ESRE

ASSOCIATION OF EUROPEAN
SPACE RESEARCH ESTABLISHMENTS

ESRE Whitepaper

Selected Trends and Space Technologies Expected to Shape the Next Decade

Provided by ESRE

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Foreword

In October 2016, the European Commission released its “Space Strategy for Europe”. The Strategy sets itself in particular the goals of:

- “Maximizing the Benefits of Space for Society and the EU Economy”, especially with regard to the needs to address related global challenges as climate change, environmental protection, migration, etc. .., and the needs to establish related global services in support of global transportation and information flow,

  as well as

- “Fostering a Globally Competitive and Innovative European Space Sector”.

The Strategy was welcomed and endorsed in 2017 both by the European Parliament and the EU Council. The Association of European Space Research Establishments (ESRE) welcomes also this strategy and shares its assessment. The main task ahead lies now in the successful implementation of the Space Strategy.

In particular, a very important set of programmes/instruments/measures will have to be defined in the context of the upcoming decision cycle related to the EU’s next Multi-Annual Financial Framework, the most prominent programmatic ones being Galileo, Copernicus and “space research” in FP9.

In this context, ESRE has worked out the present document as a contribution to the upcoming Space Strategy implementation process, written from the angle of view of space research and technology development.

Our recommendations are addressed to all European space stakeholders involved in the 2016 space strategy implementation process.

I. Executive Summary

The global space sector is undergoing rapid transformations. Due to the importance of its services for modern societies, new players from all parts of the world are entering the sector paving the way to the "space economy" growth.

In order to be able to maintain its position as one of the world's leading space actors, the European space sector has also to review its working methods, to adapt, where needed, the inner-European cooperation between public and private players and to invest earlier into the most promising future technologies.

With the present document, the Association of European Space Research Establishments (ESRE) wants to provide its contribution to the implementation of the "Space Strategy for Europe" which was endorsed by the European Union in 2017.

In this context, this document focuses very much on the "research and technology development policy" and "global challenges" dimensions of the Space Strategy and provides the related views of the main public European space research organisations on future space research and technology development needs.

ESRE recommends to:

- Make a stronger use of commonly agreed Technology Roadmaps, also in the context of the EU's R&I framework programmes, in order to guarantee the timely availability of technologies needed for competitiveness and for tackling the global challenges.
- Re-focus R&TD on specific space technologies (not replaceable by COTS-/adapted COTS-components) and enhance the funding of related low-medium TRL R&TD in order to secure the long-term competiveness of the European space sector.
- Provide in public procurements more engineering freedom to foster innovation and competitiveness by focusing on high-level-requirements and by adapting the public ECSS-standards where possible (after proper testing and validation).

In the Annexes the document proposes focused technology roadmaps aiming to allow Europe to remain at the leading edge of space technology in several specific priority areas.

The list of technology roadmaps for the proposed priority areas is far from being exhaustive. However, ESRE believes that it provides a valuable complement to other technology plans, in particular to ESA's ESTMP and to European industry roadmaps.

ESRE therefore intends to update the document and its Annexes on a regular basis in order to provide an additional public input to Europe's R&I policy.

II. Introduction – The Global Space Sector in Transformation

Three overarching elements are driving innovation in the space sector:

- national security and science objectives,
- the expansion of downstream space applications (user requirements),
- the pursuit of human space exploration.

The European institutional actors still remain key performers and customers of innovation in the space sector. The space research organisations role is essential in bridging fundamental research towards mature technologies.

Space technologies and space-based data and services have become an integrated and indispensable part of modern economies and global society.

Prominent examples of satellite-based or satellite-supported services are TV broadcasting, car navigation, weather forecasting, agricultural management or the provision of accurate time for electronic transactions.

Due to their capability to provide global coverage, space technologies and space-based data and services play a key role in the monitoring of the global climate, natural disaster management and security and defense activities.

A paradigm change is however taking place: new technologies and processes (robotisation, AI, miniaturisation…); Internationalisation of Global Value Chains, new commercial actors from the Internet economy modifying the classical incumbents cycles; Innovative uses of satellite links and data detached from traditional space sector, with needs to adapt to new requirements (real time…).

Traditionally, a key source of innovation for the space sector have been public R&TD, space agency programmes and governmental funding, which all supported the development of the next generation of space technologies.

More recently however, and in particular in the US, new companies have entered the space sector, adding a new source of innovation based on new business models, disruptive technologies and the rigorous spinning-in of terrestrial technologies, mass production components and mass production methods from other mature terrestrial industries ("New Space Economy").

