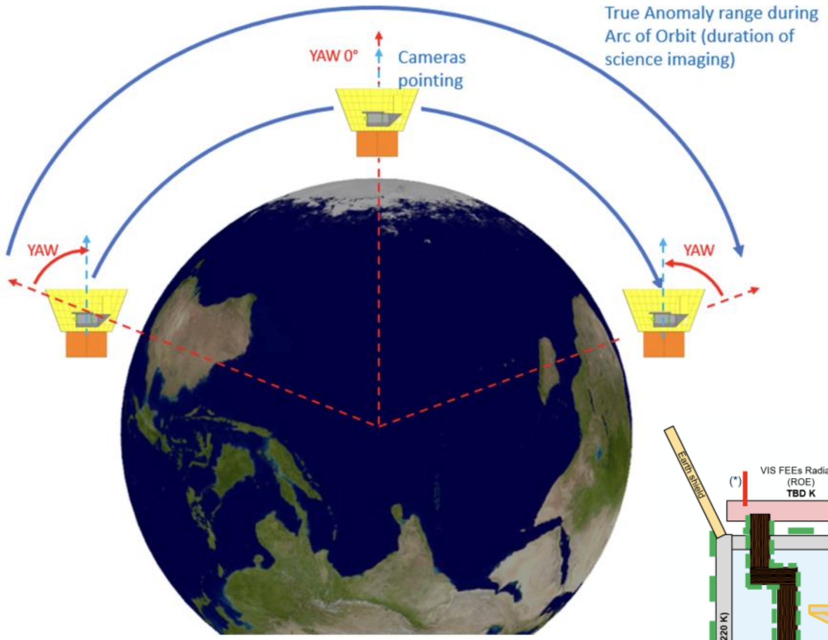
Trade-off exercise: detector choice example

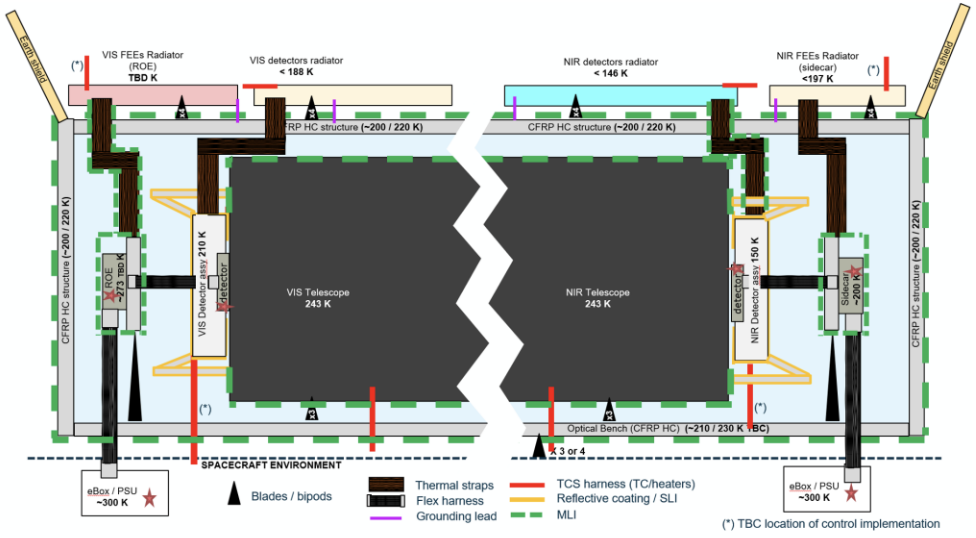
A trade-off is the process of chosing a baseline solution (chosing a baseline) by systematically checking for different domains the impact of different options.

