ESA Unclassified
For official use
ESA/IPC/THAG(2018)2bis

EUROPEAN SPACE TECHNOLOGY HARMONISATION

PROPOSED WORKPLAN FOR 2019

AND LIST OF TECHNOLOGIES EARMARKED FOR 2020 AND 2021

Page intentionally left blank

1 INTRODUCTION

This document aims to present the proposed technologies which will be covered by the European Space Technology Harmonisation in 2019 and to provide a preliminary list of technologies which are to be considered for harmonisation for the period 2020 – 2021.

The process of defining the list of subjects for 2019 involved the Technology Harmonisation Advisory Group (THAG), ESA Technology, Engineering and Quality Directorate, ESA Programme Directorates and Industry, and consists of the following steps:

a. Feedback from Industry, through Eurospace and SME4Space, on 2019 Harmonisation topic selection (based upon topics earmarked for 2019 in the 2018 Workplan)

b. Determination of the list of Harmonisation subjects for the year 2019, discussed with THAG at the restricted session of the 1st cycle 2018 Mapping Meeting held on 6th February 2018

c. Finalisation of 2019 Workplan with THAG and agreement at the restricted session of the 2nd cycle 2018 Mapping Meeting held on 12th April 2018

d. Submission of the Harmonisation Workplan 2019 to the June 2018 IPC for approval.

2 CRITERIA FOR IDENTIFICATION AND SELECTION OF TECHNOLOGIES

The technologies for this Workplan are identified from the following input:

a. Actions from previous Harmonisation Meetings

b. Review of the previous Harmonisation subjects and coverage of the ESA Technology Tree

c. Proposals received from THAG Delegations, Industry via Eurospace and SME4Space, ESA Directorates

d. Results of the analysis of the implementation of past harmonised Roadmaps (tracking) and the need to revisit some Technologies.

In order to define the level of priority and identify the subjects to be proposed for next year, the following criteria are taken into account.

1. Technology maturity level
Harmonisation Roadmaps aim at bringing the addressed technologies and products to the necessary maturity, performance and competitiveness levels for the benefit of European institutional and commercial programmes. Harmonisation should not and is not compromising advanced basic research or innovation.

2. Strategic relevance for Europe
Leading edge technologies enabling new missions and technology areas strategic for ensuring European non-dependence have high priority.

3. Mission needs and market potential
Technologies answering to mission requirements or to a market demand.

4. Technology gap or unnecessary duplication
Experts' inputs to assess gaps and overlaps

5. Need to revisit a technology roadmap
As a general rule, it is intended to revisit previously harmonised subjects every 3-5 years, to check technology or industrial landscape evolution. If not possible within this time frame, the objective is to at least revisit the subject before most of the activities in the previously approved Roadmap are planned to end, in order to ensure Roadmap continuity and avoid gaps. The revisit however depends on the specific subject and a decision on this must be supported by the results of an analysis of past roadmap implementation using the harmonisation tracking system.

3 LIST OF TECHNOLOGIES FOR 2019

Table 3-1 lists the ten technologies proposed for 2019. For each of the topic the relevant Competence Domains[1].

Table 3-1 List of Technologies for 2019

Competence Domain(s)	**Title**	**Revisit**	**New**
1st cycle 2019			
CD07	Chemical Propulsion - Micropropulsion	2011	
CD02	Composite Materials	2014	
CD02, CD05	Cryogenics and Focal Plane Cooling	2013	
CD04	Electrochemical Energy Storage	2014	
CD04	Power Management and Distribution	2013	
2nd cycle 2019			
Competence Domain(s)	**Title**	**Revisit**	**New**
CD03, CD08, CD09	Big Data From Space	2017	
CD07	Fluid mechanics and Aerothermodynamic Tools	2012	
CD03	On-Board Radio Navigation Receivers	2013	
CD05	Technologies for Optical Passive Instruments – Mirrors	2013	
CD05, CD02	Technologies for Optical Passive Instruments – Stable & Lightweight Structures	2013	

The 2019 IPC-THAG Meeting dates are as follows:

5-7	February	2019	1st	cycle	Mapping Meeting
16-18	April	2019	2nd	cycle	Mapping Meeting
10-12	September	2019	1st	cycle	Roadmap Meeting
3-5	December	2019	2nd	cycle	Roadmap Meeting

Note that these dates may be subject to change to minimise conflict with other ESA events and calendars.

[1] The list of Competence Domains is shown in section 7, Table 7-1

4 DESCRIPTION OF TECHNOLOGIES FOR 2019

The following descriptions of the technologies proposed for the Harmonisation Workplan for 2019 may be refined at the start of the cycles.

4.1 CHEMICAL PROPULSION – MICROPROPULSION

The last harmonisation of the topic “Chemical Propulsion – Micropropulsion” took place in 2011. The next would be the fourth harmonisation of this topic.

4.1.1 Technology Overview

The technology overviewed in this section is chemical Micropropulsion. Chemical propulsion can be divided in different categories and in many different ways. One area of special interest, both in the US and Europe, is micro-propulsion and miniaturization of components. A common denominator and enabler for these two areas is Micro Nano Technologies (MNT), also often referred to as Micro System Technologies (MST) (in Europe) and Micro Electro Mechanical Systems (MEMS) (in US).

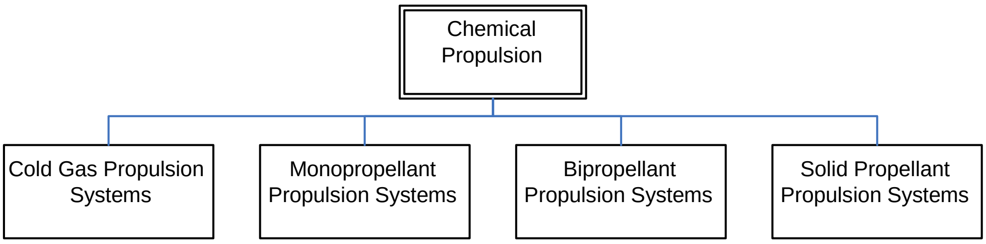

Figure 3-1: Chemical propulsion divided into different propellant categories

Chemical Micropropulsion is as of today primarily using gaseous or liquid mono-propellants. However, liquid bi-propellants and solid propellants are emerging as candidates for future chemical Micropropulsion systems.

Definition of chemical Micropropulsion

The following two definitions are both applicable to chemical Micropropulsion systems:

Definition 1:
- Predominantly traditionally fabricated technologies;
- Very low thrust levels in the order of 1 to 100 microNewton (μN) with very high precision requirements;
- Applicable to larger spacecraft with stringent requirements on precision and stability (e.g. formation flying, precision pointing or rendezvous and docking missions);

Definition 2:
- Predominantly MEMS fabricated technologies;

- Low thrust levels in the order of 0.1 to 100 milliNewton (mN) with limited precision requirements;
- Applicable to a wide range of micro- or nano-spacecraft (including Cubesats);

All chemical Micropropulsion systems are therefore characterized by one minimized design parameter (which is a design driver for micro- or nano-spacecraft):

*Thrust*Mass*Volume*

For larger spacecraft as well as constellations, competitiveness is also a driver.

The upcoming chemical Micropropulsion roadmap includes also a few closely related generic technologies relevant beyond the strict definition of chemical Micropropulsion.

Micro Nano Technology / Micro System Technology / Micro Electro Mechanical Systems (MEMS)

There are several synonyms to describe the same micro-fabrication technology sometime referred to as Micro System Technology (MST) or Micro-Electro-Mechanical Systems (MEMS). Another synonym used in the space segment is Micro Nano Technology (MNT). The MNT, or equivalent MEMS, manufacturing technology has evolved from the planar technology used in microelectronics or integrated circuit (IC) industry. A third dimension has been added by exaggerating the micromachining processes that selectively etch away parts of the substrate (bulk micromachining) or adds new structural layers in order to integrate micro mechanical elements onto the substrate (surface micromachining), which commonly is a semi-conducting silicon wafer. In this way MEMS with integrated mechanical structures, sensors, actuators, and electronics can be realized on micrometer to centimetre scale. The manufacturing is ideally suited for mass production but has to be performed in a clean room environment. There are mainly two types of fabrication processes in MEMS; surface micromachining and bulk micromachining. Other important key words in MEMS are lithography, batch processing, and process compatibility.

High Performance Chemical Micro-thrusters

Chemical micro-thrusters are generally based on four different technologies:

- Cold Gas Thruster: Thruster technology where an inert gas e.g. N2 or Xe is exhausted through the nozzle (note that performance can be enhanced by thermally heating the propellant).
- Monopropellant (catalytic decomposition): A monopropellant thruster is a technology where a catalytically decomposed monopropellant is exhausted through the nozzle.
- Bipropellant: A bipropellant thruster is a technology where the chemical reaction products of two propellants are exhausted through the nozzle.
- Solid Propellant: A solid propellant thruster is a technology where the chemical reaction products of a mixed solid propellant/oxidiser are exhausted through the nozzle.

