The Euclid space mission and the origin of the accelerating Universe

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CERN, Geneva

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Overview

- Intro about ESA ESA Corporate
- Science Projects: a short excursus
- Euclid programme implementation
- Main technology challenges
- Project Status

THE EUROPEAN SPACE AGENCY

January 2016

ESA facts and figures

- Over 50 years of experience
- 22 Member States
- Eight sites/facilities in Europe, about 2200 staff
- 5.2 billion Euro budget (2016)
- Over 80 satellites designed, tested and operated in flight

Purpose of ESA

"To provide for and promote, for exclusively peaceful purposes, cooperation among European states in **space research** and **technology** and their **space applications.**"

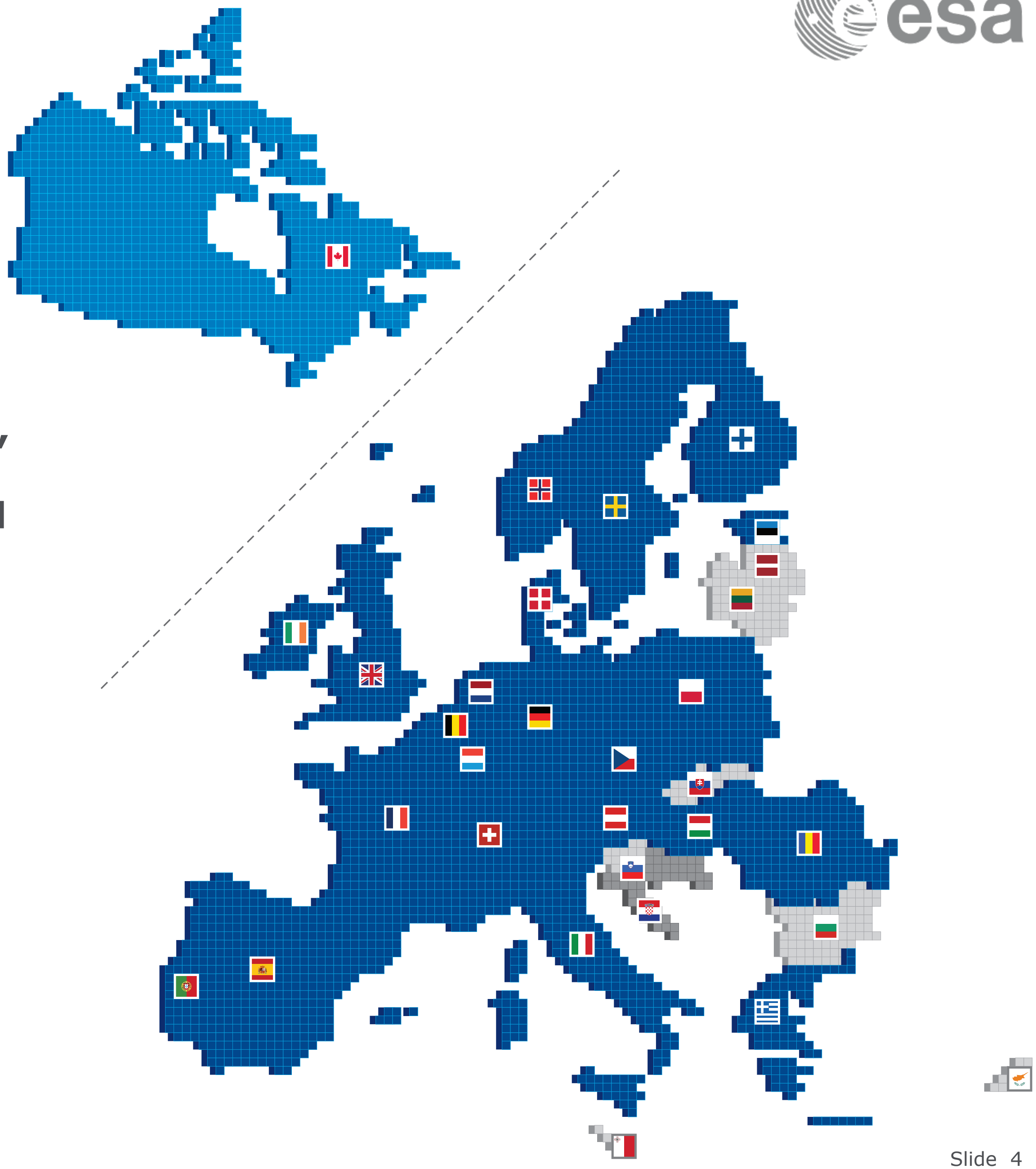
Article 2 of ESA Convention

Member States

ESA has 22 Member States: 20 states of the EU (AT, BE, CZ, DE, DK, EE, ES, FI, FR, IT, GR, HU, IE, LU, NL, PT, PL, RO, SE, UK) plus Norway and Switzerland.

Seven other EU states have Cooperation Agreements with ESA: Bulgaria, Cyprus, Latvia, Lithuania, Malta, Slovakia and Slovenia. Discussions are ongoing with Croatia.

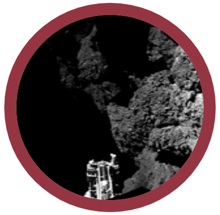
Canada takes part in some programmes under a long-standing Cooperation Agreement.



Activities

ESA is one of the few space agencies in the world to combine responsibility in nearly all areas of space activity.

* Space science is a Mandatory programme, all Member States contribute to it according to GNP. All other programmes are Optional, funded 'a la carte' by Participating States.



space science

human spaceflight

exploration

earth observation

launchers

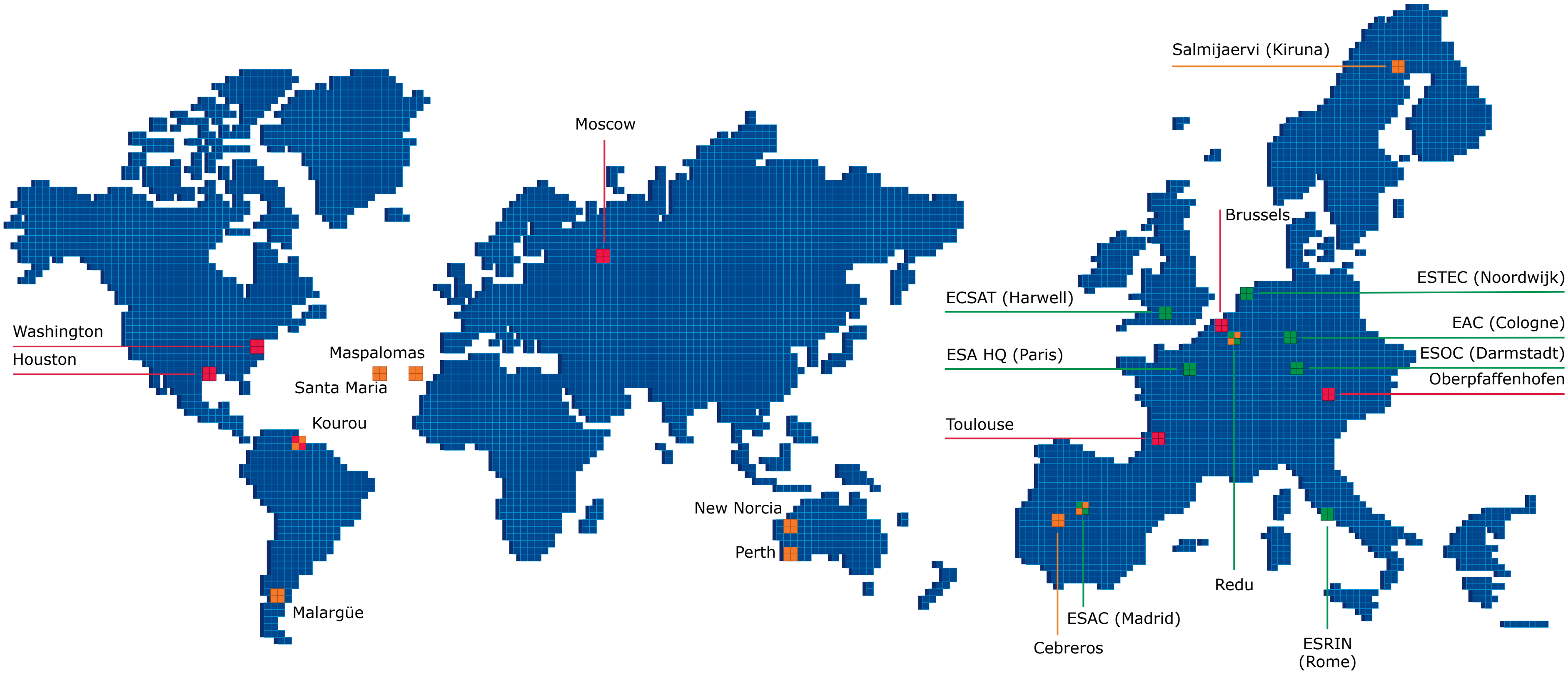
navigation

operations

technology

telecommunications

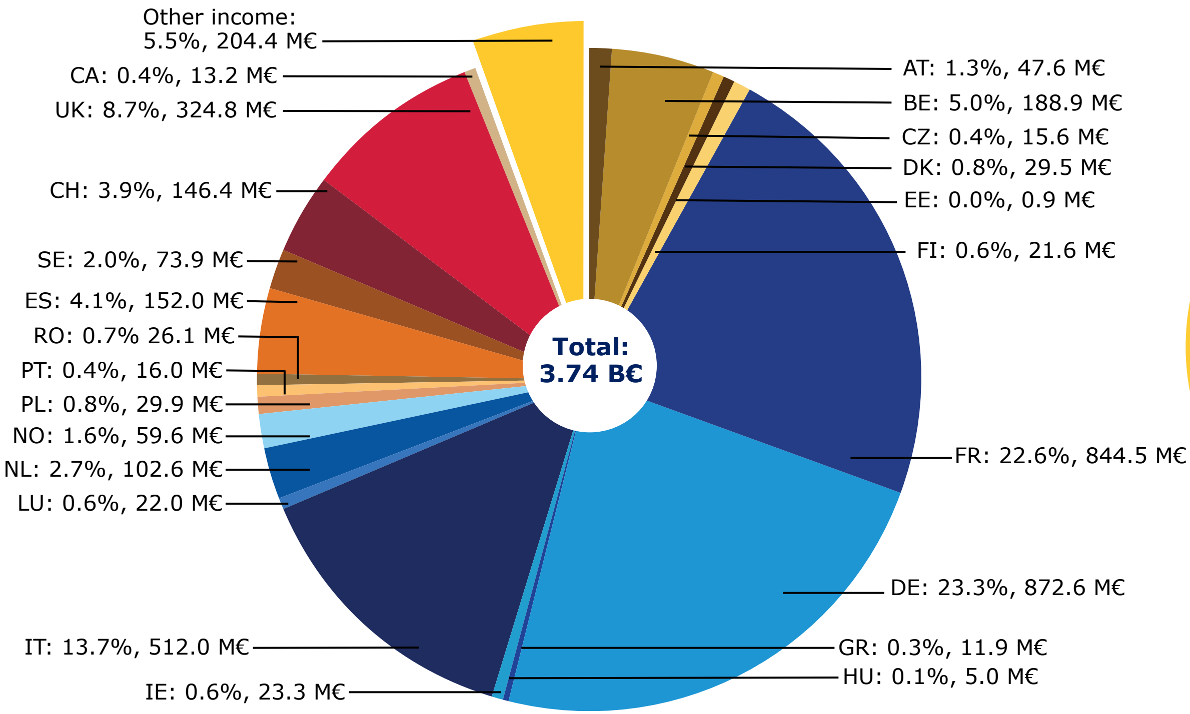
ESA's locations



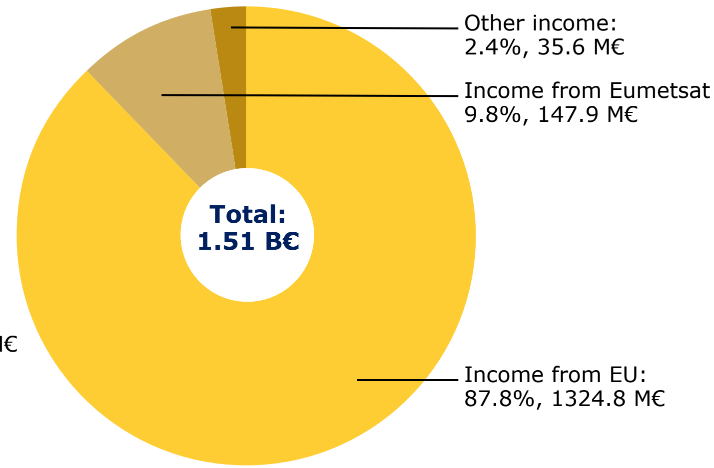
- ESA sites
- Offices
- ESA Ground Station
- ESA Ground Station + Offices
- ESA sites + ESA Ground Station

ESA budget for 2016

ESA Activities and Programmes



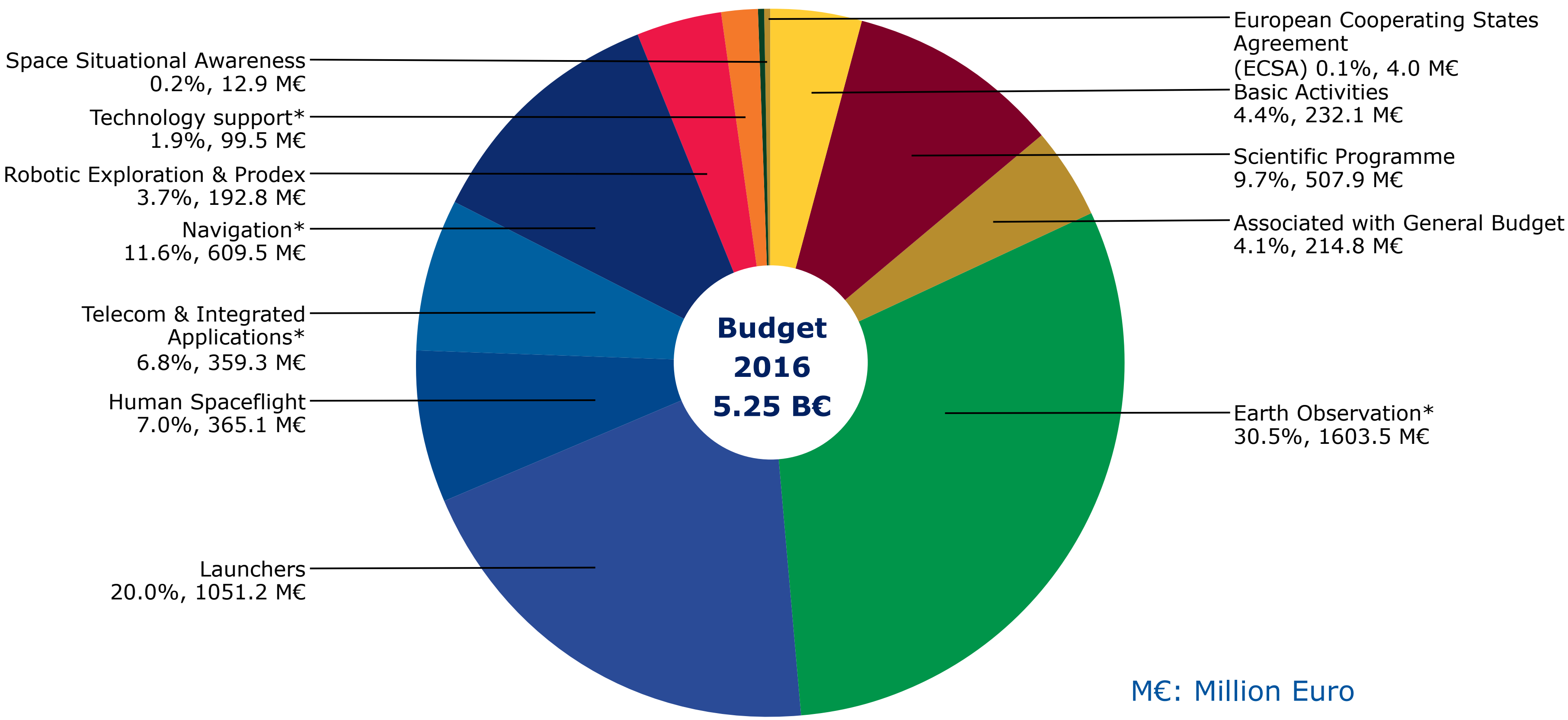
Programmes implemented for other Institutional Partners



