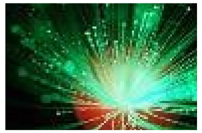
Requirements definition at ESA: practices, challenges and emerging processes

04/02/2025

About me



CIENA Corporation

Senior Photonic Engineer

2000

brimrose

...we invent your tomorrows

Spectrometer Designer

2003

MIRI Lead SE & Manager

2005

Euclid Mission & Payload System Engineer

2012

2018

PLATO Mission, Performance and Operations Manager

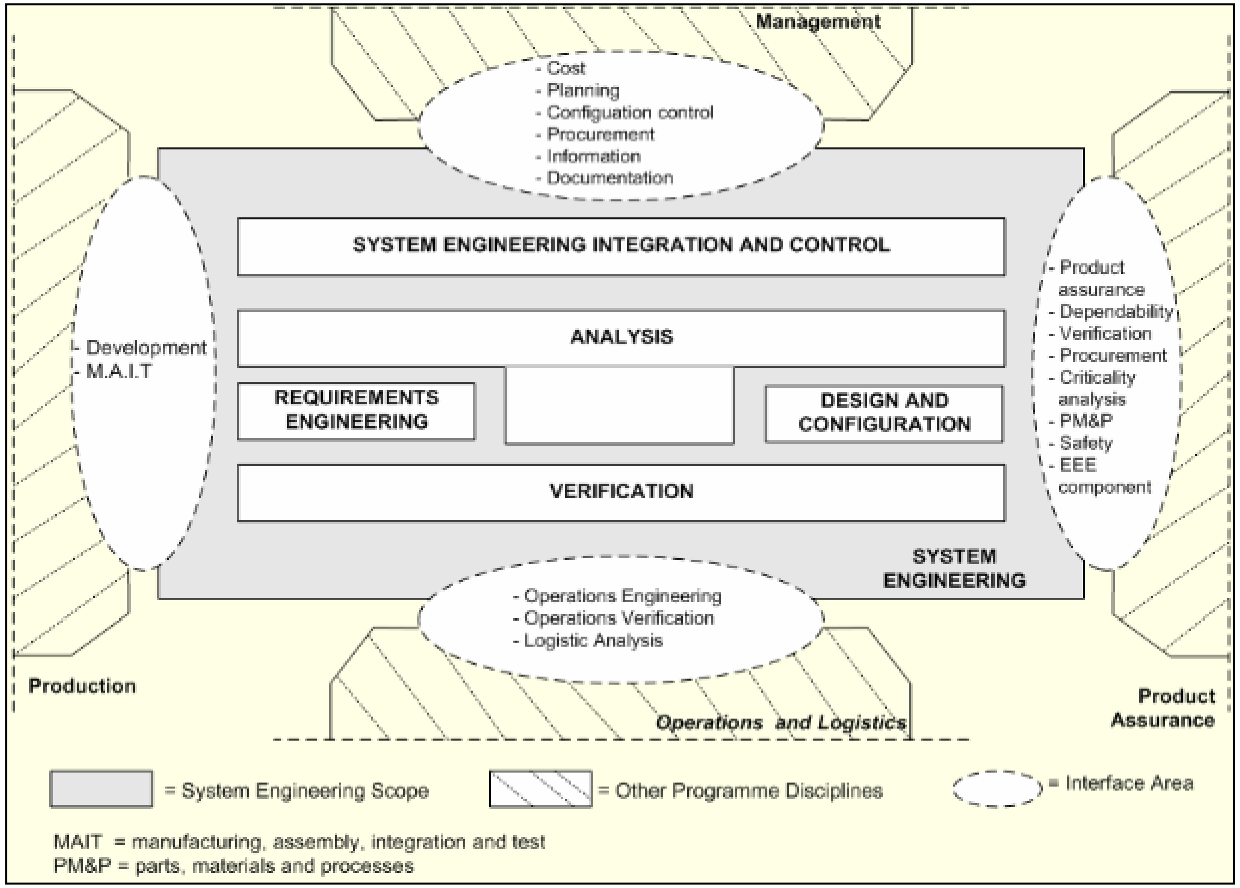
2020

PLATO Mission and Payload Manager

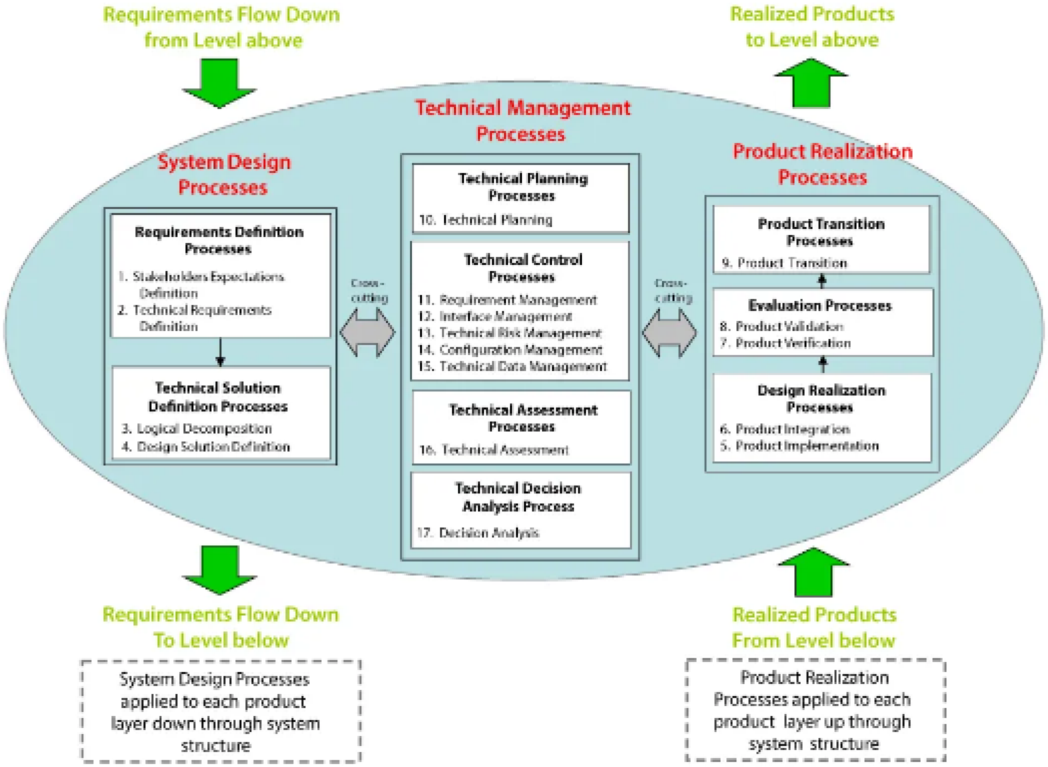
UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

UNIVERSITY OF MARYLAND

Requirements Engineering in Context



> SYSTEMS ENGINEERING FUNCTIONS (ECSS-E-ST-10C)