Related Technologies

Related to each of the above high performance chemical micro-thrusters are a range of technologies that are needed to produce a functioning micro-propulsion system. This includes propellant storage devices, valves, filters and regulators to feed the propellant at the correct conditions to the micro-thrusters, as well as sensors to monitor propellant pressure, temperature and flow rates. Such devices already exist in the form of conventional technologies, but to enable a fully miniaturised and modular micro-propulsion system to be developed. These related technologies must also be developed in MEMS technology and integrated with the micro-thrusters to produce a complete micro-propulsion system.

Quality Assurance and MEMS Reliability
In space applications the reliability assurance is a very important matter and so far there are, as of today, no generally accepted standards for MEMS reliability. An important challenge is not only to qualify the device itself, but one must also examine the entire process surrounding the part, from conception to finish including for MEMS the critical packaging and bonding steps. This implies the logic of process qualification, followed by product qualification, and last product acceptance.
It is in the nature of MEMS that the procedure is not from structure via component to system as it is the case in conventional manufacturing. In MEMS the system is finalised in the last manufacturing step since it is governed by compatibility issues and has to be processed in this order. This implies a new technical approach to achieve reliability, where process qualification becomes more critical than usual and where most of the effort has to be put.

4.1.2 Areas Covered by this Technology Topic

The following technologies will be addressed in the next harmonisation exercise:

- MEMS Technology
- Chemical Micro Thrusters
    - Cold Gas / Hot Gas
    - Monopropellant (Catalytic decomposition)
    - Bipropellant
    - Solid (digital propulsion)
- Valve Technology (high and low pressure)
    - MEMS based Isolation Valve: to replace pyro-valves
    - MEMS-based Proportional Valves for flow control
        - Gases
        - Liquids
    - Micro Check Valve
    - Micro Pressure Relief Valve
    - Micro Actuator Concepts: Piezo, Paraffin, Solenoid, Linear motor type
- Pressure Regulators
    - MEMS-based Integrated Pressure Regulator, without export limitations
- Micro Filters
- Pressure Transducers
    - MEMS-based Pressure Sensors (+ with integrated ASIC and A/D converter) o High pressure, high accuracy digital sensor
    - Low pressure, high accuracy digital sensor
    - Differential pressure sensor
    - Ultra high temperature
- Mass Flow Sensors (likely MEMS based + with digital output**)**
- Micro Miniaturization of propellant storage and feed system

- Miniaturization and integration of driver electronics
- Quality Assurance and MEMS Reliability
- Advanced Propellants for Chemical Micro-propulsion
- Advanced Materials Applications
- Erosion resistant coatings
- Catalytic Nano-coating for High-performance Micro-propulsion
- Material Compatibility Studies (generic)

The relevant Competence Domain is CD07 (see Table 7-1 in Annex).

Chemical Micropropulsion technologies forms part of the Technology Domain 19 (Propulsion), sub-domain A (Chemical Propulsion Technologies), of the ESA technology tree. Chemical Micropropulsion Technologies represent a subset of this Technology Domain, as described in the definition provided in the previous section, partly covering technology groups I (Liquid Propulsion Systems) and II (Solid Propulsion Systems).
Chemical Micropropulsion also partly covers other Technology Domains as per Table 4-1:

TD	TECHNOLOGY DOMAIN	TSD	TECHNOLOGY SUBDOMAIN	TG	TECHNOLOGY GROUPS
15	Mechanisms	E	MEMS technologies	-	-
19	Propulsion	A	Chemical Propulsion Technologies	I	Liquid Propulsion Systems
				II	Solid Propulsion Systems
		B	Electric Propulsion Technologies	II	Electro-thermal Systems
		D	Supporting Propulsion Technologies and Tools	III	Propellants
24	Materials and Processes	B	Materials Processes	II	Coatings

Table 4-1: Technology Tree Coverage – Chemical Propulsion - Micropropulsion

4.2 COMPOSITE MATERIALS

The last harmonisation of the topic "Composite Materials" took place in 2014. The next would be the third harmonisation of this topic.

4.2.1 Technology Overview

A composite material is composed of at least two phases, matrix and reinforcement, working together.
The matrix phase is continuous, the reinforcement phase is uniformly dispersed and is typically in the form of continuous/chopped fibres or particles. The mechanical properties of engineering materials usually depend on the number of defects within the structure of the material and are much lower than theory would predict. Defects for the case of composites may influence the performance of fibres (breakage), matrix (cracking), or the interface (debonding).
It has been found that fine particles and fibres have properties much closer to their theoretical maximum. For instance the tensile strength of silica glass is about 50 MPa. In the form of a fibre the tensile strength could be in excess of 1400 MPa. In order to utilise these properties the stresses from the application must be transferred to the fibre reinforcement.
This is done by the matrix, which both transfers the load to the reinforcement and protects the reinforcement from attack or degradation by the environment.

The major composite classes include polymer matrix composites (PMCs), metal-matrix composites (MMCs) and ceramic matrix composites (CMCs). Further, composites can be classified according to the reinforcement form – particles, platelets, whisker or short fibres, continuous fibre either unidirectional, UD, laminated or woven composites (including braided, knitted and tri-axial architectures).

- Polymer Matrix Composites (PMCs): PMCs consist of polymer-based resin (thermoset or thermoplastic) as the matrix, and a variety of fibres such as glass, carbon and aramid as the reinforcement. PMCs are the most widely used composite materials for space applications.
- Metal-Matrix Composites (MMCs): MMCs consist of a metal such as aluminum as the matrix and are reinforced with fibres or particles that can resist the manufacturing process such as silicon carbide or high melting-point metal
- Ceramic Matrix Composites (CMCs): CMCs are mainly used in very demanding applications (high temperature environments, high stability). The most common are carbon and/or silicon carbide matrices reinforced with carbon fibres. Other applications require composites systems such as a ceramic as the matrix reinforced with short fibres or whiskers such as those made from silicon carbide and boron nitride

The most widely used composite materials for space applications, and subject of the last Harmonisation Topic, were PMCs with continuous carbon fibre reinforcement and epoxy matrix or in some cases cyanate ester matrix. For the purpose of this Harmonisation Topic, the scope should be widened to all relevant composite materials used for space applications, include MMCs and CMCs. Within each of the groups defined above, a large variety of fibre and resin systems are available, for example many different carbon fibre products exist, each with specific characteristics and properties.

4.2.2 Areas Covered by this Technology Topic

This review shall cover all relevant families of composite materials for space applications, including fibre-reinforced thermoset (such as epoxy and cyanate ester) and thermoplastic (such as PEEK) composites, carbon-carbon composites, ceramic matrix composites, and metal matrix composites.

Concerning additive manufacturing processes, they will be covered in the topic when related to continuous or short or fibre reinforcement. Coordination with the "Additive Manufacturing" harmonisation topic will be ensured to avoid duplication.

The relevant Competence Domain is CD02 (see Table 7-1 in Annex).

The composite materials technology mainly covers the Technology Domain of material and processes in the ESA technology tree (TD 24). Other TDs are partially covered, as many different equipment in launcher and satellite use composite materials; please refer to Table 4-2.

Table 4-2: Technology Tree Coverage – Composite Materials

TD	TECHNOLOGY DOMAIN	TSD	TECHNOLOGY SUBDOMAIN
24	Materials and Processes	A	Novel Materials and Materials Technologies
		B	Materials Processes
		D	Space Environment Effects on Materials and Processes
		E	Modelling of Materials Behaviour and Properties
		F	Non-Destructive inspection
		G	Materials and Process Obsolescence

4.3 CRYOGENICS AND FOCAL PLANE COOLING

The last harmonisation of the topic "Cryogenics and Focal Plane Cooling" took place in 2013. The next would be the fourth harmonisation of this topic.