B€: Billion Euro

Total ESA budget for 2016: 5.25 B€

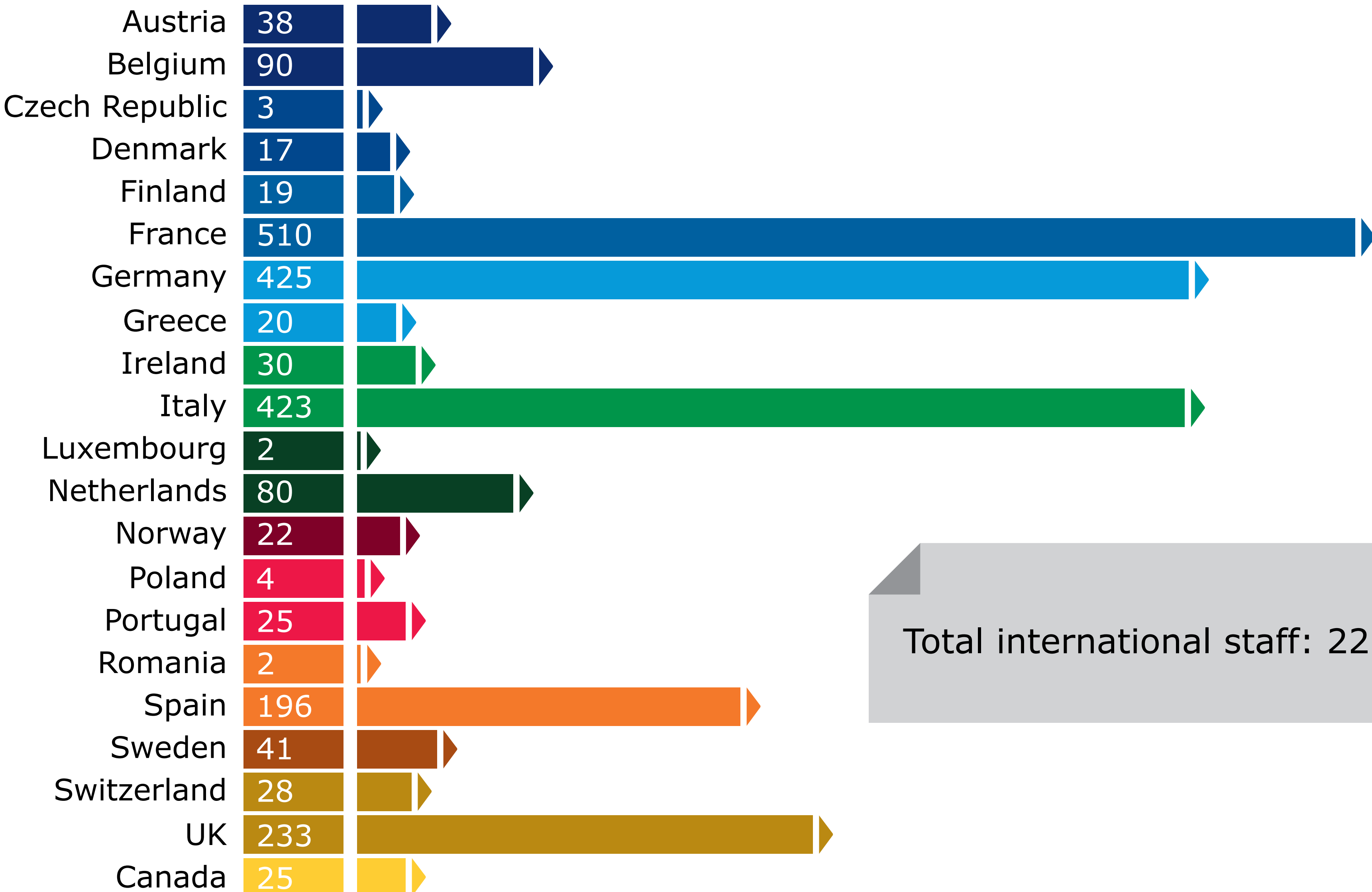
ESA 2016 budget by domain



M€: Million Euro

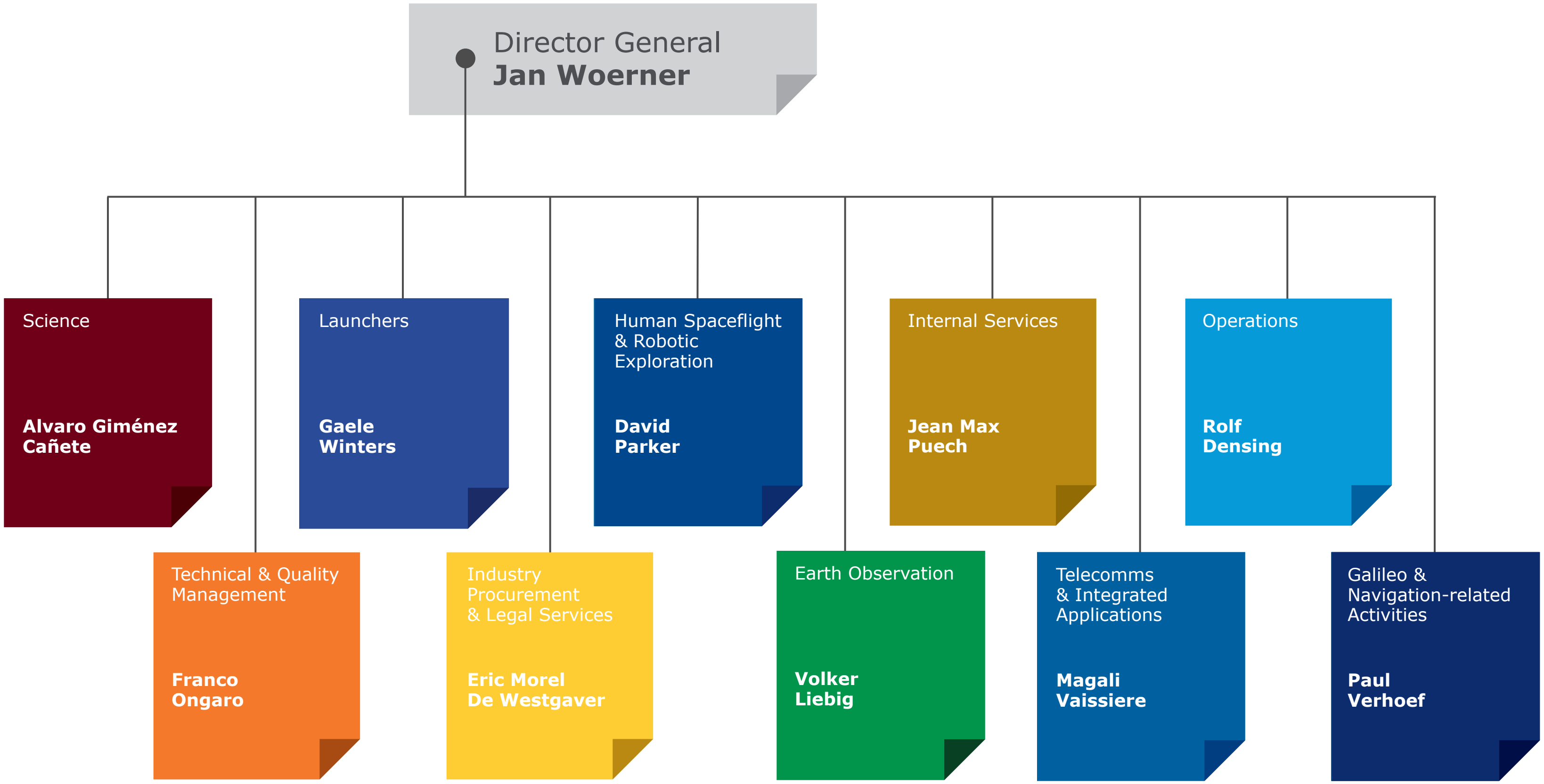
*includes Programmes implemented for other Institutional Partners

Staff by nationality in 2014



Total international staff: 2233

ESA directors



ESA and the European space sector

ESA Member States finance 50% of the total public space spending in Europe. Because of the cooperation between ESA, EC and the national space agencies:

- the European space industry sustains around 35 000 jobs;
- Europe is successful in the commercial arena, with a market share of telecom and launch services higher than the fraction of Europe's public spending worldwide;
- European scientific communities are world-class and attract international cooperation;
- research and innovation centres are recognised worldwide;
- European space operators (Arianespace, Eumetsat, Eutelsat, SES Global, etc.) are the most successful in the world.

ESA's industrial policy

About 85% of ESA's budget is spent on contracts with European industry.

ESA's industrial policy:

- ensures that Member States get a fair return on their investment;
- improves competitiveness of European industry;
- maintains and develops space technology;
- exploits the advantages of free competitive bidding, except where incompatible with objectives of the industrial policy.

Birth of commercial operators

ESA's 'catalyst' role

ESA is responsible for R&D of space projects. On completion of qualification, they are handed to outside entities for production and exploitation. Most of these entities emanated from ESA.

Meteorology: Eumetsat

Launch services: Arianespace

Telecomms: Eutelsat and Inmarsat

ESA Council

The Council is the governing body of ESA.

It provides the basic policy guidelines for ESA's activities. Each Member State is represented on the Council and has one vote.

Every two to three years, Council meets at ministerial level ('Ministerial Council') to take key decisions on new and continuing programmes and financial commitment.

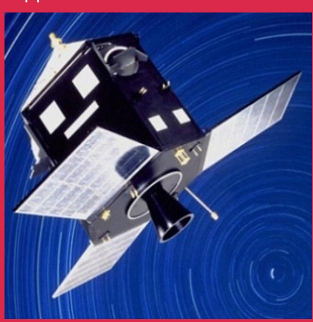
The ESA Council at ministerial level also meets together with the EU Council to form the European 'Space Council'.

SCIENCE

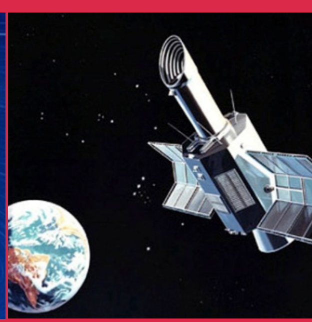
ESA's pioneers of space science (1)

- **Hipparcos** (1989–93) first comprehensive star-mapper
- **IUE** (1978–96) longest-lived orbital ultraviolet observatory
- **Giotto** (1986) first close flyby of a comet nucleus
- **Ulysses** (1990–2008) first spacecraft to fly over Sun's poles
- **ISO** (1995–8) first European infrared observatory
- **SMART-1** (2003–6) first European mission to the Moon

Hipparcos

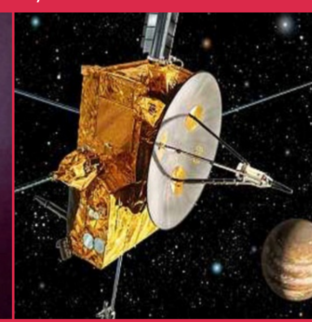


IUE

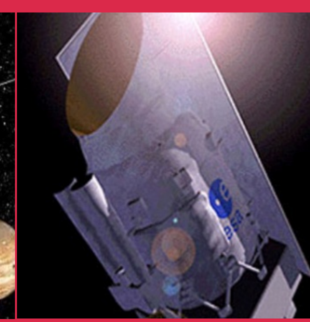


Giotto

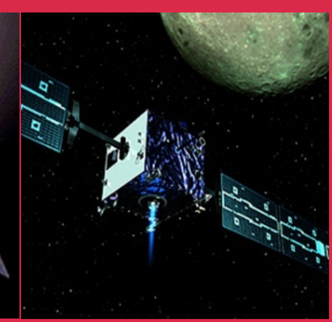
Ulysses



ISO



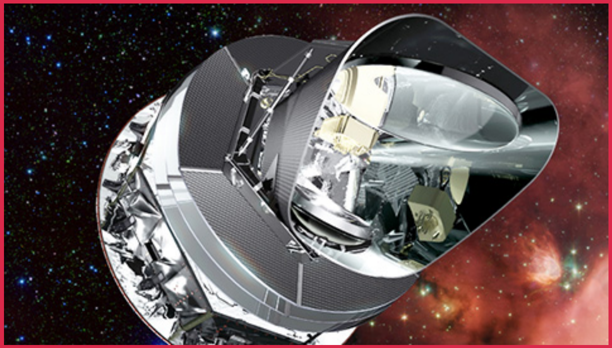
SMART-1



ESA's pioneers of space science (2)

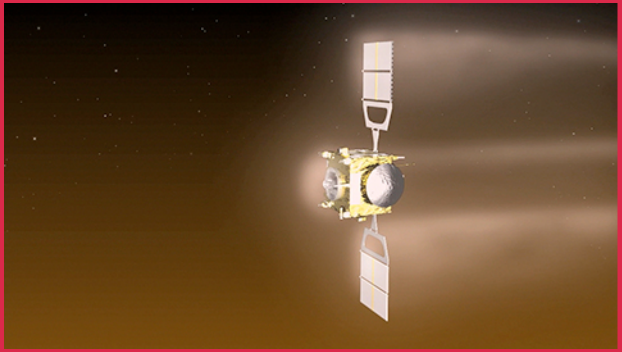
- **Planck** (2009–13) detecting first light of Universe and looking back to the dawn of time
- **Herschel** (2009–13) unlocking the secrets of starbirth and galaxy formation and evolution
- **Venus Express** (2005–15) first global investigation of dynamic atmosphere of Venus