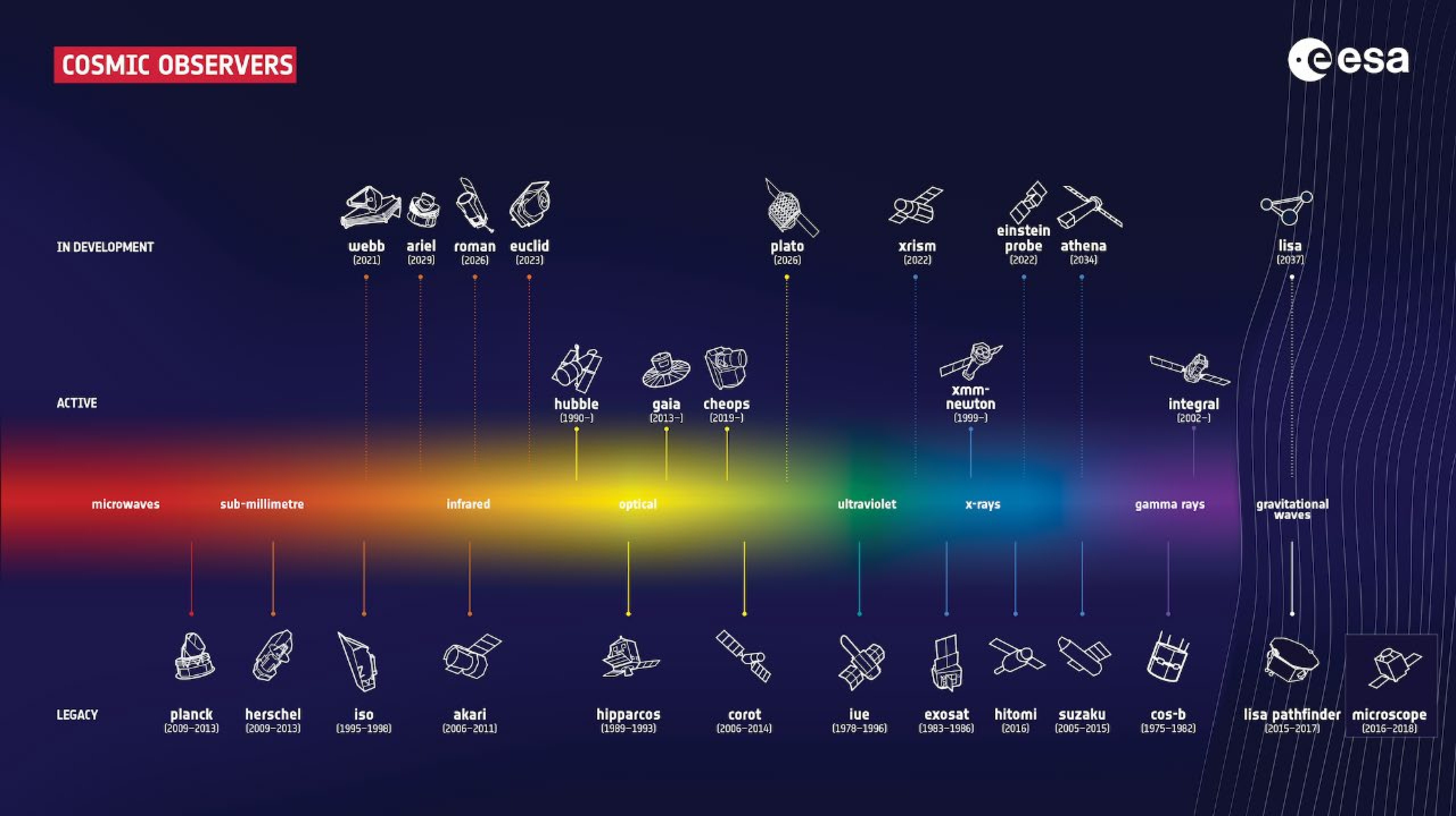


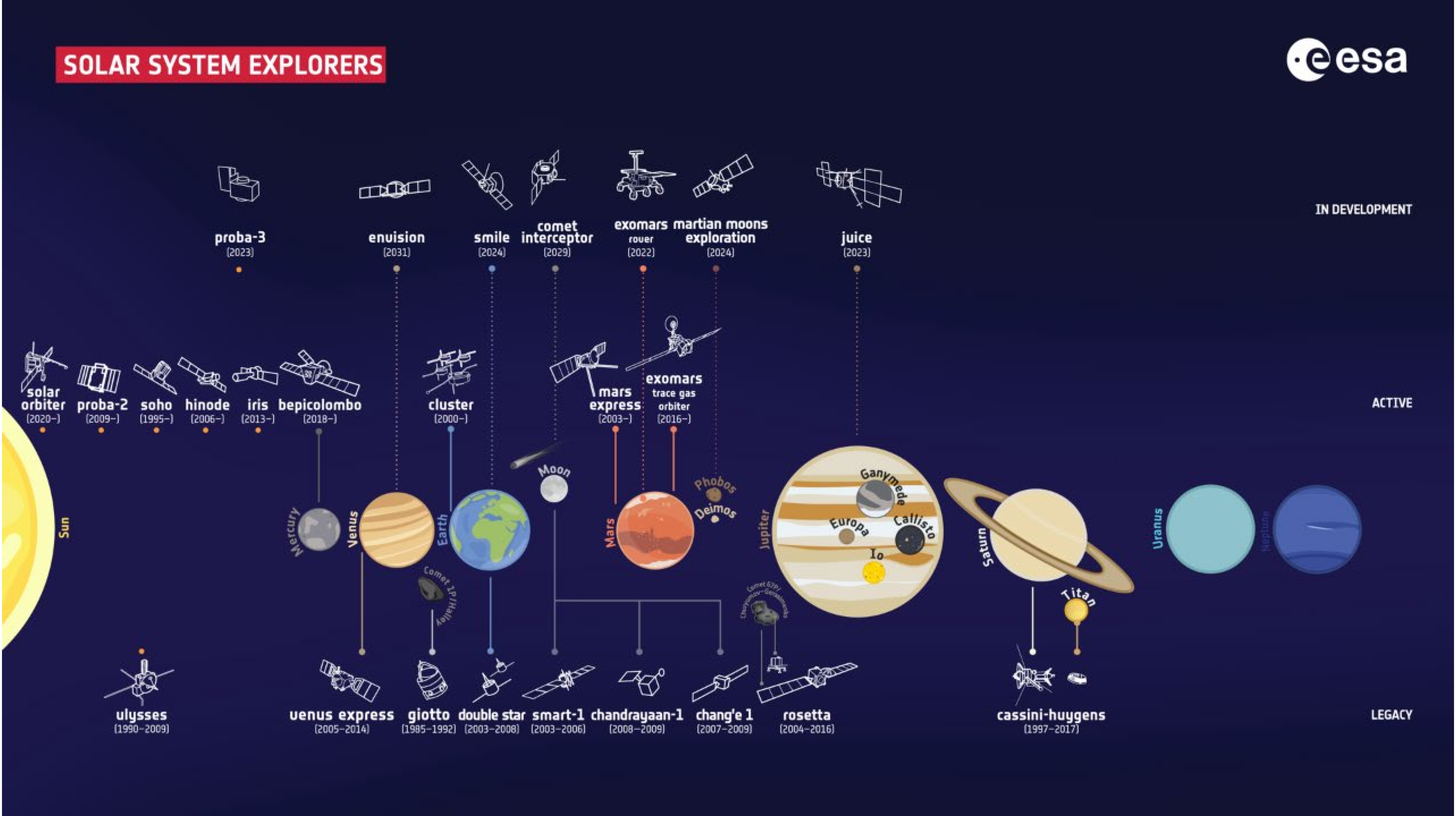
> NASA SYSTEMS ENGINEERING HANDBOOK

Space Systems developments evolving

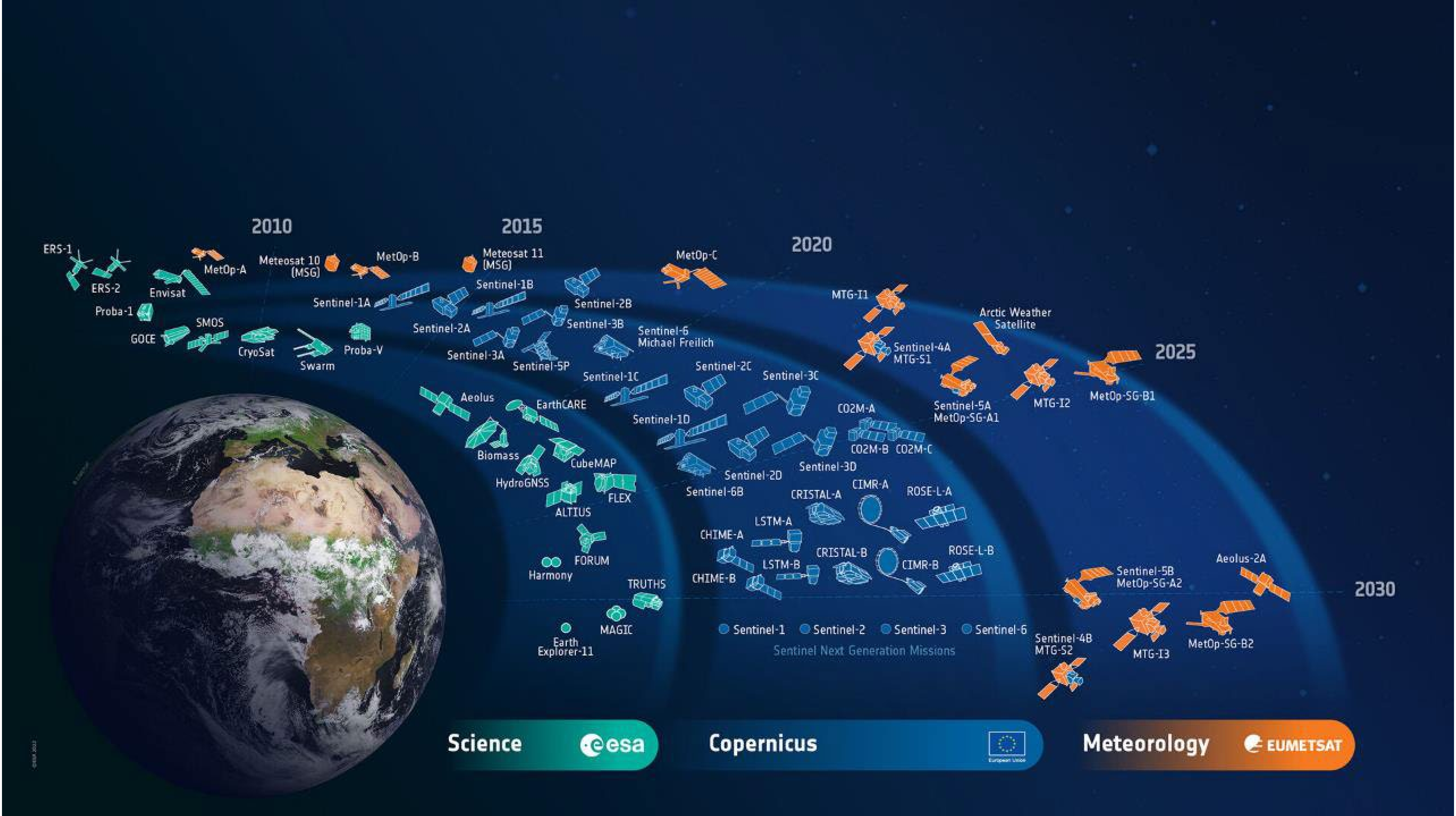
Space landscape changing rapidly:

Traditional Space	VS	New Space
Large "one-of" missions		Significant re-use and increase capacity of small systems to operate together
Institutionally / governmentally driven		Emerging private space industry driven by market and applications
Focused user base and limited stakeholders		Broad area of applications, users and customers
Driven by reduced industrial base (LSIs)		Many new industrial players

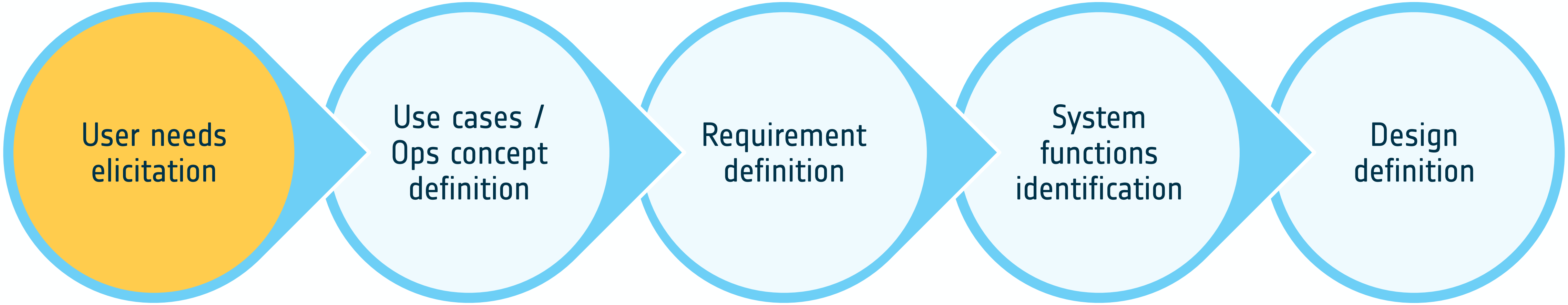

COSMIC OBSERVERS
esa
IN DEVELOPMENT
webb (2021)
ariel (2029)
roman (2026)
euclid (2023)
plato (2026)
xrism (2022)
einstein probe (2022)
athena (2034)
lisa (2037)
ACTIVE
hubble (1990–)
gaia (2013–)
cheops (2019–)
xmm-newton (1999–)
integral (2002–)
microwaves
sub-millimetre
infrared
optical
ultraviolet
x-rays
gamma rays
gravitational waves
LEGACY
planck (2009–2013)
herschel (2009–2013)
iso (1995–1998)
akari (2006–2011)
hipparcos (1989–1993)
corot (2006–2014)
iue (1978–1996)
exosat (1983–1986)
hitomi (2016)
suzaku (2005–2015)
cos-b (1975–1982)
lisa pathfinder (2015–2017)
microscope (2016–2018)



SOLAR SYSTEM EXPLORERS
esa
IN DEVELOPMENT
proba-3
(2023)
envision
(2031)
smile
(2024)
comet interceptor
(2029)
exomars rover
(2022)
martian moons exploration
(2024)
juice
(2023)
ACTIVE
solar orbiter
(2020–)
proba-2
(2009–)
soho
(1995–)
hinode
(2006–)
iris
(2013–)
bepicolombo
(2018–)
cluster
(2000–)
mars express
(2003–)
exomars trace gas orbiter
(2016–)
Sun
Mercury
Venus
Earth
Moon
Comet 1P/Halley
Mars
Phobos
Deimos
Jupiter
Ganymede
Europa
Callisto
Io
Saturn
Titan
Uranus
Neptune
LEGACY
ulysses
(1990–2009)
venus express
(2005–2014)
giotto
(1985–1992)
double star
(2003–2008)
smart-1
(2003–2006)
chandrayaan-1
(2008–2009)
chang'e 1
(2007–2009)
rosetta
(2004–2016)
cassini-huygens
(1997–2017)