4.3.1 Technology Overview

Cryogenics in general is the domain of thermal science dedicated to the study and the production of temperature below 200K (according to ECSS-E-ST-31C definition). Applied to the Space Sector, this term describes the different types of technologies that permit to reach such temperatures. The need of Cryogenics Temperature range for Space is motivated by different applications: Focal Plane Cooling below 200K, biological samples conservation, Boil-Off mitigation of Propellants, superconductive applications etc.
Under the expression "Focal Plane Cooling" are lumped the technical solutions required, for Earth Observation and Scientific instruments, to actively reach and stabilise the operational temperature of detectors and optical systems below ambient temperature. Those technologies can cover a temperature range above 200K. The types of technology that falls under this category are for example Thermo-Electrical Coolers or Laser Coolers.
This topic does not address cryogenic technologies purely dedicated to launchers, even though some of the technologies described within this document might also be useful for the launcher sector.
A list of the main technologies that comply with those 2 definitions is summarized in the following table:

Table 4-3: list of Cryogenic Technologies addressed in the Harmonisation Topic

Technologies	Typical Temperature Range	Comment
Passive radiators	Ambient to 80K (LEO) 40K (L2)	Standard radiators are not addressed
Thermo-Electric Cooler	Ambient to 210K	Solid state cooler, very low efficiency at low temperature
Stored Cryogens	80K to 2K	Operational Temperature depends on the nature of the fluid. Open cycle thus limited lifetime
Stirling and Pulse Tube Coolers	180K to 7K	1 stage cooler down to 40K, 2-3 stages cooler down to 10K, >3 stages cooler <10K
Reverse Turbo Bryton	200K to 4K	Active cooling using high speed rotors
Joule-Thomson Cooler	150K to 1.7K	Operational temperature depends on the nature of the fluid. Requires pre-cooling. Different compressor technologies available
3He Sorption Pump Coolers	900mK to 250mK	Requires pre-cooling below 2K
Dilution Cooler	500mK to 50mK	Two types: open or closed cycle
Adiabatic de-magnetisation refrigerator	4K to 20mK	Requires pre-cooling below 10K

4.3.2 Areas Covered by this Technology Topic

The following types of Cryocooling technologies will be addressed:

- Radiators (*Focal Plane cooling consisting of classical radiators and heater control are not addressed*)
- Thermoelectric Coolers
- Cryostats
- Mechanical Coolers (Active Cooling systems from 2K to 190K)
  - Stirling cooler
  - Pulse Tube cooler
  - Joule Thomson expansion cooler
  - Reverse Turbo-Brayton cooler
  - Microcooling
- Sub-Kelvin Cooler:
  - Adiabatic Demagnetisation Refrigerators (ADR)
  - Dilution Refrigerator
  - 3He-sorption pump cooler
- Cryogenic System Equipment: This covers all equipment required to integrate the above mentioned cooling systems with the detectors and the Spacecraft (e.g. Cryo Heat Switch, Energy Storage Unit)

The electronics associated with those coolers (Cooler Drive Electronics) are also covered by this Harmonisation subject.

Other technologies not yet qualified for space (e.g. Laser Cooling, Claude Collins Cycle) can also satisfy in principle those cooling needs.

Please note that Cryogenic Two-Phase Heat Transport Systems (e.g. cryogenic Heat Pipe or Loop Heat Pipe) are not part of is Harmonisation subject but can be found in the dedicated TPHTS Roadmap. The last Harmonisation round on the subject was held in 2017.

The relevant Competence Domains are CD02 and CD05 (see Table 7-1 in Annex).

The harmonisation covers only and totally the ESA Technology Domain TD21-B “Cryogenics and Refrigeration”.

Table 4-4: Technology Tree Coverage – Cryogenics and Focal Plane Cooling

TD	TECHNOLOGY DOMAIN	TSD	TECHNOLOGY SUBDOMAIN
21	Thermal	B	Cryogenics and Refrigeration

4.4 ELECTROCHEMICAL ENERGY STORAGE

The last harmonisation of the topic “Electrochemical Energy Storage” took place in 2014. The next would be the fifth harmonisation of this topic.

4.4.1 Technology Overview

Electrochemical Energy Storage is required aboard almost all spacecraft. By far the most common requirement is for batteries to provide electrical power when power from solar arrays is temporarily unavailable or insufficient due to eclipses, user peak loads, before solar panels are deployed or in case of emergencies or special manoeuvres.

These require rechargeable (often referred to as ‘secondary’) storage. In other cases, typically science probes, but also short-mission manned vehicles, one shot or primary energy storage may be required because the use of solar panels is impractical.

The reasons for this can for instance be distance from the sun (deep space probes), atmospheric absorption (planetary landers) or mechanical constraints (manned vehicles). Future exploration missions to the lunar surface or Mars may have substantially increased energy storage demands which can only be met by Fuel cell technology

4.4.2 Areas Covered by this Technology Topic

The following technologies are covered by this harmonisation Topic:

- **Batteries**, including:
    - Primary batteries,
    - Secondary batteries,
    - high power batteries,
    - low temperature batteries,
    - high temperature batteries
- **Supercapacitors**, including:
    - Li-ion capacitors
- **Fuel Cells**, including:
    - fuel cells
    - electrolysers

The relevant Competence Domain is CD04 (see Table 7-1 in Annex).

Batteries, supercapacitors and fuel cells are covered under the Technology Tree group 3-C-I “Electro-chemical storage”.

Table 4-5: Technology Tree Coverage – Electrochemical Energy Storage

TD	TECHNOLOGY DOMAIN	TSD	TECHNOLOGY SUBDOMAIN	TG	TECHNOLOGY GROUPS
3	Spacecraft Electrical Power	C	Energy Storage Technologies	I	Electrochemical Energy Storage

4.5 POWER MANAGEMENT AND DISTRIBUTION

The last harmonisation of the topic "Power Management and Distribution" took place in 2013. The next would be the fourth harmonisation of this topic.

4.5.1 Technology Overview

Power Management and Distribution (PMD) is a wide technology area covering from satellite power subsystems architecture (including topologies, sizing, modelling and simulation tools and techniques) to generic power conditioning and distribution technologies (including regulation, control and distribution).
Power conditioning and distribution can be related to the spacecraft power subsystem itself (management of solar array power and battery storage including protection and distribution to the loads), as well as to any electrical equipment (power converters, distribution, protections) used in a spacecraft for any application (supplies to analogue and digital users, motor driving, pyro or other types of actuators, RF equipment, heaters, etc).
The PMD domain also covers the relevant sub-technologies (basic materials, processes, PCBs and EEE components) and harness (including high voltage cables and connections).
High voltage power management (>200V) and high voltage and high temperature potting materials are also included (for applications like power supplies for Travelling Wave Tubes, Electrical Propulsion electronics, etc).

4.5.2 Areas Covered by this Technology Topic

The areas covered by this topic are the following ones (Technology Domain/Subdomain 3A and 3D, according to ESA Technology Tree, see Table 4-6):

- 3A: Power systems architecture (including Power subsystem topologies, sizing, modelling and simulation tools and techniques)
- 3D: Power conditioning and distribution (including regulation, control and distribution) within the spacecraft Power subsystem itself (management of solar array power and battery storage including protection and distribution to the loads) Power conditioningin any electrical equipment (power converters, distribution, protections) used in a spacecraft (any service domain). Note that power conversion is needed in every satellite unit to adapt the main power bus voltage to the voltage levels needed by the electrical circuits of the unit.

Examples of served electrical equipment is rather long since, as mentioned before, power conversion is needed in every spacecraft unit: we might mention here EPCs for TWTAs, power supplies for SSPA, power supplies for EP, low level primary and secondary power converters, pre-regulators and actuator electronics for motors and other servo-mechanisms, power supplies for radars-continuous or pulse operation-cryocoolers, up and down Solar Array Regulators to improve flexibility of use of standard batteries and solar arrays, etc.

Harness is meant to be included in distribution.

High voltage (HV) power management (>200V) is also included. This is a very specific field that is needed to power some key applications like EP and TWTAs. HV power units need special topologies, components, materials and processes in order to have a reliable operation at those voltage levels.

Note that power conditioning and distribution domain is an enabling technology for other technologies: for example, the power conditioning and distribution element of a complete subsystem for EP or for an ultrasonic drill might be the heaviest and most expensive part of it.
It is also an enabler for the most modern and demanding digital electronics (FPGAs, microcontrollers, etc) since the newest (and also the future) components have very demanding power specifications that can only be fulfilled by very special conversion techniques.

Basic materials, processes and components technologies used in power conditioning, power distribution and analogue domain These technological areas will be assessed in close cooperation with relevant quality materials, processes and components specialists. Examples of materials and processes for the domain in question are the ones related to heat removal, HV insulation, hybridisation and integration of power and relevant control electronics, etc. Integration at all levels is a strategic line of action in PMD in order to achieve more compact, lighter and functional units.In particular, a strong cooperation with component experts is needed to achieve significant progress and innovation in the PMD domain. New components based on GaN and SiC, the use of COTS components in power applications, the integration of multiple functions in a single IC or ASIC are paramount for the power domain.

Cooperation with digital experts will be also very important. Both at hardware level (FPGAs, microcontrollers, etc) and software level. Digitisation of power units is deemed as a key technological step in order to improve the functionality of the units and increase the integration levels.

In addition, consistency and possible overlap with relevant ESCC documents will be checked as part of the work on this dossier.