This shift in paradigm is further being enhanced by the entrance of commercial actors from the internet economy into the space sector, which promotes in addition the stronger spinning-in of software and artificial intelligence techniques.

Consequently, the rate of innovation in the sector has substantially increased and standard costs in many areas have been brought down significantly.

Clearly, the capability of rapidly and efficiently spinning-in terrestrial mass production components and methods, while maintaining appropriate levels of safety and reliability, will be one of the key determinants of the future competitiveness of space companies. However, the above developments do not only represent a challenge for European space industry.

Complementarily, the public side in Europe, that is governments, agencies and research centers have to find ways to better foster the new sources of innovation coming with the "New Space Economy" approach, e.g. by revisiting their management and procurement procedures as well as their R&TD agendas.

The merits of such an adaptation of the public side are twofold: it would not only strengthen industry and its competitiveness but also the public side itself, as it will remain a key owner and customer of space infrastructures and services and with its public research centers a key driving force in space-related innovation.

III. Trends in the Space Sector and its main Activity Fields

1. Transversal Trends

One transversal trend in the "New Space Economy" are the growing pressures on governments to adopt reforms that reinforce and enable innovation and entrepreneurial activity throughout the space sector. This should create a business environment that encourages investment in technology and in knowledge-based capital (e.g. allowing to experiment with new ideas, technologies and business models).

As a special feature of the spinning-in approach of the "New Space Economy", a major new horizontal trend in the space sector is being given by the so-called Commercial-off-the-Shelf (COTS)-approach, in the context of which space companies procure standard terrestrial commercial hardware in order to fly it directly in space or in order to modify it for spaceflight.

The approach represents a transition from the traditional specialised prototype or low-volume development and production established in the space sector towards the exploitation of the benefits of existing mass production technologies. Therefore, the approach speeds up development times and lowers substantially production costs, in particular in cases where mission profiles allow also for a lowering of the traditional safety and reliability standards.

However, appropriate terrestrial components do not always exist, in particular when it comes to inherently space-related issues (e.g. propulsion) and dedicated scientific instruments.

Still, it is obvious that public procurement standards, in Europe given by the ECSS[1] standards, have to be regularly revisited and revised where possible, in order to avoid that public standards drive up costs and undermine commercial trends without increasing safety.

Another trend hugely impacting the space sector transversally is given by the miniaturization in electronics. It allows putting more and more capabilities in ever smaller satellites. In combination with the COTS-approach, Constellations of Small Satellites, in particular in LEO, become possible, featuring both new capabilities as well as existing capabilities at much lower costs.

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[1] European Cooperation for Space Standardization

Applications of collaborative and small satellite constellation mission concepts may include e.g. communication (see e.g. build-up of OneWeb), Earth observation (e.g. constellation of Planet or Blacksky), navigation, but also astronomy and planetary exploration.

With regard to LEO, the emergence of the Small Satellite Constellations also increases the need for mitigation and avoidance technologies with regard to "space debris". The extent to which the "space debris" can be controlled via technology and regulatory measures will ultimately decide upon the long-term feasibility of all space activities.

Recommended key issues/technologies to be addressed:

Build-up of a publicly available inventory of flight suitable COTS-components and related testing, revision of ECSS standards, elaboration of new concepts for Small Satellite constellations, Investigation of avoidance and removal technologies related to "space debris".

2. Access to Space

Access to space represents the first and indispensable element of the space-related value chain, its costs determine to a substantial degree the costs of entry into the space market and its dynamics. Furthermore, access to space, that is the provision of launch services, represents a business field of its own.

Recently, two American launch providers succeeded not only in recovering the first stages of their launchers, but also in successfully re-flying them. It is expected that in the mid- to long-term reusability will allow substantial reductions in the cost of access to space.

The major challenges posed by reusability are not only of technical but also of economic nature. The latter, since the introduction of reusability into a launch service, comes with three major economic penalties:

- Loss of performance and thus loss of related income, due to additional structural and component masses and additional amounts of fuel needed for the recovery of the stage(s),
- Refurbishment costs,
- Loss of economies of scale in production lines.

As a consequence, a key requirement for the successful introduction of reusability is a high enough launch volume, in order to make full use of the gained mission flexibility (launcher can in principle be economically flown with less than maximum payload) and to mitigate the effects of loss of economies of scale in production.

Due to its potential for cost reductions, reusability will in the long-term likely become a key determinant for the competitiveness of commercial launch providers.

With a view to the emergence of capable small satellite and small satellites constellations, also small launch vehicles are showing a promising commercial potential.