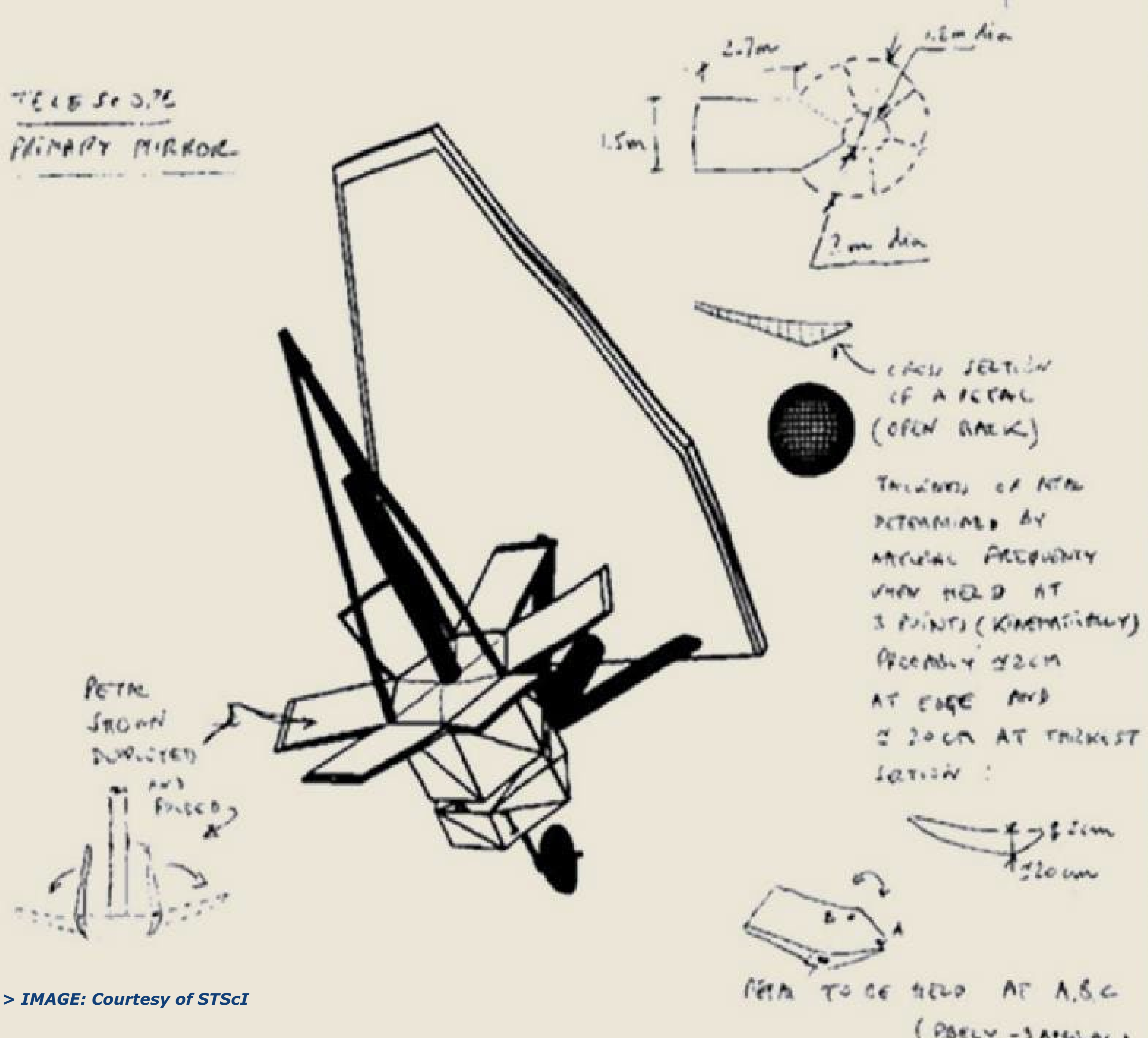

2010
2015
2020
2025
2030
ERS-1
ERS-2
Envisat
MetOp-A
Proba-1
GOCE
SMOS
CryoSat
Swarm
Proba-V
Meteosat 10 (MSG)
MetOp-B
Meteosat 11 (MSG)
Sentinel-1A
Sentinel-1B
Sentinel-2A
Sentinel-2B
Sentinel-3A
Sentinel-3B
Sentinel-5P
Sentinel-6 Michael Freilich
MetOp-C
MTG-I1
Arctic Weather Satellite
Sentinel-4A MTG-S1
Sentinel-5A MetOp-SG-A1
MTG-I2
MetOp-SG-B1
Sentinel-1C
Sentinel-2C
Sentinel-3C
Sentinel-1D
Sentinel-2D
Sentinel-3D
Sentinel-6B
CO2M-A
CO2M-B
CO2M-C
Aeolus
EarthCARE
Biomass
CubeMAP
HydroGNSS
FLEX
ALTIUS
FORUM
Harmony
TRUTHS
MAGIC
Earth Explorer-11
CRISTAL-A
CIMR-A
ROSE-L-A
LSTM-A
CHIME-A
CRISTAL-B
CIMR-B
ROSE-L-B
LSTM-B
CHIME-B
Sentinel-1
Sentinel-2
Sentinel-3
Sentinel-6
Sentinel Next Generation Missions
Sentinel-5B MetOp-SG-A2
Aeolus-2A
Sentinel-4B MTG-S2
MTG-I3
MetOp-SG-B2
Science
esa
Copernicus
European Union
Meteorology
EUMETSAT

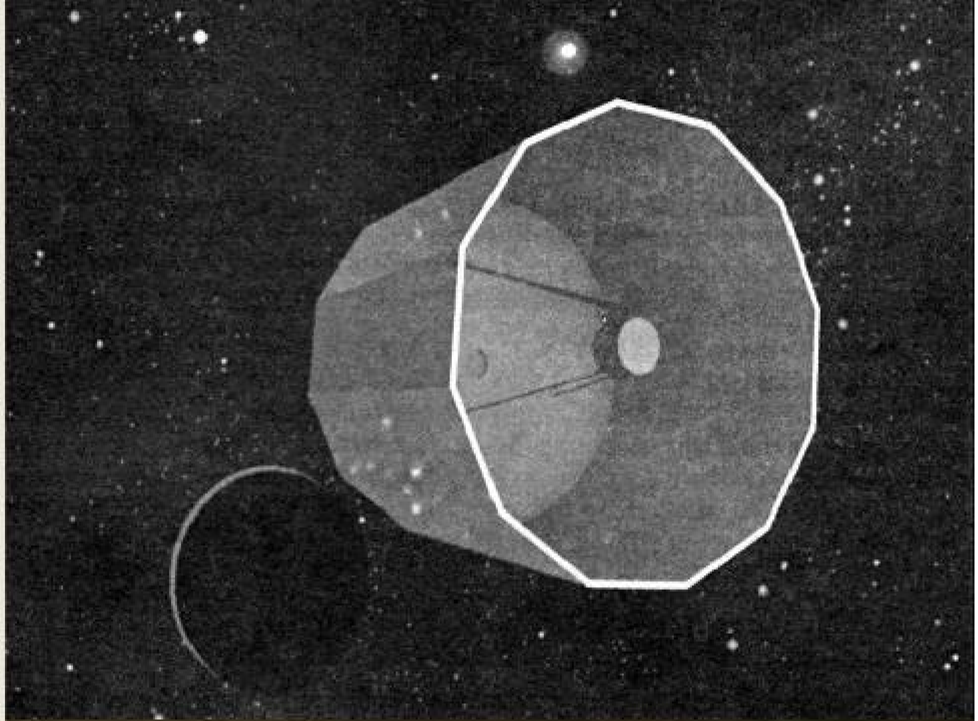
The mission architecting process

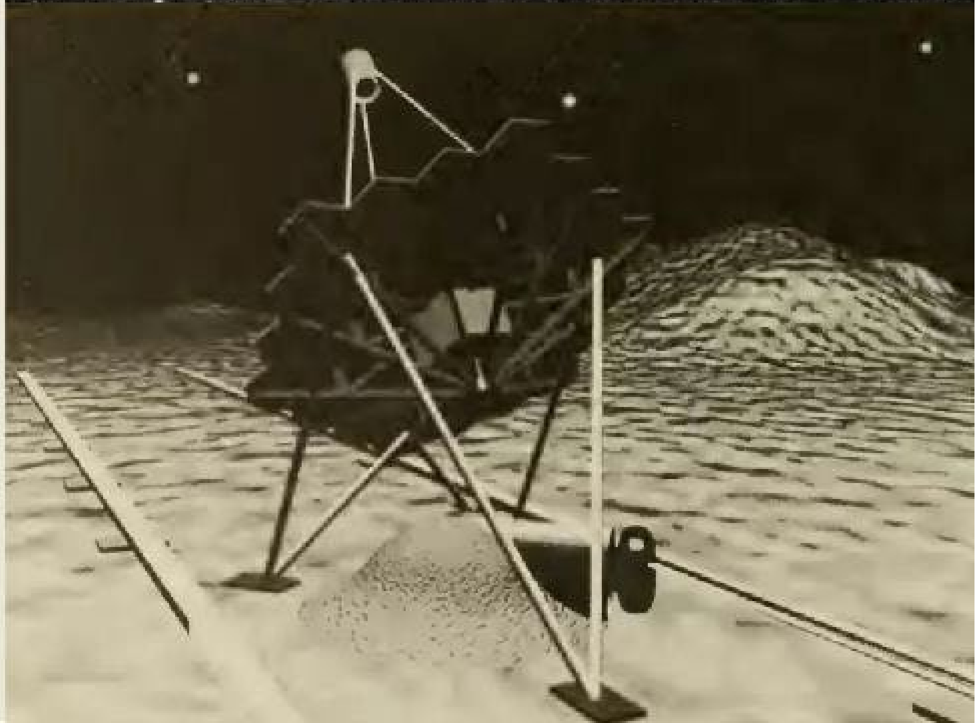


- Requirements definition is (should be) **User Centric.**
- Assessment should identify **minimum set of needs** to be covered for the system to provide a <u>value</u>