The relevant Competence Domain is CD04 (see Table 7-1 in Annex).

Table 4-6: Technology Tree Coverage – Power Management and Distribution

TD	TECHNOLOGY DOMAIN	TSD	TECHNOLOGY SUBDOMAIN
3	Spacecraft Electrical Power	A	Power System Architecture
		D	Power Conditioning and Distribution

4.6 BIG DATA FROM SPACE

The last visit of the topic "Big Data from Space" took place in 2017. The next would be the second harmonisation of this topic.

4.6.1 Technology Overview

Big Data from Space refers to Earth and space observation or spacecraft housekeeping data collected by space-borne and ground-based sensors, as well as other space applications such as Satellite Navigation and Satellite Telecommunications. Whether for Earth or space observation, they qualify being called 'big data' given the sheer **volume** of sensed data (archived data reaching the Exabyte scale), their high **velocity** (new data is acquired almost on a continuous basis and with an increasing rate), their **variety** (data is delivered by sensors acting over various frequencies of the electromagnetic spectrum in passive and active modes), as well as their **veracity** (sensed data is associated with qualified uncertainty and accuracy measurements). Last but not least, the **value** of big data from space depends on our capacity to extract information and meaning from them.

Big Data from Space is an emerging domain given the recent sharp increase in all three main dimensions of big data: volume, velocity, and variety. Fortunately, this increase is paralleled by tremendous amount of new developments related to big data in other fields and enabled by technological breakthroughs and new challenges in hardware and software developments, high performance/throughput computing, cloud networking and storage, data science, and visualisation. In addition, the recent multiplication of open access initiatives to big data from space is giving momentum to the field by widening substantially the spectrum of users as well as awareness among the public while offering new opportunities for scientists and value-added companies.

Big Data from Space is now recognized as an emerging domain, also given the recent sharp increase in all three main dimensions of Big Data: volume, velocity and variety. Fortunately, this increase is paralleled by new developments related to Big Data in other fields, and it is at the same time enabled by technological breakthroughs in hardware and software developments, like e.g. high performance computing, global memory capacity, cloud networking and storage, global connectivity worldwide, data science disciplines, etc. In addition, the recent multiplication of open access initiatives towards Big Data is giving momentum to the field, widening substantially the spectrum of users as well as the awareness among the general public, and offering new opportunities for scientists and value-added companies.

With the first European Data Relay Satellite (EDRS-A) launched on the 29th of January 2016, the Space Data Highway is now revolutionising satellite communications as Europe's first optical space communication network, capable of relaying user data in near-real time at an unprecedented 1.8 Gbit/s. Its extension program, called GlobeNet, will even enlarge the network, providing quasi-real-time services on a global scale. Via GlobeNet, data can be picked up from LEO satellites and transferred via laser link even between geostationary satellites, and can be delivered into European territory in no time. In such a context, GlobeNet and its laser communication technology represent a strategic element for Europe to boost European technology adoption. As a global communications system and service, it could support public data infrastructures, similarly to what GEANT does for interconnecting European research networks. GlobeNet could be a key element for interconnecting relevant European space resources, enhancing the provision and availability of data to the broad user community, and contributing to the successful implementation of the so-called Big Data economy.

Another important element of Big Data from Space is represented by the series of the Sentinels satellites, operated by ESA in the framework of the Copernicus program, funded and managed by the European Commission. At today, six Sentinels satellites have been already launched: Sentinel-1A and 1B, Sentinel-2A and 2B (which completed the two first constellations), Sentinel-3A and recently (13 October 2017) Sentinel-5P, the forerunner of Sentinel-5 to provide timely data on a multitude of trace gases and aerosols affecting air quality and climate. Sentinel-5 will then monitor the atmosphere from polar orbit aboard a MetOp Second Generation (MSG) satellite, whilst Sentinel-4, devoted as well to atmospheric monitoring, will be embarked upon a Meteosat Third Generation-Sounder (MTG-S) satellite in geostationary orbit. Finally, Sentinel-6 will carry a radar altimeter to measure global sea-surface height, primarily for operational oceanography and for climate studies. Furthermore, the Sentinels are and will be complemented by additional national and international missions. In full operational capacity, ESA and EUMETSAT will coordinate the delivery of TB of image data per day from upwards of 30 satellites that form the Contributing Missions, as key enablers of the Copernicus monitoring services (Land, Marine, Atmosphere, Climate, Emergency and Security).

Regarding Space observations, virtual observatories are gaining increased attention as well as the GAIA global space astrometry mission, launched in December 2013 and steadily populating its catalogue towards 1–2 billion sources by the end of the mission in 2022. The objective is to create the largest, most precise three-dimensional map of our Galaxy. GAIA will monitor each of its target stars about 70 times over a five-year period. It will precisely chart their positions, distances, movements, and changes in brightness. It is expected to discover hundreds of thousands of new celestial objects, such as extra-solar planets and brown dwarfs, and observe hundreds of thousands of asteroids within our own Solar System. The mission will also study about 500 000 distant quasars, creating an extraordinarily precise three-dimensional map of more than a thousand million stars throughout our Galaxy and beyond, mapping their motions, luminosity, temperature and composition. This huge stellar census will provide the data needed to tackle an enormous range of important problems related to the origin, structure and evolutionary history of our Galaxy.

From such a brief overview of current status and developments in the Big Data from Space technology area, it is clear that this technology focuses on the whole data lifecycle, ranging from data acquisition (e.g. by space borne, low and high altitude sensors, ground-based sensors, etc.) to data management, data analysis and data exploitation in various domains and applications, like e.g. Earth Observation, Space Science, Satellite Telecommunications, Satellite Navigation, etc..

4.6.2 Areas Covered by this Technology Topic

When addressing the Big Data from Space technologies, various space-related domains come into play: Satellite Telecommunication, Satellite Navigation, Spacecraft Operations, Space Science, Earth Observation, etc. In order to map and discuss the key cross-cutting technology needs and challenges associated to Big Data from Space, we propose to use the *data lifecycle* model.

Data Lifecycle

When talking about Big Data from Space, it is evident that various space-related domains and applications are concerned, like e.g. Earth Observation, Space Science, Satellite Operations, Satellite Telecommunication, Satellite Navigation, etc. Synergies and cross-fertilization opportunities between the various domains and applications shall therefore be fostered and exploited to address common Big Data issues and to achieve the maximum benefit from research and technology development activities in the field. The contribution from each domain shall be developed and extended. In order to enable the development of common cross-cutting solutions in the field of Big Data, which require diverse approaches due to the data characteristics (the so-called *Five-V paradigm*: *Volume*, *Velocity*, *Variety*, *Veracity and Value*), a common model is deemed as necessary. Using inputs from the analysis of use cases and reference architectures collected during the past Big Data from Space Conferences, a vendor-neutral and technology-agnostic conceptual model has been derived, based on the entire space *data lifecycle*. It is based on four conceptual layers (i.e. the lifecycle steps):

1. *Data Acquisition*;
2. *Data Storage and Organization;*
3. *Data Analysis and Visualization;*
4. *Information Provision (for decision making).*

This model is graphically presented in Figure below.

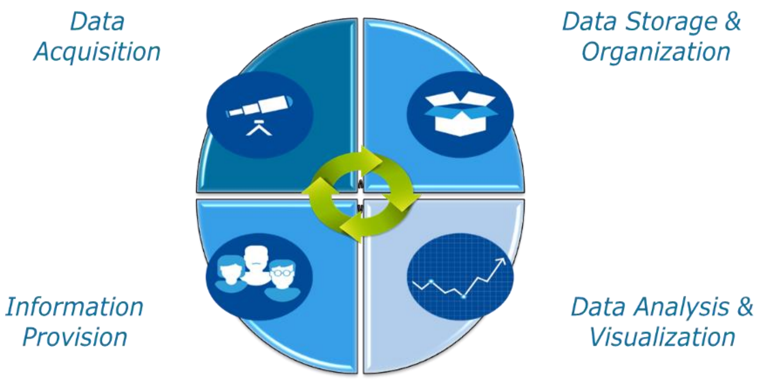

Figure 4-1: Big Data Lifecycle

Supporting Resources for Big Data

The data and information flow along the lifecycle steps shall be supported by suitable IT resources (infrastructures, tools, applications, etc.). A preliminary non-exhaustive list of resources addressed in this Technology Topic is reported below:

- On-board data handling functions and technologies: data capture, data storage, compression, on-board processing. Next generation instruments will collect increasing volumes of measures at increasing rate, due to the technological evolution of sensors' capabilities. The huge amount of data generated on-board is competing with the limited channel resources available for the transmission of data to the ground. The result of this scenario is that on-board payload data reduction is increasing in importance in the framework of a spacecraft design. Two main technology areas involved in this field are the data compression and the compressive sensing.