Planck



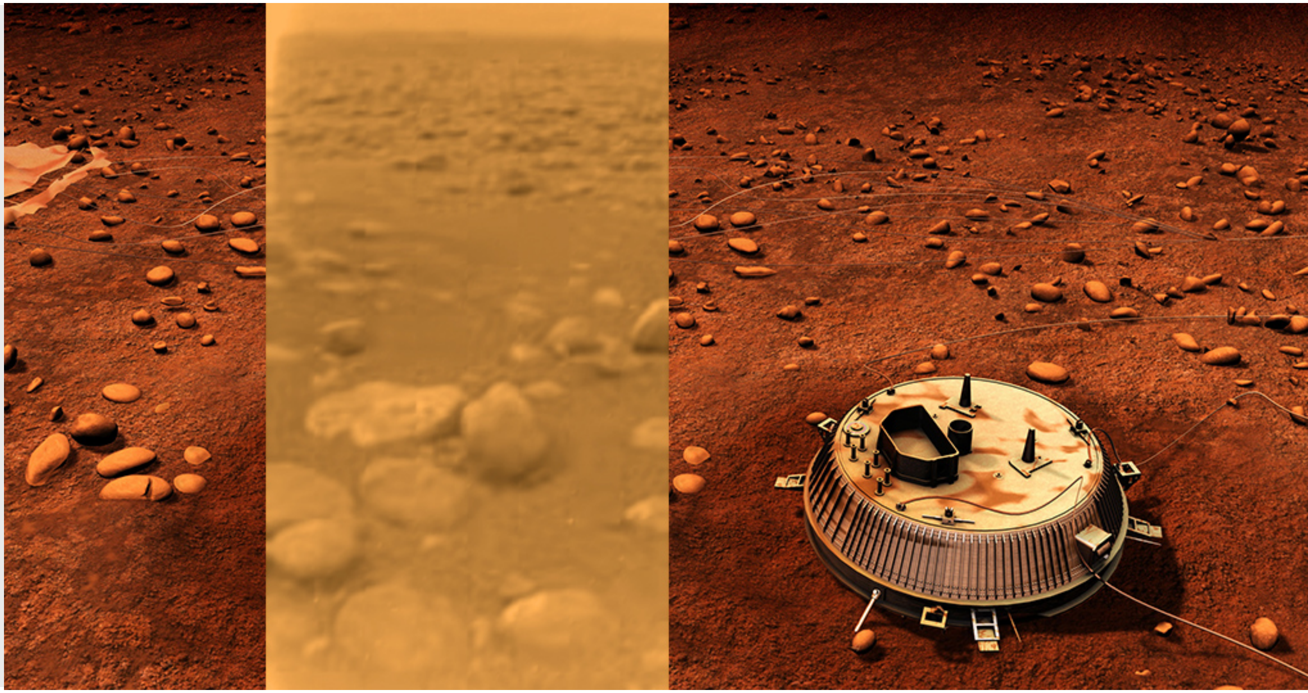
Herschel

Venus Express



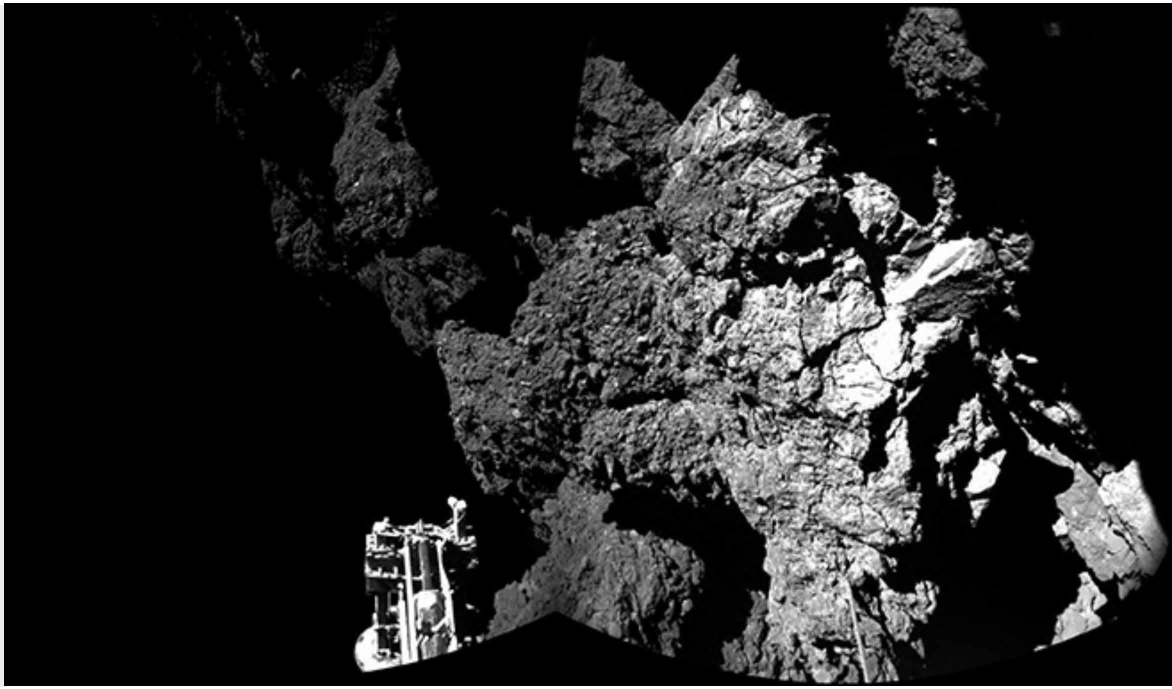
First landing on a world in the outer Solar System

On 14 January 2005, ESA's **Huygens** probe made the most distant landing ever, on Titan, the largest moon of Saturn (about 1427 million km from the Sun).



First rendezvous, orbit and soft-landing on a comet.

On 6 August 2014, ESA's **Rosetta** became the first spacecraft to rendezvous with a comet and, on 12 November, its Philae probe made the first soft-landing on a comet and returned data from the surface.

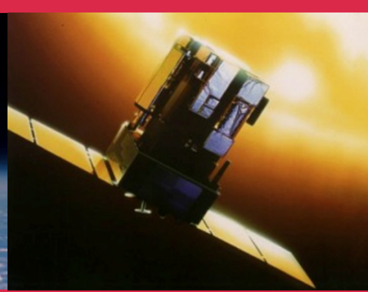


Today's Science missions (1)

- **Hubble** (1990–) orbiting observatory for ultraviolet, visible and infrared astronomy (with NASA)
- **SOHO** (1995–) studying our Sun and its environment (with NASA)
- **XMM-Newton** (1999–) solving mysteries of the X-ray Universe
- **Cluster** (2000–) studying interaction between Sun and Earth's magnetosphere
- **Integral** (2002–) observing objects simultaneously in gamma rays, X-rays and visible light

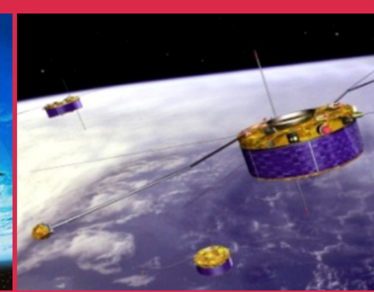
Hubble

SOHO



XMM-Newton

Cluster

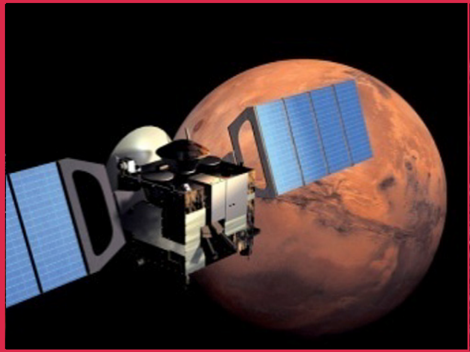


Integral

Today's Science missions (2)

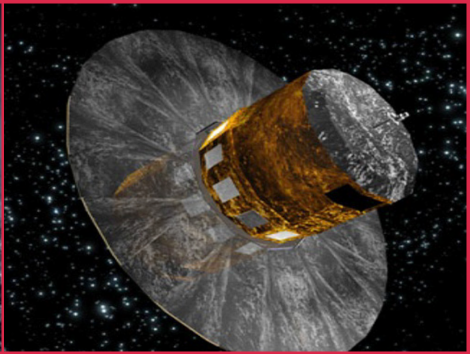
- **Mars Express** (2003–) studying Mars, its moons and atmosphere from orbit
- **Rosetta** (2004–) the first long-term mission to study and land on a comet
- **Gaia** (2013–) mapping a thousand million stars in our galaxy
- **LISA Pathfinder** (2015–) testing technologies to detect gravitational waves

Mars Express

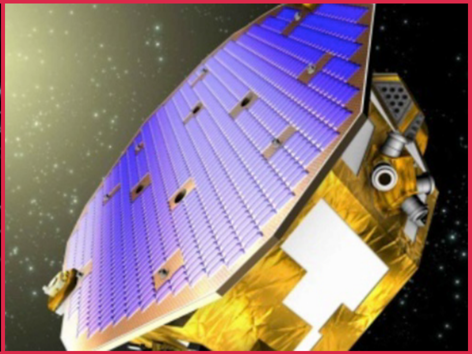


Rosetta

Gaia



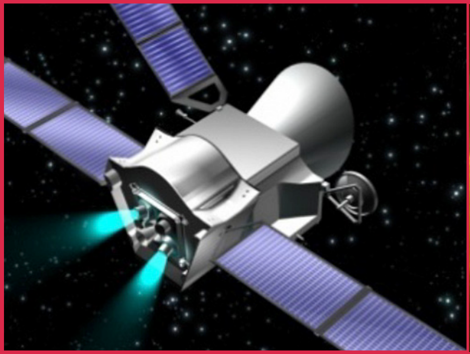
LISA Pathfinder



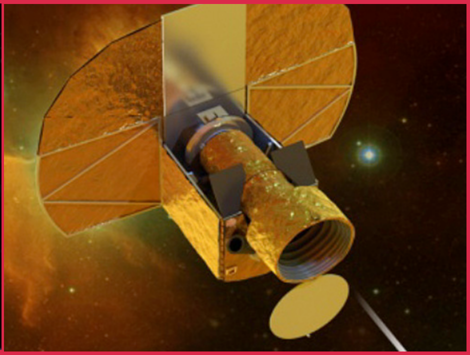
Upcoming missions (1)

- **BepiColombo** (2017) a satellite duo exploring Mercury (with JAXA)
- **Cheops** (2018) studying exoplanets around nearby bright stars
- **Solar Orbiter** (2018) studying the Sun from close range
- **James Webb Space Telescope** (2018) studying the very distant Universe (with NASA/CSA)

BepiColombo



Cheops



Solar Orbiter

James Webb Space Telescope

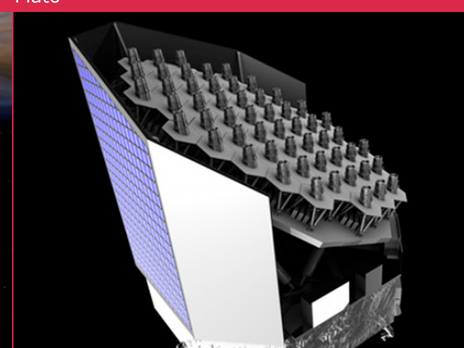
Upcoming missions (2)

- **Euclid** (2020) probing ‘dark matter’, ‘dark energy’ and the expanding Universe
- **JUICE** (2022) studying the ocean-bearing moons around Jupiter
- **Plato** (2024) searching for planets around nearby stars
- **Athena** (2028) space telescope for studying the energetic Universe
- **Gravitational wave observatory** (2034) studying ripples in spacetime caused by massive objects in the Universe

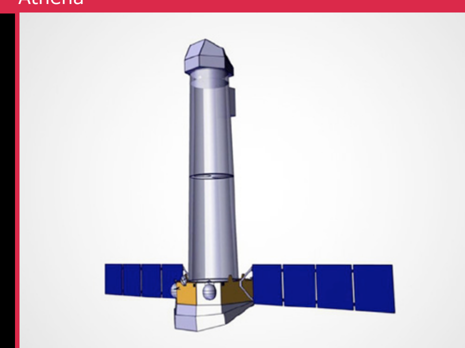
Euclid

JUICE

Plato



Athena



Science operations

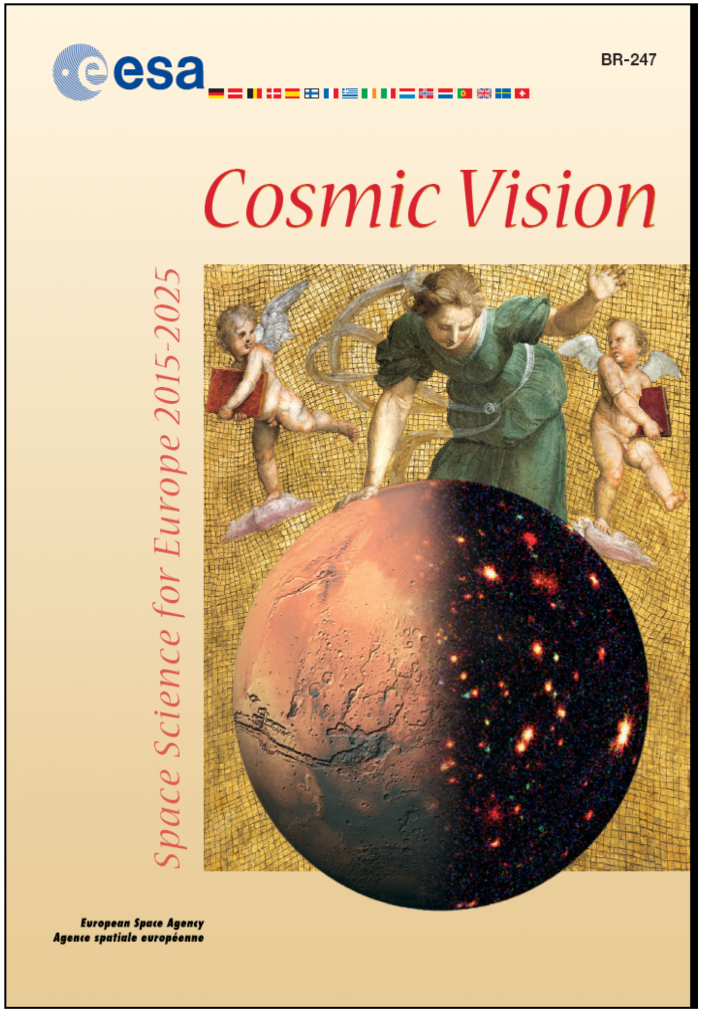
ESAC (near Madrid, Spain) is ESA's centre for science operations.

ESAC hosts ESA's Science Operation Centre (SOC) for ESA astronomy and Solar System missions.

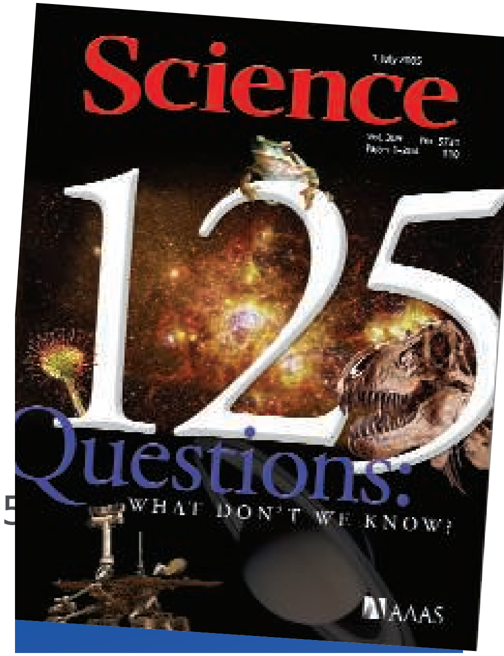
Science operations include the interface with scientific users, mission planning, payload operations and data acquisition, processing, distribution and archiving.

The scientific archives for the majority of ESA's science missions are kept here so that researchers have a single 'entry point' for accessing the wealth of scientific data.

