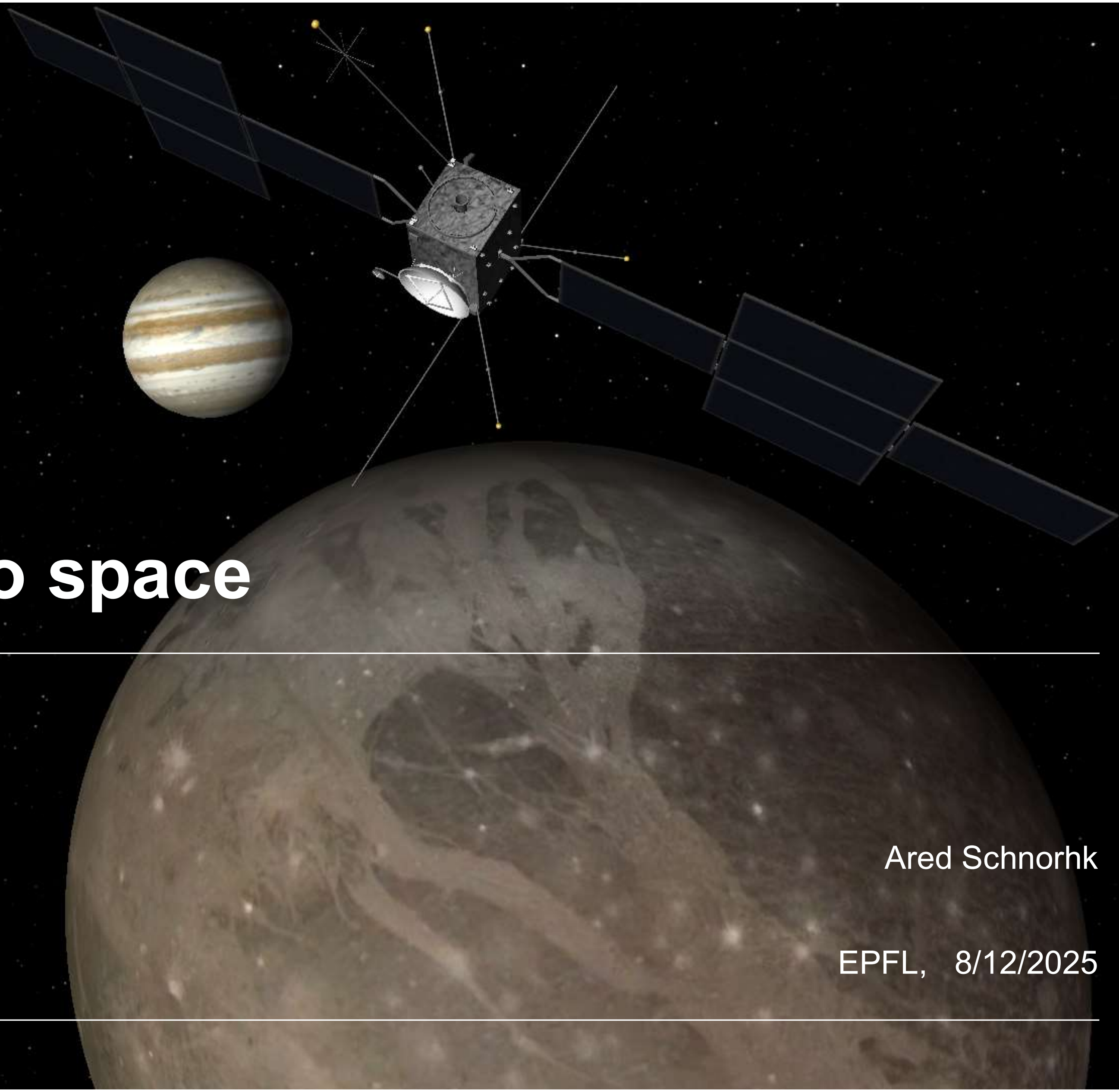


Spacecraft AIT

JUICE from design to space

Ared Schnorhk

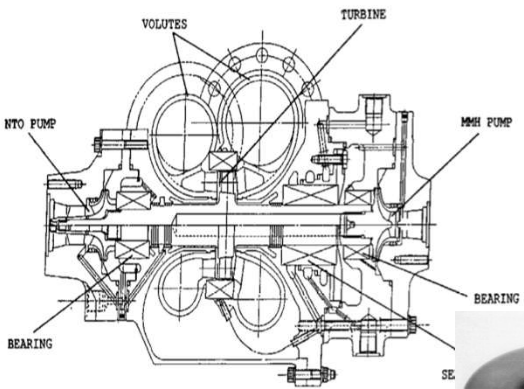
EPFL, 8/12/2025

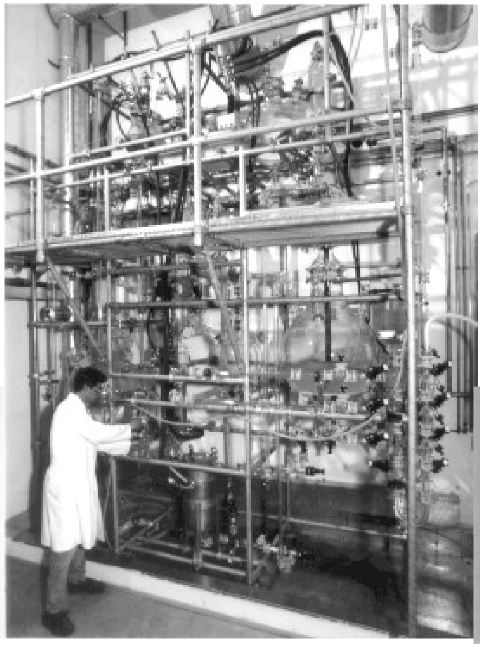
Content

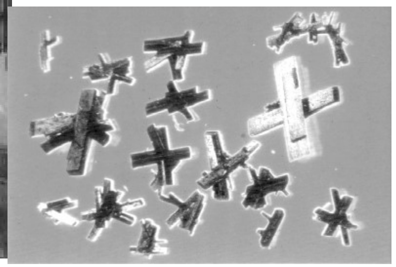
- Introduction
- Spacecraft AIT
- The JUICE case (launched 14. Apr. 2023)
- Other experienced cases (very shortly)
- A few lessons learnt

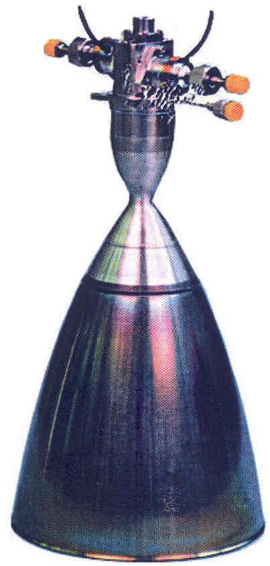
My 35 years of experience at ESA-ESTEC
(from propulsion trainee to JUICE AIT & Launcher IF manager)

- Ared Schnorhk, Swiss from St-Maurice in Bas-Valais.
- EPFL diploma in 1987 and started as Young Graduate Trainee for a year at ESA-ESTEC in Noordwijk, the Netherlands
- Support on design of turbomachinery for rocket engines, new solid propellant development, support to science projects like: **SOHO** (launched in 1995), **XMM** (1999) and **INTEGRAL**





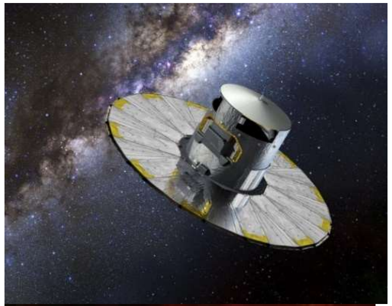


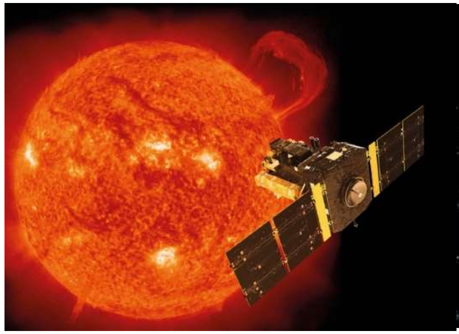


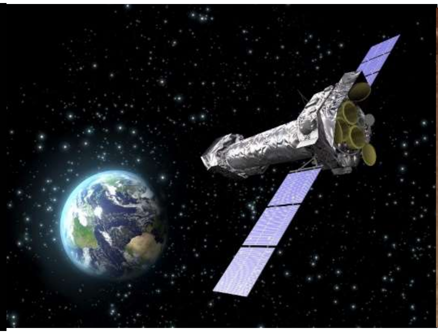
My 35 years of experience at ESA-ESTEC

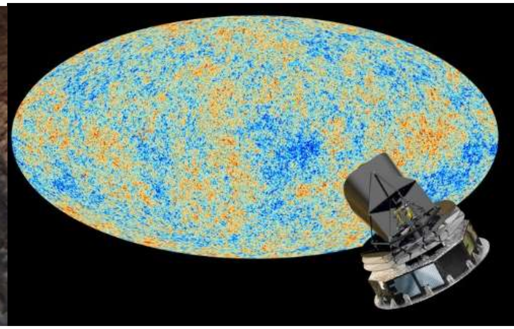
Joined in 1998 the Science Projects department after SOHO Recovery and participated to:

Project	Launch	Launcher	Function
CLUSTER2	2000	1st Soyuz Fregat	Mechanical & propulsion
MarsExpress	2003	Soyuz Fregat	Mechanical, propulsion, launcher
VenusExpress	2007	Soyuz Fregat	Mechanical, thermal, propulsion, launcher
Herschel/Planck	2009	Ariane 5	Mechanical, propulsion, launcher
GAIA	2013	Soyuz Fregat	AIT & Launcher interface manager
JUICE	2023	Ariane 5	AIT & Launcher interface manager









My 35 years of experience at ESA-ESTEC

In Total

- **12 S/C launched** (all completed better than the planned mission, 9 are still in operation)
- Participation to **8 Launch campaigns**
- **3 different launchers:** Atlas, Soyuz, Ariane 5
- **from 3 different launch sites** Kennedy (KSC), Baikonur and Kourou (CSG)

Content

- Introduction
- What's Spacecraft AIT
- The JUICE case
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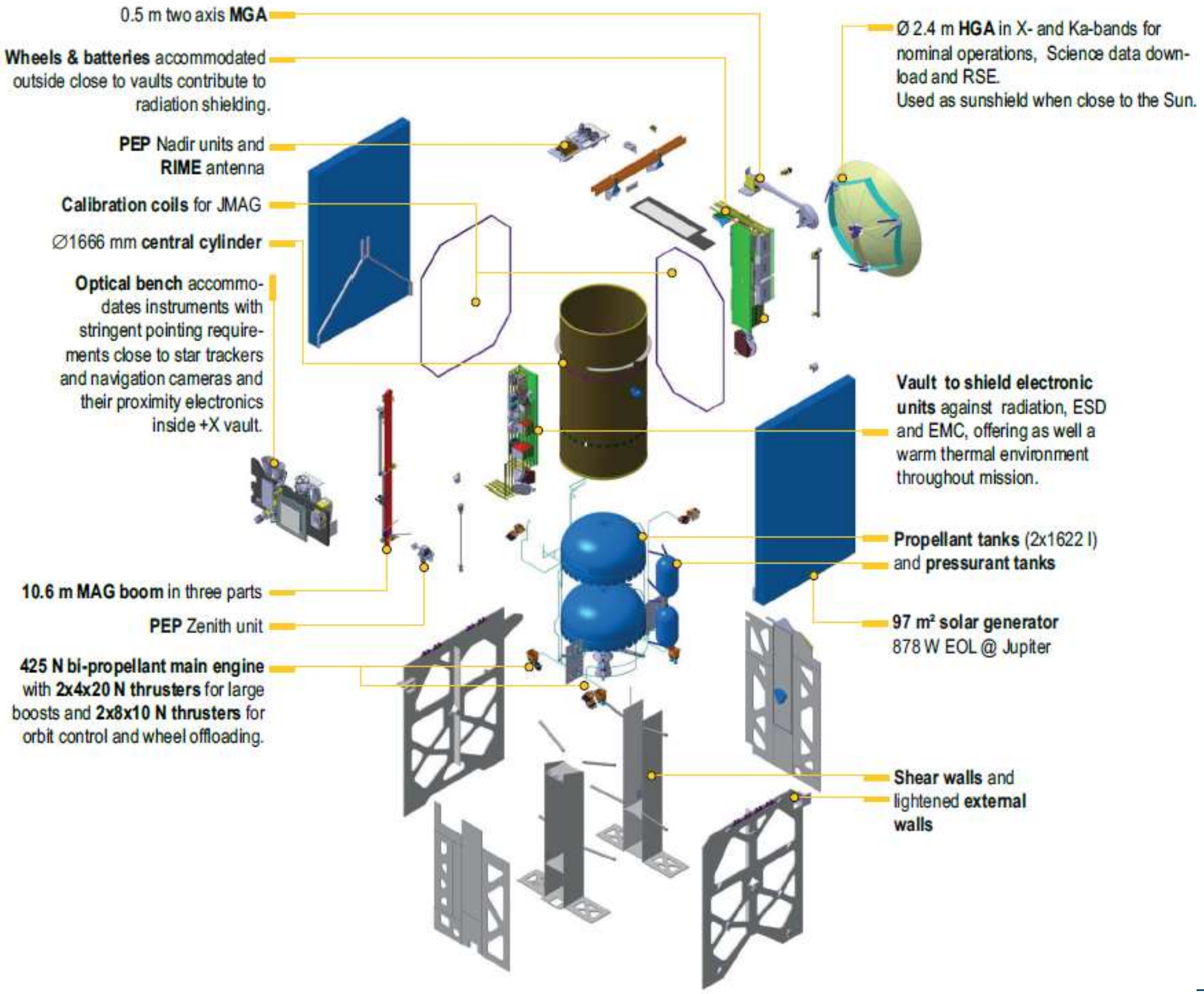
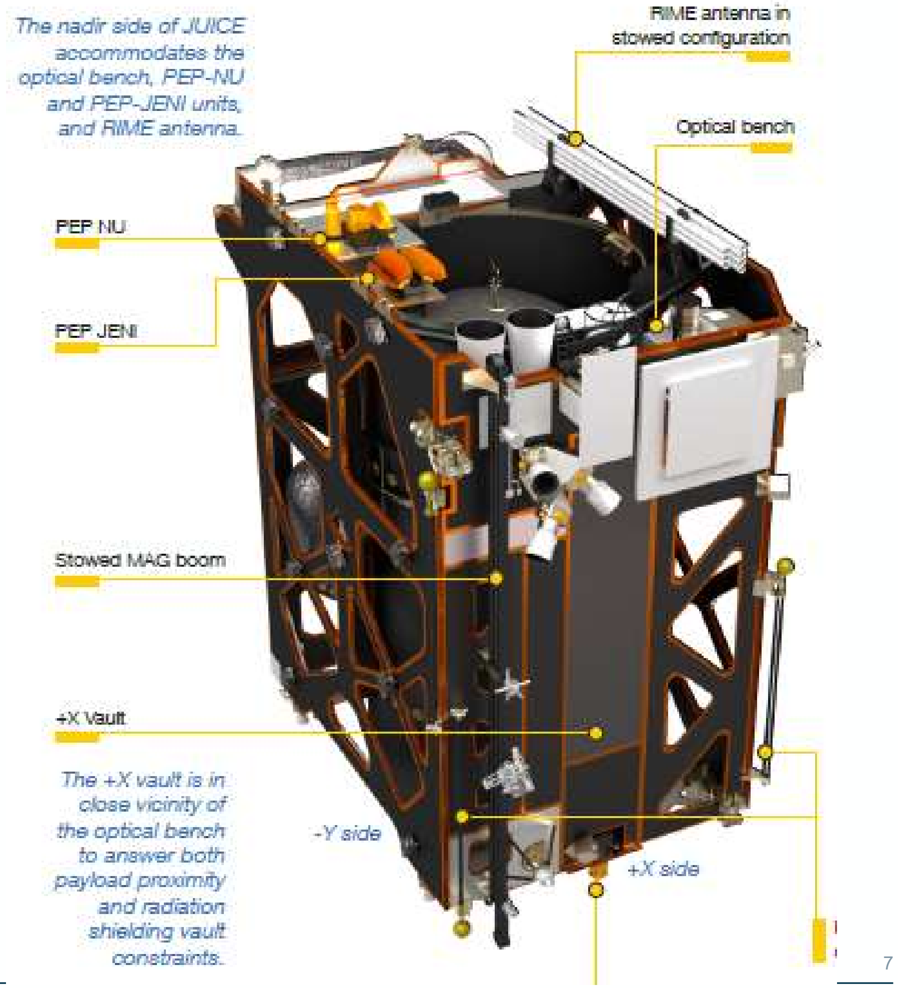
What's a Spacecraft (JUICE JUpiter ICy moons Explorer)