- Data transfer methodologies (from satellite to ground, from ground to ground, relay satellites, modulators and demodulators, RF and Optical transfer systems, inter-satellite links, etc.). EO satellites have also only limited capabilities to store recorded data on-board. Technological improvements are required for the satellite downlink capacity, to cope with increasing data rates and volumes; for the performance of data transfer, from receiving stations to processing and archiving facilities; for the archiving methods (e.g. distributed repositories and mirroring sites), which require end-to-end path of network data transfers to ensure optimum performance while maintaining security in a multi-user environment.

- Data storage and computing platforms, data centers and computing services: private clusters, open clouds, hybrid clouds, etc. Scale requirements can be addressed by both vertical (adopting faster processors and bigger disks, driven by hardware improvements) and horizontal (e.g. partitioning and replicating datasets across a clusters of servers, or deploying processing chains in parallel on a cloud infrastructure, etc.) scaling approaches, valid for both storage and processing functionalities.

- Data discovery, access and dissemination: long-term archiving, availability, search-ability, delivery. More advanced technologies for data discovery and access are required, in order to allow (near) real-time and tailored access to large volumes of full-resolution EO datasets, access or download of tailored coverages already prepared for specific applications, content-aware access methods, control and grouping of associated data, etc. This also goes together with improvements of standards implementations to harmonize data access across distributed data holdings and ensure interoperability of components.

- Data preservation and retrieval. Maintenance and operation of long-term curated data archives, including historical, heterogeneous and auxiliary data, processing tools and related documentation is necessary to ensure the usability of long data series now being available, coupled with efficient data retrieval mechanisms, data ingestion and re-processing deployment, etc.

- Data analytics and visualization tools. It includes various aspects, like e.g. write-heavy workloads, with data partitioning and/or replication, variable request loads and optimization of overall system performance and resources, computationally intensive data analytics, e.g. using machine learning approaches (deep neural networks, support vector machines, etc.), advanced analysis algorithms and powerful visualization tools to trigger and support the analysis (now being called visual analytics), virtual research environment offering petabyte-scale processing resources for scientists and researchers and e-collaboration and knowledge sharing tools, etc.

- Satellite Telecommunication systems, networks and services. GEO, MEO and LEO satellites and their combination in hierarchical schemes, with simultaneous use of Inter-Satellite Links (ISL) and/or European Data Relay System (EDRS) and eventually High-Altitude Platforms (HAPs) are the game changers for the future. Main technological challenges are related to flexible, modular and programmable solutions for end-to-end satellite system and network design according to the verticals, highly integrated terminals (users segment), highly efficient traffic gateways, enablers of end-to-end Quality of Service (QoS) and security guarantees, optimized air interface (sensors waking up capability), energy consumption awareness (for longer sensor battery lifetime), etc.

- Global Navigation Satellite System (GNSS) equipment. For what concerns the Satellite Navigation and the Integrated Applications, data acquisition starts in this case with GNSS signals processing by the receivers, which could be implemented in hardware (dedicated chip) or in software (in the device or in a remote processor). Receiver algorithms consists of estimating the distance to each satellite and determine the receiver position, with a certain accuracy. The main challenges at this point are the time to first fix (i.e. the time it takes to determine a first position, typically 30 seconds, which can be significantly reduced thanks to the ephemeris), and the power consumption. The computed position data is then used for multiple applications, e.g. Location Based Services (LBS) or the use of crowdsourcing applications, for instance to detect and localize jammers and spoofers in a complex urban environment.

- Use of sensors' networks and Remotely Piloted Aircraft Systems (RPAS). It includes the connection of sensors networks (ad-hoc, mobile, fixed, RPAS) through on ground Machine-to-Machine (M2M) and Internet-of-Things (IoT) gateways, aggregating data and relaying with terrestrial edge network M2M or IoT nodes, global synchronization of networks, etc.

- Data openness, privacy and security. Develop secure in network data processing and caching technologies to enable data reformatting into tailored resolutions with the required QoS, reliability, data privacy, content identification, publisher and subscriber privacy, access control, as requested by the specific verticals' customers.

- Data quality, provenance and trust. Information records resulting from sensing and successive processing shall be characterized with quality and provenance information to ensure trust. The most important aspects relate to explanation, accountability, and repeatability, including consideration of artifacts.

- New networking paradigms: Software Defined Networking (SDN) and Information Content Networking (ICN), where edge network nodes are capable of data processing, caching and decision-making. It includes technologies for federated satellite and terrestrial communication networks management, for services chaining, and data paths combining transmitted through different satellite and terrestrial communication paths, context aware data networking systems to allow tailored data publishing or subscription, according to the verticals' needs, etc.

- Crowdsourcing and citizen science approaches. The second case includes crowdsourcing applications, for instance to detect and localize jammers and spoofers in a complex urban environment, and modeling user's geographical behavior and environment. This user data is very valuable to telecom operators, but also allows new types of businesses, like e.g. Google Maps, where the user gets a free service in exchange of his data (most of the time the user does not realize this). Data acquisition for the third parties consist of accessing users data remotely, using most of the time wireless networks (cellular, WiFi), as connectivity is becoming a commodity. Data collection agents are residing in user's applications on their device.

From the preliminary list of Supporting Resources reported above, it is needed to define priorities and identify the main technology drivers (in term of methods, algorithms and tools) that could foster the technology development in the Big Data field. This shall be subject to discussion in the Mapping phase.

The relevant Competence Domains are CD03, CD08 and CD09 (see Table 7-1 in Annex).

With reference to the ESA Technology Tree, this topic covers the following Technology Domains:

Table 4-7: Technology Tree Coverage – Big Data from Space

TD	TECHNOLOGY DOMAIN	TSD	TECHNOLOGY SUBDOMAIN
1	On-Board Data Systems	A	Payload Data Processing
		B	On Board Data Management
		C	Microelectronics for digital and analogue applications
2	Space System Software	A	Advanced Software technologies
		B	Space Segment Software
		C	Ground Segment Software
		D	Ground Data Processing
		E	Earth Observation Payload Data Exploitation
6	RF Systems, Payloads and Technologies	A	Telecommunication (sub-)Systems
8	System Design & verification	A	Mission and System Specification
		C	System Analysis and Design
9	Mission Operation and Ground Data systems	C	Ground Data Systems (MCS)

4.7 FLUID MECHANICS AND AEROTHERMODYNAMIC TOOLS

The last harmonisation of the topic "Fluid Mechanics and Aerothermodynamic Tools" took place in 2012. The next would be the fourth harmonisation of this topic.

4.7.1 Technology Overview

Fluid mechanics (FM) is a branch of physics concerned with steady or transient fluid kinematics and dynamics in its various states, i.e. liquids, gases, solids and plasmas, and the forces on them. In a wider context, it covers as well descriptions of state (real gas effects, vaporisation, condensation), chemical reactions... Further classification depends whether we have internal flow (tubes, reservoirs,) versus external flow (flow around bodies), continuum versus free molecular flow.

It encompasses the whole spectrum from take-off, ascent to (super) orbital speeds, descent and back to landing, aero heating and propulsion thermodynamics. Its challenge is to provide appropriate data for the optimisation of vehicles to achieve minimal structural and heating loads and maximum engine performances, leading to reduced design margins and reduced operational costs.

Aerothermodynamics (ATD) is a particular branch, of Fluid Mechanics, studying the thermodynamic properties of gases, especially when travelling at a high velocity (physical processes, pressure and thermal fields) within any atmosphere. Aerothermodynamics is the key to successful design, development and flight of any space vehicle because it provides the necessary databases for the choice of the trajectory, for guidance, navigation and control, for the sizing of the thermal protection systems as well as for the assessment of the propulsion system performances.

Fluid mechanics and Aerothermodynamics have evolved into a wide field of applications and its use is becoming increasingly multidisciplinary. Its demands profound knowledge in physics, chemistry, applied mathematics and computer science. As an engineering discipline, it provides crucial information to all the other key disciplines like structures, materials, including thermal protection systems, propulsion, flight dynamics, guidance, navigation and control. Fluid dynamics and Aerothermodynamics are particular disciplines with a strong need of interaction between research and applied engineering. Its driving force is physical modelling and its working tools are computational tools, ground based facilities and flight testing. Indeed, accurate physical models used in computational tools are the roots of aerothermodynamics, and they require good validation-data acquired in ground facilities and in flight.