Category	Param	Euclid readout chain	TBD CIS
Instrument performance	**FoV** (vignetting/format) **Resolution** **SNR** Readout noise Smear QE Saturation PRNU/DSNU Other (persistence/lag)	49 x 49 mm 12um 4e- 333 kHz max (9s frame time) Cannot be tuned for VIS1 FWC>150 ke-	45x43 mm 10um <2e- but spread (+ NDR/UTR) No smear Better blue response Low FWC Possibly worse than CCD 2nd order eff. less known/glow
Payload development	Readout chain FPA implications Testing	Well understood but mods still TBD Extension cables, ROE location TBD MSSL, ESA	Feasibility study - IP cores exchanged Easier to accommodate ESA, Satlantis
Radiation hardness	CTI, Read noise, Dark SEE	Depending on proton fluence, very detrimental effect to performance -	Read noise evolution with TID, TNID, dark current TBC Digital output chip
System	Temperature of operation FGS	< 200 K CCD temp. driven by radiation-induced CTI -	>200K CIS temp. driven by eol dark current NDR and/or windowing enable VIS FGS
Programmatics	TRL Cost	TRL8-9 high	TRL3-4 medium

Phase 0/A/B activities: thermal activities example

Identifying needs, deriving requirements, establishing concept(s), trading, budgeting, verifying through modelling and analysis





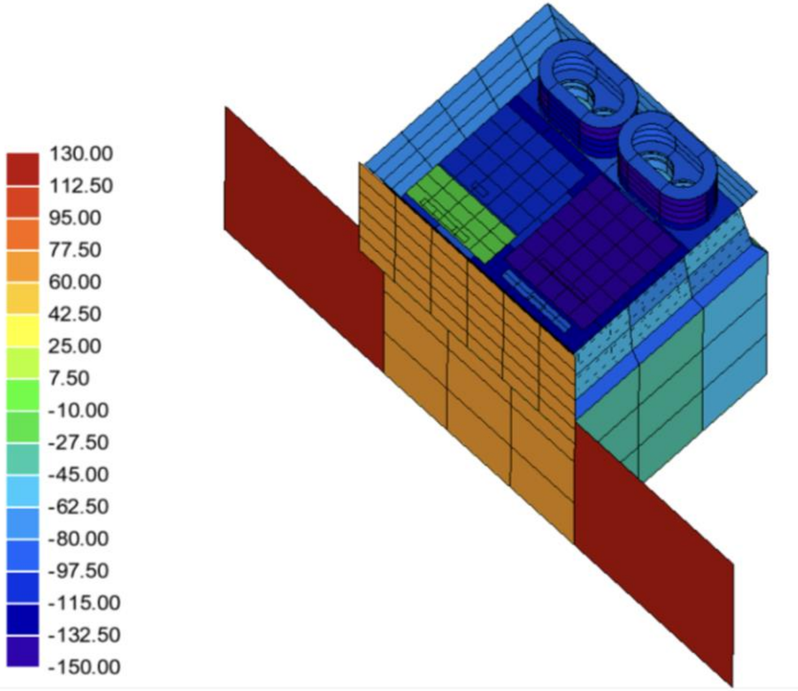
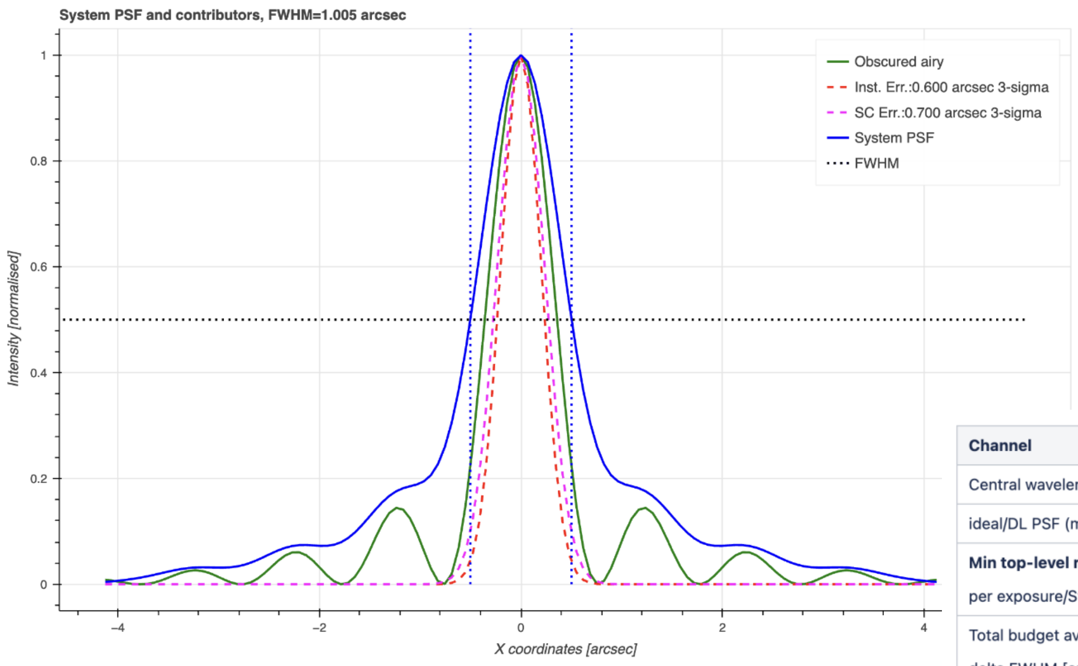