What is spacecraft AIT ? (the theory)

In short :

The manufacturing of a design, including:

- its Verification and
- its Validation

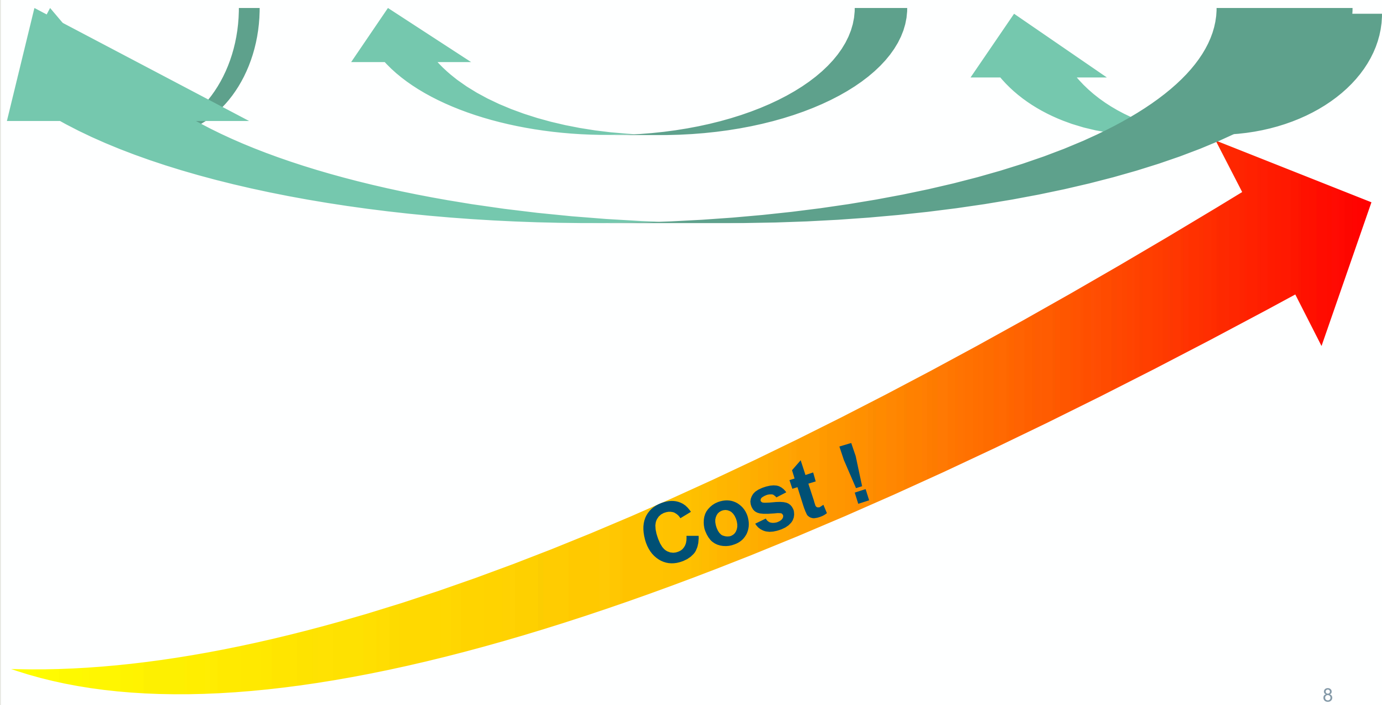
within an allocated:

- Schedule
- Budget
- Quality & Risk level

Major constraint: No physical access after lift off

Applied to all system levels:

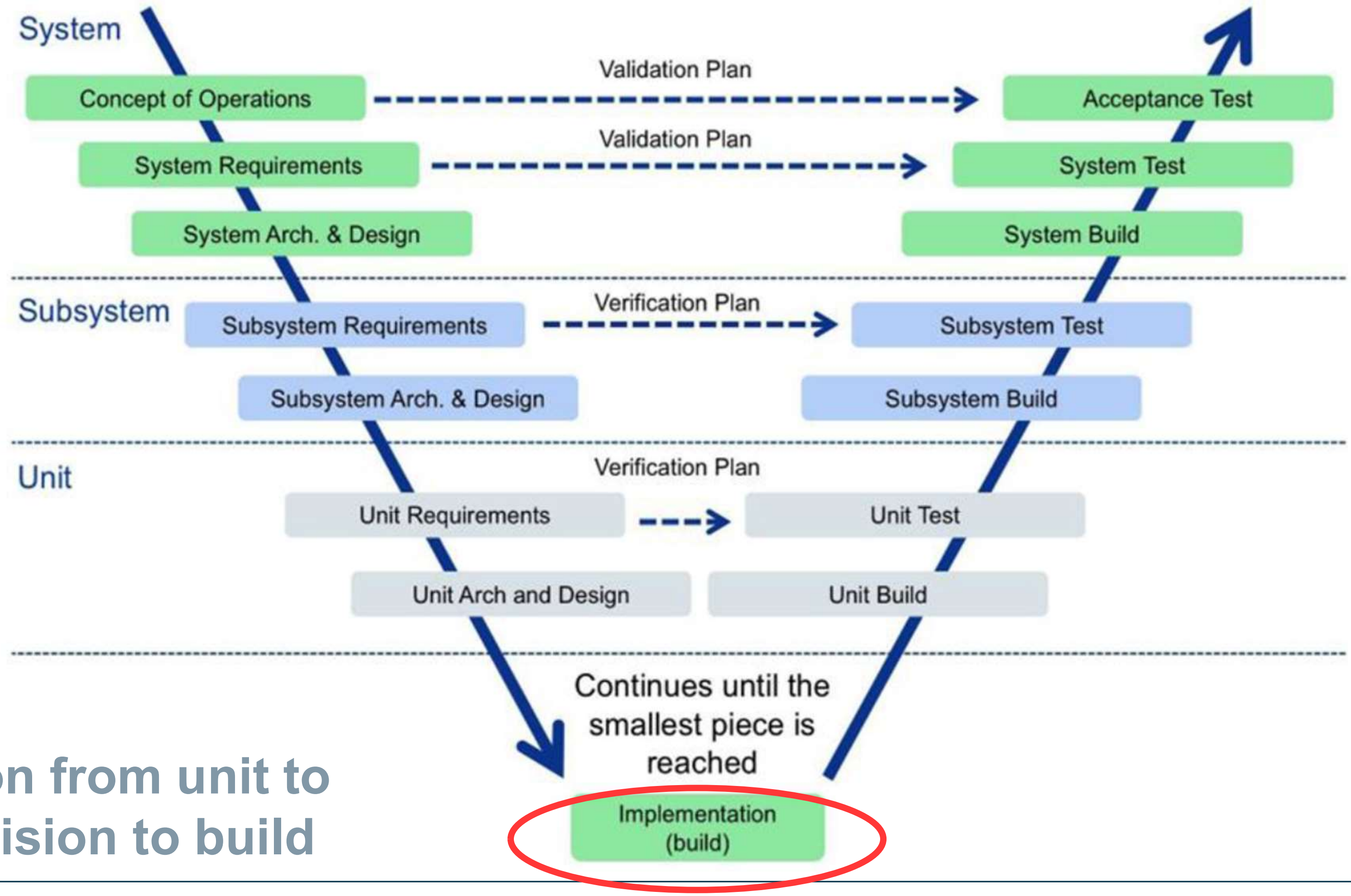
Unit → Subsystem → System



What is spacecraft AIT ? (the theory)