Euclid in the Cosmic Vision 2015-2025



- Science Magazine 2005: What don't we now?
- 1st Priority: What is the Universe made of?
- In 2005 ESA Space Science Advisory Committee prepared Cosmic Vision 2015-2025
- 4 themes were defined

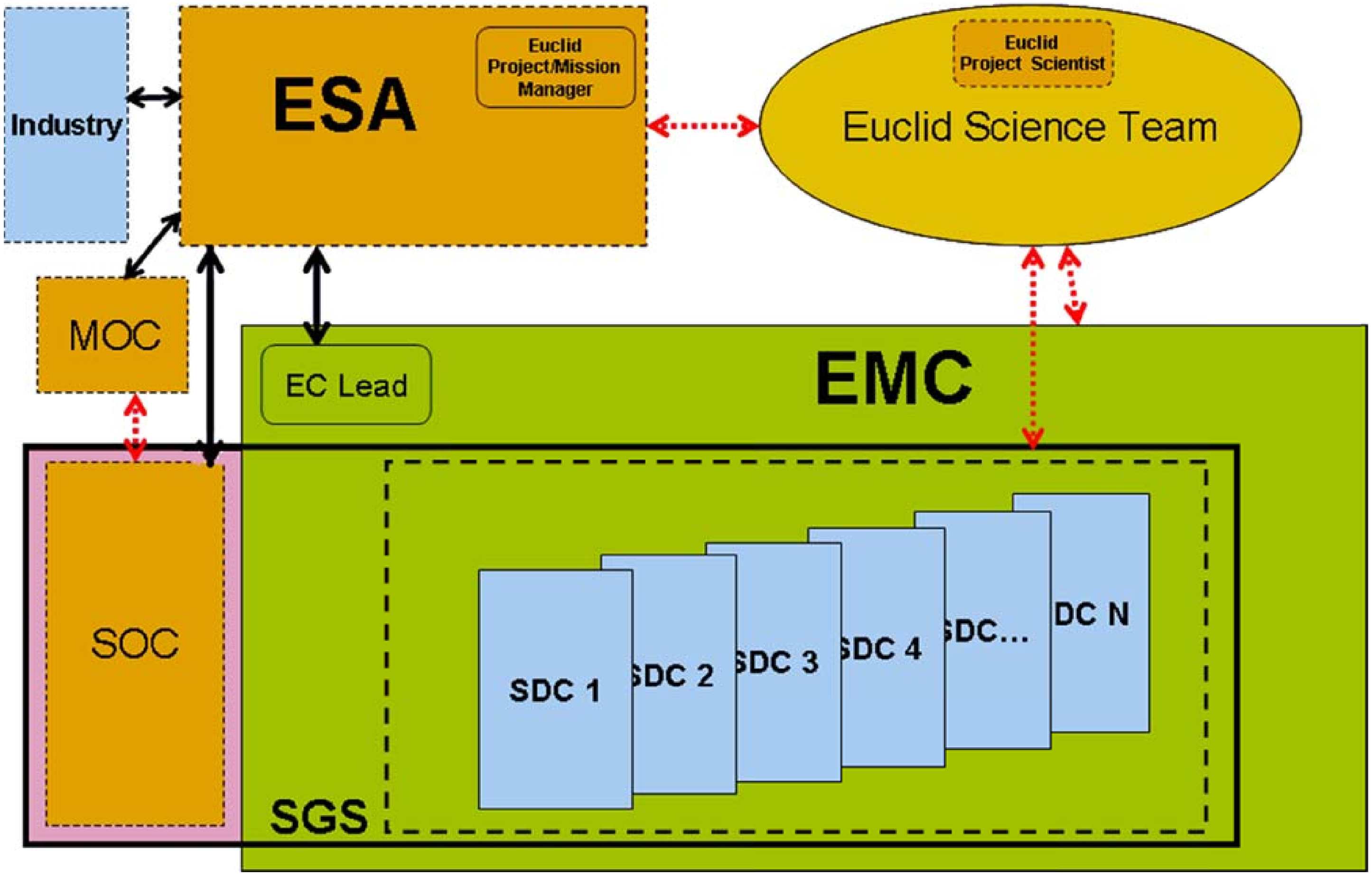


- Theme 4 question: How did the Universe originate and what is it made of?
- Investigate the nature and origin of the Dark Energy that is accelerating the expansion of the Universe.

Selection process

- 2007: two "dark energy missions" proposals were received from the community: Dune, a wide field imager and SPACE, a new near-infrared all-sky cosmic surveyor;
- 2009: Euclid was born, a visible/near-infrared survey of all galaxies and clusters of galaxies out to a *z~2*. Euclid was in competition with other 5 missions;
- 2010: Euclid, Plato (to study frequency of planets around other stars, including terrestrial planets in a star's habitable zone) and Solar Orbiter (closest look at our Sun, approaching 62 solar radii) were selected;
- 2011: Solar Orbiter and Euclid were selected for implementation;
- 2012: Euclid mission is adopted (blueprint completed) for launch in 2020. Top-level science management principles of the mission, main organisational units, roles and responsibilities of ESA, the Euclid Consortium (EC) funded by the Member States, and the scientific community at large are established in the Science Management Plan SMP.
- While ESA D/SCI retains overarching responsibility for all aspects of the mission, EC provides the two instruments (with contribution by ESA and NASA) and part of Science Ground Segment and the Euclid Science Team oversees the preparations and execution of scientific operations, and endorses distribution of the data products to the community via the Euclid Legacy Archive.

Original organisational structure



Mission Implementation Process

- Science Management Plan defined the roles and responsibilities;
- Science Requirements Document (SciRD) approved by Science Team defines:
  - Top level requirements for Weak Lensing;
  - Top level requirements for Galaxy Clustering;
  - Instrument requirements for WL and GC;
  - Survey requirements (Wide, Deep and Calibration);
  - External Data (ground observation).

- Science Requirements (SciRD)
- Science Management Plan (SMP)
- Definition Phase Baseline Concept (Euclid Red Book)

- Euclid Mission framework agreement
  - Euclid Multilateral Agreement (MLA)
  - Euclid Memorandum of Understanding (MoU)

- Agency Standards:
  - ESA/ADMIN/IPOL(2007)11 (Applicability of ESA standards)
  - ESA/ADMIN/IPOL(2008)2 (Space Debris mitigation)

Inputs

Mission Requirements Document (MRD)

EUCL-EST-RD-1-001

The MRD contains the top-level Euclid requirements under responsibility of the ESA project.

Euclid Requirements definition (1/3)

MRD top-level functional requirements

Functions
- Perform Wide Survey: 15,000 deg2
- Perform Deep Survey: 40 deg2
- Visible imaging
- Near-Infrared Slitless Spectroscopy
- Near-Infrared Photometry
- Provide mission data products in a Euclid Legacy Archive (ELA)

Architecture
- Space Segment
  - Single Telescope
  - VIS Instrument provided by EC
  - NISP Instrument provided by EC
- Ground segment
  - MOC at ESOC
  - SOC at ESAC
  - EC-SGS
  - GSN with X & K-band capability
- Launch Segment
  - Soyuz Launcher

Mission
- Science Lifetime 6 years
- L2 orbit

Agency Constraints
- ECSS Standards
- Decommissioning
- Passivation

Euclid Requirements definition (2/3)

MRD Main Weak-Lensing Science requirements

Galaxy Shape Measurement

Galaxy sample selection

- **Survey size**
  - 15,000 deg^2
  - 85% survey efficiency
- **Average Galaxy density 30 gal/arcmin^2**
  - Sensitivity: mAB = 24.5 (10σ)
- **Median redshit Z>0.8**
  - VIS spectral range 550-950mn

Measurement Bias Control

- **VIS PSF Shape**
  - FWHM < 0.18″
  - $\varepsilon_i < 0.15$
  - $(R_{PSF}/R_{ref})^2 < 4$
- **VIS PSF knowledge**
  - $\sigma(R_{PSF})^2 / \langle R^2 \rangle < 10\text{-}3$
  - $\sigma(\varepsilon_i) < 2\times10^{-4}$
- **Distortion**
  - Residual < 0.003%
- **CTI effects**
  - $\sigma(\varepsilon_{NC})$ < 1.1x10-4
- **Shear Model bias**
  - Additive $\sigma[c]$ < 5x10-4
  - Multiplicative σ[[illegible]] < 2x10-3

Photometric red-shift determination

- **Photo-z precision and uncertainty**
  - σ(z)/(1+z) < 0.05
  - σ(<z>)/(1+z) <0.002
  - f_{cat} < 10%
- **Image quality**
  - Encircled Energy
  - Pixel scale: 0.3″/pix
- **Sensitivity**
  - m_{AB} = 24 (5σ) in all bands
- **Calibration**
  - Relative Photometric error post-calibration <1.5%
- **Number of photo-z bins**
  - NISP-P wavelength range
  - 3 Euclid NIR bands
  - External g,r,i,z data under EC responsibility

Euclid Requirements definition (3/3)

MRD Main Galaxy Clustering Science requirements

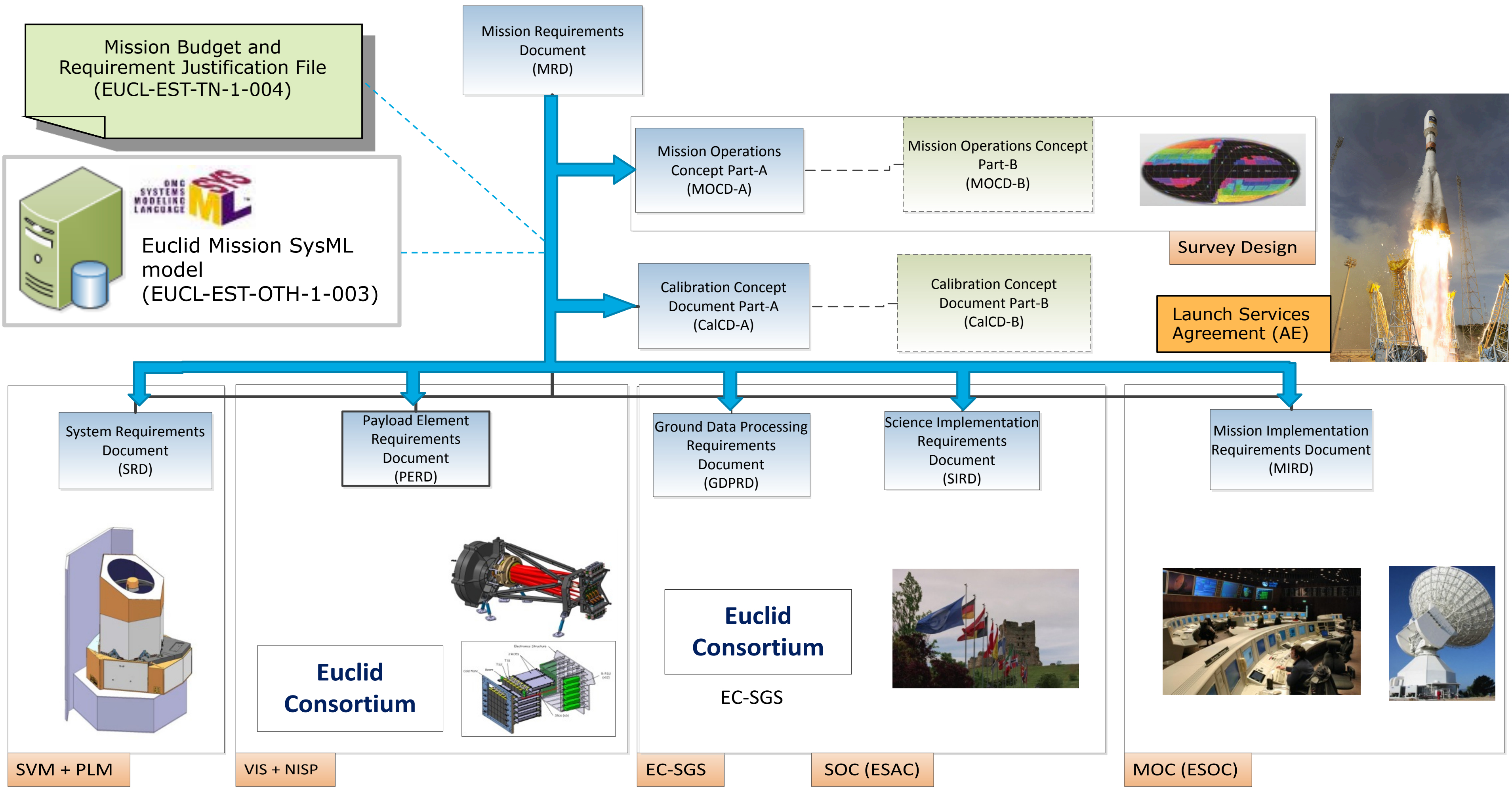
Galaxy sample selection

- Survey size
  - 15,000 deg^2
  - 85% survey efficiency
- Average Number of galaxies
  3500 gal/deg^2
  - Flux limit Hα-line: 3×10^{-16} erg cm^{-2} s^{-1} @ 1600nm
  - Flux limit other wavelenghts: 3.6×10^{-16} erg cm^{-2} s^{-1}
- Galaxy redshift distribution
  - Completeness > 45%
- Median redshit 0.7<Z<2.05
  - NISP-P spectral range 1100-2000nm

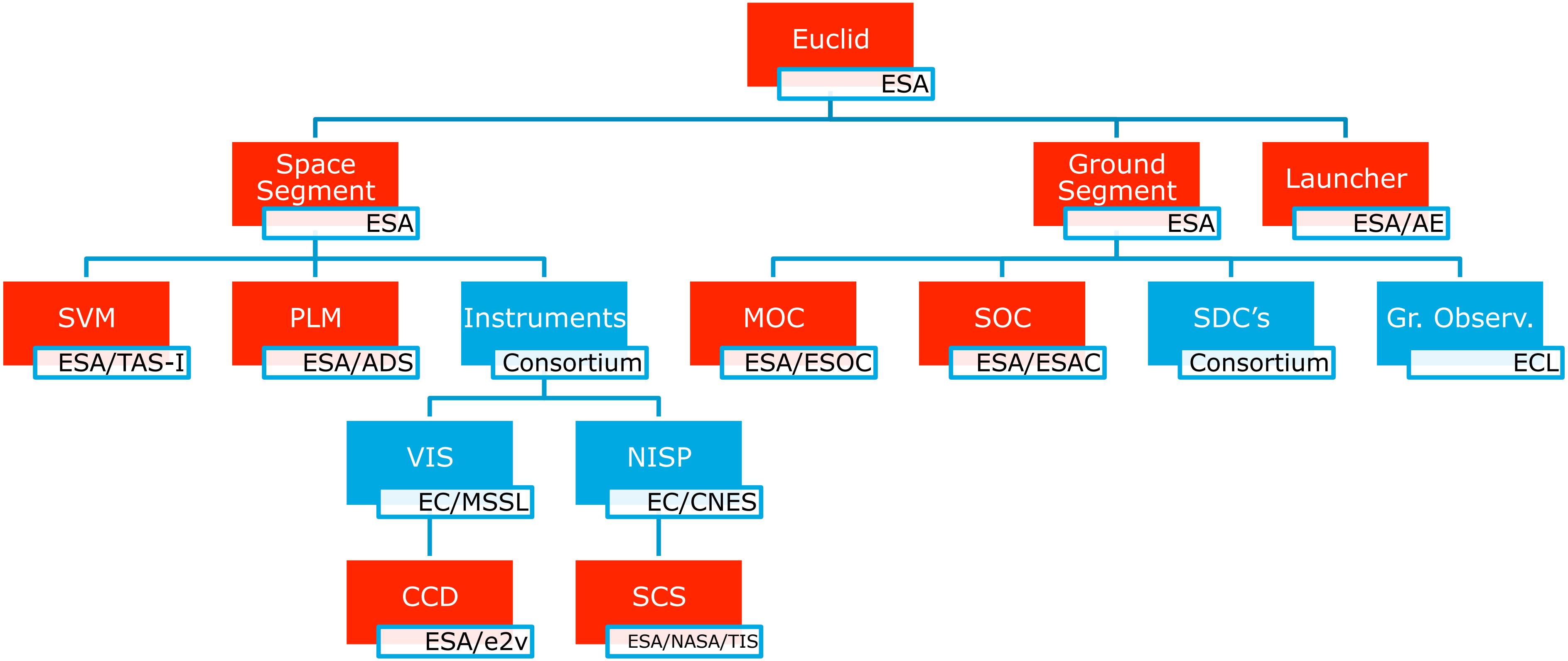
Spectroscopic red-shift determination

- Redshift (z) precision, uncertainty and systematic offset
  (see SciRD)
  - Wavelength error
  - NISP-S Imaging of the NISP-P field with sensitivity m_{AB} = 24 (5σ)
  - Spectral resolution > 250
- Redshift catastrophic error fraction
  f_{cat} < 0.2%
  And
  f_{cat} knowledge better than 1%
  - Z measurement purity > 80%
  - Subsample with purity > 99%
  - External data under EC responsibility