> IMAGE: ESA/NASA/CSA



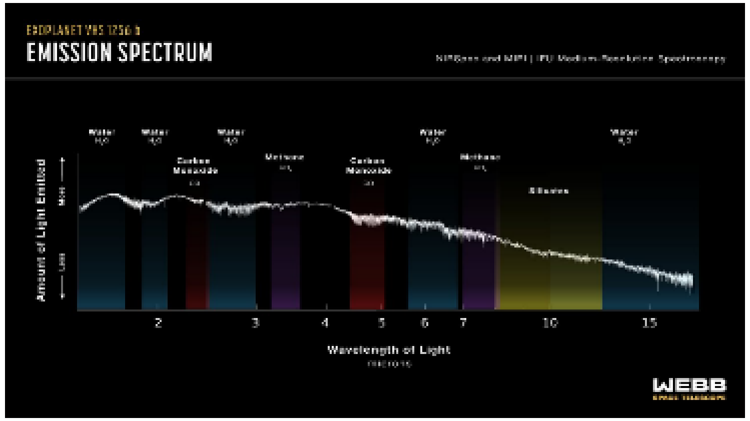


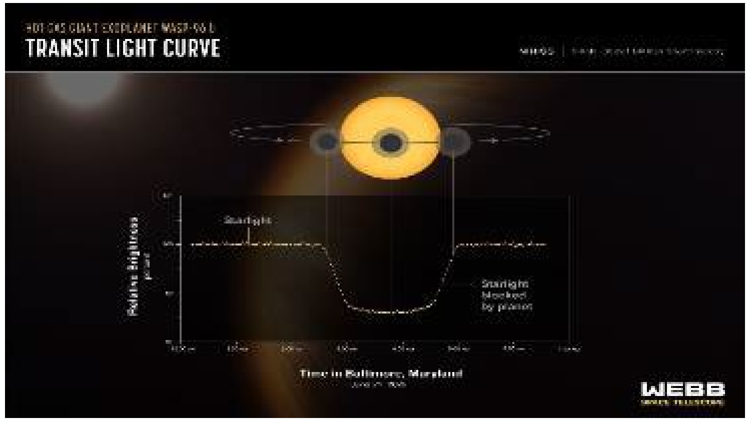


> *IMAGE: Courtesy of STScI*

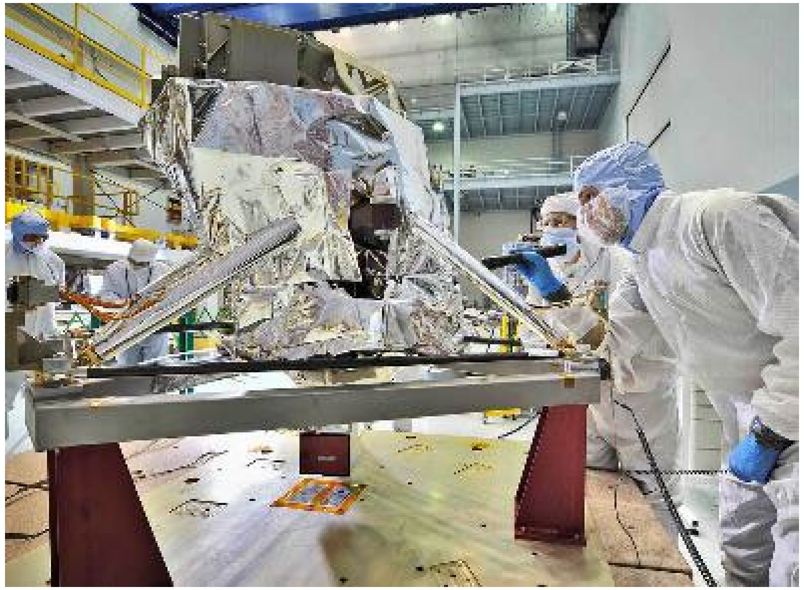
> IMAGE: NASA

Challenge – Understand what is needed by user

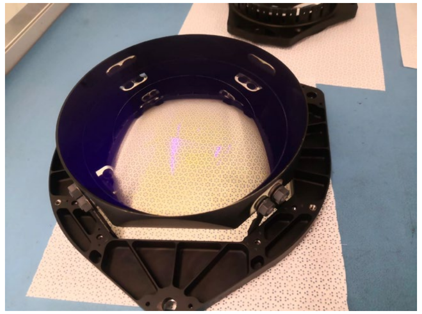




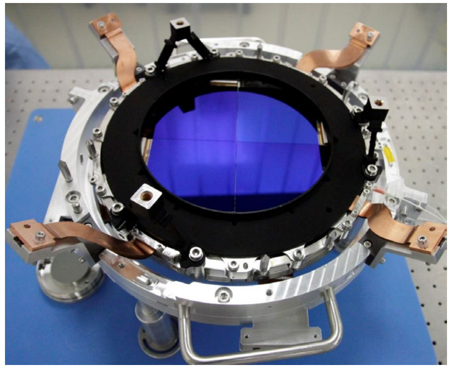
Requirements Engineering Process



Maximum contamination levels



Lenses/mirrors roughness



Detection elements quantum efficiency and noise

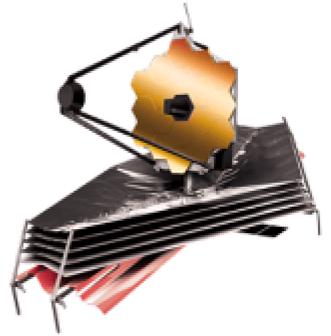
Etc….

What we want to achieve

What is required

Nature of users changes depending on the application

Scientific Community
(Consumer / User)



Development Agencies
(Customer / Developer)

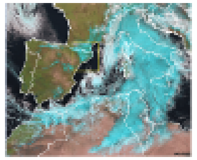
Development industry/groups
(Suppliers)

Funding Agencies
(Sponsors)

Meteorologists

National disaster management agencies

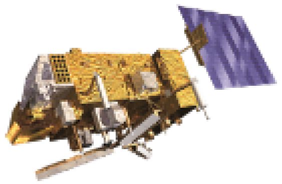
(User)



EUMETSAT

Satellite data agency

(Consumer / Layer 1 costumer)



Development Agencies
(Layer 2 Customer / Developer)

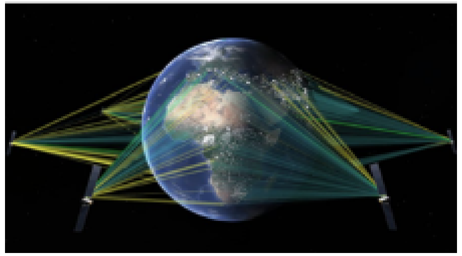
Development industry/groups
(Suppliers)

Funding Agencies
(Sponsors)

TV Consumer
(User)

Broadcaster
(Consumer / Layer 1 costumer)

Agencies
(User / Layer 1 costumer)



Commercial Satellite Network provider
(Customer / Developer)

Development industry/groups
(Suppliers)

Private funding / Publically traded
(Sponsors)

Requirements Elicitation

- Final user defines the ***needs/objectives:*** expressed in science terms
- User often has an identified **technique and observable** to achieve those needs

- These top-level needs should be agnostic from specific design implementation or architecture
  - In practice, users bring in past projects/experience on the needs:
    - Potentially to hide real objectives
    - Introduction of unnecessary constraints

Systems Engineering most important task in early phases:

Validate the requirements:

"Is this what we need?" / "Will we build the right thing?"

User needs and requirements

Phase 0

Stakeholder needs

- Level-0 requirements: Mission objectives

- Mission statement

Science requirements

- Level-1 requirements: mission level scientific requirements and needs
- Basic architecture

- Science Reqs. Doc (SciRD)
- *Yellow Book*

(*ex: Ariel Yellow Book* https://sci.esa.int/s/8zPrb9w)

Phase A

Mission Constraints

Mission Requirements

- Level-2: Performance and functional requirements
- Basic architecture

- Mission Reqs Doc (MRD)
- *Red Book*

(*ex: Euclid Red Book* https://sci.esa.int/s/wKd0PPW)

Phase B1

System and Sub-system Specifications

- Level-3: implementation requirements

- System RD (SRD)
- Instrument RD

User needs / requirements examples: JWST

The JWST Science Themes

User needs / requirements examples: JWST

- Level 1 Baseline Science Requirements- JWST **shall**

The scientific objectives of the JWST:

JWST-L1.1: Measure the space density of galaxies to a 2µm flux density limit of 1.0×10^{-34} $Wm^{-2}Hz^{-1}$ via **imagery** within the 0.6 to 27 µm spectral band to enable the determination of how this density varies as a function of their age and evolutionary stage.

JWST-L1.2: Measure the **spectra** of at least 2500 galaxies with spectral resolution of approximately 100 (over 0.6 to 5µm) and 1000 (over 1 to 5µm) and to a 2µm emission line flux limit of 5.2×10^{-22} Wm^{-2} to enable determination of their redshift, metallicity, star formation rate, and ionization state of the intergalactic medium.

JWST-L1.3: Measure the physical and chemical properties of young stellar objects, circumstellar debris disks, extra-solar giant planets, and Solar System objects via **spectroscopy**, and **imagery** within the 0.6 to 27µm spectral band to enable determination of how planetary systems form and evolve.

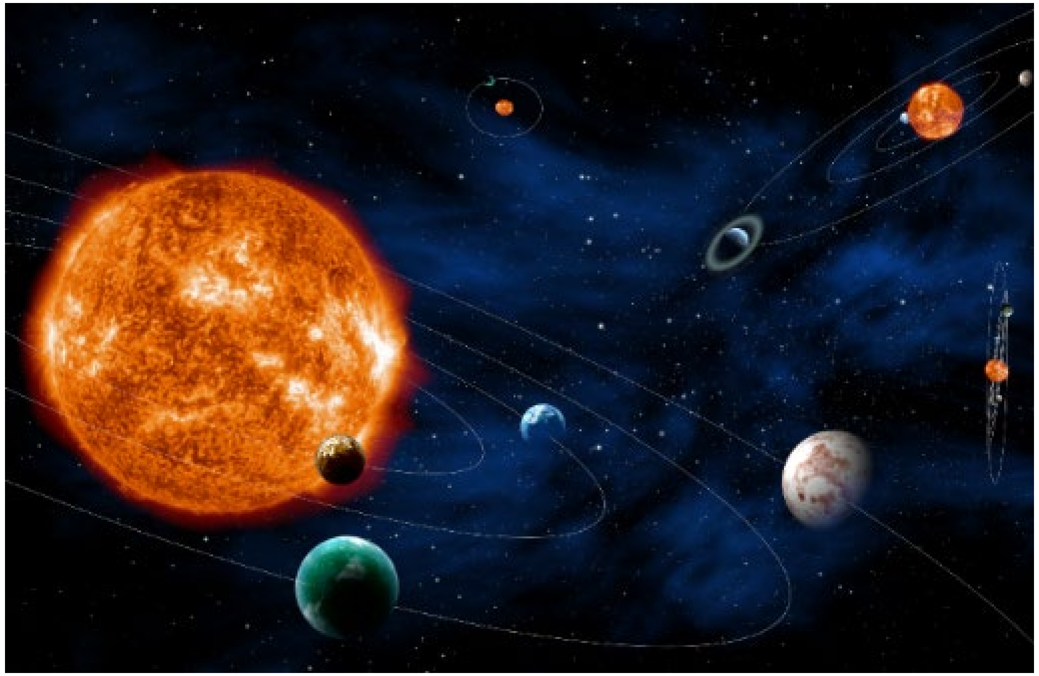
High level **functional** and **performance** requirements expressed to be further detailed and flow-down at Level 2 considering a mission architecture.