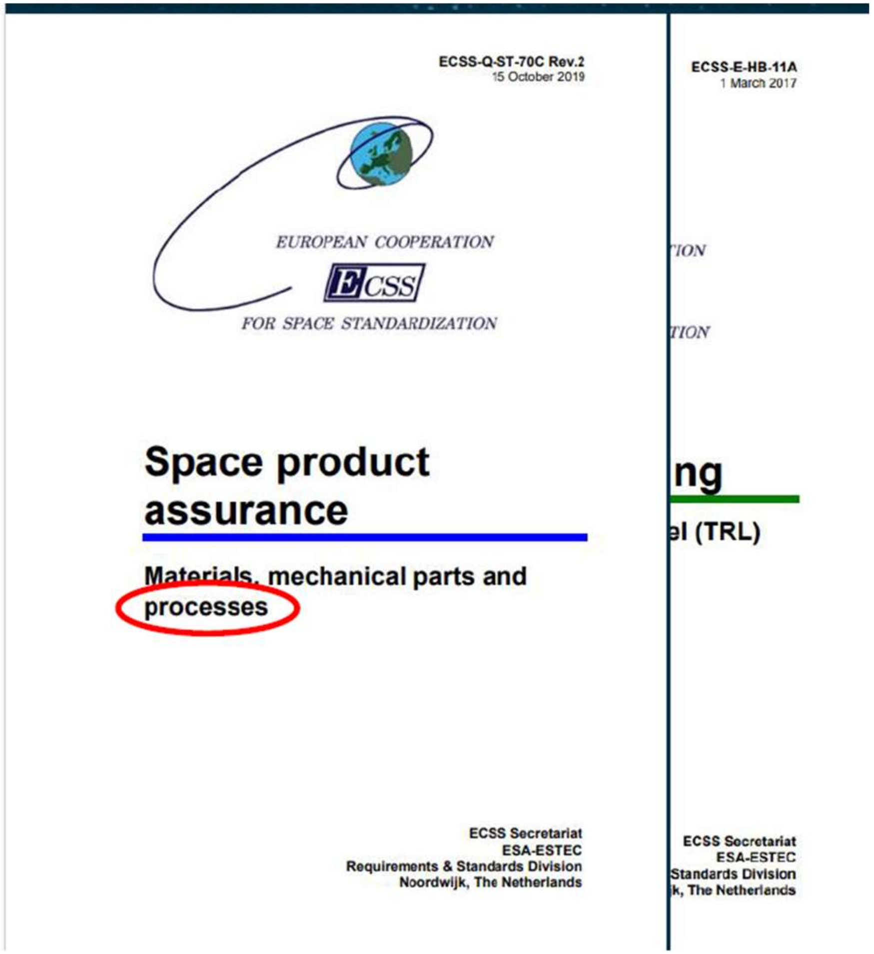
V – Shape

Development approach

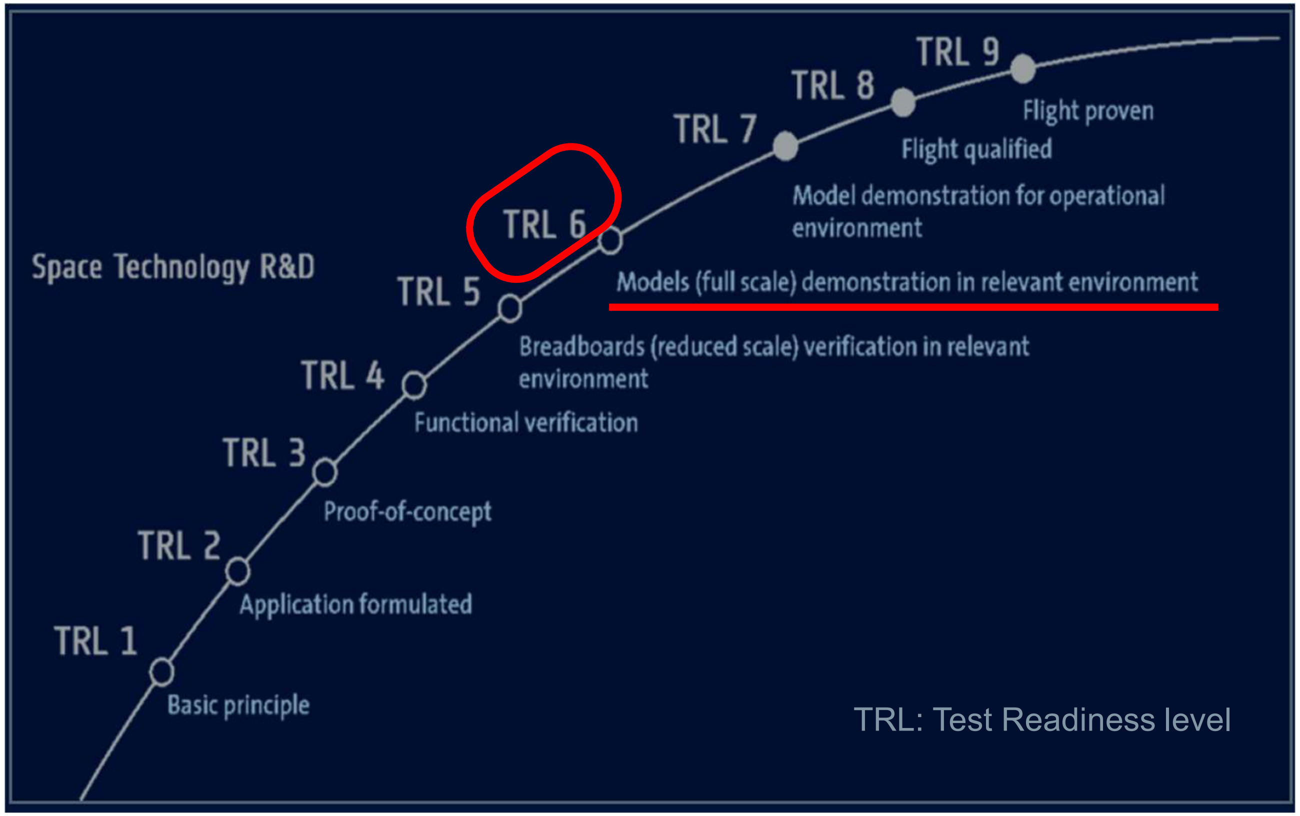


Critical transition from unit to assembly / Decision to build

What is spacecraft AIT ? Technology & Processes Readiness



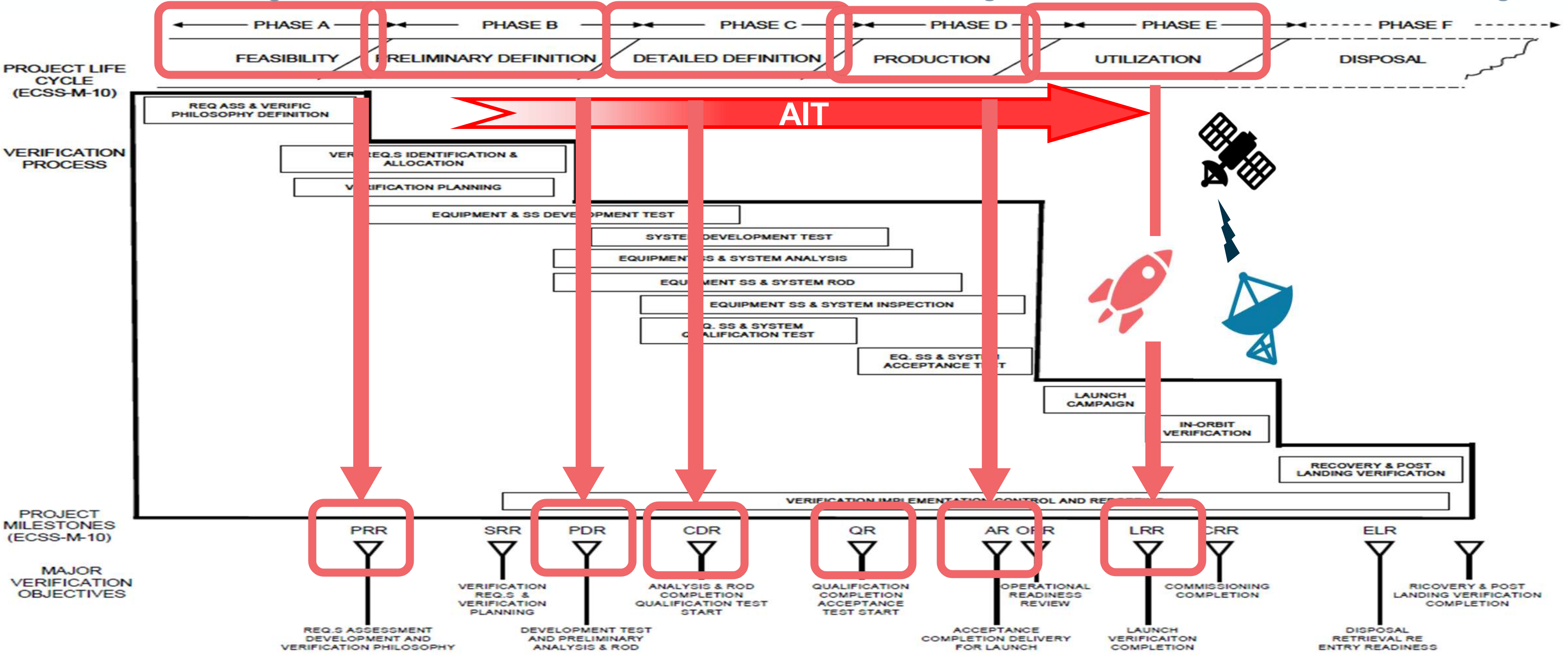
Transition from unit to assembly/system level for critical technologies at TRL > 5



What is spacecraft AIT ? (Planning & Phasing)

Project Phasing as per ECSS-E-HB-10-02A Verification Handbook

ECSS-E-ST-10-03C Testing ECSS-E-ST-10-02C Verification; ECSS-M-ST-80C Risk Mangmt; ECSS-M-ST-60C Cost & Schedule Mangmt



What is spacecraft AIT ? (Documentation)

❑ Documentation in preparation of AIT activities (Phase B & C) …

- Several ESA – ECSS, ISO and MIL standards defining development phases (A,B,C…) and reviews
- Statements of Work (SoW), AIT and Test plans (at unit, subsystems and systems levels)
- Schedules

❑ Lot of tests to prepare (at unit, subsystems and systems levels)

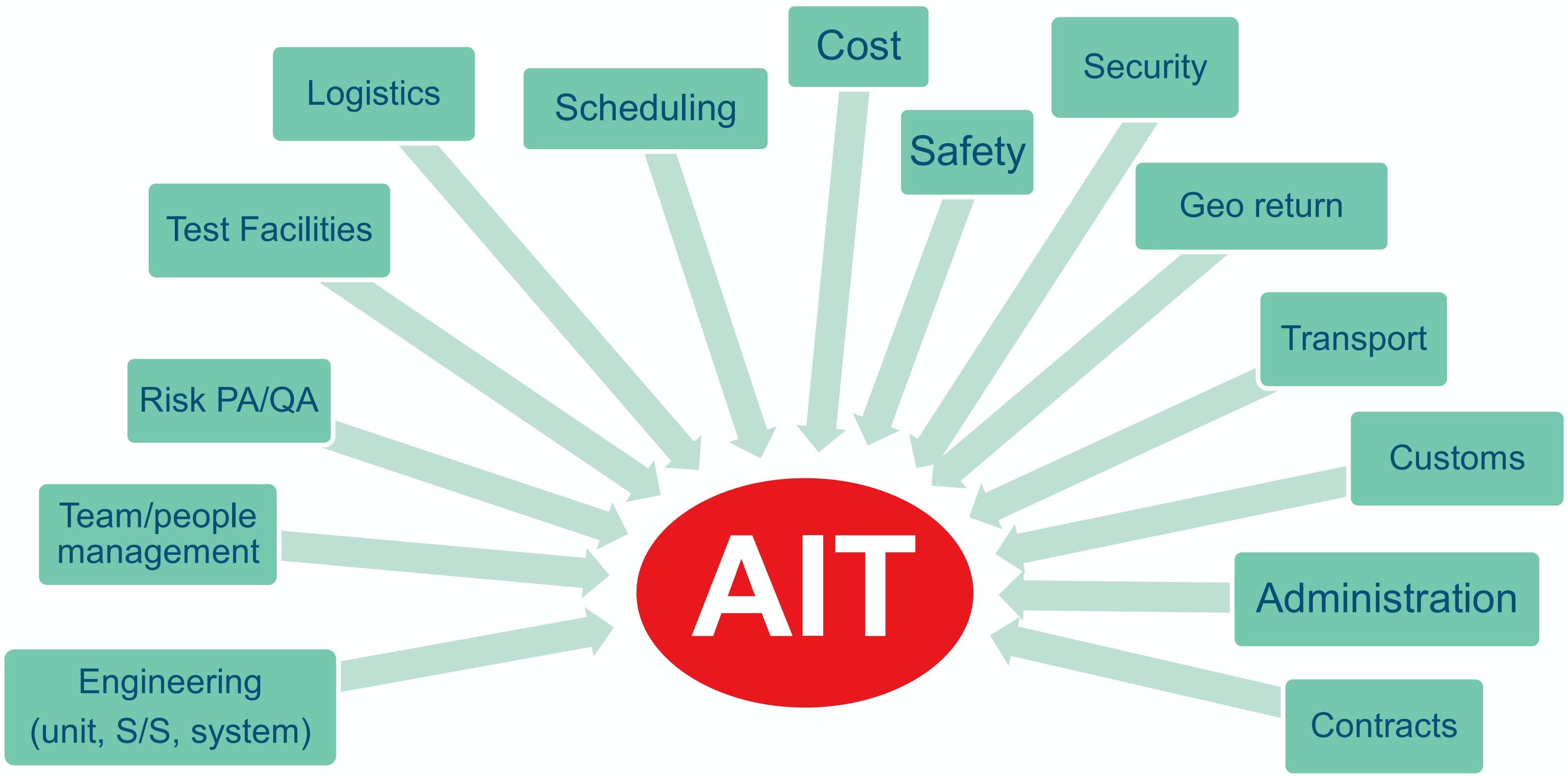
- Functional & RF — for S/W & RF verification & validation (S/C Electrical Model)
- Vibration (sine & acoustic) — for launch environment compatibility verification/validation
- Thermal — for space environment compatibility verification/validation
- EMC — for conductive, emissivity, susceptibility verification/validation

❑ Test documentation and reviews (at unit, subsystems and systems levels)

- Specification ➔ Test Specification Reviews (**TSR**) ➔ Procedures ➔ Test Readiness Reviews (**TRR**) ➔ **Test** ➔ Post-Test Reviews (**PTR**) ➔ Analyses ➔Test Review Board (**TRB**)
- Anomalies management system (under **PA/QA**) to trace issues later-on, solve them efficiently and eventually draw generic lessons

What is spacecraft AIT ? (the practice)

… and a lot of different disciplines brought into PRACTICE (Phase D)



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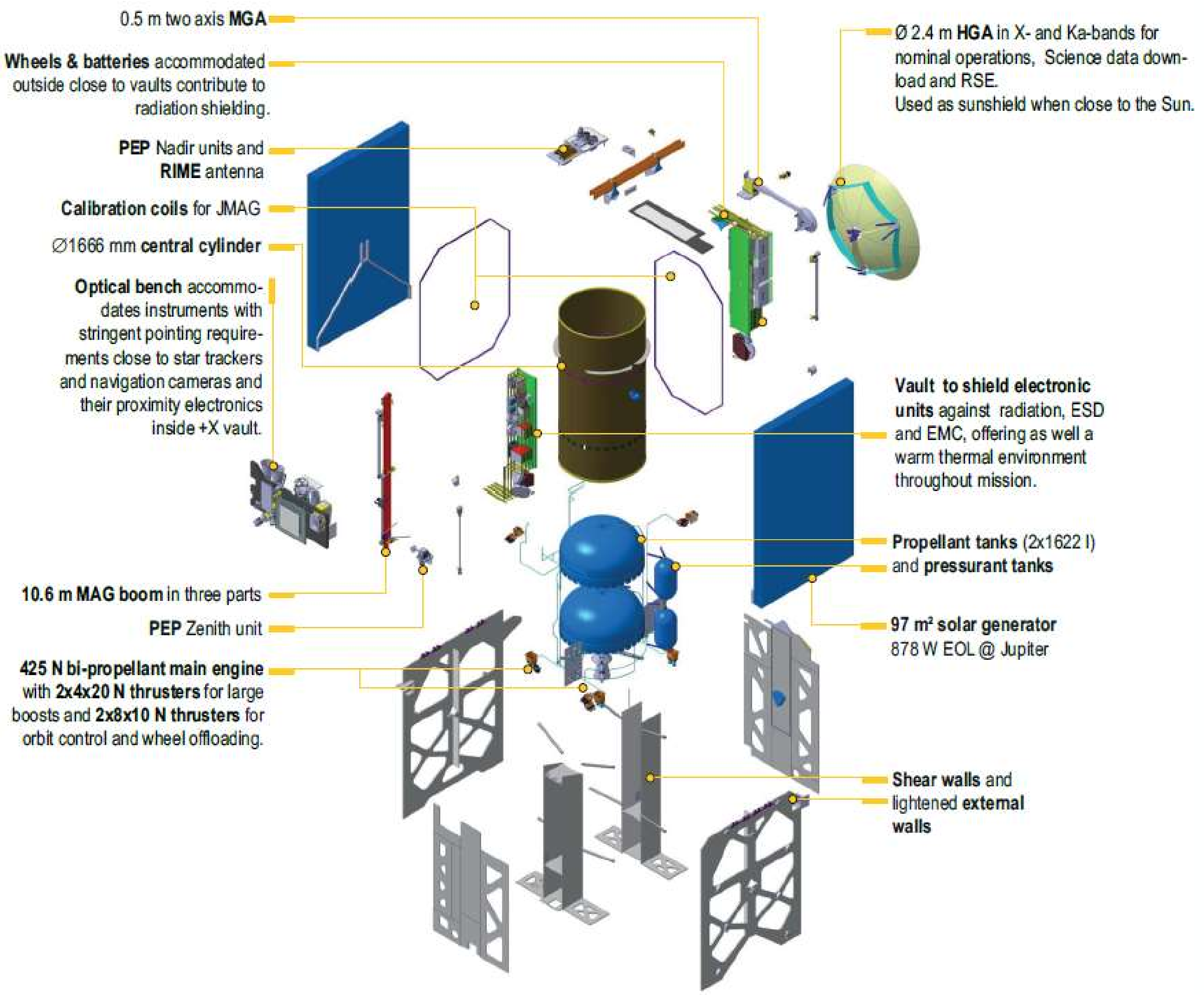
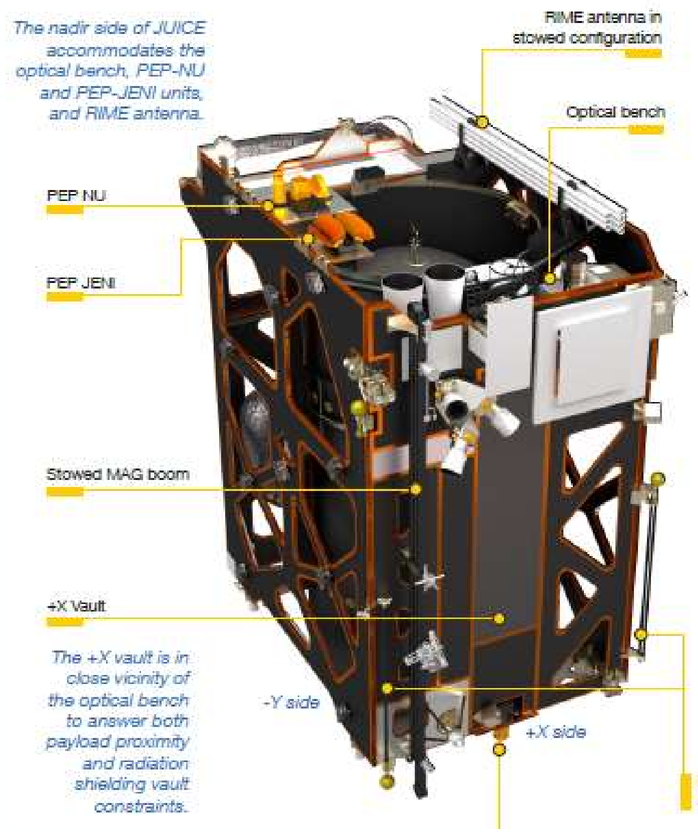
JUICE key design drivers (1/2)