4.7.2 Areas Covered by this Technology Topic

The present technology dossier addresses all Technology Subdomains and corresponding Technology Groups of the ESA technology tree for the Technology Domain 18, Fluid Mechanics and Aerothermodynamic Tools (see Table 4-8):

Table 4-8: Technology Tree Coverage – Fluid Mechanics and Aerothermodynamic Tools

TD	TECHNOLOGY DOMAIN	TSD	TECHNOLOGY SUBDOMAIN	TG	TECHNOLOGY GROUPS
18	Aerothermodyanics	A	Computational Fluid Dynamics	I	Computational Fluid Dynamics (CFD)
				II	Engineering Techniques
				III	Multidisciplinary techniques
		B	Ground-based Facilities	I	Cold Gas Facilities
				II	Hot Gas Facilities
				III	Dedicated Facilities
		C	Sensor and Measurement Techniques	I	Intrusive Measurements
				II	Non-Intrusive Measurements
				III	Wireless Measurements
		D	Flight Databases	I	User Interface
				II	Informatics Environment

In particular, within each Technology Group, the following topics are addressed:

- 18-A-I Computational Fluid Dynamics (CFD): including Euler, Navier-Stokes, Rarefied and Molecular Flow codes for both steady and transient flows, single- or multi-phase flow applications associated with launcher, (destructive) (re)-entry aero and propulsion issues. It entails also associated grid generation tools.
- 18-A-II Advanced Numerical Methods: including Large Eddy Simulation (LES), Direct Numerical Simulation (DNS) for e.g. improved simulation of smaller scale eddy turbulence development and propagation, computational (aero)-acoustics (CAA), Magneto-Hydro-Dynamics (MHD), radiation, fluid-structure interaction
- 18-A-III Physical Models: including thermochemistry, turbulence, transition, radiation, gas surface interactions (oxidation, catalysis, ablation), cooling (active, passive), decomposition, multi-phase/multi-component, atomization/vaporization and combustion (liquid, solid, airbreathing), sloshing, microgravity, deployment (parachutes/foils)…
- 18-A-IV Engineering, FM, ATD and Propulsive System Design Tools: including analytical, fast parametric engineering design tools coupled with combustion, heat release and simple trajectory analysis tools including parachute aerodynamics. Database generation and related tools for overall vehicle system design and analysis.
- 18-B-I Low Enthalpy Facilities: includes classical subsonic, transonic, supersonic and hypersonic wind tunnels and its intrusive and nonintrusive measurements techniques.
- 18-B-II High Enthalpy Facilities: includes shock tubes, hot shots, ballistic ranges and its measurement techniques.
- 18-B-III Plasma Facilities: includes arc-jets and plasmatrons for TPS and material testing and its measurement techniques.
- 18-B-IV Rarefied Gas and Molecular Flow Facilities: includes high-vacuum facilities to be representative for high-altitude flights and its measurement techniques.
- 18-B-V Engine and Propulsive Test Stands: includes facilities for hot firings and jet interaction, turbomachinery, combustion… and their measurement techniques.

- 18-B-VI Dedicated Fluid Facilities: cryogenic, fluid hammer, acoustics, multi-phase,.. and their measurement techniques.

- 18-C-I In-Flight Research: includes ATD experimental vehicles for the study of critical phenomena
- 18-C-II In-Flight Measurement Techniques (intrusive and non-intrusive): includes Air Data Systems (ADS), miniaturization of flight measurement techniques, Data Acquisition System (DAQ), sensors, HMS (Health Monitoring Systems), FDI (Fault Detection and Isolation)…
- 18-C-III In-Flight Testing Facilities: includes development of both carriers (booster, gun…) and platforms (support system, vehicle…).
- 18-D-I Multi-Disciplinary Tool Development: includes the software environment for coupling tools and databases of different technical disciplines.
- 18-D-II Multi-Disciplinary Optimisation: includes advanced optimisation algorithms.
- 18-E-I Vehicle Design and Performance Tools: includes the software environment for coupling tools and databases to design and assess the performance of different vehicle types.

The relevant Competence Domain is CD07 (see Table 7-1 in Annex).

4.8 ON-BOARD RADIO NAVIGATION RECEIVERS

The last harmonisation of the topic “On-Board Navigation Receivers” took place in 2013. The next would be the fourth harmonisation of this topic.

4.8.1 Technology Overview

The Global Navigation Satellite Systems (GNSS) are space-based radio navigation systems that provide to the users location and time information. Each GNSS satellite transmits signals and messages that include the time the message is transmitted and the satellite position at time of the message transmission. With this information, the GNSS receiver determines the transit time of the signal and computes the distance to each GNSS satellite. These distances and satellites' locations are used to compute the location of the receiver using the navigation equations. Typically four GNSS satellites must be visible to obtain position and time results.

GNSS space receivers are used on spacecraft platforms to determine the spacecraft position and attitude. These space receivers can also compute the relative position between two or more spacecraft by exchanging and processing with appropriated navigation filters the raw measurements. GNSS space receivers are also used as scientific instruments, performing precise orbit determination, radio occultation or reflectometry for Earth Observation and Scientific missions. The majority of LEO satellites launched over the last years rely primarily on GNSS receivers for navigation purposes. The use of GNSS space receivers for GEO/GTO/HEO orbit has been demonstrated in few ESA and non-ESA missions..

Several studies has been conducted to show the feasibility of the use of GNSS signals beyond GEO, including Moon transfer orbit and Moon orbit injection. The exploitation of Precise Point Positioning (PPP) techniques for space user has been studied in the last years and showed to be promising for space applications allowing on-board real time POD. Typically, GNSS receivers, from technology point of view, are classified by the number of frequencies, single or multiple frequency receivers, and according to the type of mission, navigation or scientific oriented receivers respectively. However, it is also possible to divide space receivers according to the performance budget of the mission, into high-end missions on the one side and medium to low-budget missions on the other, where receivers with a good performance-to-cost relation are fundamental for the latter category.

Key advantages of employing GNSS sensors in space are the high navigation accuracy, the on-board autonomy and the cost savings in both satellite equipment and operational costs. Various functionalities traditionally provided by separate devices, such as absolute and relative positioning, attitude determination and time synchronisation, can be combined into a single unit.

4.8.2 Areas Covered by this Technology Topic

This technical dossier provides an overview of the various kinds of GNSS space receivers and of their applications with the aim of providing a picture of the present status of technology and an overview of the expected future trends.

The Harmonisation addresses all types of On-Board Navigation Receivers, GNSS receivers and their core technologies, including:

- High reliability receivers for high-end and mid-range performance: platform receivers to determine absolute and/or relative PVT, including POD (on ground or on-board).

- High-End Rx: typically multi frequency (MF) receivers with meter level navigation accuracy and sub-decimeter accuracy in case of on-board real time POD.
- Mid-Range Rx: typically single frequency (SF) receivers with tens of meter level navigation accuracy

- EO/Scientific receivers, e.g. for Reflectrometry and RO instruments.
- Low Cost (LC) receivers, based on COTS parts, and with limited reliability and level of qualification status, including products for Cubesat.
- Supporting GNSS core technologies: Radio Frequency (RF), Base-Band (BB) processing and GNSS antennas[2]

The relevant Competence Domain is CD03 (see Table 7-1 in Annex).

The harmonisation covers only and totally the ESA Technology Domain TD6-B, Groups I and III.

Table 4-9: Technology Tree Coverage – On-Board Radio Navigation Receivers

<table>
<tr><th>TD</th><th>TECHNOLOGY DOMAIN</th><th>TSD</th><th>TECHNOLOGY SUBDOMAIN</th><th>TG</th><th>TECHNOLOGY GROUPS</th></tr>
<tr><td rowspan="2">6</td><td rowspan="2">Rf Systems, Payloads and Technologies</td><td rowspan="2">B</td><td rowspan="2">Radio Navigation Systems/Subsystems</td><td>I</td><td>Navigation System Tools</td></tr>
<tr><td>II</td><td>On-Board Receivers</td></tr>
</table>

[2] Coverage within other Harmonisation RoadMaps to be checked and coordinated

4.9 TECHNOLOGIES FOR OPTICAL PASSIVE INSTRUMENTS - MIRRORS

The last harmonisation of the topic “Technologies for Optical passive Instruments – Mirrors” took place in 2013. The next would be the third harmonisation of this topic.

4.9.1 Technology Overview

Mirrors are a small subset of passive optical components, but essential for the success of current and future space missions. A large majority of telescopes for space programs ranging from Earth Observation to Science and covering all the electromagnetic spectrum from X rays to Infrared are based on mirrors. Moreover mirrors are extensively used as common components for Earth observing and Science instruments as spectral imagers and radiometers.
In the context of this Harmonisation Topic ‘Mirrors’ shall be considered as reflectors tailored to operate at a range of electromagnetic wavelengths from far infra-red to x-ray. Therefore, the topics of materials and manufacturing technologies of mirrors have to be considered in relation to the particular performance requirements of a specific mission (Earth observation, scientific observation, etc…) and of the chosen mirror design concept (monolithic, active/adaptive, segmented,…). Mirrors can perform the following functions:

- Folding mirrors (flat, i.e. no optical power and fixed), requiring a focus on mass and stability;
- Steering mirrors (flat, but at least one degree of freedom in movement), focusing on mass, inertia, stiffness and stability;
- Mirrors with an optical power (i.e. for telescopes or beam expanders), focusing on mass, stability and alignment, as well as metrology;
- Mirrors can attenuate straylight if used as reflecting baffles;
- Mirrors can be used as non-imaging light concentrators.