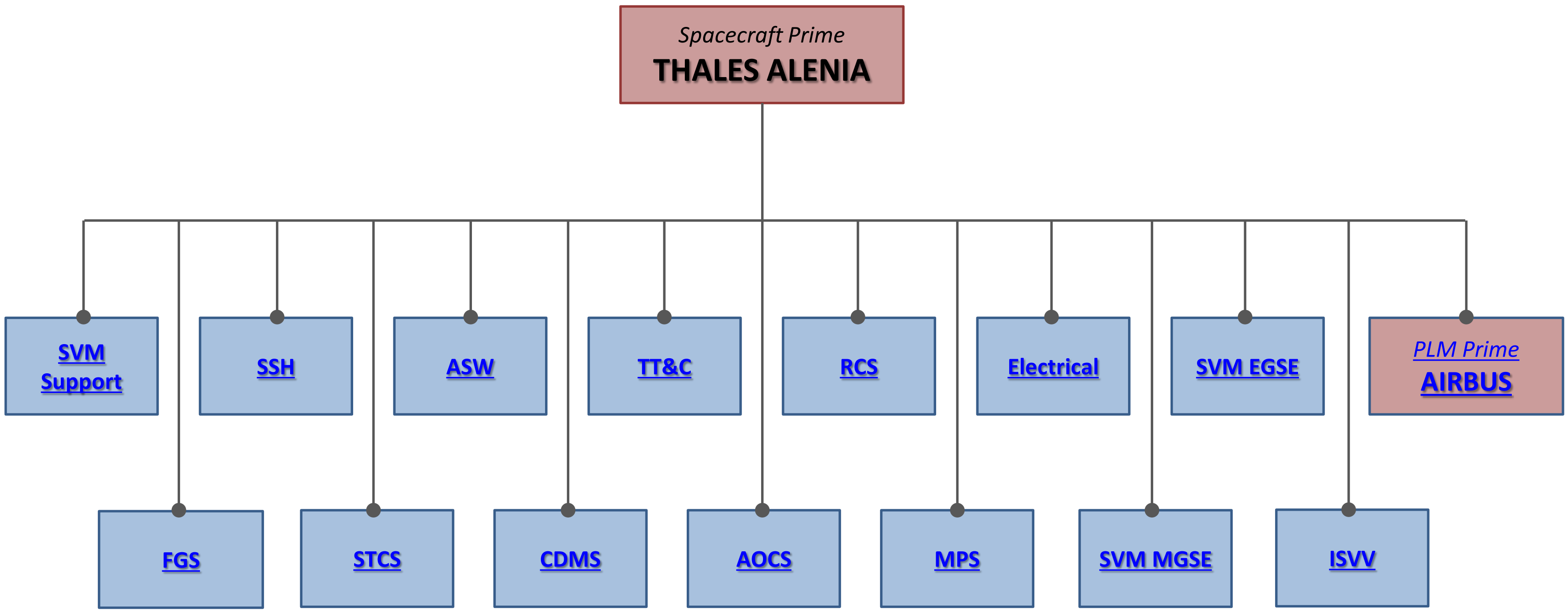
Euclid Requirements Flow-down



Euclid Product Tree

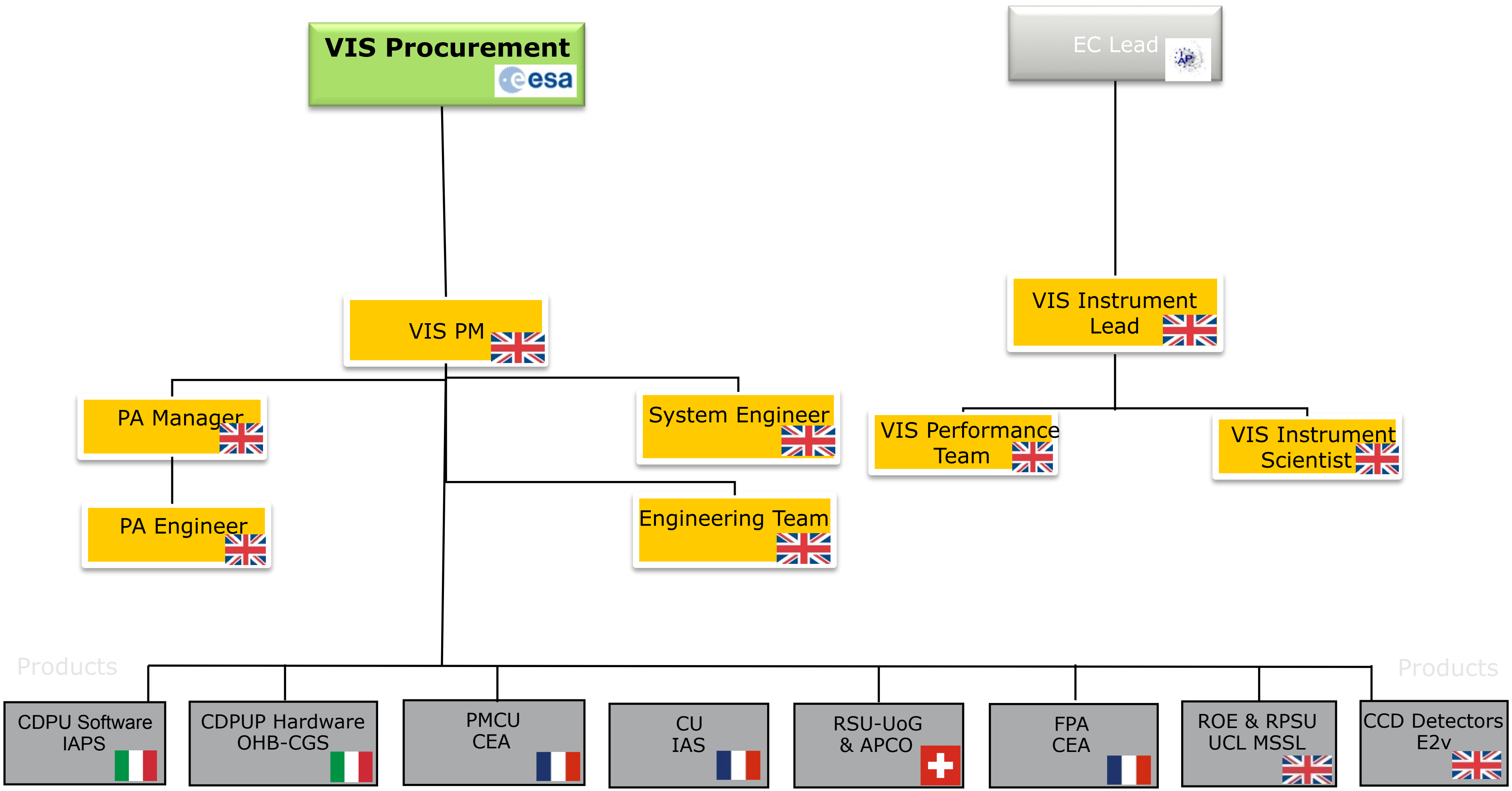


Euclid Spacecraft Industrial Consortium

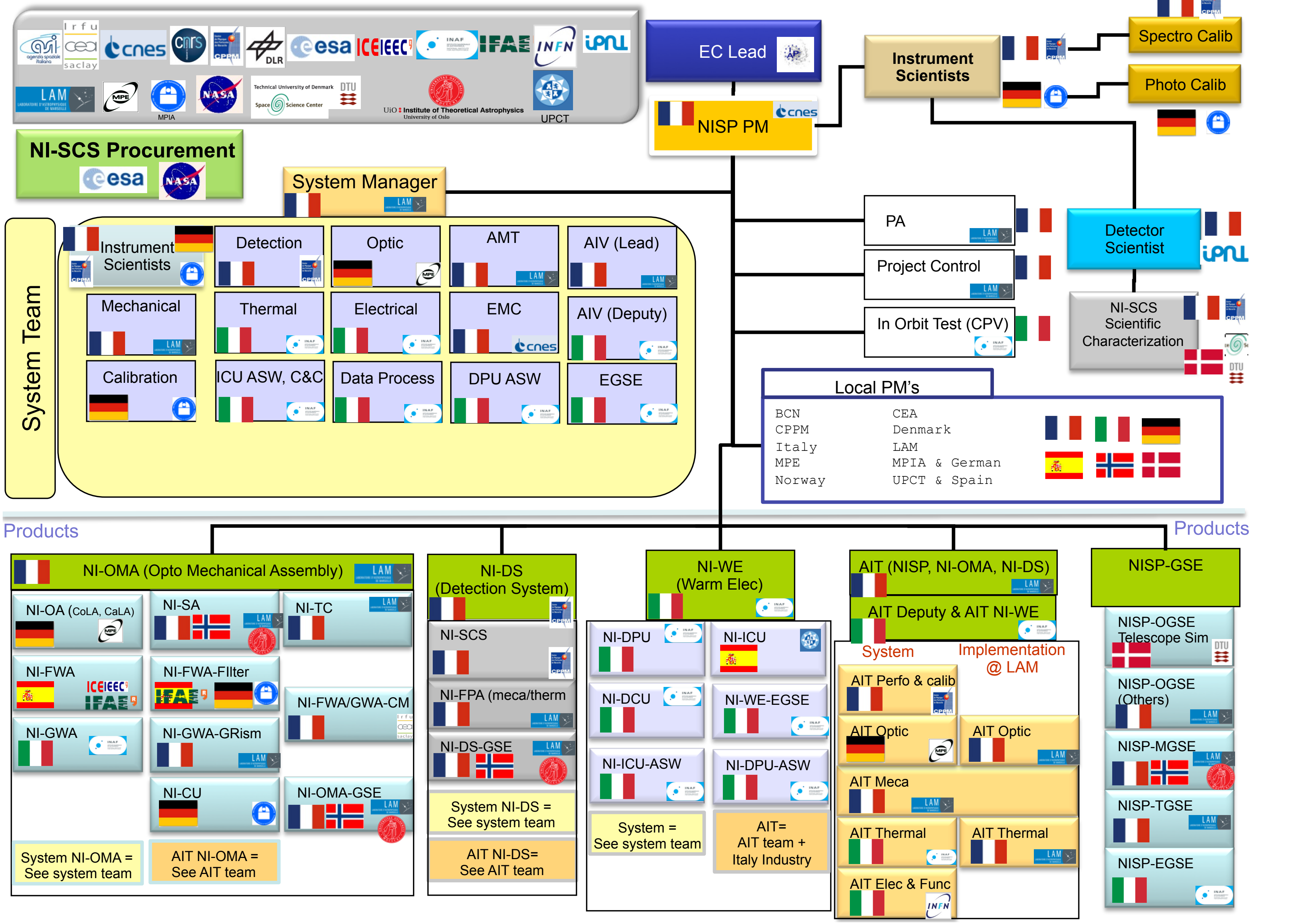


- PLM (telescope and cold compartment) contract with Airbus D&S of Toulouse was kicked off in Jan 2013;
- Prime (including Service module) contract with Thales Alenia Space of Turin was kicked off in Jul 2013;
- Pre-development of HgCdTe detectors with Teledyne Imaging Sensors of Camarillo (CA) was performed in 2012-2015;
- Pre-development and flight production of the CCD with e2v of Chalmsford kicked off in 2012;
- Few more smaller industrial contracts are on going;

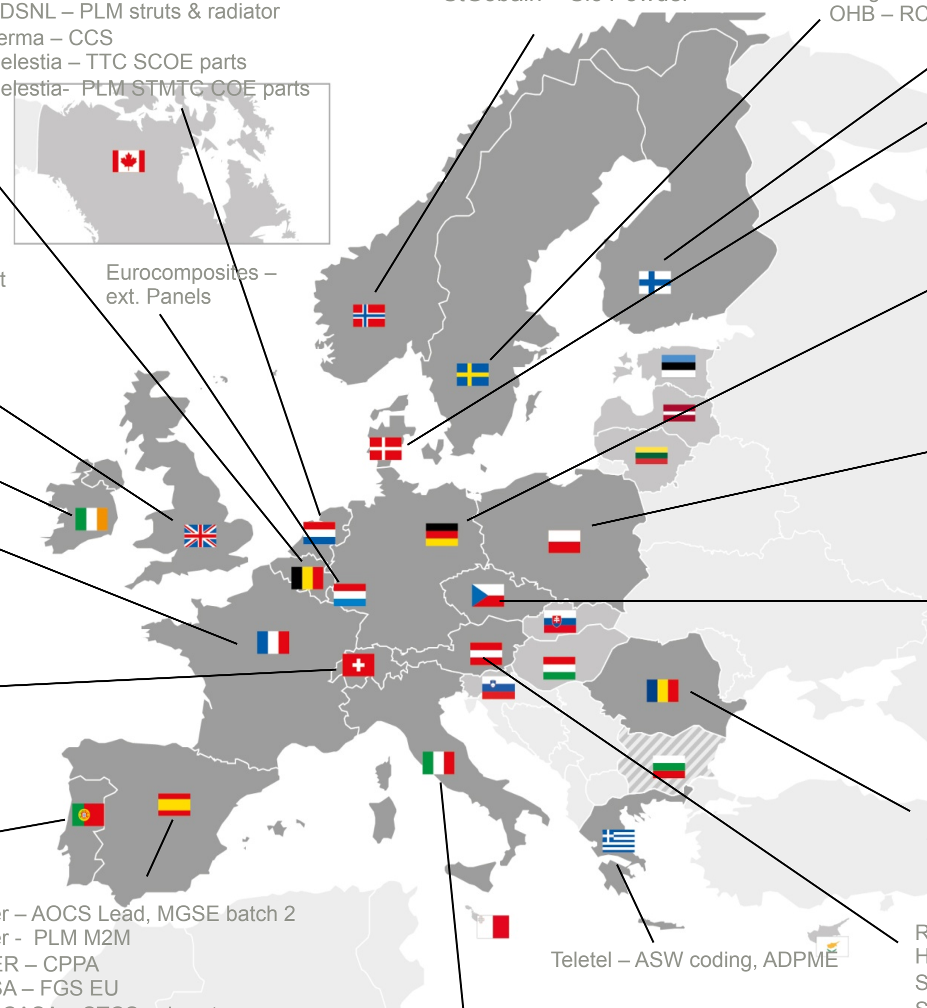
VIS instrument industry/institute consortium