User needs / requirements examples: PLATO

PLAnetary Transits and Oscillations of stars (PLATO) is a mission to detect and characterise exoplanets and study their host stars

Focus on Earth-size planets in orbits up to the habitable zone of bright Sun-like stars to address 3 main questions:

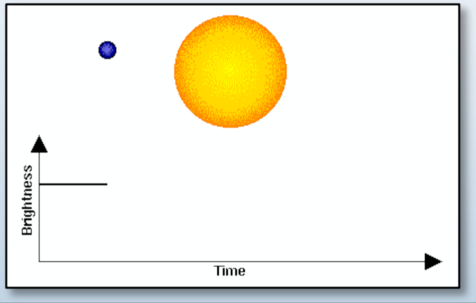
1. How do planets and planetary systems form and evolve?
2. Is our Solar system special or are there other systems like ours?
3. Are there potentially habitable planets?



User needs / requirements examples: PLATO

High-precision photometry in space

Transit method

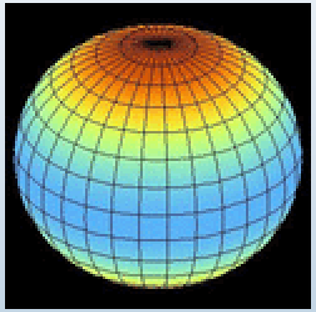


Orbit parameters

Orbital inclination, i

Planet-to-star radius ratio

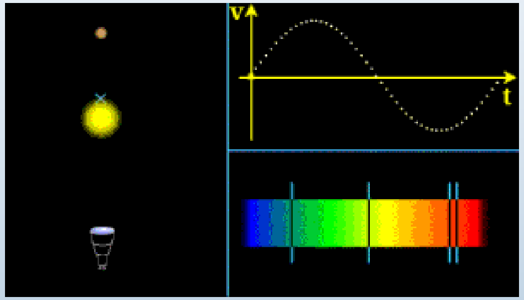
Asteroseismology



Precise stellar
R, M, age

Ground-based observations

Radial velocity



Orbit parameters

Minimum
planet mass, M sin i

Bulk characterisation:

Orbit parameters

Planet R, M, age

User needs / requirements examples: PLATO

Earth-like planet around Sun-like star

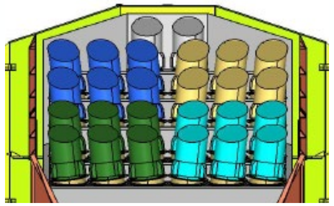
Ref star: G0V, mv=11 → low Noise/Signal

low Noise/Signal → micro-vibration requirements

low Noise/Signal → Enclosed Energy

low Noise/Signal → throughput over λ (500-1000nm)

low Noise/Signal → number of telescopes



planet orbital period=1 year → long duration stable pointing-> pointing requirements

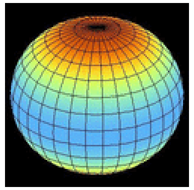
long duration stable pointing-> pointing requirements → focussing ability

long duration stable pointing-> pointing requirements → FGS in the loop

long duration stable pointing-> pointing requirements → Low thermo-elastic distortions

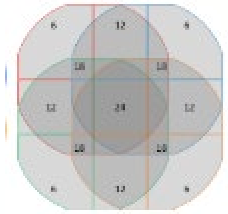
long duration stable pointing-> pointing requirements → co-alignment

stellar characterisation (asteroseismology)

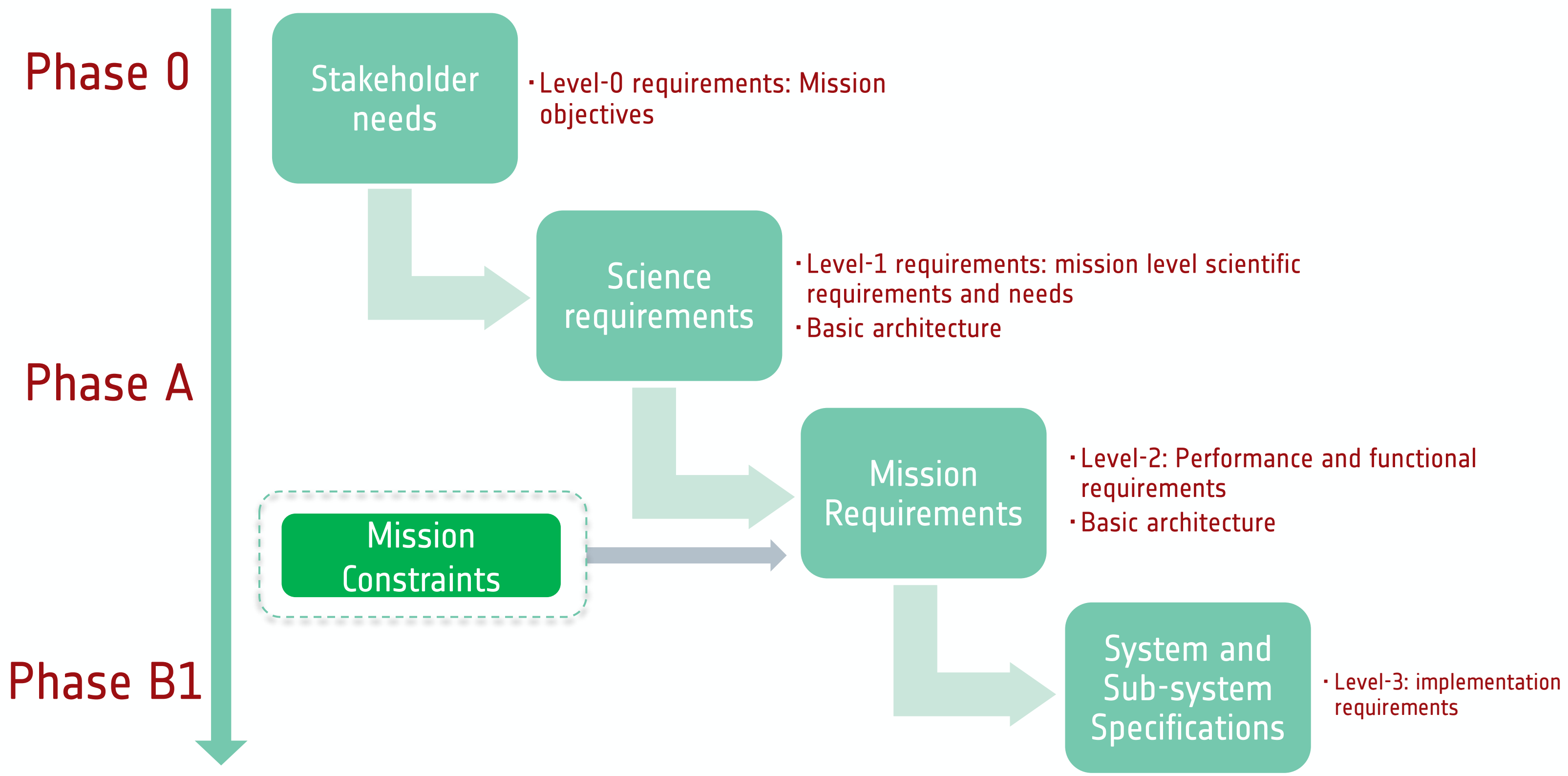


planet yield & statistics → large sample

large sample → large field of view



Other mission Requirement Sources



- Mission statement

- Science Reqs. Doc (SciRD)
- *Yellow Book*

(ex: Ariel Yellow Book https://sci.esa.int/s/8zPrb9w)

- Mission Reqs Doc (MRD)
- *Red Book*

(ex: Euclid Red Book https://sci.esa.int/s/wKd0PPW)

- System RD (SRD)
- Instrument RD

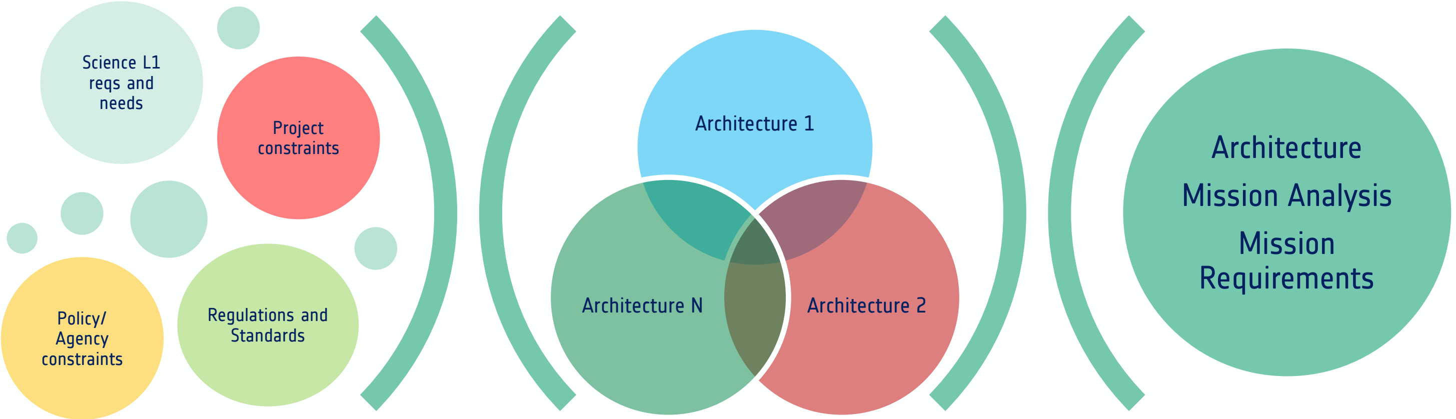
Other mission Requirement Sources

Project Constraints:
- Maximum Cost
- Maximum development duration
- Launch date
- Technology maturity (TRL level)
- Risk exposure index

Policy/Agency Constraints:
- Use of European launcher
- International collaboration needs
- Funding model: consortium, geo-return, etc

Regulations and Standards:
- Debris mitigation
- Material limitations

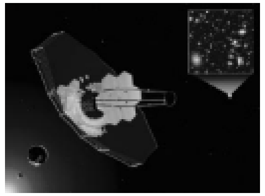
Middle-out Engineering:
- Reuse of existing hardware / SW

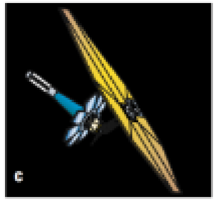


Inputs

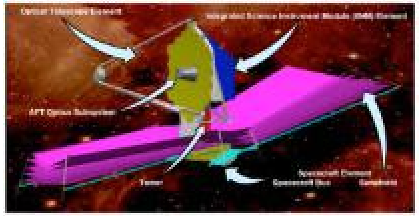
Architecture trade-off

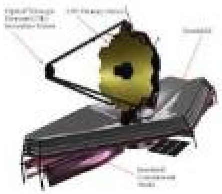
Baseline

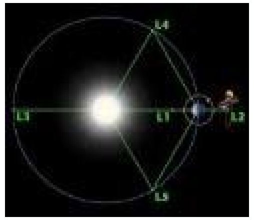


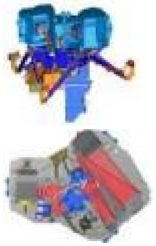


➢ STOCKMAN ET AL (1997) THE NEXT GENERATION SPACE TELESCOPE.