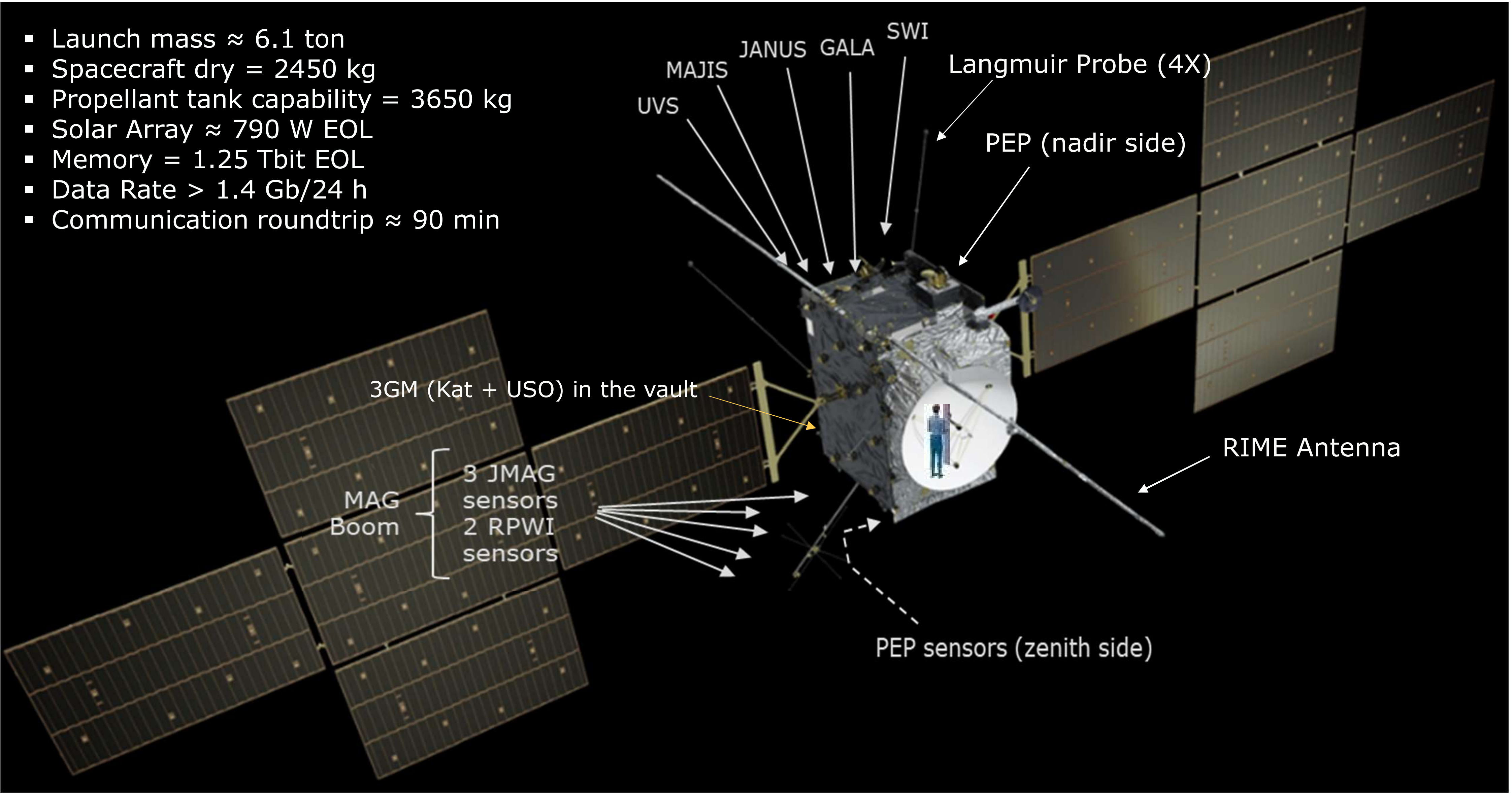
- **Power availability**
  - Jupiter is at 778.5 Million Km from the Sun (5.2 times further than Earth)
  - Solar flux is around 50 W/m2
  - Solar cell efficiency 26% (BOL), degradation (EOL), power distribution efficiency, margins for failure cases
  - Solar array size 85 m2 → 725 W
- **High and low temperatures**
  - Very hot around Venus fly-by → 3.3 kW/m2 → solar array at 150 C
  - Very cold at Jupiter → 50 W/m2 → solar array down to -220 C
- **Radiation Environment**
  - Harsh radiation environment in the Jovian system → TID up to 25 Mrad external to the spacecraft
  - Careful selection of radiation resistant electrical component and materials
  - Shielding of all electronic equipment and harness → mass
- **EMC**
  - Several instruments measuring fields and particles; very sensitive to EMC disturbances on ground (during S/C test) and in flight from the S/C itself from: - Reaction Wheels - Solar array - Solar array drive mechanisms - Power Control and Distribution Unit
  - E.g. the spacecraft generated magnetic field shall be < 1 nT (10-9 Tesla) which is 50000 times less than the Earth magnetic field
- **Mechanisms**
  - Number of deployment mechanisms, some to be developed

JUICE key design drivers (2/2)

- **Launcher**
  - Powerful and reliable launcher
  - End of Ariane 5 at production and several delays impacted Ariane 6 development
  - Last Ariane 5 available to be ordered and booked very early
  - 2 launch windows of a month per year
- **Navigation**
  - 5 fly-by during the cruise to Jupiter and critical JOI (Jupiter Orbit Insertion) in autonomy
  - Signal turnaround time at Jupiter (Earth station-spacecraft-Earth station) 1.5 h
  - 26 fly-by during the Jupiter Tour: Europa (2x), Ganymede (11x), Callisto (13x)
  - Ganymede orbit insertion and 500 km polar orbit (gradually lowered to few 10’s of km before controlled crash)
  - Navigation Camera for autonomous operation
- **Contractual set-up**
  - Unit procurement spread over all ESA member states (>85 contracts from companies in >20 countries)
  - Some companies with very limited experience in space
  - 11 scientific instruments from 18 universities & institutes with limited autonomy on budget and manpower
  - No contracts with Scientific instruments ie. limited lever arm to stimulate compliance with schedule for deliveries


0.5 m two axis **MGA**
Wheels & batteries accommodated outside close to vaults contribute to radiation shielding.
PEP Nadir units and **RIME** antenna
Calibration coils for JMAG
Ø1666 mm **central cylinder**
Optical bench accommodates instruments with stringent pointing requirements close to star trackers and navigation cameras and their proximity electronics inside +X vault.
10.6 m MAG boom in three parts
PEP Zenith unit
425 N bi-propellant main engine with **2x4x20 N thrusters** for large boosts and **2x8x10 N thrusters** for orbit control and wheel offloading.
Ø 2.4 m **HGA** in X- and Ka-bands for nominal operations, Science data download and RSE.
Used as sunshield when close to the Sun.
Vault to shield electronic units against radiation, ESD and EMC, offering as well a warm thermal environment throughout mission.
Propellant tanks (2x1622 l) and **pressurant tanks**
97 m² solar generator 878 W EOL @ Jupiter
Shear walls and lightened **external walls**

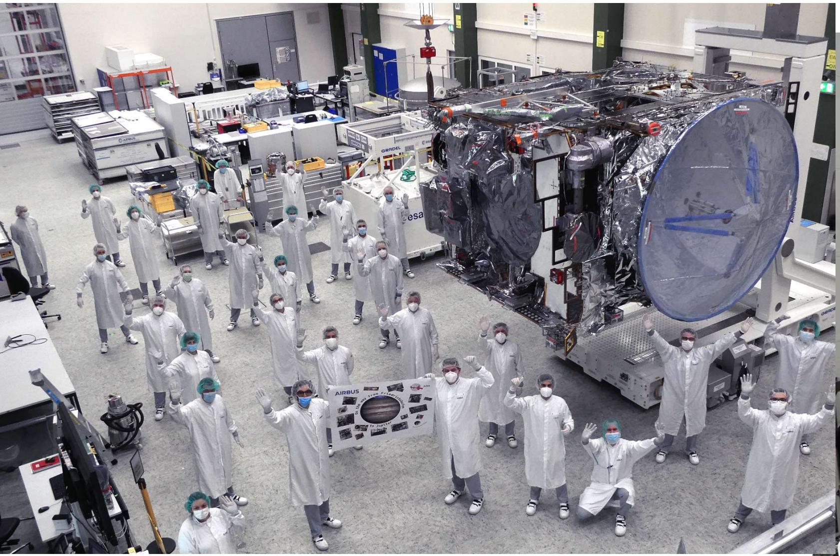

The nadir side of JUICE accommodates the optical bench, PEP-NU and PEP-JENI units, and RIME antenna.
RIME antenna in stowed configuration
Optical bench
PEP NU
PEP JENI
Stowed MAG boom
+X Vault
The +X vault is in close vicinity of the optical bench to answer both payload proximity and radiation shielding vault constraints.
-Y side
+X side



Launch mass ≈ 6.1 ton
Spacecraft dry = 2450 kg
Propellant tank capability = 3650 kg
Solar Array ≈ 790 W EOL
Memory = 1.25 Tbit EOL
Data Rate > 1.4 Gb/24 h
Communication roundtrip ≈ 90 min
UVS
MAJIS
JANUS
GALA
SWI
Langmuir Probe (4X)
PEP (nadir side)
3GM (Kat + USO) in the vault
MAG Boom
3 JMAG sensors
2 RPWI sensors
RIME Antenna
PEP sensors (zenith side)

JUICE AIT

https://youtu.be/HDWb2rK72kk?si=9zB-ySpvohlGoNaW; https://www.youtube.com/watch?v=TOKyzXulb-Y



Team motivation, flexibility and experience are good assets.

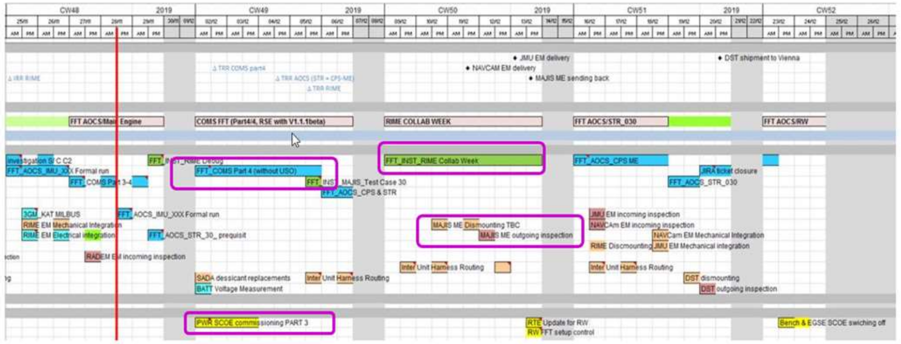
Large teams particularly when working in shifts.

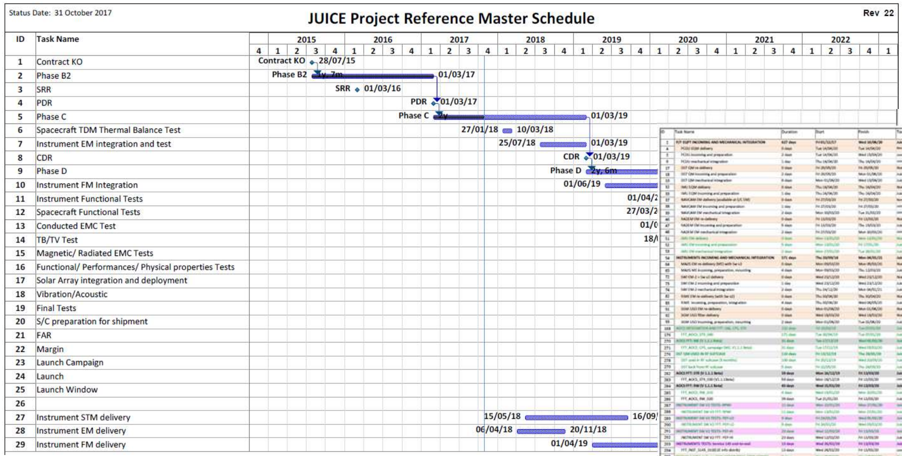
All participants are important (including cleaners) with adequate competence

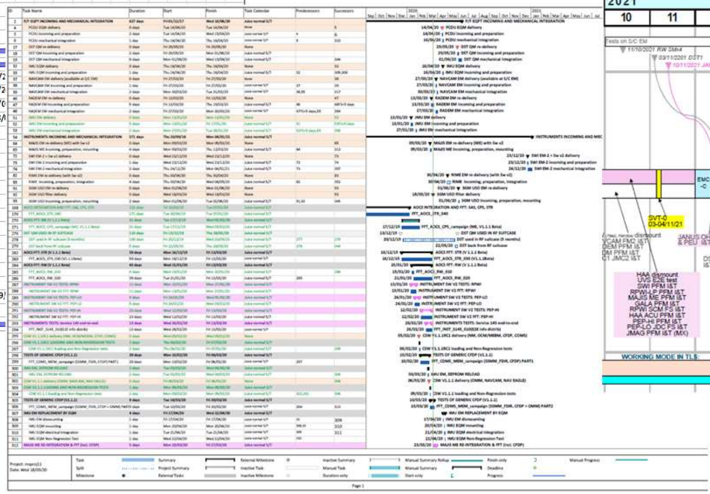
Schedule approach & control

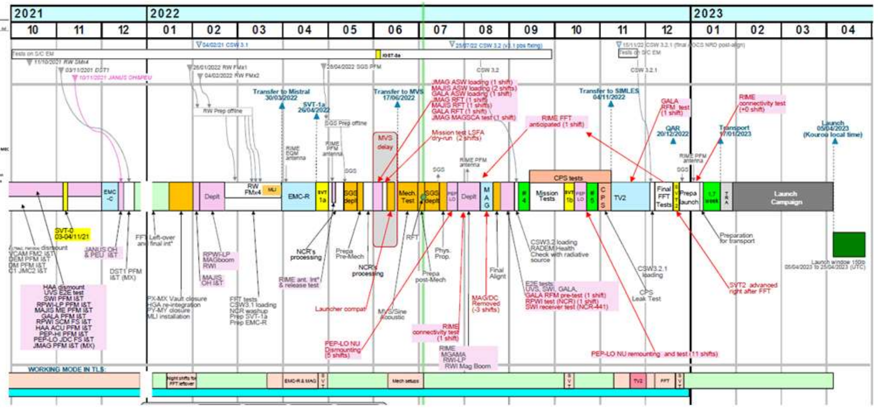
Different levels of schedules:

- Master schedule (top level, overall view, public)
- Detailed schedules (mid-term view, trade-offs, decision)
- AIT schedule (3 weeks working level detailed)
- Simulations to select best approach for long term

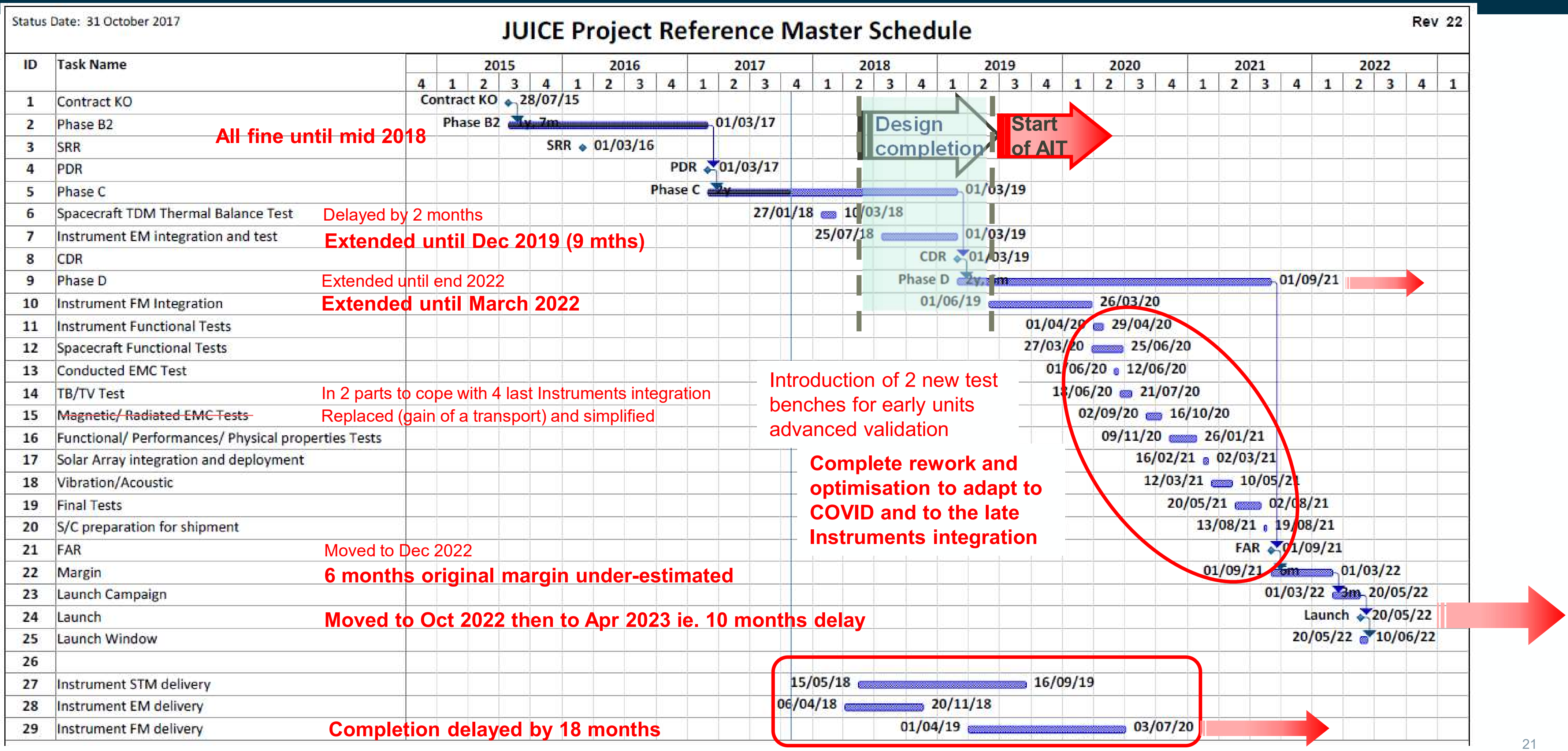








JUICE Master Schedule (at end 2017)



Issues impacting the original schedule

Issue	*Mitigation action*
Late start (and then delivery) of several instruments ▪ 6 months impact	*Management pressure via state representatives, implementation of support from ESA, introduction of 2 new test benches, simplified magnetic test and introduction of a 2nd thermal test*
COVID pandemic ▪ 2,5 -3 months impact	*Authorisation from highest level for on-site team work and travel*
2x flooding of the S/C Engineering Model (SEM) ▪ 3-4 weeks impact	*Removal of dirt from nearby works then piping correction*
“zero risk” approach on the validation of a complex S/W ▪ 2-3 weeks impact	*ESA support for coordination with instruments*
Divergence in AIT approach to apply between Prime teams ▪ 1 week impact	*ESA project management pressure*
Priority to access some facilities given to other projects ▪ 1 week impact	*ESA project management pressure*
2 Launch windows per year	*Early launcher procurement, clear schedule information, ESA project management pressure*

AIT Start and early development models

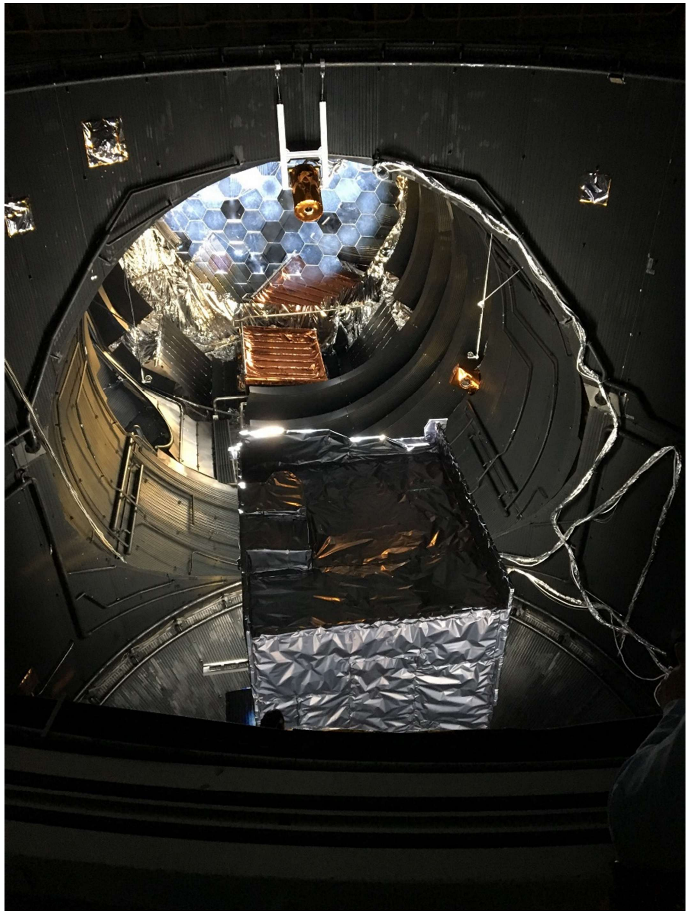
Apr-May 2018

Development of the new thermal protection with 2 solar constants LSS simulator.

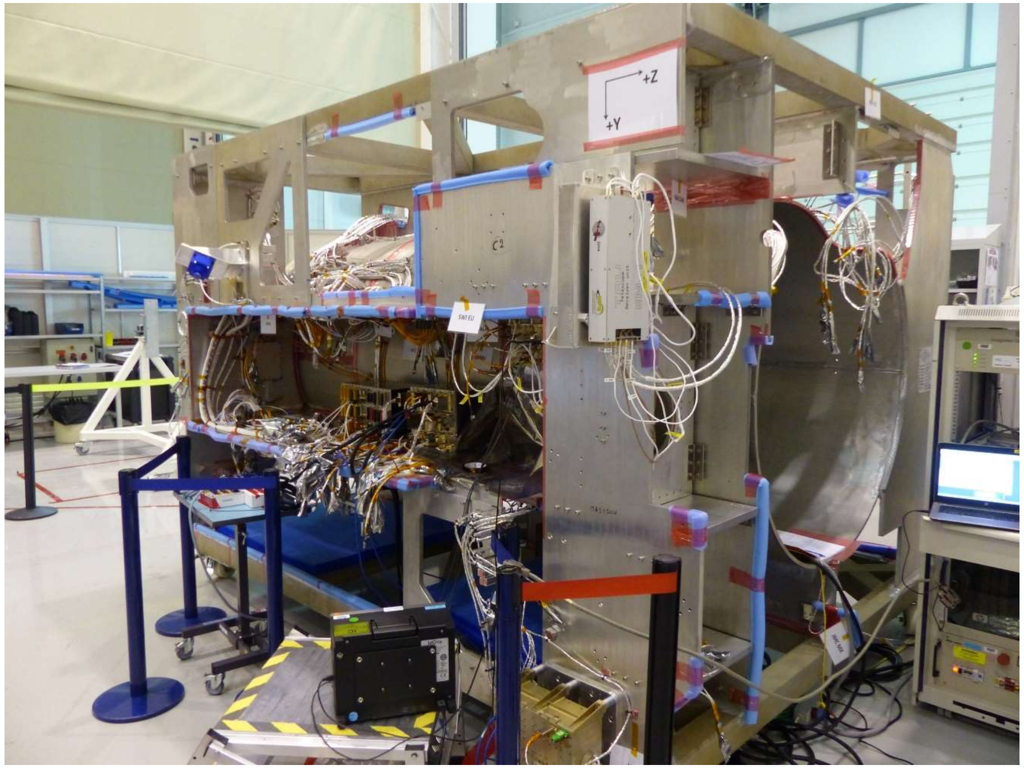
Detection of possible Sun trapping hotspots.

(TDM= Thermal Development Model)

TDM in ESTEC LSS



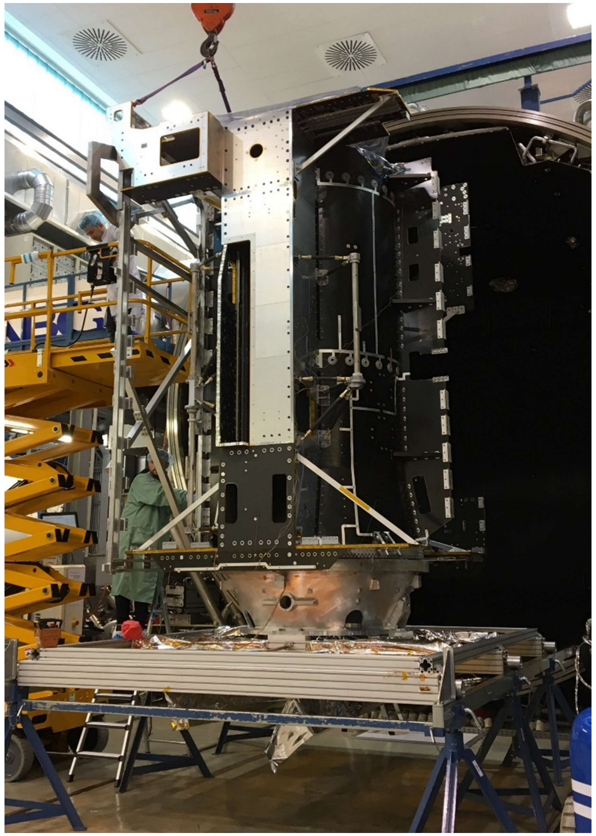
S/C EM (from Sept 2019)



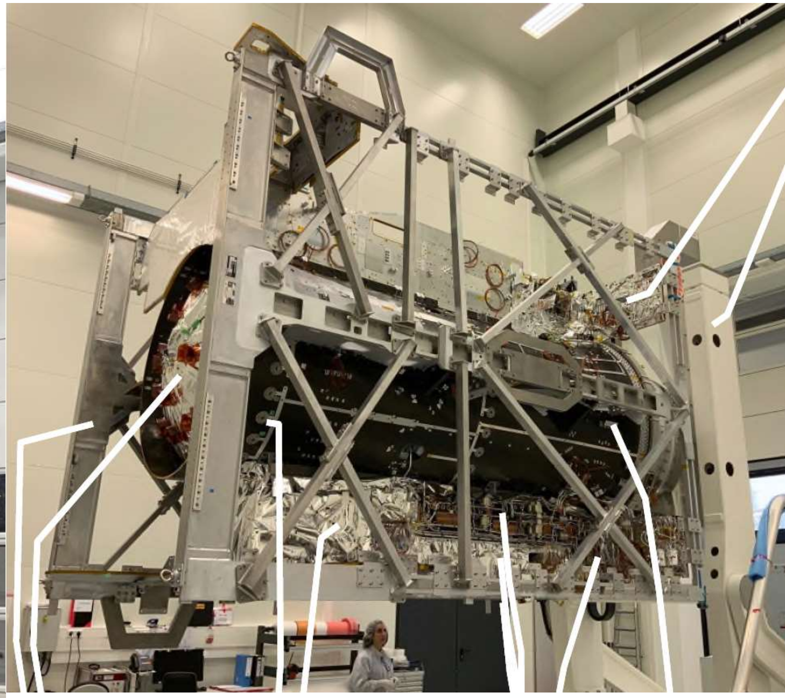
Development of harness, unit accommodation and magnetic characterisation. The S/C EM is still in use to support S/C flight operations

JUICE FM start of integration (from end 2019)

FM primary structure fresh from AIRBUS Madrid, ready for outgassing at IABG, Ottobrunn



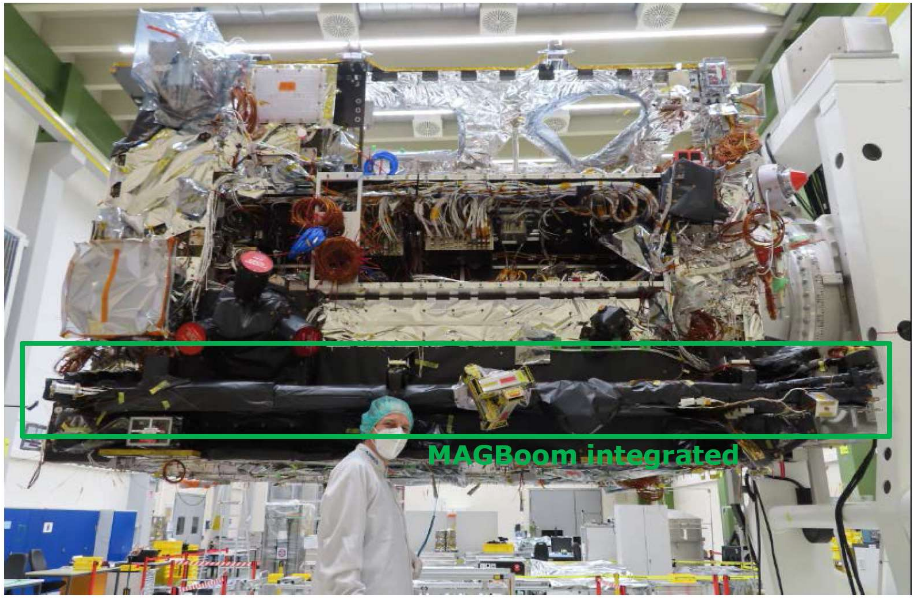
FM primary structure at ArianeGroup Lampoldshausen for Chemical Propulsion System (CPS) integration



JUICE FM Integration in AIRBUS Friedrichshafen

~ all year 2020

Spacecraft Flight Model



I-PIF test bench in AIRBUS Toulouse for Instrument FM units advanced preparation before integration on S/C.