This technology topic addresses different types of telescopes that might be used for space applications like Newton, Schmidt, Cassegrain, Ritchey-Chretien, Three Mirror Anastigmat (TMA), Korsch telescope, Wolter telescope and Dual Anamorphic Reflector Telescope (DART).

4.9.2 Areas Covered by this Technology Topic

The technology areas are applicable to the design and manufacturing of mirrors are:

- High stability and/or well predictable distortion behaviour over operating temperature range,
- High strength and stiffness,
- Material characteristics (Isotropy/ high homogeneity/ reproducibility/ no CME/ low CTE),
- Low mass per unit area of reflector surface,
- Surface finished to comply with required operational wavelength ranges and specified surface quality,

- In case a surface is made out of a material with attractive mechanical/thermal properties, but cannot be polished to the required optical surface finish, there is a need to develop a coating technology for the given substrate,
- Special electrical properties regarding certain coatings (e.g. metallic),
- Interface layers potentially needed in some cases (e.g. between ceramic and metals),
- Metrology,
- Tolerances in fabrication/machining; roughness & homogeneity of surface.
- Technologies and design tools for design and manufacturing freeform mirrors
- Active mirrors and segmented mirrors capable of operating in the visible range are enabling technologies for next generation large space telescopes.

Any mirror requires a matching support and interface structures. Many of the requirements applicable to mirrors are directly applicable to the associated supporting structures. To address the definition and performance of an optical instrument, technologies and materials for structures and optical benches shall also be covered. However, within the context of this harmonization exercise, and differently from the previous revisit, this dossier is limited to the technologies for the design and manufacturing of the mirrors.

Therefore, the topic will cover:

- High stability and/or well predictable distortion behaviour over operating temperature range. In particular, improving knowledge of high stability material properties (in particular CTE, Young's Modulus, thermal conductivity…) at low temperatures. - Strength and stiffness.
- Low CTE, thermal shock behaviour, special surface quality (of substrate and/or coating layer). Combination of several kind of surface layers.
- Manufacturing technologies (sizing of finished components).

The relevant Competence Domain is CD05 (see Table 7-1 in Annex).

The Technology Domains interested by this Topic is 16. The excerpt from the ESA Technology Tree relevant these two technologies is reported in Table 4-10:

Table 4-10: Technology Tree Coverage – Technologies for Optical Passive Instruments – Mirrors

<table>
<tr><th>TD</th><th>TECHNOLOGY DOMAIN</th><th>TSD</th><th>TECHNOLOGY SUBDOMAIN</th><th>TG</th><th>TECHNOLOGY GROUPS</th></tr>
<tr><td rowspan="4">16</td><td rowspan="4">Optics</td><td rowspan="3">B</td><td rowspan="3">Optical Component technology & materials</td><td>I</td><td>Optical Components</td></tr>
<tr><td>III</td><td>Mirror and telescope technologies</td></tr>
<tr><td>IV</td><td>Optical bench and mounting technologies</td></tr>
<tr><td>C</td><td>Optical equipment and instrument technology</td><td>V</td><td>High Precision Optical Metrology</td></tr>
</table>

4.10 TECHNOLOGIES FOR OPTICAL PASSIVE INSTRUMENTS – STABLE AND LIGHTWEIGHT STRUCTURES

The last harmonisation of the topic "Technologies for Optical Passive Instruments – Stable and Lightweight Structures" took place in 2013. The next would be the third harmonisation of this topic.

4.10.1 Technology Overview

In combination with the technology drivers for large lightweight and stable mirrors, is the need for lightweight structures to provide stable platforms for mirrors and instrument components and mechanical interface to the spacecraft. Such structures are needed both for optical benches and telescope/instrument support.
Chemical compatibility with both interfaces and mission requirements (e.g. outgassing) is also an important aspect of stable structures and should be given appropriate attention.
Furthermore, developing mounting, alignment, and integration techniques using those stable and lightweight structures is essential, as well as elaborating optical verification methods (essential for THz/FIR and UV domains, and for large telescopes in all classes of wavelength range).

Importance of Stable and Lightweight Structures
High stability structures are required to provide the supporting framework for high precision space based instruments. Coupled with this is the need to minimise launch mass of such missions and for reliable operation over several years possibly in extreme environmental conditions i.e. vacuum, low (even cryogenic) temperatures, or with large temperature fluctuations. Finally the structure has to be sufficiently robust to survive the mechanical loads
Chemical compatibility with both interfaces and mission requirements (e.g. outgassing) is also an important aspect of stable structures and should be given appropriate attention.
Some specific parameters which will drive the design and development of sensitive and high stability instruments are as follows:

- High Specific Strength & Stiffness
- Operating temperature (e.g. cryogenic instrument)
- Thermal gradients in instrument envelope during operation

Other parameters to be taken into account are ranging from general concerns (radiation effects,…) to more specific application-dependent considerations (e.g. effect of high power laser).

Materials
All materials have been subject to technology improvement to make the best use of their intrinsic characteristics and to reduce their drawbacks.
In practice, none of the materials currently in use or under study for applications in large lightweight mirrors and stable structures can adequately satisfy all the requirements. Materials which are currently in use or under study and their relative strengths and weaknesses are summarised below.

- Ceramic Materials
- Zerodur

- Aluminium
- Carbon Fiber Reinforced Plastic (CFRP) Composites
- Reinforced Carbon-Carbon (RCC) Composites
- Metal Matrix Composites
- Monocrystalline Crystal Silicon
- StarSiC®

In addition to the (generic) materials listed in Table 4-2, there are potentially other materials (homogeneous or composite), which may demonstrate superior properties to those identified. Therefore, for this technology domain, there is a clear need for ongoing materials research.

Other relevant aspects

- Testing
    - Material Level
        - Coefficient of thermal expansion
        - Strength properties
    - Product Level
- Manufacturing
    - Joining
    - Finishing and Coating
    - Metrology
- Analysis

4.10.2 Areas Covered by this Technology Topic

Stable and lightweight structures are complementary to the production of scientific instruments and Earth Observation remote sensing payloads operating in the “optical” spectral domain. Such structures are needed to provide stable support to high stability Mirrors/RF Reflectors and instrument i.e. telescope structures, optical benches, etc. Many of the requirements applicable to mirrors are directly applicable to the associated supporting structures. However, within the context of this harmonization dossier, it is necessary to consider the definition and performance of the complete payload or instrument.

- High stability and/or well predictable distortion behaviour over operating temperature range. In particular, improving knowledge of high stability material properties (in particular CTE, Young’s Modulus, thermal conductivity…) at low temperatures.
- Strength and stiffness.
- Low CTE, thermal shock behaviour, special surface quality (of substrate and/or coating layer). Combination of several kind of surface layers.
- Manufacturing technologies (sizing of finished components).
- Joining technologies.
- Assembly/disassembly (aiming at quick/reliable/reproducible processes)
- Metrology and verification, including during the alignment and integration phases.
- Machining tolerances

In some cases of high stability payloads, structure material cannot be dissociated from mirror material. For instance, provided that thermal homogeneity in the payload remains within acceptable limits, using a single material for structures and mirrors allows for an athermal

behaviour of the optical payload, and favors the reduction of the number of mirrors/structures interfaces with a good quality of modeling and prediction.
Practically, with current materials and structures technology it is not possible to satisfy all requirements simultaneously. Therefore, the design of optical (or near optical) instruments and similar high stability structures currently requires a compromise between conflicting requirements. Though some current candidate materials exhibit a good maturity level and offer excellent compromises, the interest in this technology domain is clearly to reduce further such trade-offs and keep improving the performance of current and future missions.

The relevant Competence Domains are CD05 and CD02 (see Table 7-1 in Annex).