➢ JAMES WEBB SPACE TELESCOPE (HTTP://JWST.NASA.GOV & HTTP://SCI.ESA.INT/JWST)

Requirements Engineering Issues

A few commonly encountered requirements pitfalls:

- Inadequate early requirement **validation**
- "Blind **reuse**" of requirements between projects
- Lack of requirements **justification** and traceability / linkage
- Lack of requirements **priorization**
- Build-up of **conservatism** across requirement / specification layers leading to **overdesign**.
- Lifecycle phasing differences

Requirements Engineering Issues

Ensure requirements are “well written”

- VALID” requirement:
  - - **V**erifiable
  - - **A**chievable
  - - **L**ogical
  - - **I**ntegral
  - - **D**efinitive

Maintain Traceability

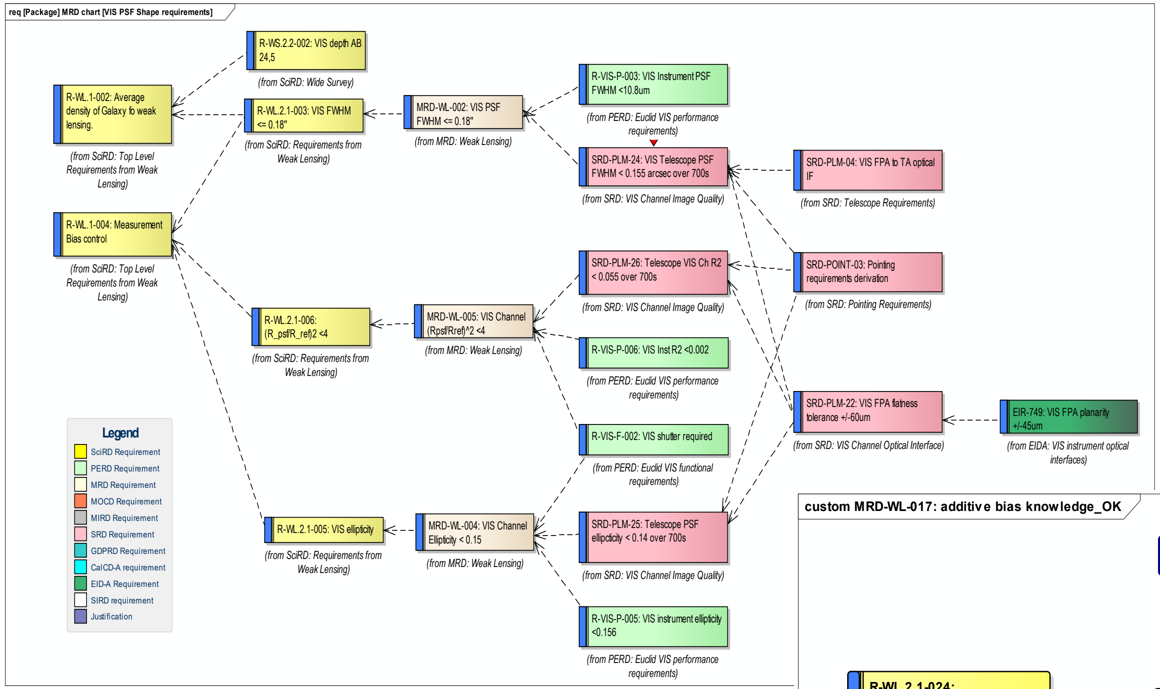
- Link related requirements.
- Few top-level needs translate in 1000s of requirements at lower levels
- Key for problem resolution

Document justification

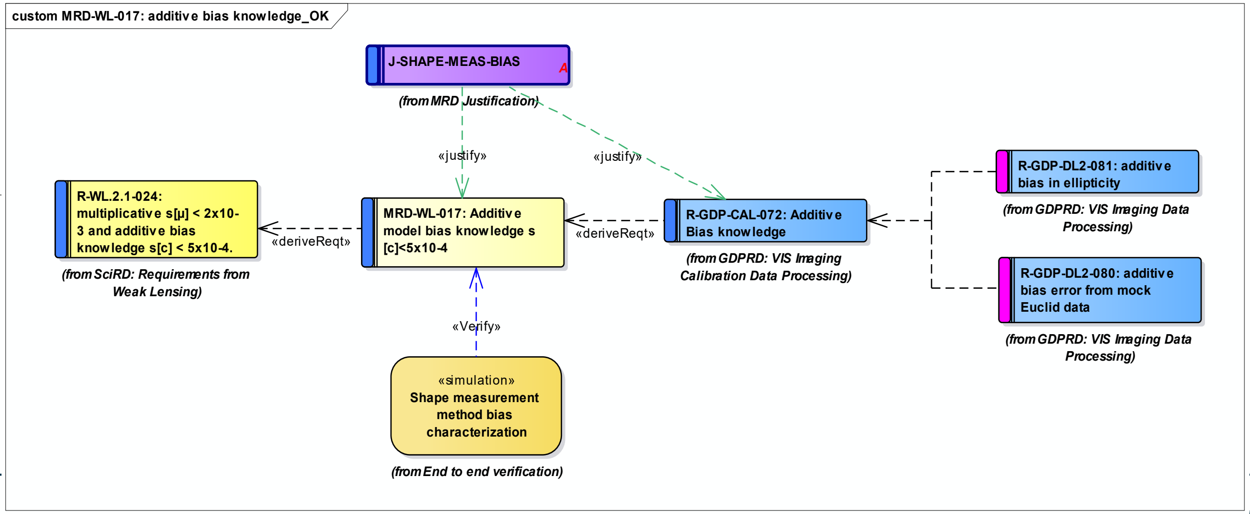
- Know why requirements are in place
- Document logic for every number selected – even if it is a guess, write-it.

Requirements Engineering Issues

Requirements maintenance and traceability



> FROM EUCLID MISSION MODEL: EXAMPLE OF REQUIREMENTS TRACEABILITY AND DOCUMENTATION.



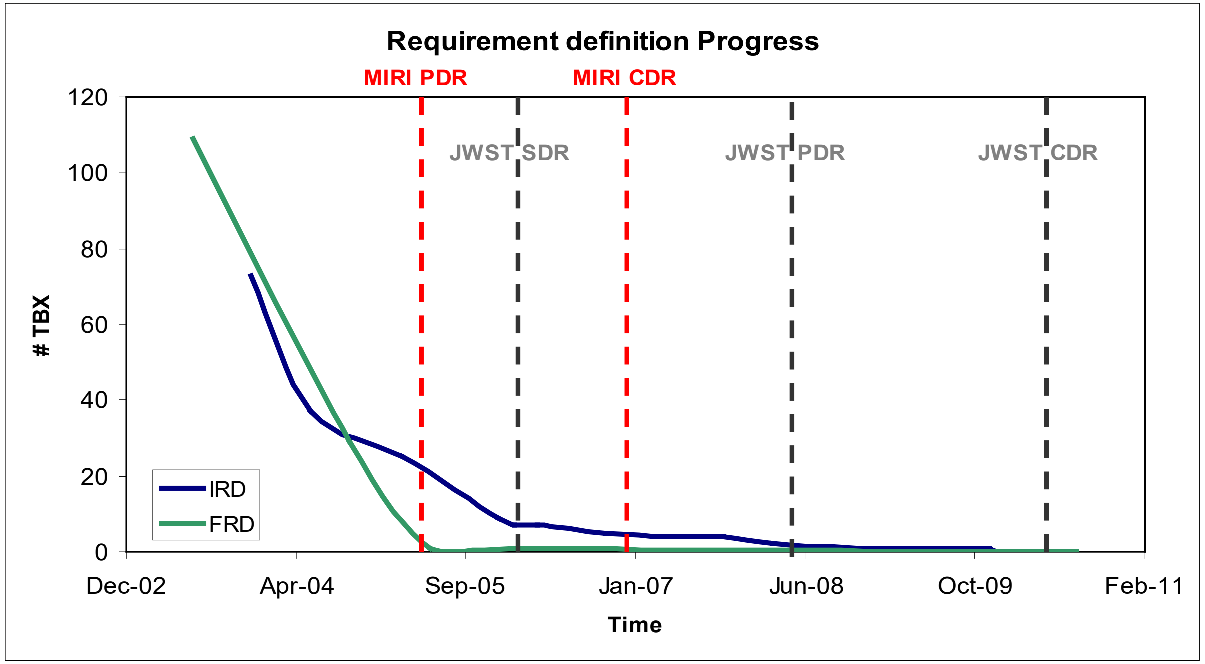
Requirements Engineering Issues

… understand where reqs come from

Requirements Engineering Issues

Common Problem in Scientific Instrument Lifecycle:

- ➢Different life-cycles scheduling between Spacecraft System and Instrument development.
- ➢Can lead to (costly) late changes in the instrument design



> EXAMPLE ANALYSIS ON REQUIREMENTS EVOLUTION FOR JWST MIRI INSTRUMENT

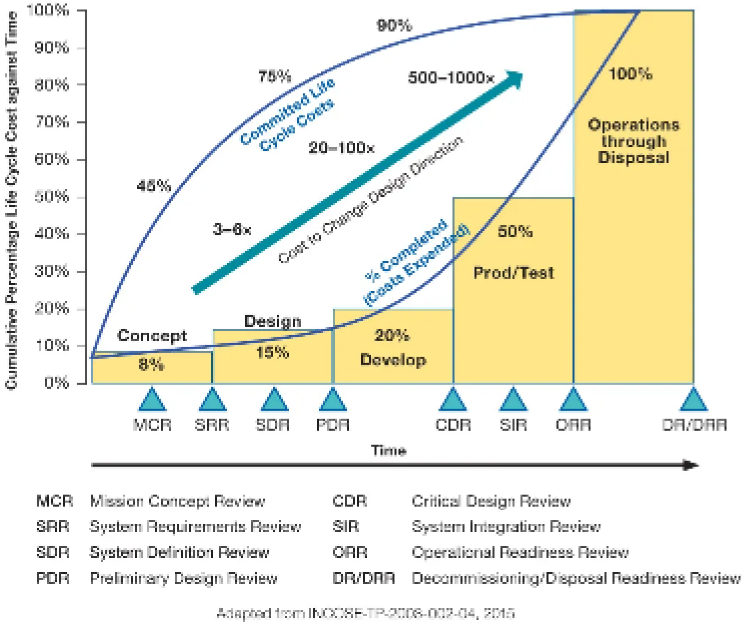


FIGURE 2.5-1 Life-Cycle Cost Impacts from Early Phase Decision-Making

> SOURCE: NASA ENGINEERING HANDBOOK

“New” Engineering Processes

Digitization & MBSE: motivations and ESA approach

Basic need for digitization of Systems Engineering practices:

- **Manage large amounts of (complex) information**
  - Maintain coherent repository(ies) for information / data
  - Record nature of information / data relationships
  - Maintain traceability and data continuity across engineering domains.
  - Allow adequate access to users to <u>common</u> and <u>coherent</u> data sets

*"Get the **right** information, at the **right** time to the **right** people"*

Digitization & MBSE: motivations and ESA approach

"Model Based Systems Engineering" (MBSE) term used loosely to refer to different aspects : digitalization concept, processes, tools, etc.