The development of such small launchers may also be helpful for low-cost testing a variety of technologies needed for reusability, be it for small or for heavy launchers.

Recommended key technologies to be addressed:

Execution of small-scale ground and flight experiments to determine optimal system configuration for (partly) reusable launcher; Research and development of dedicated RLV avionics and health monitoring systems; Investigations on lightweight structures and tanks; Elaboration of concepts/research and development for and of (partly) reusable micro-launcher; Elaboration of concepts and research for low-cost reusable propulsion, including throttle able engines et cross-feeding, and thermal protection.

3. Communication

Access to the information infrastructure is a prerequisite for economic development and the transition towards an information society.

Developing economies and remote areas in developed economies can often access the global information infrastructure only via satellites (or mid-term via high-flying unmanned platforms (HAPs)).

Space technologies can therefore contribute to bringing billions of people into the global economy. Also billions of (remote) devices – part of the Internet of things (IoT) – will benefit from space communication technology. Space-based telecommunication represents the largest commercial activity of all space-related markets.

Today’s satellite technology is mainly based on information exchange via radio frequencies. This technology exhibits one major advantage: the possibility to transmit information from a point in space (satellite) to a large area on earth. Unfortunately, the available radio frequencies for this approach are strongly limited.

This latter problem can however be circumvented by resorting to optical communication, the “space” equivalent to the terrestrial “optical glass fibre” cable. While optical inter-satellite communications are already being used operationally in some constellations (e.g. the European EDRS), optical links from satellite to ground and vice versa are still in a testing and verification phase. Regarding the latter, the main problems to be overcome relate to the signal attenuation caused by the atmosphere.

However, optical communication does only provide point-to-point connections. Therefore, it will have in most cases to be combined with some terrestrial backhaul technology to reach the end customer.

On the other hand, the utilisation of radio frequency technologies will remain the only possible choice where a point-to-area approach is required (e.g. satellite-based TV broadcasting).

While the traditional telecommunications market based on geostationary satellites is expected to remain fairly stable, new dynamics to the market are expected to be provided by low-flying Small Satellite Constellations using hundreds or even thousands of satellites (e.g. OneWeb).

Also these constellations, which presently are being designed to work exclusively on the basis of radio frequencies, could benefit in the future from optical communication.

Recommended key technologies to be addressed:

Research and development of bi-directional optical feeder links to geostationary orbit and HAPS, Elaboration of concepts for next generation collaborative small satellite data telecom constellations, Research and development of small-scale transmitters/receivers for optical inter-satellite links, Research and development of quantum-safe optical telecommunication.

4. Earth Observation

With its huge portfolio of different possible passive and active sensors, spanning the optical, infrared and radar regions of the electromagnetic spectrum, the full potential of satellite-based earth observation has still not been unveiled.

The range of possibilities already provided now by satellite-based Earth observation are best exemplified by the fact that about two thirds of the 50+ Essential Climate Variables needed for the work of the Intergovernmental Panel for Climate Change (IPCC) can be reliably measured from space.

Apart from this more governmentally driven market for environmental protection, satellite-based observation also spurs a growing commercial market, mainly by the provision of high-resolution optical and radar imagery.

Such information also plays a vital role in the areas of natural disaster management as well as security and defence activities.

Further momentum in the field is expected to come from the development of new classes of sensors (e.g. hyperspectral, active (LIDAR) trace gas detectors,…) but also from the emergence of small satellite constellations providing low-cost medium and high resolution imagery and video at low costs and very short revisiting times.

Furthermore, additional opportunities will arise from an enhanced combined use of space-based data with locally measured data, a potential that also has to be better exploited in the context of the Copernicus programme.

The main benefits of such a combined use of space-based and non-space-based remote sensing platforms (e.g. High Altitude Platform Stations) lie in substantially higher spatial/temporal and spectral resolution data, even allowing for the monitoring of living species.

Finally, the whole sector will benefit from the new techniques provided by information technology in the areas of big data and data mining.

Recommended key technologies to be addressed:

Research and development of active LIDAR-sensor for GHG-measurements, in particular, CO_2, Elaboration of concepts for the combination of systems and data from space-, air and terrestrial-based sensors, Research and development on next generation of sensors: hyperspectral, L-Band, remote sensed (multispectral/hyperspectral/SAR) image processing, multi-temporal image processing, geo-information services development, remote sensed data fusion, ground systems for integrated EO task planning, software for unmanned aerial systems integrated mission planning, mission interoperability software.