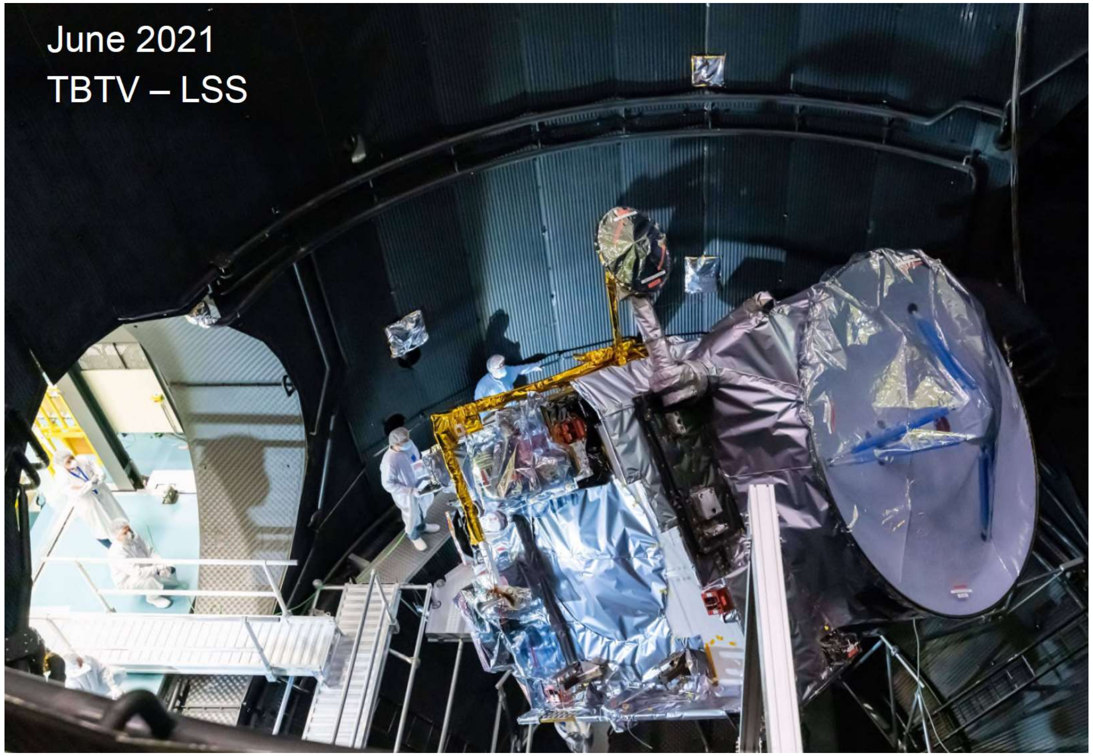
Early Bird test bench in AIRBUS Friedrichshafen for FM units advanced validation before integration into S/C Vaults

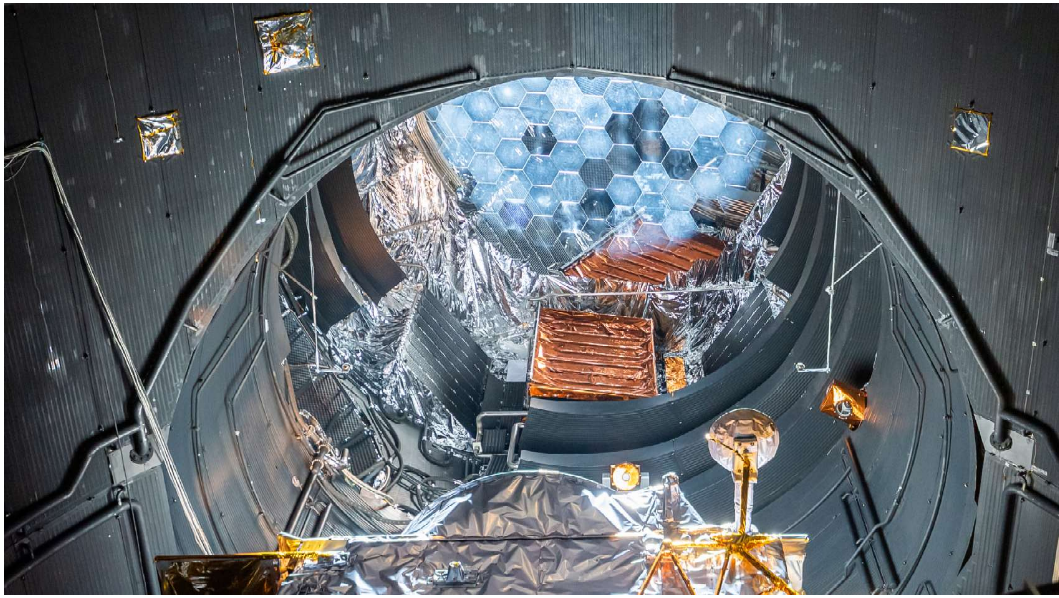
Preparation for 1st Thermal test in LSS ESTEC

May 2021

S/C thermal preparation

S/C in LSS for the 1st Thermal test

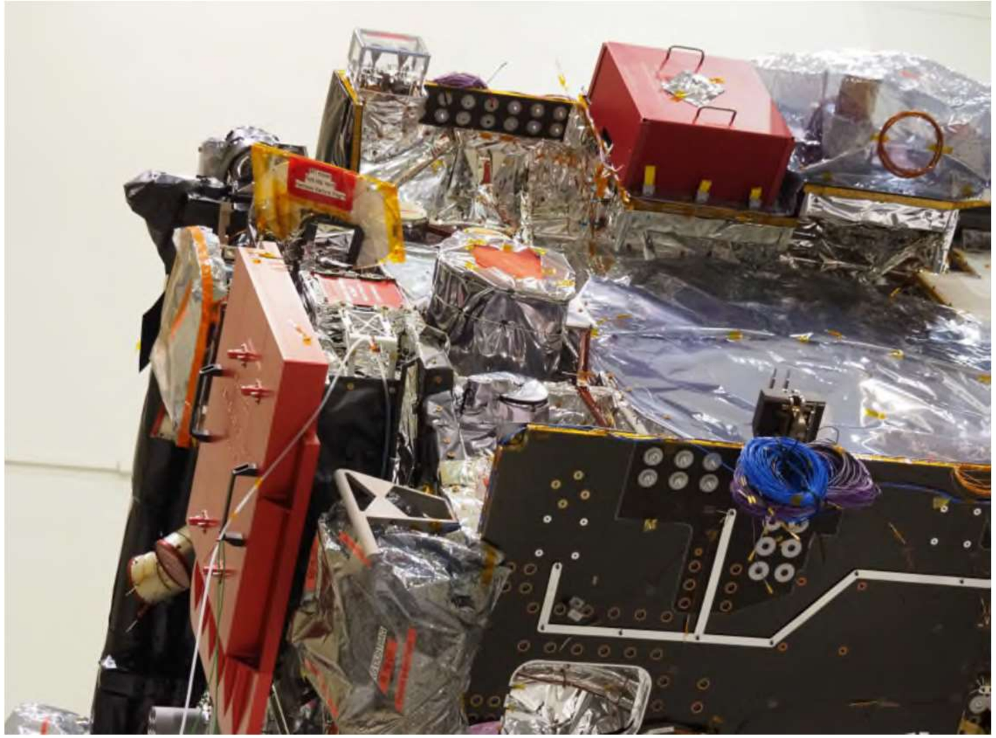




Final integration in AIRBUS Toulouse

End 2021 – beginning 2022

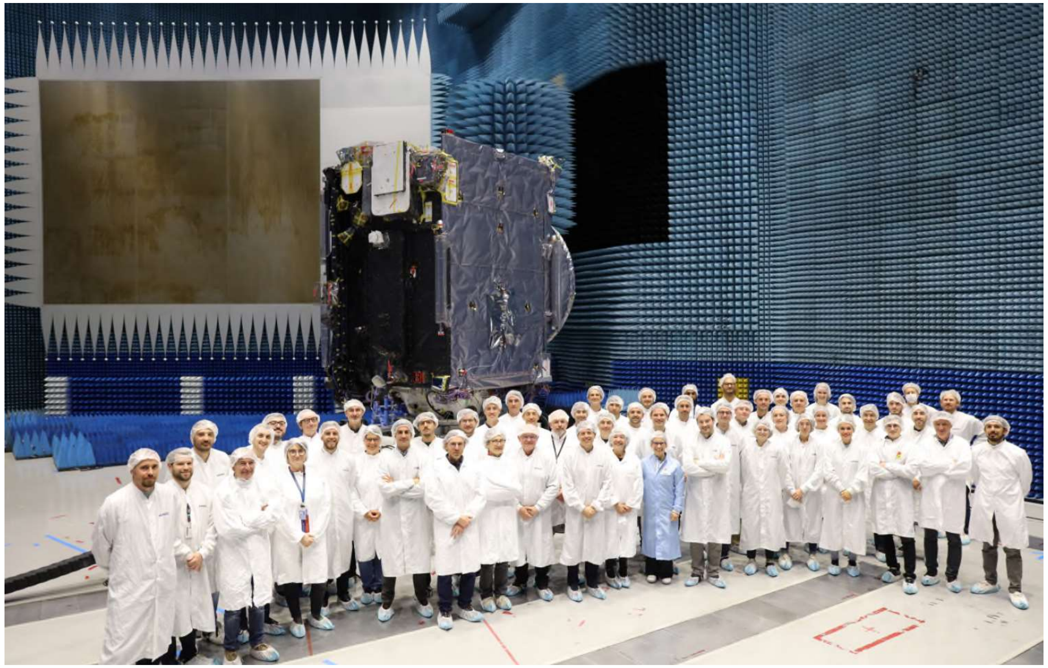
Last instruments unit integration



Deployment test

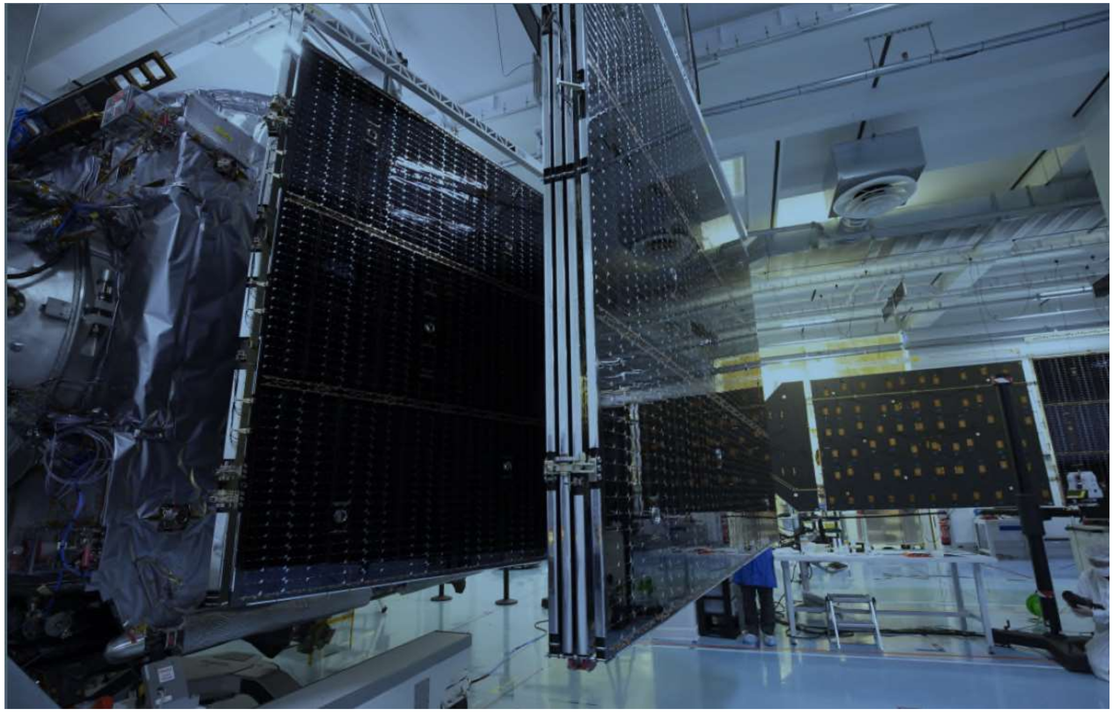
System testing in AIRBUS Toulouse

March 2022



EMC Test

Solar array deployments

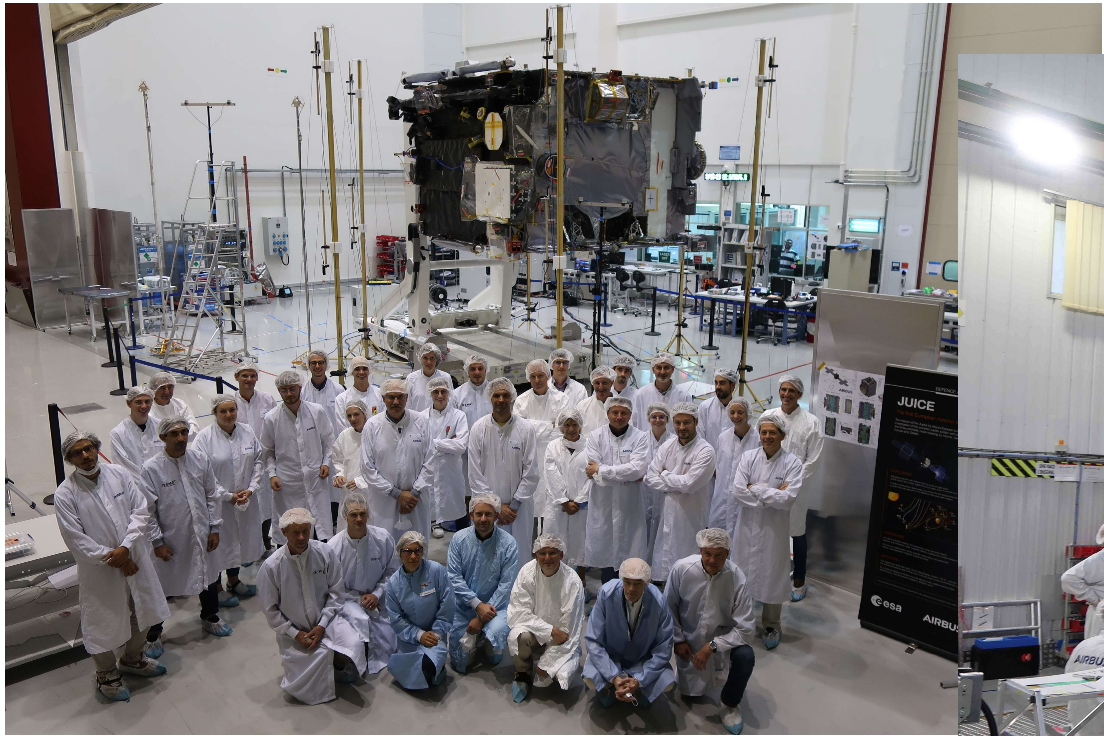


Vibration tests AIRBUS Toulouse (June 2022)