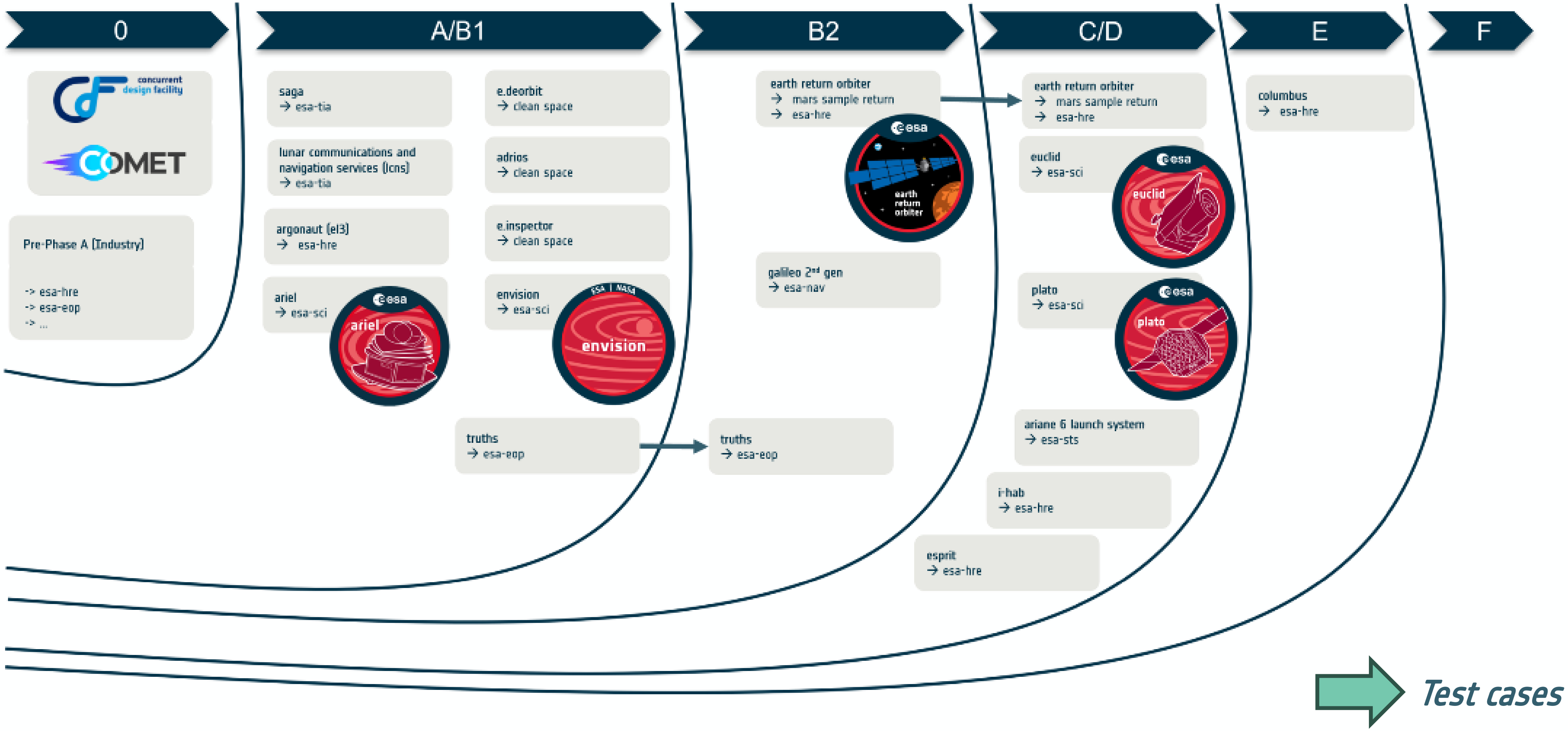
The definition of MBSE we adopt:

- Framework to represent complex systems.
- Model centric approach to data and information management providing unambiguous source-of-truth
- Data models defined to create digital representation of (space) mission elements and their interdisciplinary relationships.
- Part of extended digital engineering approach allowing data continuity across:
    - Disciplines
    - Project life-time
    - Supply chain

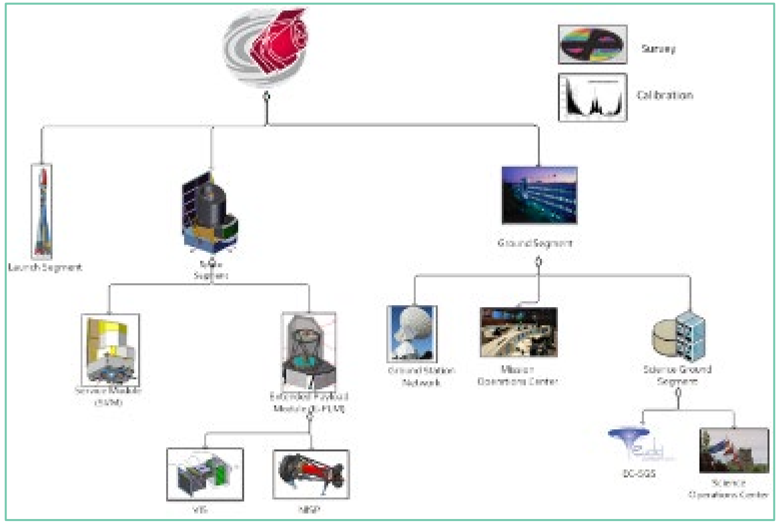
But we are not there yet…

MBSE at ESA

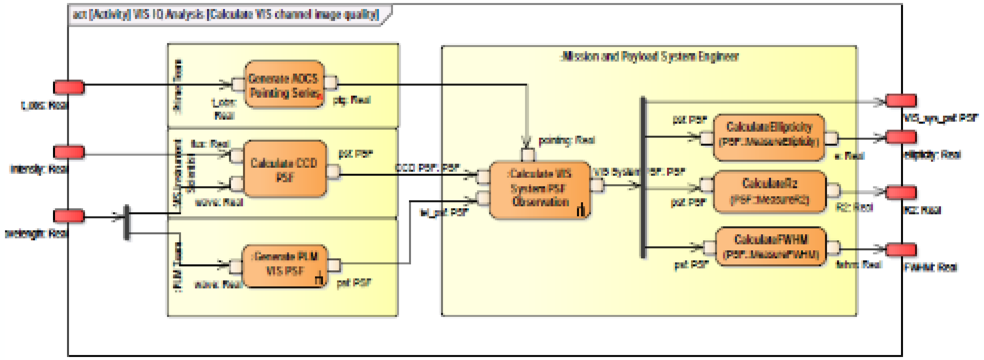
Several ESA missions embraced MBSE approaches already at different project phases



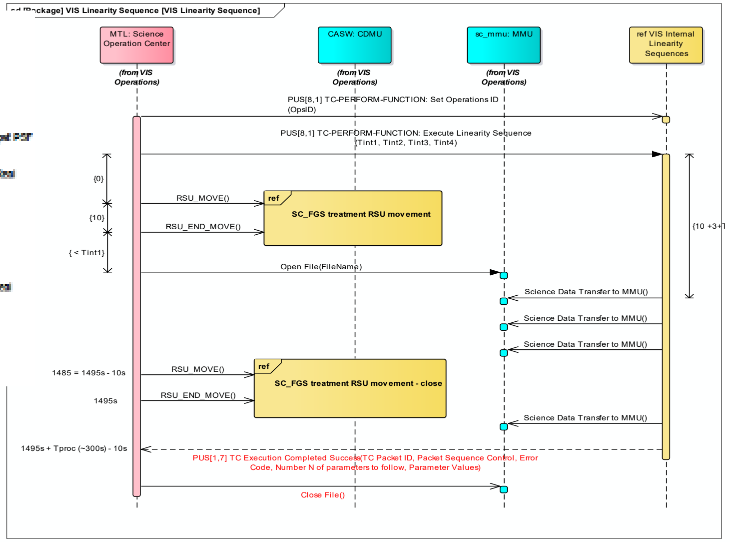
MBSE at ESA



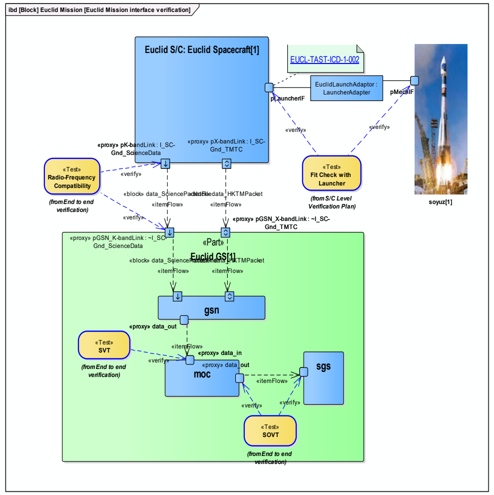
Survey
Calibration
Launch Segment
Ground Segment



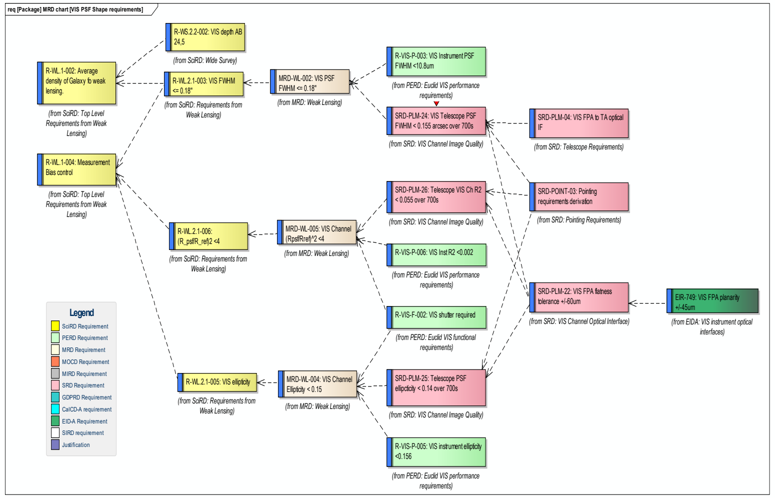
Mission and Payload System Engineer



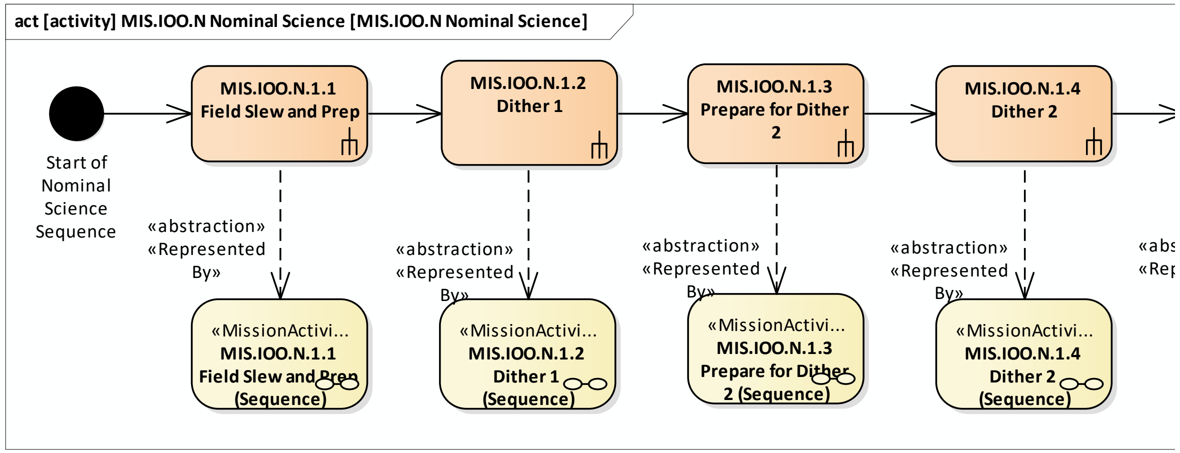
SC_FGS treatment RSU movement
SC_FGS treatment RSU movement - close