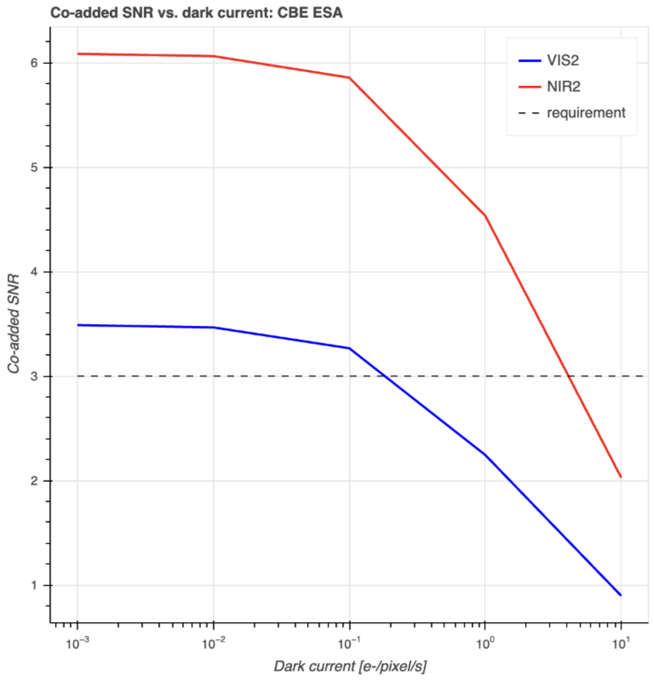
Figure 10: Temperature mapping - reference case 32|55

ARRAKIHS phase A
Courtesy of M. Broussely (ESA)

Phase 0/A/B activities: budgeting & sensitivity analyses



Channel	VIS1
Central wavelength [nm]	455
ideal/DL PSF (monochromatic): FWHM [arcsec]	0.52
Min top-level requirement	
per exposure/System PSF FWHM [arcsec]	1
Total budget available	
delta FWHM [arcsec]	0.85
equivalent standard deviation* (3-sigma) [arcsec]	0.93
Proposed spacecraft error contribution	
delta FWHM [arcsec]	0.55
equivalent standard deviation (3-sigma) [arcsec]	0.70
Proposed instrument error contribution	
delta FWHM [arcsec]	0.44
equivalent standard deviation (3-sigma) [arcsec]	0.60
Reserve	None
delta FWHM [arcsec]	
equivalent standard deviation (3-sigma) [arcsec]	