NISP instrument industry/institute consortium



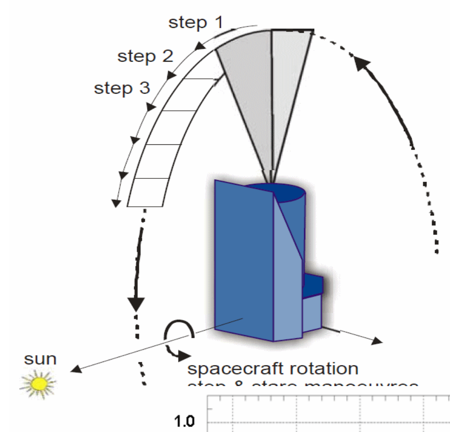
Industrial Geographical distribution

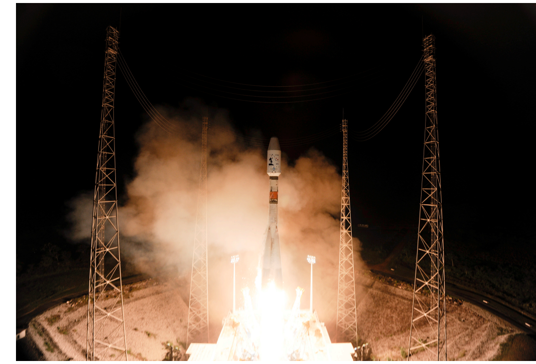


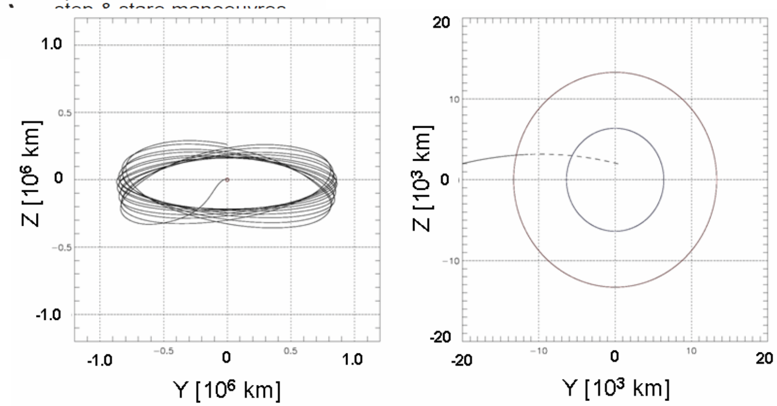
euclid European Space Agency

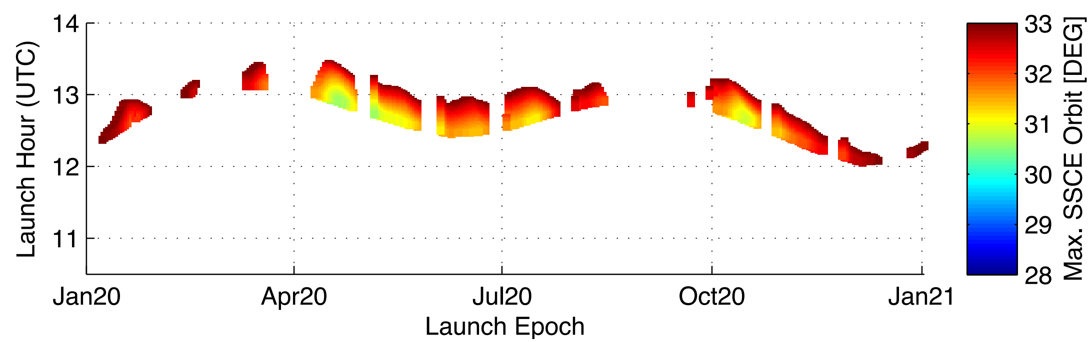
Mission Design

- Soyuz 2.1B + Fregat ascent trajectory and direct SEL2 transfer orbit;
- Y-Z plane of the co-rotating frame;
- Maximum Sun-spacecraft-Earth angle of 33º-36º;
- Step-and-stare scanning of the sky;
- Telescope LOS is kept perpendicular to the Sun direction (87º < SAA< 121º)
- Launch window constraints: perigee velocity, SSE angle, no eclipses, telescope vs. sun direction ≤ 30º.



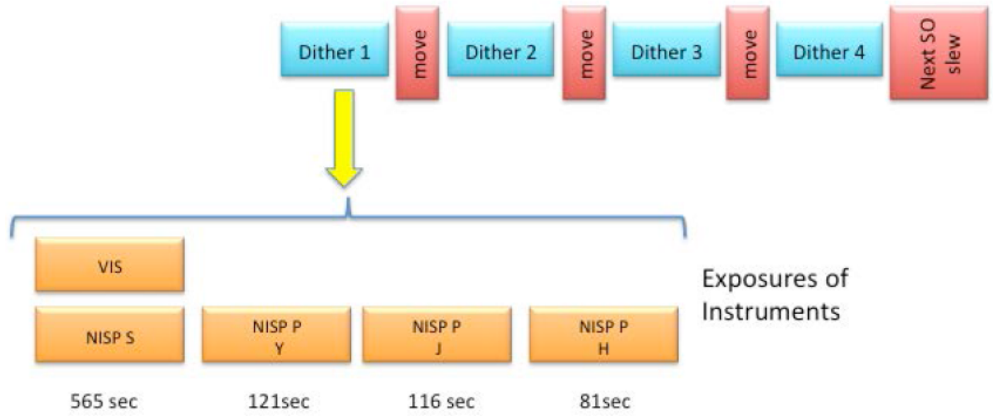


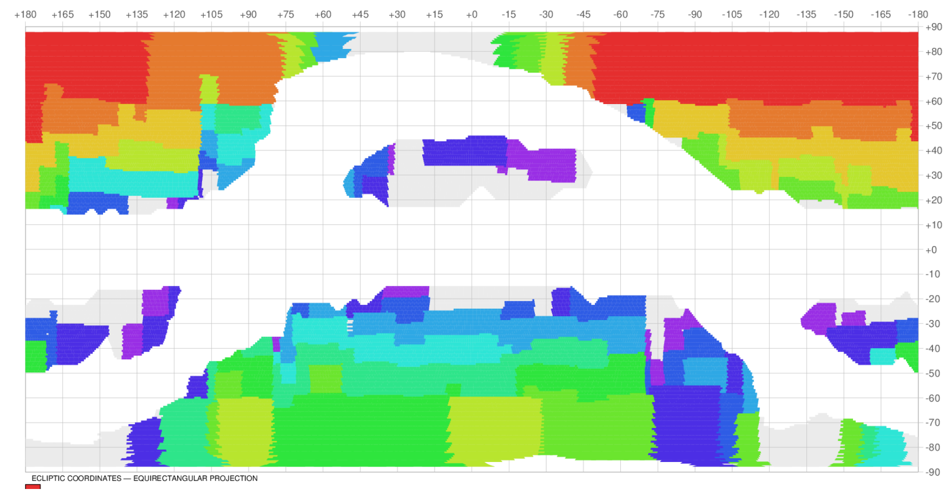




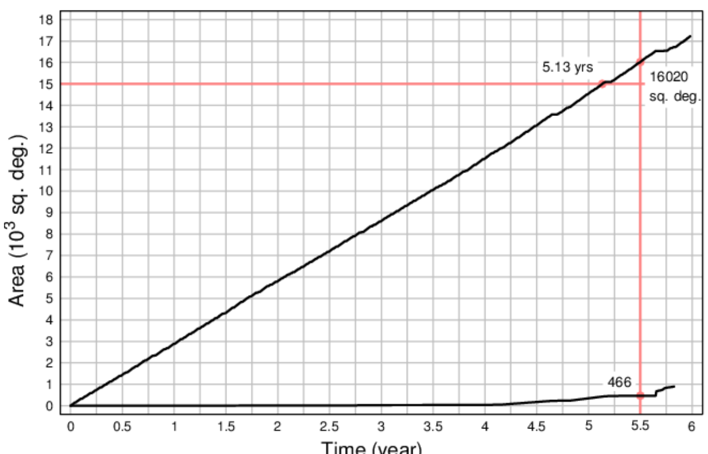
Survey Design

- Instruments observation sequence of one field =>
- |b|>30º
- Minimise SAA variations;
- Minimise zodiacal light => high ecliptic latitude;
- Low galactic extinction;
- Specific pointed calibration (high star density);
- Deep survey observation;

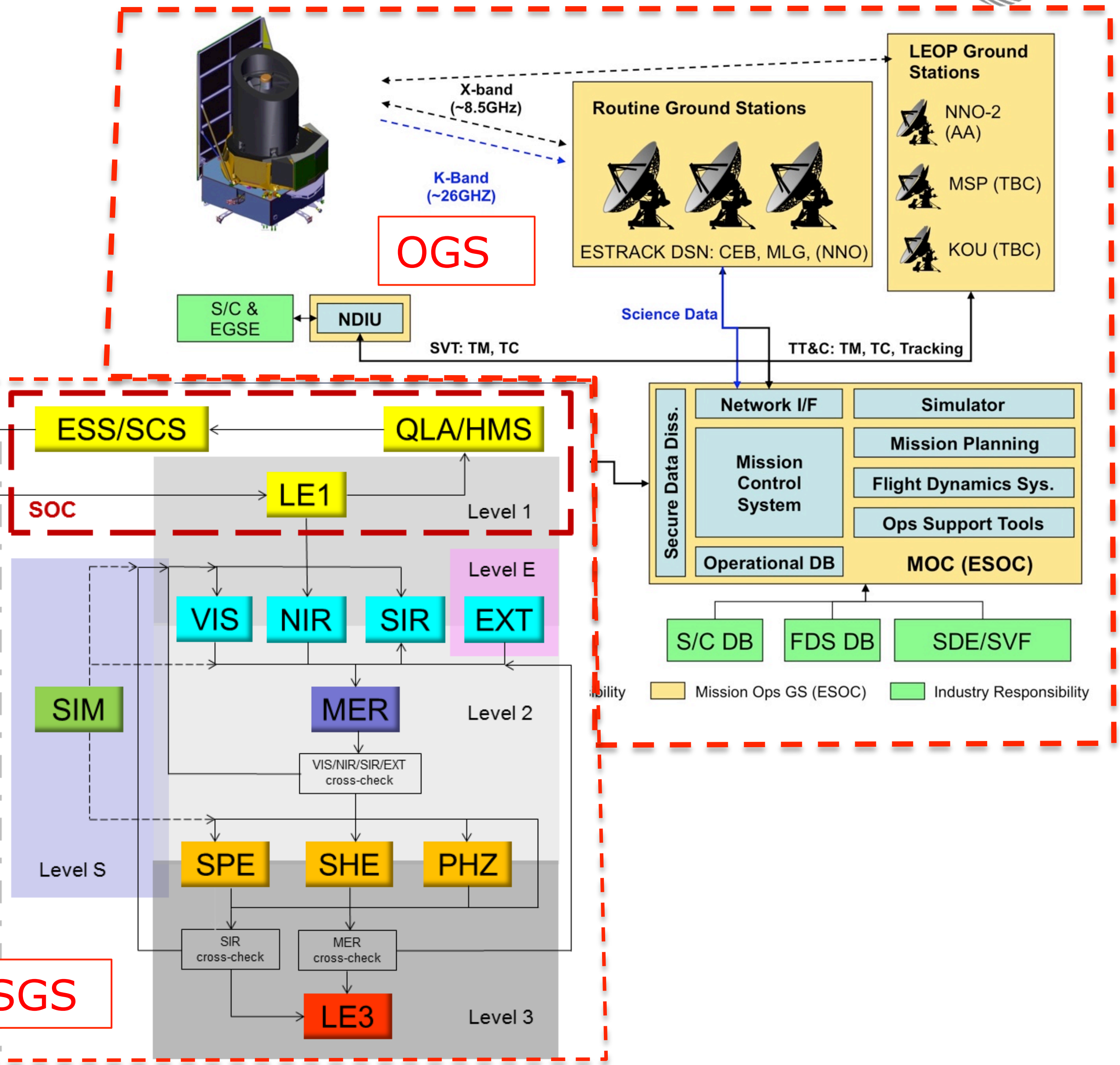




area covered by the wide survey (ecliptic coordinates, colour coding follows the epoch of observation). The empty regions reflect the ecliptic equator and the galaxy plane.
Left: growth curve, the increase of the area covered by the wide survey as a function of time.

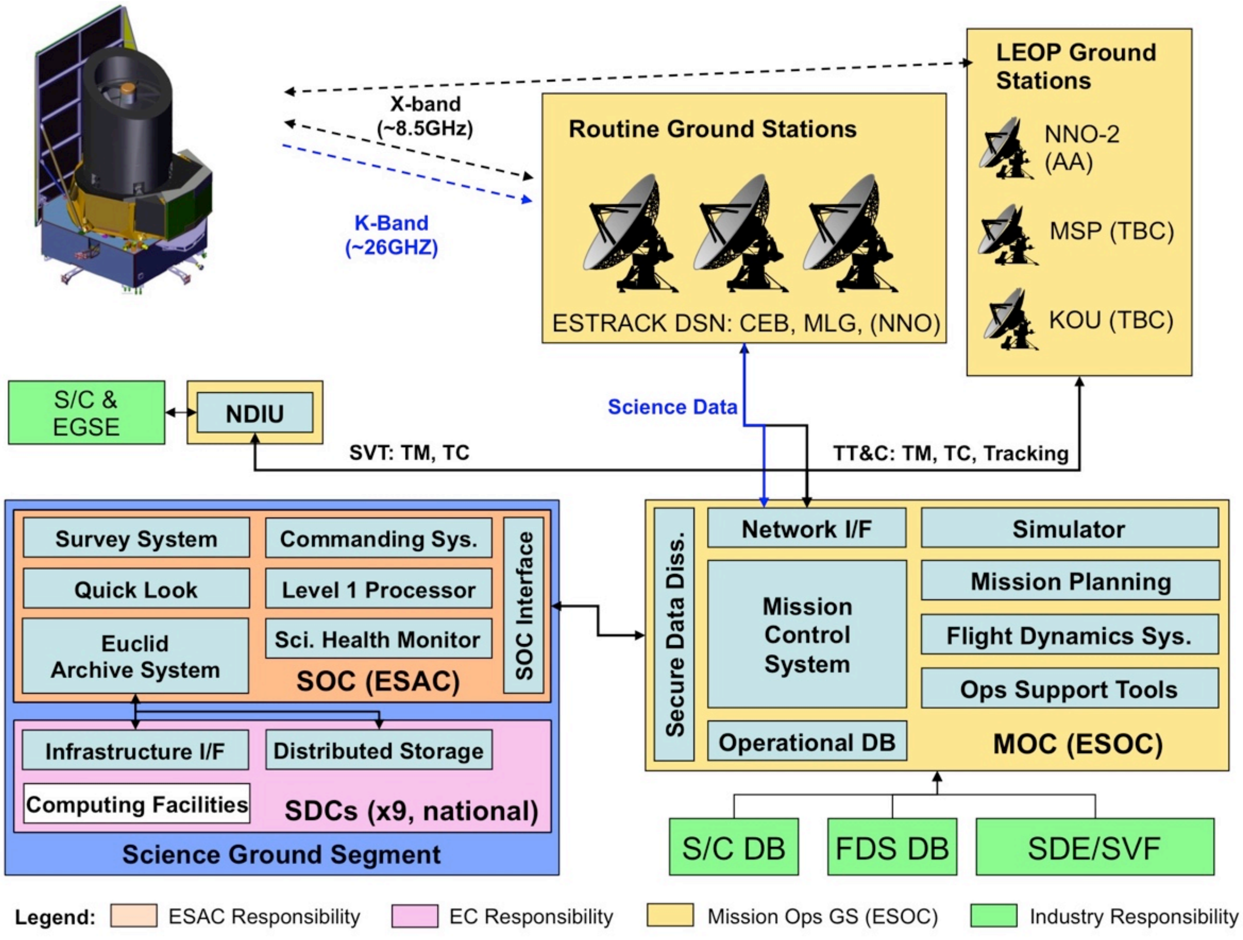


Ground Segment – OGS and SGS



Legend:
ESS: Survey planning
SCS: Instrument commanding
QLA: Quick look analysis
HMS: Scientific health monitoring
LE1: Level 1 processing
VIS: VIS processing
NIR: NISP photometry processing
SIR: NISP spectroscopy processing
EXT: External data ingestion
MER: Merge
SPE: Spectroscopy redshift
SHE: Shear measurement
PHZ: Photometric redshift
LE3: Level 3 processing