Euclid S/C: Euclid Spacecraft[1]
gsn
moc
sgs



Legend



act [activity] MIS.IOO.N Nominal Science [MIS.IOO.N Nominal Science]
Start of Nominal Science Sequence
MIS.IOO.N.1.1 Field Slew and Prep
MIS.IOO.N.1.2 Dither 1
MIS.IOO.N.1.3 Prepare for Dither 2
MIS.IOO.N.1.4 Dither 2
«abstraction» «Represented By»
«abstraction» «Represented By»
«abstraction» «Represented By»
«abstraction» «Represented By»
«MissionActivi... MIS.IOO.N.1.1 Field Slew and Prep (Sequence)
«MissionActivi... MIS.IOO.N.1.2 Dither 1 (Sequence)
«MissionActivi... MIS.IOO.N.1.3 Prepare for Dither 2 (Sequence)
«MissionActivi... MIS.IOO.N.1.4 Dither 2 (Sequence)

MBSE Enablers

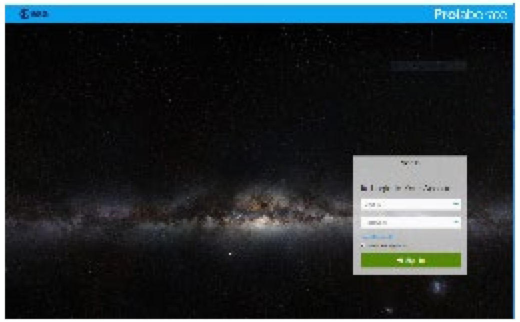
Methodology → MBSECORE

- *Methodology defined*
- *'Toolbox' created based on Space centric datamodel*

Tools and infrastructure → *Infrastructure in D-SCI*

- *Common internal Cloud infrastructure created.*
- *Simplified overhead effort for new projects*
- *Standard model structure defined*

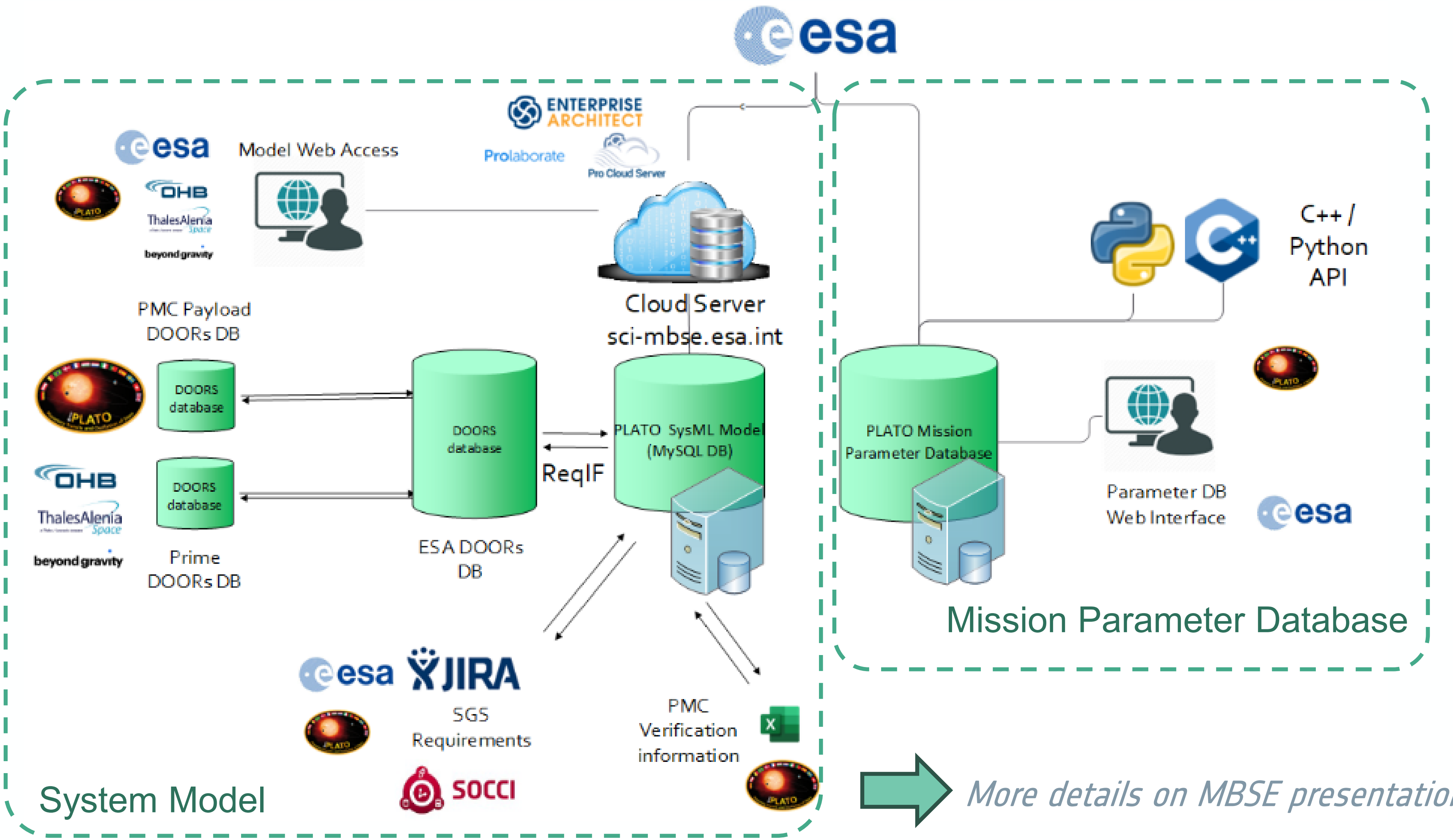
Accessibility →



- *Improvement on web access tools*
- *Creation of Dashboards for model access and search.*

Toolsets becoming more user friendly

PLATO MBSE Architecture



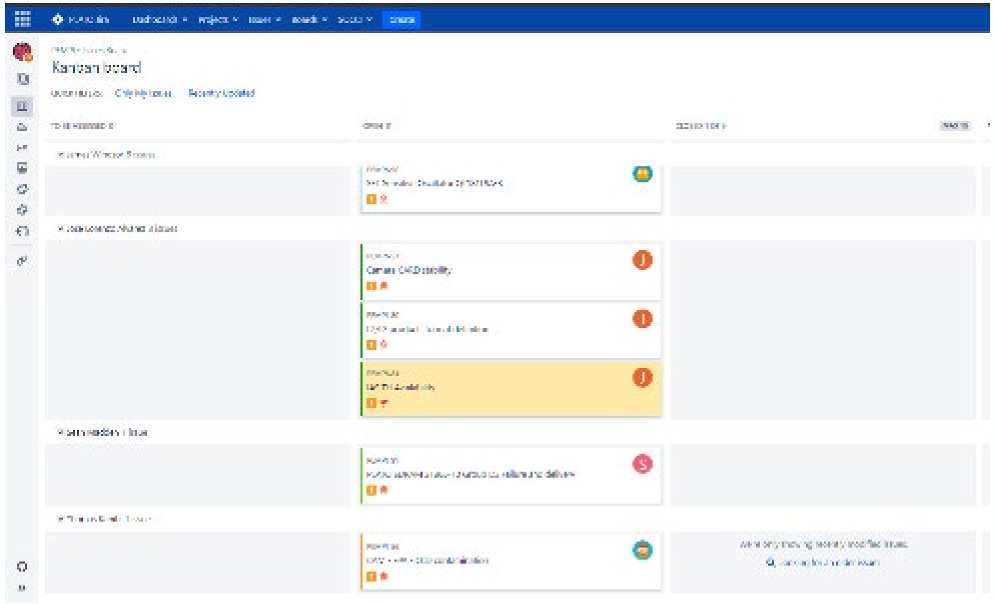
More details on MBSE presentation tomorrow

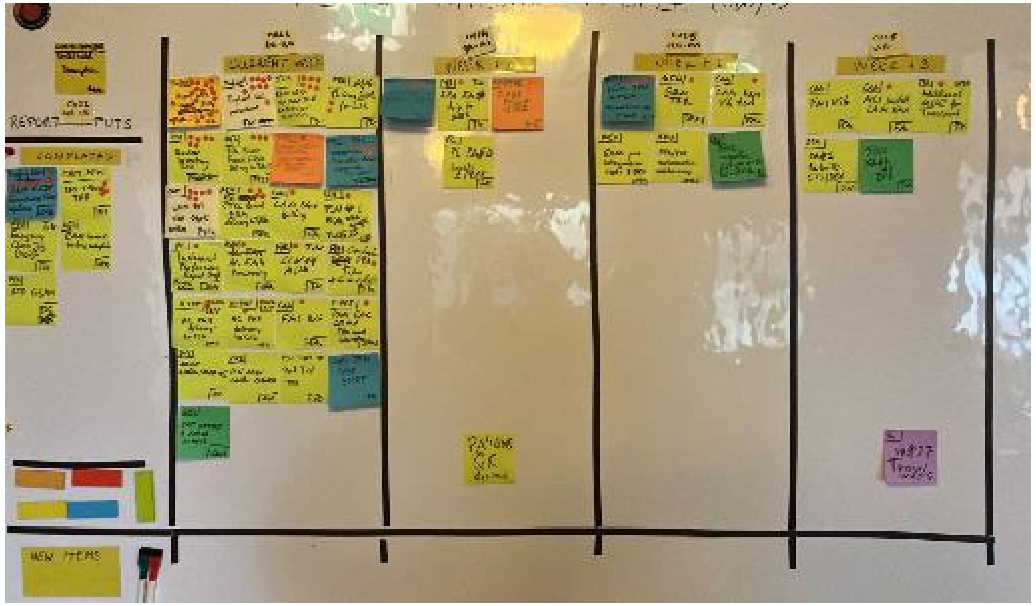
Agile Systems Engineering

Agile methodologies widely used for Software projects development.

- Development broken down into 'features' **incrementally** incorporated and validated in dedicated **Sprints.**

Approach extended to manage team activities and tasks in HW/SW development





Would be glad to exchange over coffee/lunch break