The Technology Domains interested by this subject are reported in Table 4-11:

Table 4-11: Technology Tree Coverage – Technologies for Optical Passive Instruments – Stable and Lightweight Structures

TD	TECHNOLOGY DOMAIN	TSD	TECHNOLOGY SUBDOMAIN	TG	TECHNOLOGY GROUPS
20	Structures	B	High Stability and high precision S/C structures	I	Advanced material technologies for stable structures
				II	Joining and mounting technologies
				III	Thermo-elastic stability verification technologies
24	Materials and Processes	A	Novel Materials and Materials Technologies	I	Material assessment
		B	Material Processes	I	Joining
				II	Coating
				III	Characterization and Feedback
				IV	Advanced Materials Manufacturing

5 LIST OF EARMARKED TECHNOLOGIES FOR 2020 – 2021

Table 5-1 and **Table 5-2** list the technologies earmarked for Harmonisation in 2020 and 2021, based upon end of current Roadmap and requests received. The actual topics for the relevant years will be selected taking into consideration previous commitments and the proposals received from ESA Technical and Programme Directorates, Industry (via Eurospace and SME4Space) and THAG Delegations during the preparation of the Harmonisation Workplan.

Table 5-1 List of Potential Technologies for the 2020 Harmonisation Workplan

	2020	**Revisit**
1	AOCS Sensors and Actuators - part I	2013
2	Critical Active RF Technologies	2014
3	Functional Verification and Missions Operations Systems	2014
4	Micro-Nano Technologies - MEMS	2014
5	Multibody Dynamic Simulation	2014*(*)*
6	On-Board Software	2014
7	Pyrotechnic Devices	2013
8	Solar Array Drive Mechanism	2014
9	System Data Repository	2014
10	TT&C Transponder and Payload Data Transmission	2012

(*) in 2014 only the Mapping took place

Table 5-2 List of Potential Technologies for the 2020 Harmonisation Workplan

	2021	**Revisit**
1	AOCS Sensors and Actuators - part II	2015
2	Electrical Motors	2015
3	Ground Station Technology	2015
4	Optical Detectors – Visible Range	2015
5	Power RF Measurements & Modelling	2015
6	Radiation Environments & Effects	2015
7	RF Metamaterials and Metasurfaces	2016
8	Solar Generators and Solar Cells	2015
9	Technologies for Hold Down, Release, Separation and Deployment Systems	2015
+	Any and all subjects proposed for 2020 and not selected for that year	See Table 6-1

6 OVERVIEW OF TECHNOLOGIES 2000-2021

The Table 6-1 reported in the following pages provides an overview of the technologies that have been harmonised since 2000, organised per Competence Domains:

Table 6-1: Harmonised Technologies organised per Competence Domain

CD ID	Competence Domain	Related Harmo Roadmap	Past Revisit	Planned/Ongoing Harmonisation
1	EEE / Components / Photonics / MEMs	Optical Detectors, Visible Range	(2006.1	2021
			2011.1)	
			2015.1	
		Optical Detectors, IR Range	(2006.1	
			2011.1)	
			2017.2	
		Micro-Nano Technologies - MEMS	2008 (MP)	2020
			2014.2	
		Photonics		2018.1
2	Structural / Mechanisms / Materials / Thermal	Electrical Motors	2002.2	2021
			2007.2	
			2015.2	
		Deployable Booms & Inflatable Structures	2003.2	2018.2
			2010.2	
		Solar Array Drive Mechanisms	2003.2	2020
			2008.2	
			2014.1	
		Electric Propulsion Pointing Mechanisms (EPPMs)	2004.2	
			2009.2	
			2016.2	
		Position Sensors	2009.1	2018.1
		Technologies for Hold Down, Release, Separation and Deployment Systems	2004.1	2021
			2008.2	
			2015.2	
		Pyrotechnic Devices	2003.1	2020
			2006.1	
			2013.1	
		Two-Phase Heat Transport Systems	2003.1	
			2009.1	
			2017.1	
		Cryogenics and Focal Plane Cooling	2001	2019
			2007.1	
			2013.2	
		Composite Materials	2005	2019
			2010.2 (MP)	
			2014.2	
		Additive Manufacturing	2015.1	
			2017.1	
		Coatings		2018.2

CD ID	Competence Domain	Related Harmo Roadmap	Past Revisit	Planned/Ongoing Harmonisation
3	Avionic Architecture / DHS / OnBoard S/W / FDIR / GNC / AOCS / TT&C (E2E)	Avionics Embedded Systems	2006.2 2010.1 2016.1	
		On-Board Payload Data Processing	2003.1 2006.2 2011.2 2016.1	
		Data Systems and On Board Computers	2003.1 2006.2 2011.2 2016.1	
		Microelectronics - ASIC & FPGA	2002.2 2007.1 2011.2 2016.1	
		On-Board Software	2003.1 2006.2 2010.1 2014.2	2020
		AOCS Sensors and Actuators (Part I & Part II)	(2001 2005.1 2009.1) 2013.1 (Part I) & 2015.2 (Part II)	2020 (Part I), 2021 (Part II)
		On-Board Radio Navigation Receivers	2002.1 2007.2 2013.2	2019
		RF & Optical Metrology	2008.1	2018.1
		TT&C Transponders and Payload Data Transmitters	2003.1 2007.2 2012.2	2020
4	Electric Architecture / Power & Energy / EMC	Solar Generators and Solar Cells	2004.2 2009.1 2015.1	2021
		Electrochemical Energy Storage	2002.1 2006.1 2010.2 2014.1	2019
		Power Management and Distribution	2003.2 2008.2 2013.2	2019

CD ID	Competence Domain	Related Harmo Roadmap	Past Revisit	Planned/Ongoing Harmonisation
5	E2E RF & Optical Systems and Products for Nav, Comms & Remote Sensing	Power RF Measurements & Modelling	2004.1 2007.2 2015.1	2021
		Critical Active RF Technologies	2004.2 2014.1	2020
		Frequency and Time Generation and Distribution (Space & Ground)	2005.2 2011.1 (G) 2013 (S)	2018.1
		Technologies for Passive Millimetre & Submillimetre Wave Instruments	2006.2 2010.2 2016.2	
		Array Antennas	2005.2 2011.2 2017.1	
		Reflector Antennas	2004.2 2009.2 2016.2	
		RF Metamaterials and Metasurfaces	2016.2	
		Microwave Passive Hardware	2017.2	
		Technologies for Optical Passive Instruments (Stable & Lightweight Structures)	2008.2 2013.1	2019
		Technologies for Optical Passive Instruments (Mirrors)	2008.2 2013.1	2019
		Optical Communication for Space	2004.1 2008.2 2012.2 2017.2	
		Lidar Critical Subsystems	2005.2 2010.1 2017.2	
		Ground Station Technology	2015.1	2021
6	Life / Physical Science Payloads / Life Support / Robotics and Automation	Automation and Robotics	2001 2007.1 2012.1 2017.2	
		Life Support Technologies		2018.2
7	Propulsion, Space Transportation and Re-entry Vehicles	Fluid Mechanic and Aerothermodynamics Tools	2002.1 2007.1 2012.2	2019

CD ID	Competence Domain	Related Harmo Roadmap	Past Revisit	Planned/Ongoing Harmonisation
		Chemical Propulsion - Micropropulsion	2002.2	2019
			2007.2	
			2011.2	
		Chemical Propulsion - Components (including Tanks)	(2002.2	2018.2
			2008.1)	
			2012.2	
		Chemical Propulsion - Green Propulsion	2002.2	
			2008.1	
			2012.1	
		Electric Propulsion Technologies	2004.2	
			2005.1	
			2009.2	
			2013-2017*	
8	Ground Data Systems / Mission Operations	Functional Verification and Missions Operations Systems	(2002.2)	2020
			(2008.1)	
			2014.2	
		System Modelling and Simulation Tools	2006.2	2018.2
			2012.1	
9	Digital Engineering for Space Missions	System Data Repository	2014.1	2020
		Multibody Dynamic Simulation	2014.1(MP)	2020
		Thermal & Space Environment S/W Tools and Interfaces	2002.1	
		Big Data from Space	2017.1	2019
10	Astrodynamics / Space Debris / Space Environment	Radiation Environments & Effects	(2005.2)	2021
			(2009.2)	
			2015.2	
		De-orbiting Technologies		2018.1

** The last revisit of the EP Harmonisation Roadmap started in 2013 and continued to 2015 when was put on-hold. It has been finalised in 2017.*

Legend:
MP: Mapping only
RM: Roadmap only

7 ANNEX – COMPETENCE DOMAINS

Table 7-1: Competence Domains' Titles

CD	Competence Domain Title
01	EEE / Components / Photonics / MEMs
02	Structures / Mechanisms / Materials / Thermal
03	Avionic Architecture / DHS / On-Board SW / FDIR / GNC-AOCS / TT&C (E2E)
04	Electric Architecture / Power and Energy / EMC
05	E2E RF&Optical Systems & Products for Navigation, Communication and Remote Sensing
06	Life / Physical Science Payloads / Life Support / Robotics and Automation
07	Propulsion / Space Transportation and Re-entry Vehicles
08	Ground Systems / Mission Operations
09	Digital Engineering for Space Missions
10	Astrodynamics / Space Debris / Space Environment