Ground Segment – OGS + SOC functions



Operations Ground Segment

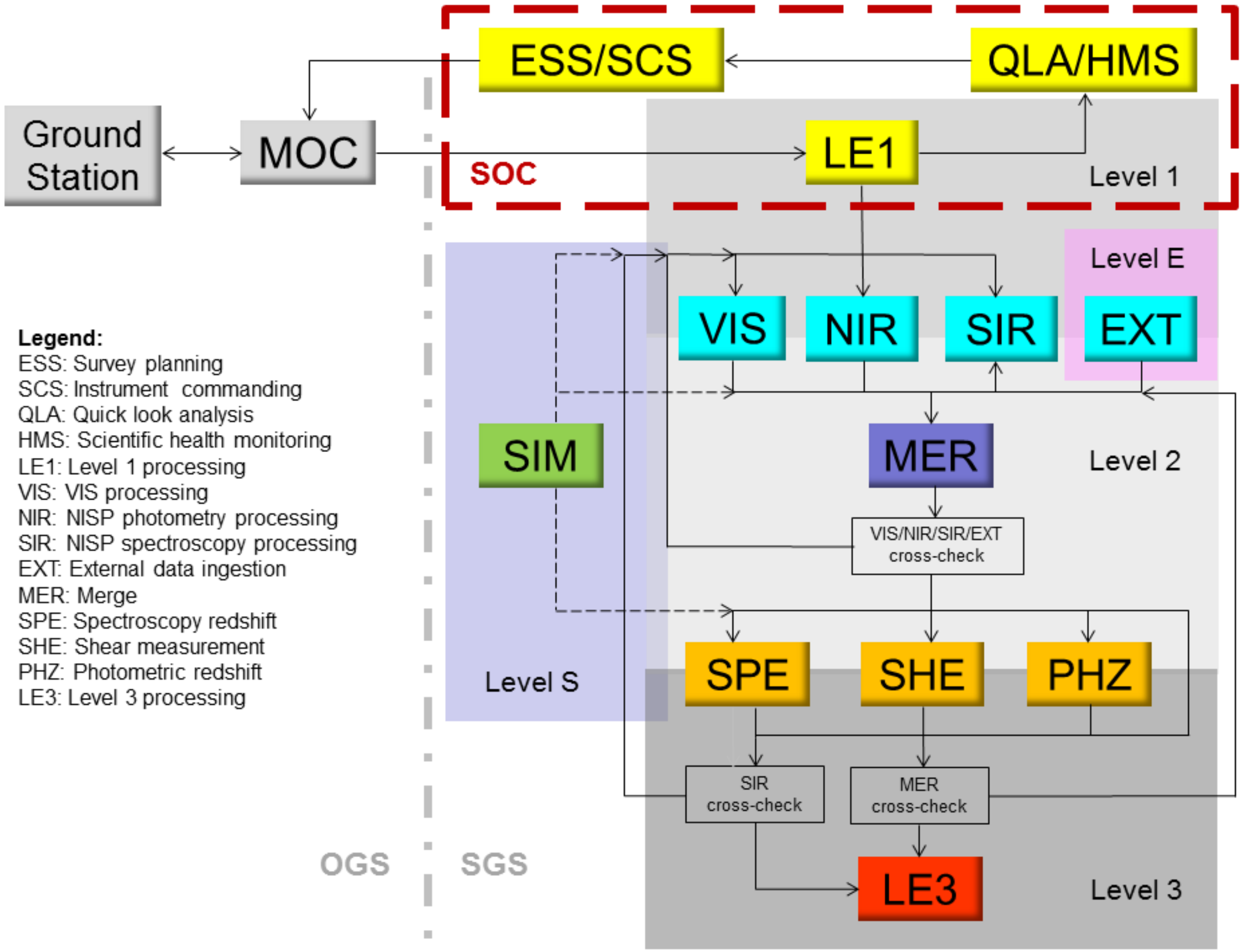
- Design, implementation, validation and operation of the MOC elements of the ground segment
- Support to Project in all development phases
- Operations of the space segment (spacecraft and instruments) during LEOP, Commissioning and Routine Phase

Science Operations Centre

- Interface between the Mission Operations Centre and the other elements of the SGS, providing all necessary mission data to the SDCs.
- Interface to the Scientific Community for the final validated science products once released through the archive system developed at ESAC.
- Overall design and engineering of the SGS, working closely with the System Team.
- It manages the execution and monitoring of the Sky Survey.

Ground Segment – SGS-EC functions

- The Instrument Operation Teams (IOTs), responsible for the maintenance of the instruments production of weekly instrument reports.
- The Science Data Centres (SDCs), host the IOC's, take Level 1 and produce Level 2. Science Processing to obtain Level3. Reprocess external data: Level E.

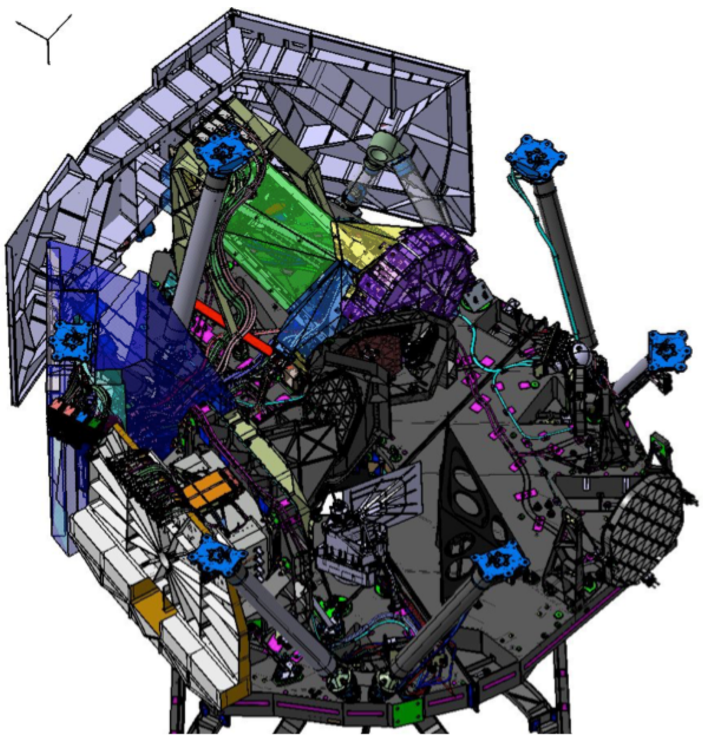


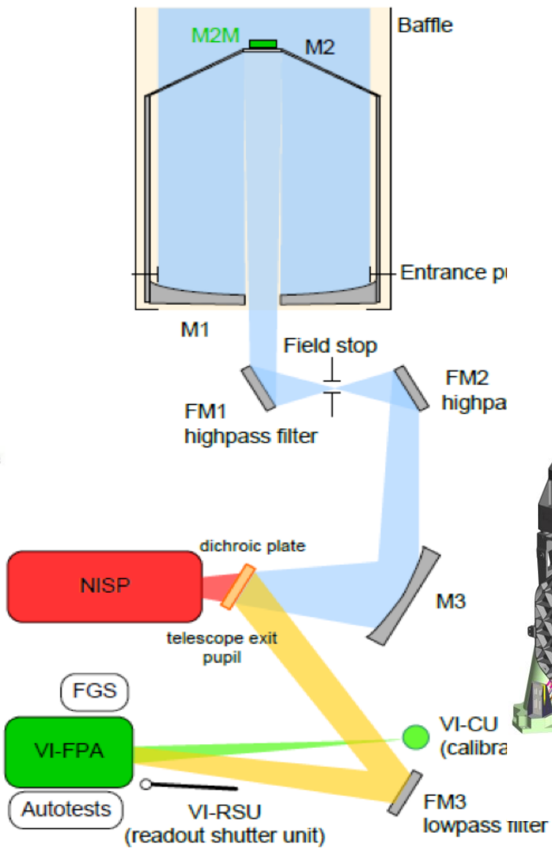
Euclid Main Challenges (requirements)

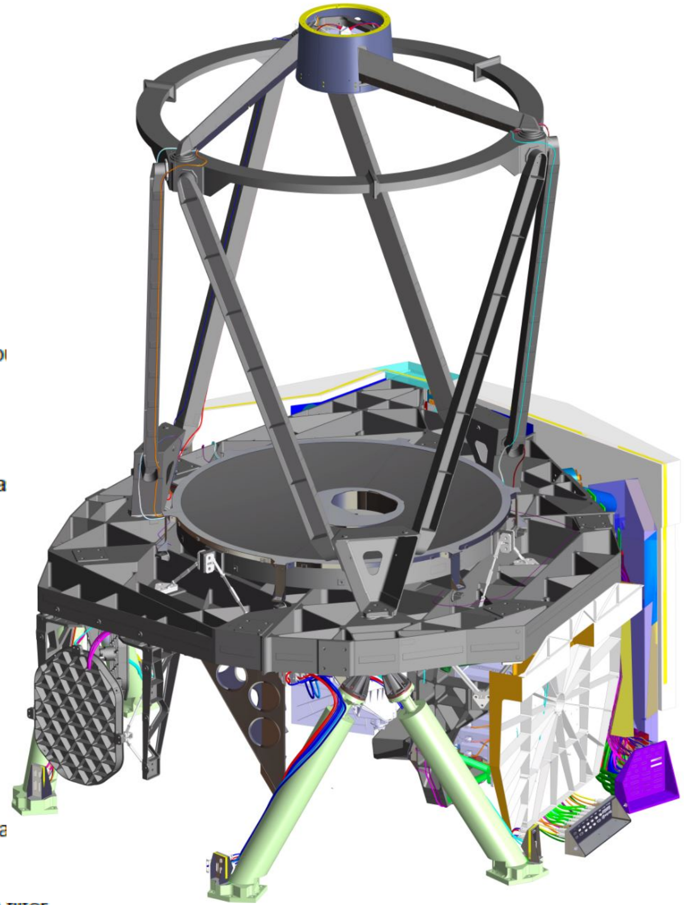
- Derive directly from the Science requirements (GC and WL probes):
  - Survey area > 15,000 deg^2, in 6 years (programmatic + science);
  - Galaxy density, wavelength coverage, PSF FWHM;
  - NIR photometry, error, PSF EE;
  - NIR spectroscopy, density, flux limit, completeness, purity;
  - Tight control of systematic errors (10^{-7}) and correct modeling
- For WL the amplitude of the signal needs to be measured accurately as a function of redshift:
  - PSF ellipticity < 0.15 and stability < $2 \bullet 10^{-4}$
  - PSF profile: FWHM < 180 mas, $R^2 < 0.057$ as^2 and stability < 10^{-3}
  - Minimum stray light (~ 20% of zodiacal light)
  - Contrast ratio to ghost < 10^{-4}
- For GC power spectrum the statistical reconstruction of large-scale structure requires the slitless spectrometer to achieve:
  - Redshift accuracy < 0.001(1+z)
  - PSF size EE80 < 600 mas
  - Subsample of galaxies > 160,000 with 99% purity

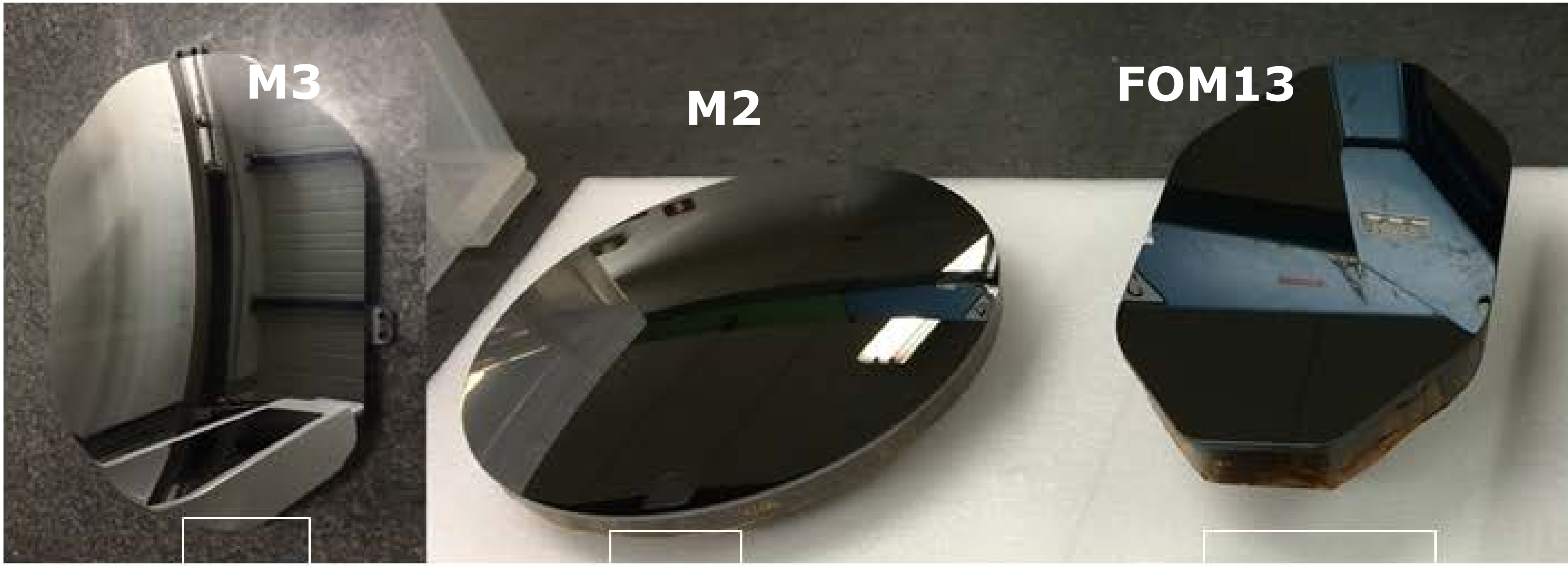
Euclid Main Challenges (solutions)

- Large field of view three mirrors anastigmatic (Korsch) telescope (1.2m primary);
- All SiC optics and structure for maximum stability;
- Cold instrument compartment (140K)