Acoustic Test

Magnetic and 2nd Thermal test (TVAC) (end 2022)

Thermal vacuum Test



Magnetic Test

Transports with Antonov 142

AN-124 unloading in Blagnac airport

Launch campaign (1. Feb. – 14. Apr 2023)

S/C arrival

S/C testing

S/C fueling

On launcher adapter

Launch campaign (1. Feb. – 14. Apr 2023)

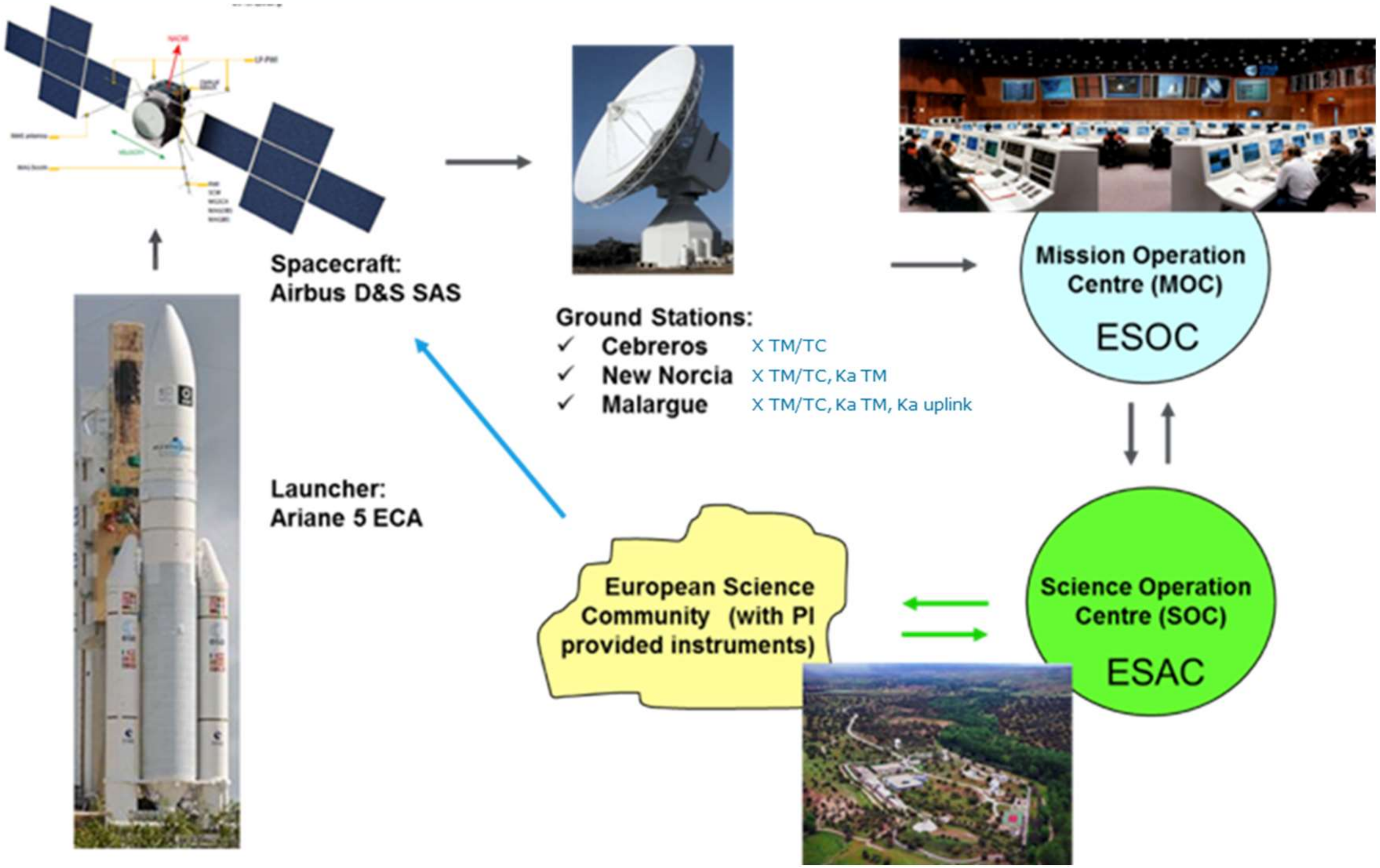
On launcher

Combined launch preparation

Transfer to launch pad

Launch on 14. April 2023 (VA260)

Elements of the JUICE program



JUICE 8 years trip to JUPITER

Where is JUICE now ? ➔ https://www.esa.int/Science_Exploration/Space_Science/Juice/Where_is_Juice_now

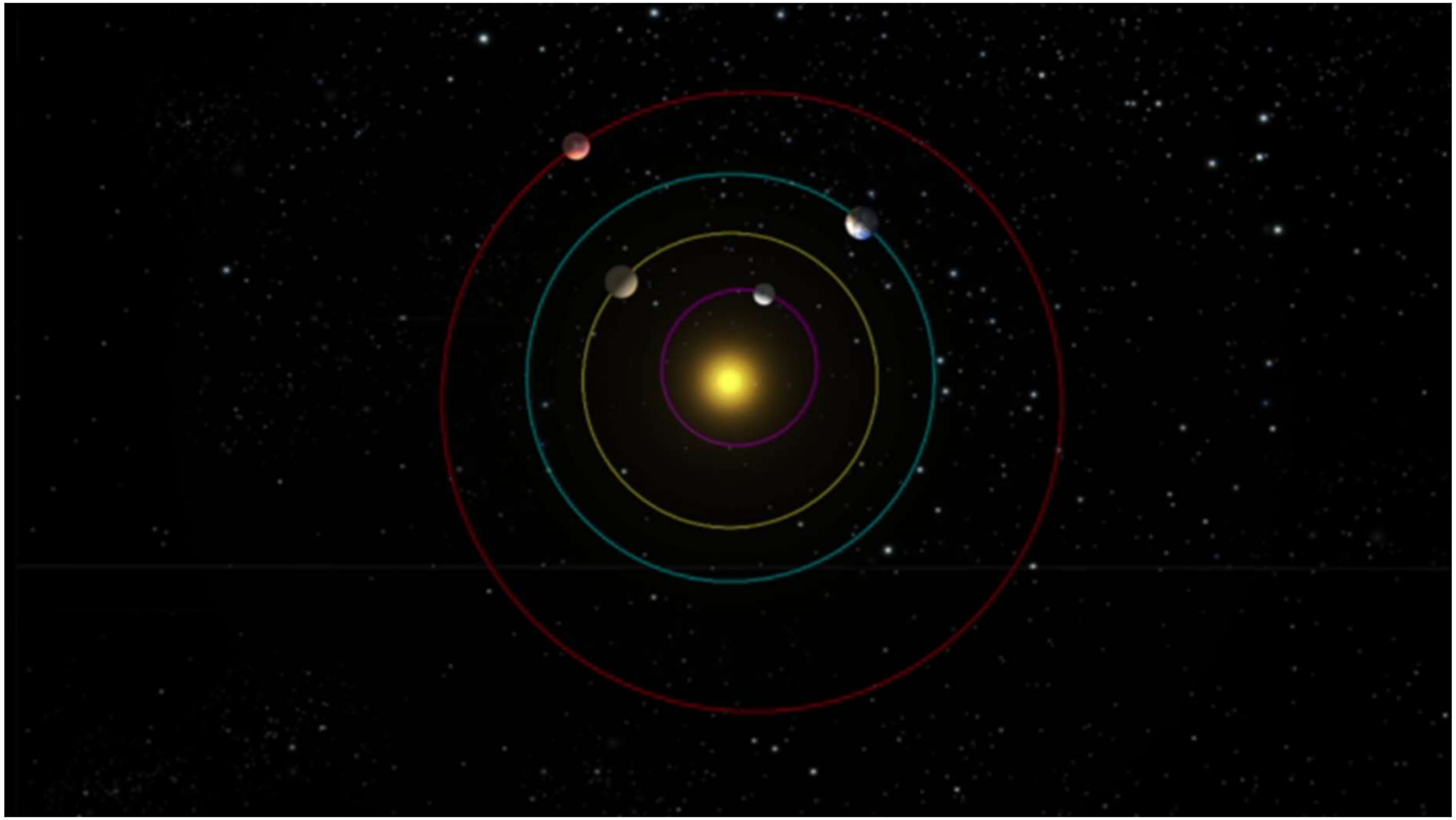
At end-Aug. 2024:
~ 1B Km completed
~ 1st Earth fly-by just completed

Earth gravity assists
Aug 24, Sept 26, Jan 29

Venus gravity assist
Aug 2025,

Jul 2031 at Jupiter (JOI)
Observation of Europa, Calisto and Ganymede

End of mission on Ganymede Mar 2035



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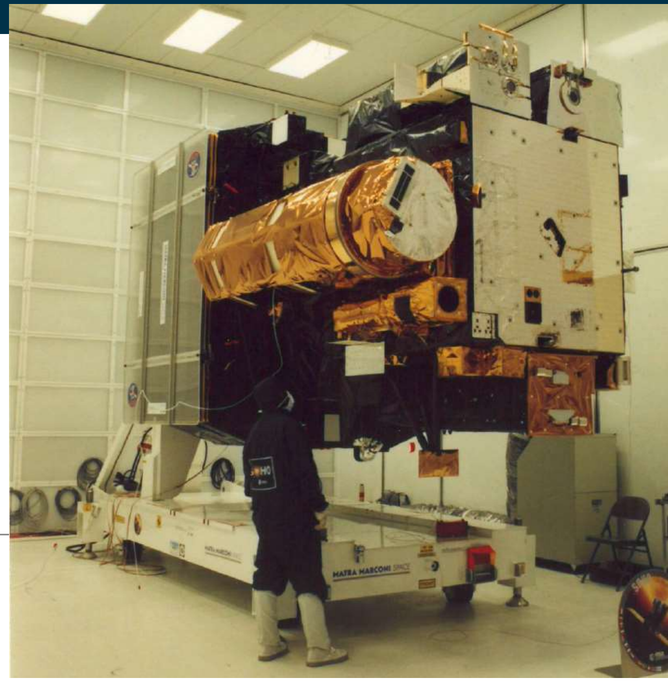
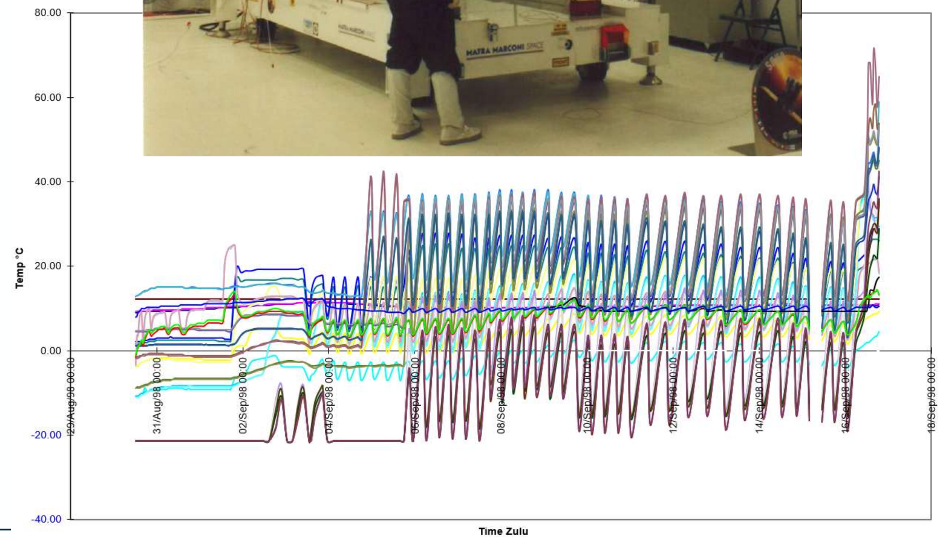
SOHO the Sun observer & its recovery

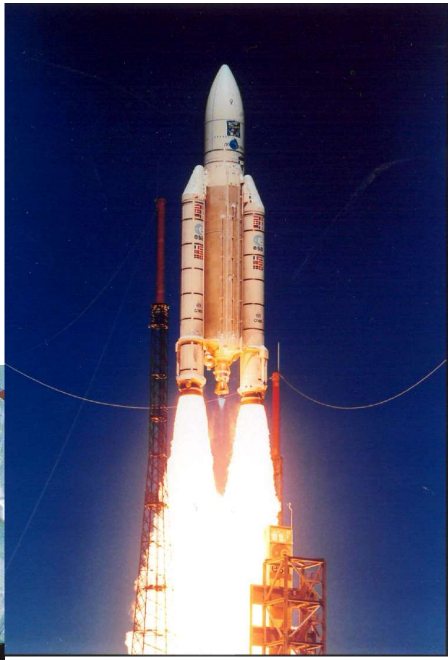
- ❑ Launched in Dec. 1995 from KSC by ATLAS
- ❑ 12 instruments; NASA cooperation for launch and operations (NASA Goddard)
- ❑ Thruster (thermal design / vapour lock) issue during launch campaign
  - ➔ thruster firing tests at manufacturer location (west coast)
  - ➔ very late AOCS change of duty cycle thruster operation
- ❑ NASA application of “Faster Better Cheaper” for S/C operation
  - ➔ loss of spacecraft 25. June 1998
  - ➔ S/C found in slow spin, oriented perpendicular to Sun, off, propellant (hydrazine) frozen
- ❑ Recovery team sent to NASA Goddard
  - ➔ New operation CSW (AOCS, power) developed within 3 mnth
  - ➔ propellant tank and lines thawed
  - ➔ S/C recovered on 25. September1998
- ❑ SOHO back in operation about 6 month after loss and still operating (Solar weather)