5. Navigation

Our present society no longer can be imagined without the positioning and timing services provided by Global Navigation Satellite Systems (GNSS). The organization and the management of today's mobility and global transport system more and more depends on GNSS, not only for navigation but also for tracking and tracing of vehicles and cargo. In this respect the Galileo programme is a major asset for Europe.

For the future, these mobility applications will demand considerably improved position accuracy, reliability, and signal availability (e.g.: in cities and indoors).

In addition, more and more critical infrastructure in our society relies on the GNSS system time for time synchronization (for example in financial transactions, management of power plants and electrical grids and telecommunication networks). As this dependence continues to grow in the near future, the potential impact of threats to GNSS such as jamming and spoofing will do as well. This development leads to an increasing demand for higher GNSS timing robustness and integrity.

Rapid developments in wireless telecommunication are also driving an increasing demand for higher timing accuracy. Applications with timing requirements as high as 10 ns are starting to appear.

The fact that (safety) critical applications such as civil aviation more and more will rely on GNSS for their navigation function increased the demands for built-in security measures into GNSS systems. Indeed violation of aircraft navigation by hostile entities such as terrorists shall be prevented at all cost. For the European GNSS system Galileo this has led to development of the concept of Open Service Navigation Message Authentication (OS-NMA) as a means to prevent signal spoofing. This authentication message, to be introduced in 2018 may be an important feature in which Galileo is currently unique. The introduction of the Commercial Service (CS) featuring encrypted ranging codes and navigation messages will offer further robustness improvements.

It can be foreseen that strict standards for the use of GNSS, such as currently for aviation, will become required for other safety-critical applications such as road and maritime transport as well.

GNSS systems are continuously evolving. The upcoming improvements in availability, accuracy and general robustness in future GNSS systems will support the envisaged facilitation of "autonomous driving" as well as UAV navigation.

Recommended key technologies to be addressed:

Research and development as to atomic clocks and system time generation. Integrity measures, processing techniques such as A-RAIM and T-RAIM. Coverage improvement, resistance to interference and spoofing. Investigations of interoperability between Galileo and other GNSS systems. Research and development of advanced receivers mitigating natural impairments (e.g. atmospheric delays, multipath of signals) and intentional disturbances such as jamming and spoofing.

6. Space Exploration and Human Spaceflight

Space science and human spaceflight were very much at the origin of the global space effort. They have not only been vital sources of inspiration and international cooperation, but were also key for the technological advancement of space technologies.

Questions related to the history of the universe and the solar system, the origin of life and the possibilities of the extension of the human presence beyond Earth will continue to remain focal areas of space exploration.

Two general trends are expected to influence the sector particularly strongly in the upcoming future.

First, due to the progresses in computational and robotic powers, autonomous capabilities will become much more advanced, both related to unmanned missions and to the assembly of human spaceflight infrastructure in space.

This trend also comprises the use of artificial intelligence in support of in-situ autonomous mission control, also by e.g. integrating collaborative teams (or swarms) of robots into mission concepts.

Second, the cost for human spaceflight activities will be further brought down substantially by co-using launchers and infrastructures being commercially available on the global market for unmanned missions or space tourism (e.g. reusable launchers, inflatable habitable modules, etc.).

These possibilities arise in particular because of the aforementioned possibilities for robotic assembly.

Recommended technologies to be addressed (taking into account that Europe is not likely to strive for an autonomous human access to space)**:**

Research and development of entry, descent and landing technologies as well as rover technologies, Research and development of low-cost (inflatable) pressurized modules and habitats, Research and development of living-off-the land technologies (e.g. bio-regenerative systems); Development of testing infrastructures for technologies and systems needed for robotic and human planetary/moon exploration, Research and development as to deep-space propulsion, long duration cryogenics storage and cryogenic propellant transfer, Research and development as to “autonomy of mission control” and the utilization of collaborative exploration robots.

7. Cybersecurity, Data Sciences, Quantum Technologies

Satellites, satellite constellations and other parts of the space segment space are and have always been IT-infrastructures sending the information from their sensors and payloads back to the terrestrial user. Vital infrastructures and services such as telecommunications, financial services, weather forecasting, safety & security services, heavily rely on space based systems.

Space security and cyber security together referred to as "cyberspace" constitute a unique technological domain that is becoming a prominent focus for international strategic, political, and economic competition.

Key feared events that could have significant impact on the mission in terms of performance, economics, or human safety are for example: 1) Unauthorised operation of satellite/launcher/spacecraft/ground facilities, 2) unavailability of TT&C communications during critical manoeuvres, 3) unavailability of services for medium or large periods in time, The currently implemented security safeguards in space based systems and its operations need to evolve in order to face the continuously changing security risk environment.