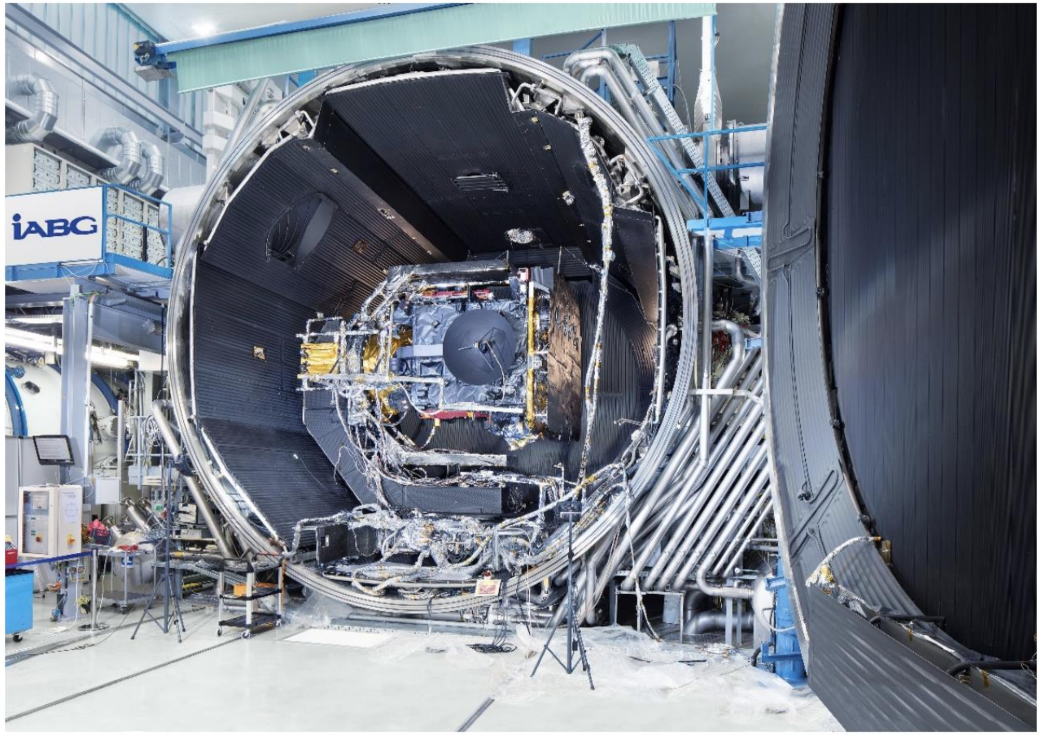
ARRAKHIS phase A

Phase C/D activities: testing example

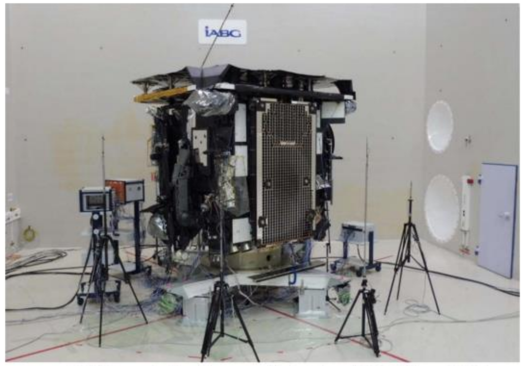
Manufacturing, Assembling, Integrating, **Testing** (e.g. Sine vibration, Acoustic, Shock, Thermal vacuum, EMC)

- **Unit level first then system**
- Qualification tests (e.g. on Structural and Thermal model) then acceptance tests (on the Flight model)

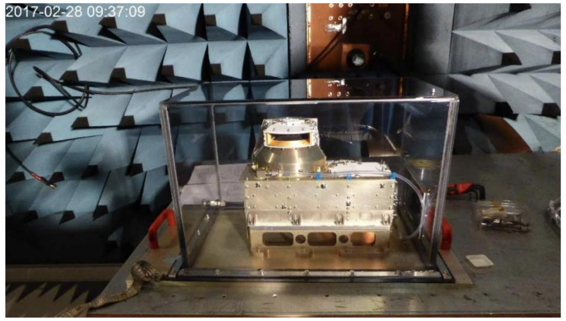
©ESA-Corvaja, (credit Airbus/IABG), at IABG space test centre



© IABG, SolO in TVTB chamber (credit ESA/Airbus/IABG)



© IABG, ready for vibro-acoustic test (credit ESA/Airbus/IABG)



Solar Orbiter phase C/D
Courtesy of A. Pacros (ESA)

To go more in-depth

ECSS (European Cooperation for Space Standardization):
https://ecss.nl/

Incose (International Council on Systems Engineering):
www.incose.org

MBSE (Model-Based Systems Engineering):
https://insights.sei.cmu.edu/blog/introduction-model-based-systems-engineering-mbse/

Previous EIROforum instrumentation schools: e.g.
https://indico.cern.ch/event/777129/contributions/3249528/