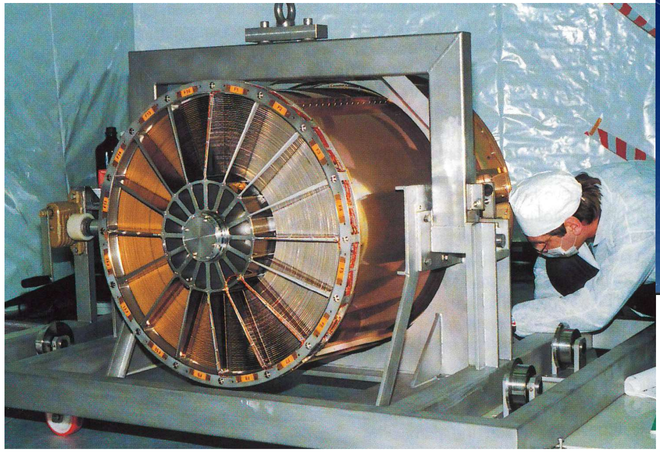




XMM – X-ray sky observer

- Launched in Dec. 1999 from CSG Kourou by Ariane5 (VA-119)
- Complex X ray detector development (58 gold plated cylinders, 450 kg), cleanliness
- Complex transport due to the size (~ 12m long)
- Vibration qualification in 2 parts + demonstration by analysis
- Safety critical fuelling operation in BAF, S/C placed in a big bucket next to the launcher !
- S/C still in operation



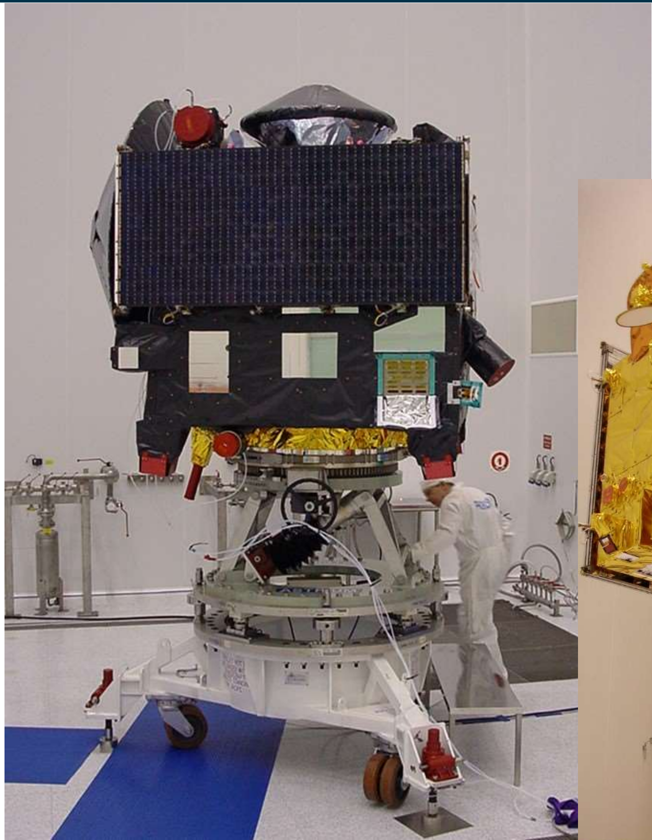


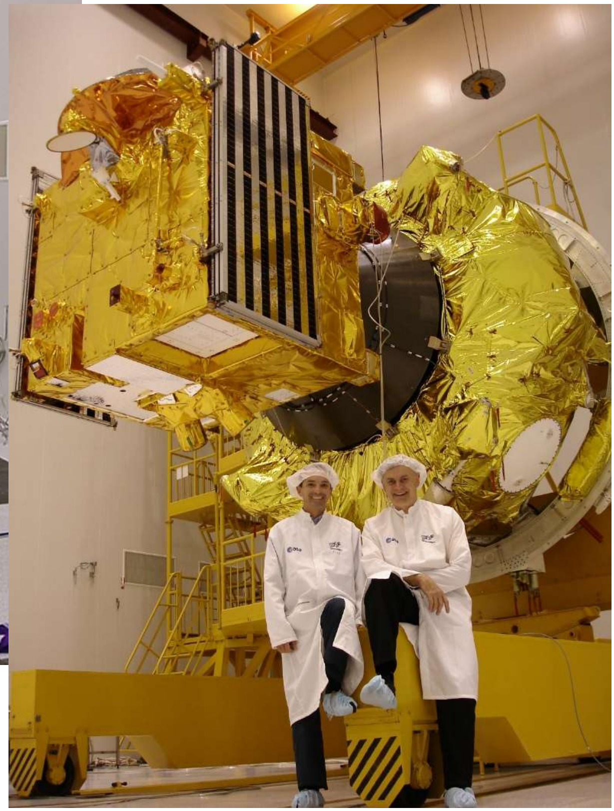
Cluster2 – Earth-Sun magnetic measurement

- 4 S/C re-built from Cluster1 spares (Cluster1 were destroyed at 1st Ariane5 flight in 1996)
- Launched in 2000 from Baikonur by 2 Soyuz-Fregat launchers
- Fregat stage development with Russia
- Horizontal phase for transport in launcher
- Small constellation, all issues are x4
- No development but very quick AIT phase of 2 years
- Magnetic characterisation, many mechanisms.
- Thruster issue just before start of launch campaign
- New facilities (particularly for bi-propellant fuel loading)
- All 4 S/C in operation until Aug. 2024
- 1st S/C (Salsa) de-orbited under control at end 2024

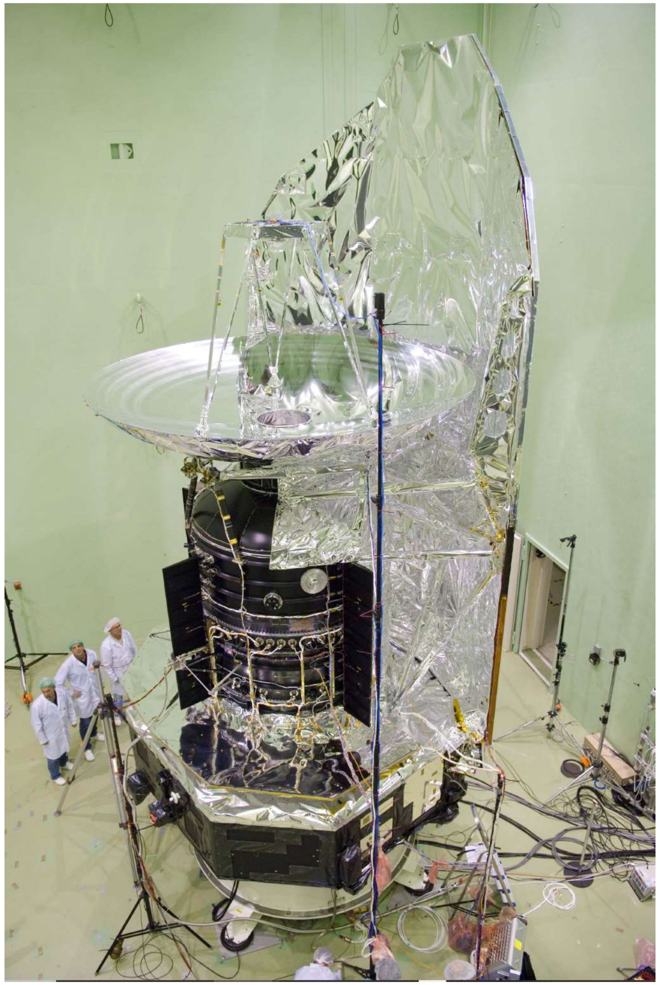
MEX / VEX Mars & Venus observers

- ❑ Launched in 2003 and 2007 from Baikonur by Soyuz-Fregat launchers
- ❑ Launch facility roof collapsed 6 months before start of launch campaign
- ❑ MEX Beagle2 incomplete qualification ➔ failed to deploy on Martian surface
- ❑ VEX late and very short development mainly a thermal change (cold to warm) ➔ specific development of thermal insulation (MLI)
- ❑ VEX TVAC test with solar simulator (2 solar constants)
- ❑ Limited launch opportunities
- ❑ VEX experience of Venus aero-braking to lower orbit
- ❑ VEX controlled crash after >8 years of operations
- ❑ MEX still in operation (observation and transmitter for NASA landers)





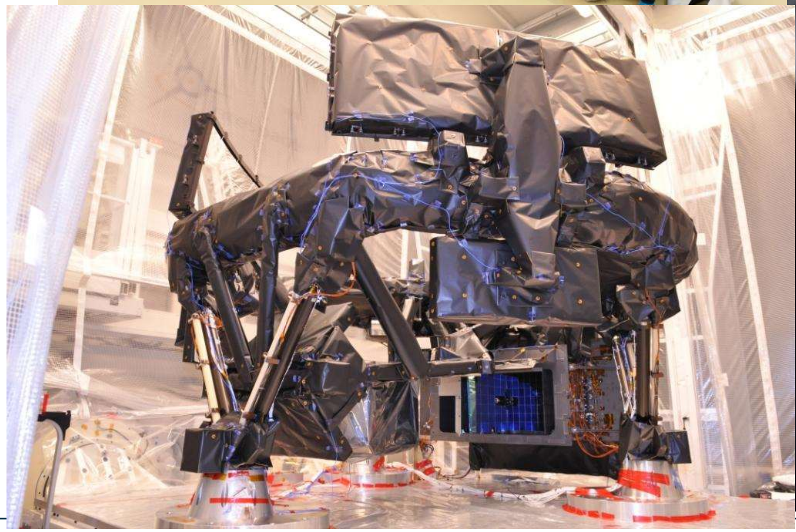
Herschel / Planck the IR observers

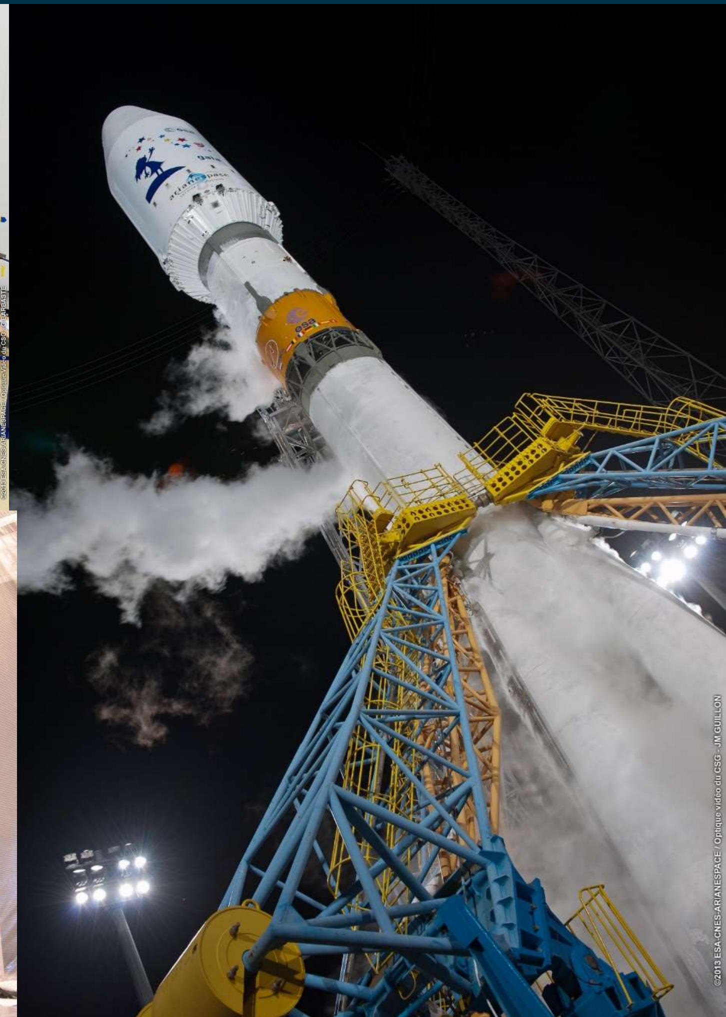


- Launched in May 2009 from CSG Kourou by Ariane5 (VA-188)
- Extreme low temperatures, cleanliness
- Instruments tests requiring CSL very low T thermal chambers
- Herschel LH2 tank requiring complex GSE and intervention under fairing just before launch
- Herschel SiC-SiC telescope accepted during launch campaign
- Planck instrument not testable on ground
- Planck tanks to fill with different He isotopes at launch site
- Both completed missions better than expected (until cooling media exhausted)

GAIA the Milky-Way Billion stars mapper

- Launched in May 2013 from CSG Kourou by Soyuz (VS-06)
- Very complex SiC-SiC double optic telescope, cleanliness
- Gigantic focal plane with 100 CCDs
- Specific instrument development before mating on Service module for system test
- Complex Sun shield mechanism deployed at launch site
- 2 propulsion systems (hydrazine system and a cold gas micro-propulsion system for spin and nutation control)
- S/C decommissioned on 27. March 2025
- Results in the most accurate catalogue of 2 billions stars of the Milky-Way
- Next catalogues in 2026 and 2030 (final)
- Up to 6000 scientific papers in a year





Content

- Introduction
- Spacecraft AIT
- The JUICE case
- Other experienced cases (vv shortly)
- A few lessons learnt

AIT Lessons 1/2

- **Test as you fly** ie. prepare tests to be as representative as in flght.
- Every scientific S/C **development is an adventure** putting AIT under pressure as soon as the unexpected occurs.
- **Zero risk does not exist**. Risk analyses may help but are far to be complete (Who predicted COVID, or the collapse of a facility shortly before arrival at launch site, repeated floodings of the S/C EM or snow in south of Italy during a S/C road transport ? …).
- Prepare **realistic schedules with adequate margin** to cope with the unexpected (as much as possible). Do not use this margin in early phases or at the first difficulty encountered. You never know what surprise may impact you later.
- **Agree with all parties on a strong development baseline approach** and prepare it well. Get support to define and achieve a **"good enough status"** at each important stage. Do not try to reach the best at all steps (too time consuming, too costly). Have backups ready.

  Note: it is very difficult to define the "good enough status". This is where experience is required.
- **Priorities** of major players in a consortium may evolve at any time leading to change of baseline or delays. Communication, transparency and reactivity are key to put solutions in place and to implement them without minimum additional stress on the team.

AIT Lessons 2/2

- All parties of a development consortium are **in the same boat**. Make sure this is well understood. It is the basis for **trustable and transparent cooperation**. This is essential if you want to be efficient.
- **Team members selection** for a project is a key to success (the best world expert in a field may not fit in a team and impact its synergy and the overall motivation) and delegate work (you cannot be everywhere and do everything).
- **Prepare each activity sufficiently in advance** to avoid late basic surprises creating delays at start of the activity.
- Make sure to have **all available team resources** with the required equipment/tools and capabilities. This becomes particularly difficult when working in 2 or 3-shifts.
- The **carrot/stick management** approach works if the carrots only are used (ie. don't use the stick). It is counter-productive since real problems are often complex, from multiple origins. It is more effective to contribute for a quick solution (the longer you wait to solve it the worst impact you'll get).
- To the young engineers: make the effort to **consult and use past experience**. It will help you to avoid repeating mistakes.