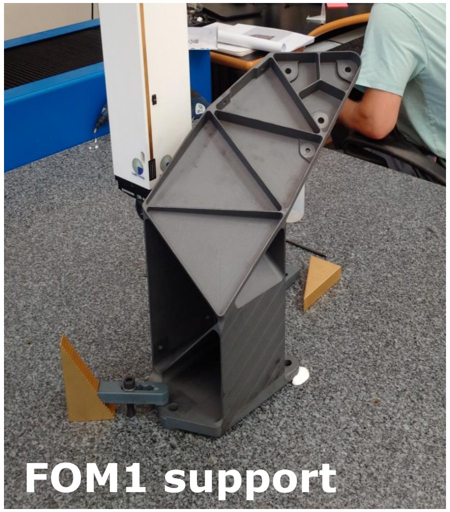


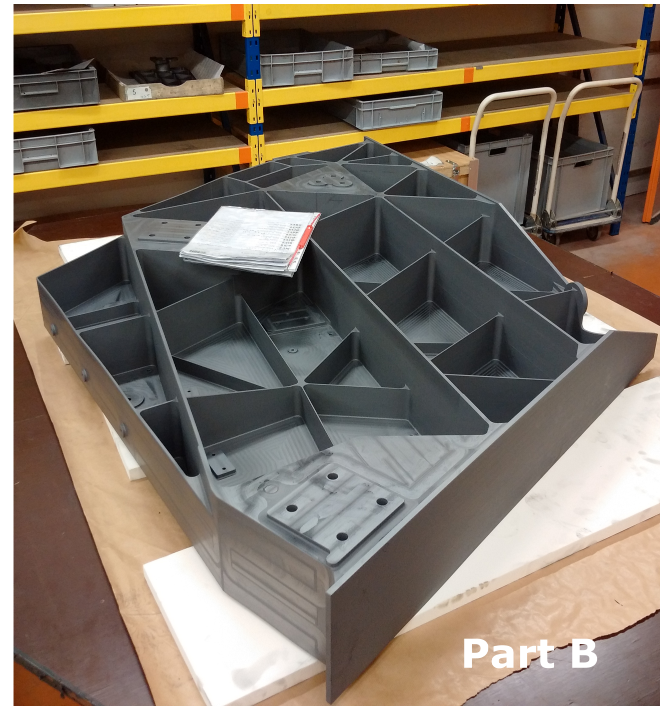




M1

SiC parts – Hardware overview

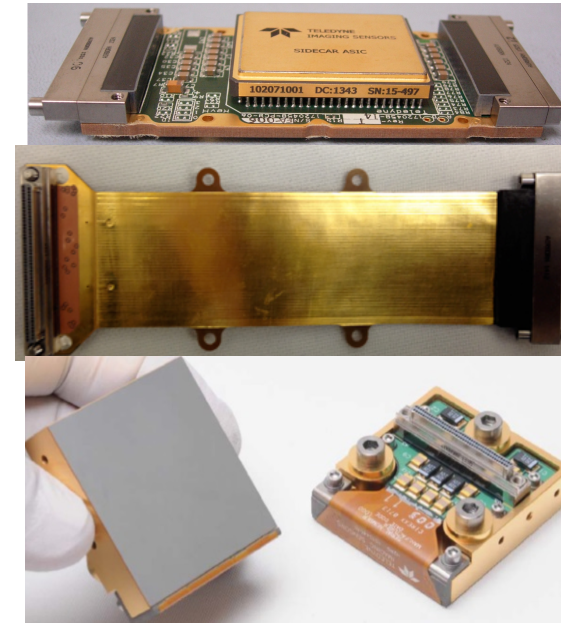




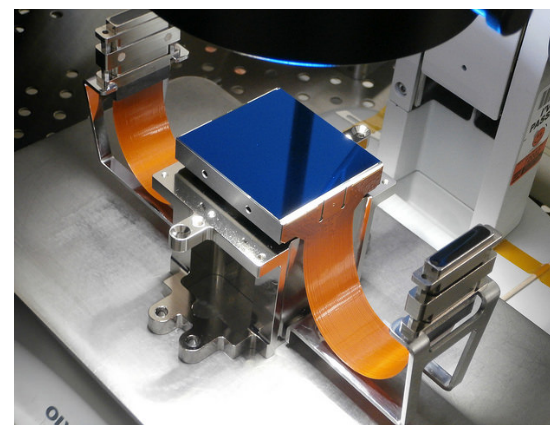
FOM3 support **M3 support**

NIR detectors and CCD's

- NIR HgCdTe detectors (Teledyne), 2040X2040 pixels, 18x18 µm, 2.3 µm cut-off, FW=130,000 e-:
  - QE ≥ 90% 1 µm to 2.2 µm
  - Spectroscopic noise ≤ 7 e- over 560 s
  - Photometric noise ≤ 5 e- over 60 s
  - Dark current ≤ 0.005 e-/s/px
  - Linearity ≤ 0.7% between 6 ke- and 60 ke-

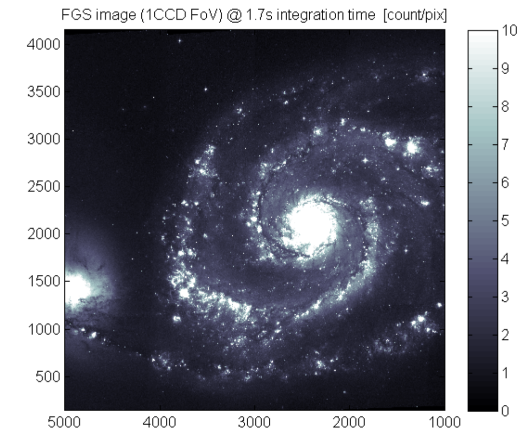


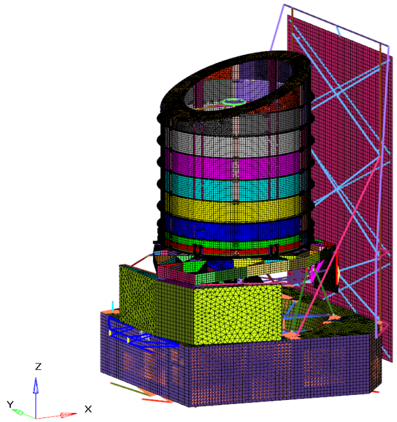
- CCD (e2v), 4096 x 4132 pixels, 12x12 µm FWC=175,000e-
  - 4 read-out nodes (in corners)
  - SiC package extremely tight flatness
  - QE ≥ 70% 500nm to 850nm (95% at 650nm)
  - PRNU much better than 2% at all spatial scales
  - Noise better than required 3.6 e- at 70 kpix/s



Spacecraft exceptional stability

- $PSF_{System} = PSF_{Tel} \otimes PSF_{LOS} \otimes PSF_{FPA}$
- AOCS performance over one dither exposure:
  - APE < 2,5/7,5 as around transverse/LoS axis (1σ)
  - RPE < 25/500 mas around transverse/LoS axis (1σ)
- Need Need of a dedicated FGS Star Catalogue (19 mag);
- FGS performance solves by design STR to VIS thermo-mechanical deformation problems;
- FGS Absolute Attitude Measurement Error @ 1Hz:
  - 0.6 as at 99.7% CL around transverse axis
  - 8.7 as at 99.7% CL around telescope boresight axes
- FGS Relative Attitude Measurement Error @ 1Hz over 700s:
  - 0.03 as at 99,7% CL around transverse axis
  - 2.1 as at 99.7% CL around telescope boresight axes
- Micropropulsion Noise ≤ 1μN/√Hz for frequency > 0.01Hz,
- Structural-Thermal-Optical-Performance analysis:
  - 500 MC cases: ≤ μm and μrad level deformation

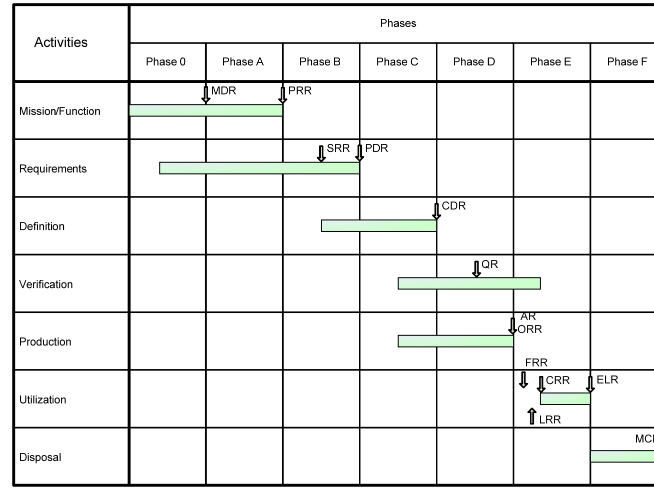


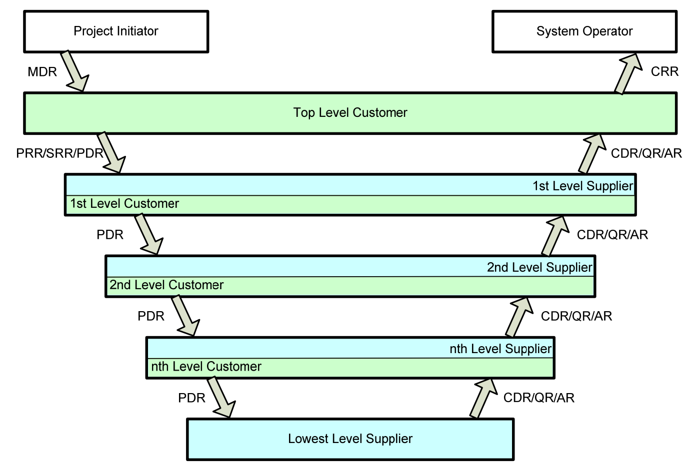


A short movie

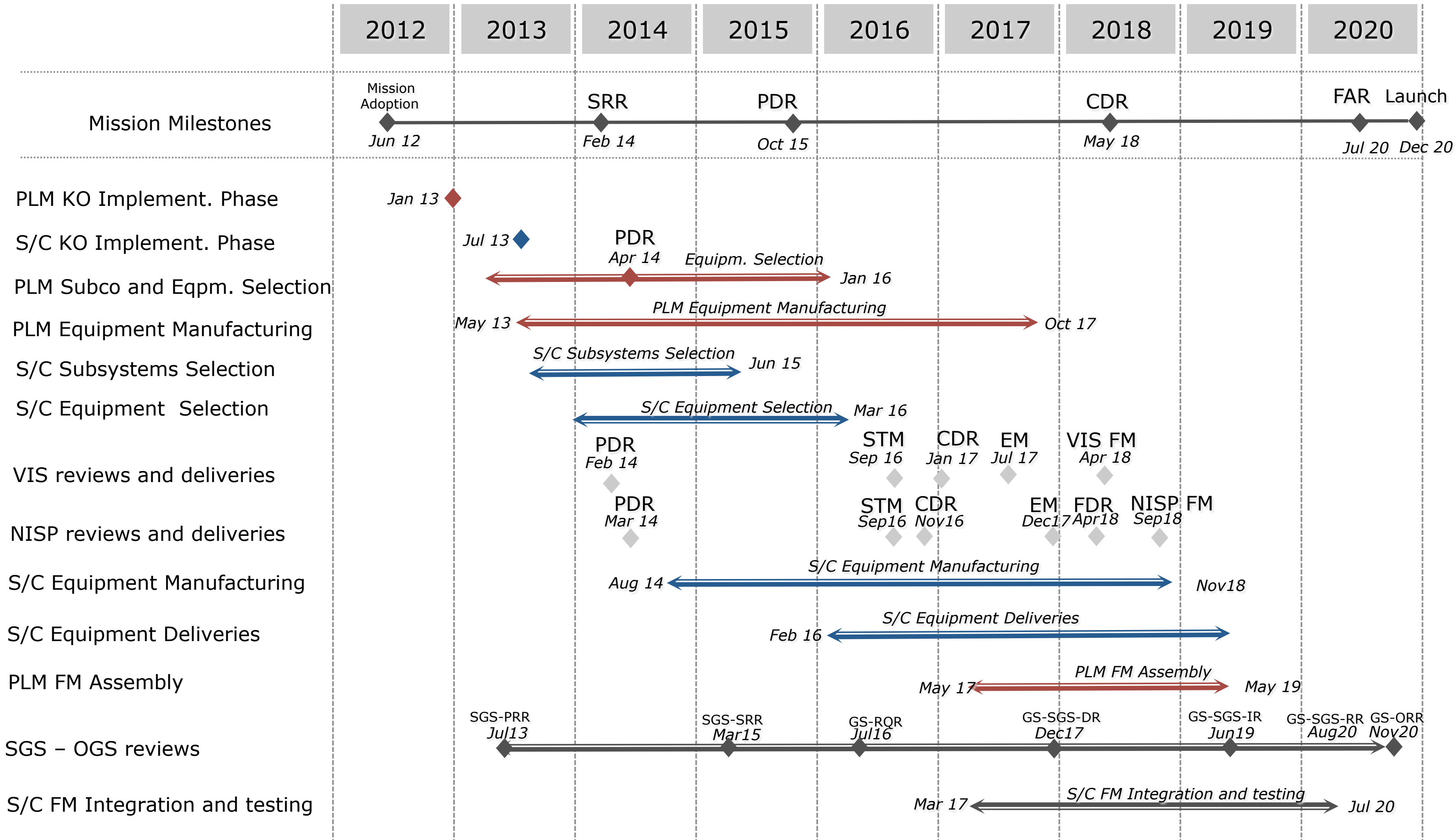
Review Cycle at ESA

- The project life cycle is clocked by Reviews at:
  - Mission level
  - Segment level (Space, ground, launcher)
  - Element level (Platform, instruments)
  - System/subsystem level
- Project Phases culminate in reviews:
  - Phase A (PRR/SRR), B (PDR), C (CDR), D (QR/FAR), E (MCR/EMR);
- Allows periodic and independent check of tasks and objectives of the sequential phases;
- From PRR to PDR, reviews are "top down";
- From CDR to FAR, reviews are "bottom up";
- ESA is top level customer and directly organises reviews to "element" level;
- External entities may also participate (e.g. CERN with Science Ground Segment)

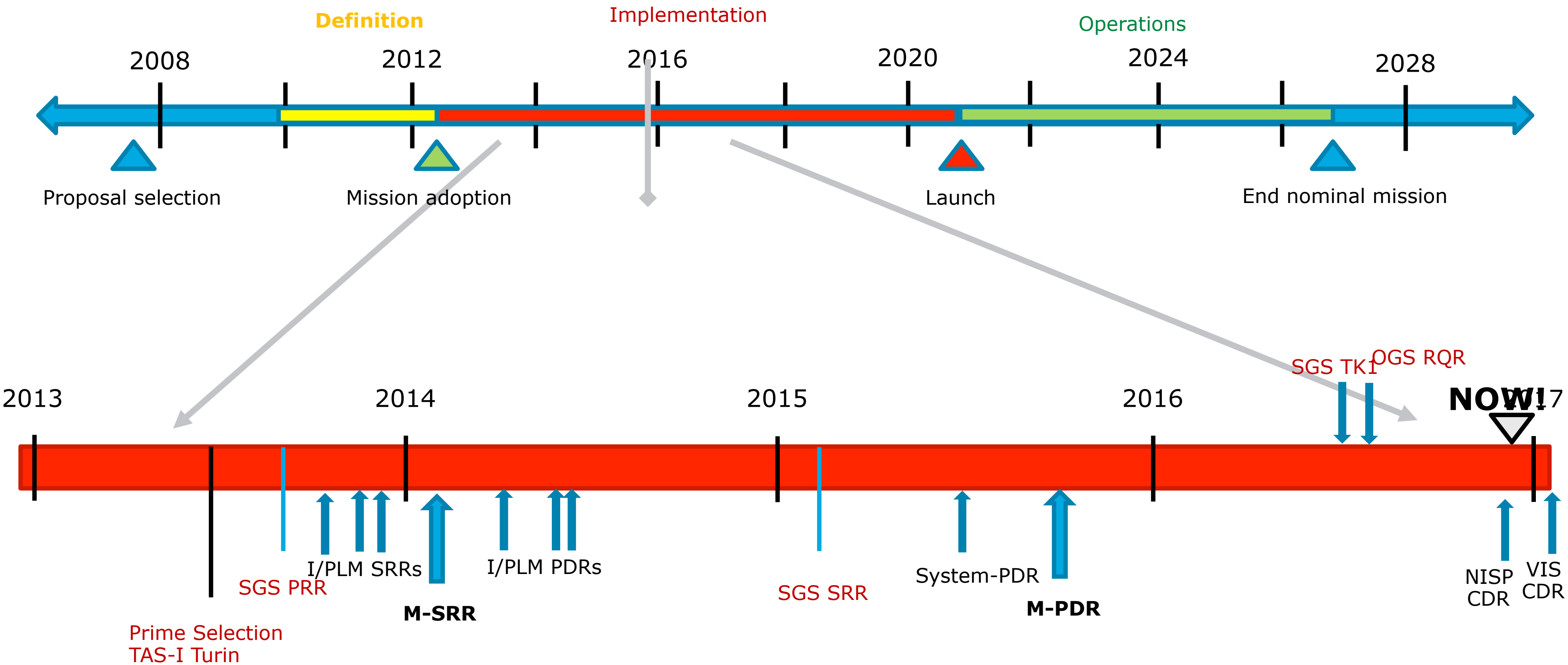




Euclid – Schedule Overview



Overview mission timeline



Major milestone recently passed: SGS TK1, GSRqR, NISP I-CDR

1st half 2017 project milestone: VIS I-CDR's, Inf-Ch#7, Sci-Ch#3, SPV KO