Due to the strongly increasing amount of data provided by the sensors on board satellites and the increasing complexity of satellite operations, the space sector can directly profit from scientific and technological progresses achieved on earth in the fields of data sciences and cybersecurity.

Equally, the space sector will be soon able to benefit from the emerging quantum technologies (2.0), both with regard to new powerful sensors and with regard to the possibility of quantum-safe telecommunication.

Recommended technologies to be watched/adapted/spin-in:

Autonomous (cyber) event detection, containment and recovery, e.g. through data mining, machine learning, artificial intelligence/neural networks, quantum measurements, strengthening of authentication and communication techniques, e.g. through signal level and data level encryption, key distribution, quantum cryptography, redundancy and resilience in space system architectures, satellites are no longer monolithic systems but follow a modular approach (a network of systems).

IV. Recommendations to the European Space Sector

A shift of paradigm is taking place in the space sector. With the advancement of computer technology and quality standards both in terrestrial commercial components and production methods, the space sector is now being offered substantial possibilities for benefiting from the spin-in of technologies and methods developed in other industrial sectors.

An adaptation to this "New Space Economy" approach is also beneficial to the public side which will remain a key owner and customer of space infrastructures and services and with its research centres a key driver of space-related innovation.

The "New Space Economy" is pushing governments to adopt reforms to reinforce and enable innovation throughout the space sector and to create a business environment that encourages investment in technology and in knowledge-based capital (e.g. allowing experiment with new ideas, technologies and business models).

At the same time, a substantial amount of specific space technologies will remain inherently "space-driven" (e.g. propulsion, habitats …). In such cases, dedicated developments are still necessary though they should take maximum advantage from new methodologies and recent R&TD results.

In order to meet the above challenges and support industry, it is recommended that the public side in Europe commits itself to the following measures:

- Increase the funding for medium/long-term oriented R&TD (over-next generation) in order to secure long-term competitiveness of the European space sector. With a view to FP 9, and taking into account the request of the European Parliament for a new industrial policy instrument, namely a Joint Technology Initiative (JTI), keep the budget for collaborative space R&TD in FP9 "space" at least unchanged from Horizon 2020 and fund the JTI under FP9 "space" via additional resources.
- Make a stronger use of commonly agreed Technology Roadmaps, which set the goals via high-level requirements for vital subsystems.
- Foster earlier cooperation (in terms of TRLs) between European space research organisations and Industry, preferably via Technology Roadmaps.
- In case the establishment of a JTI will be decided in the framework of FP 9, involve in its creation apart from industry also research establishments early on and ensure that for the agreed R&TD fields of the JTI not only higher TRL activities (TRL 4/5-6/7) are being incorporated (preferably via technology roadmaps) but also relevant lower TRL activities (2/3<TRL< 4).
- Fund some research directly via the European infrastructure programmes, in order to secure the possibility of a rapid take-up of specifically required next/over-next generation technology by those programmes, here in particular Galileo and Copernicus.
- Support COTS-approaches by funding/co-funding public and industrial R&TD activities aiming at validating COTS-components, Build-up a related public inventory.
- Adapt ECSS-standards to allow for new approaches.

- Implement policies that encourage in particular innovation and entrepreneurial activity promoted by start-ups engaging in the "New Space" approach, e.g. by dedicated financial instruments in FP9 and the European Fund for Strategic Investment (EFSI).
- Last but not least, in public procurements, resort as much as possible to high-level requirements, thereby leaving more engineering freedom to industry (and to research centres with regard to science instruments) in order to foster innovation and competitiveness.

In the Appendix some preliminary technology roadmaps are recommended for ensuring the medium/long-term competitiveness of the European space sector.

These technology roadmaps also lend themselves as key elements for "mission-oriented" approaches in the context of FP9, e.g. for the following "missions[2]":

- "Low-cost Access to Space, and Reusability".
- "Removal of Digital Divide: Collaborative Small Satellite Constellations; Optical Communication".
- "Industrial Competitiveness: Satellite Subsystem Technologies, Collaborative Small Satellite Constellations".
- "Paris Agreement and Environmental Protection: CO_2-Monitoring via LIDAR and integration of space-based, air-based and terrestrial Monitoring Technologies; Collaborative Small Satellite Constellations";
- "Environmental monitoring at a local scale integrating measures by space, stratospheric (HAPS), aerial and terrestrial platforms".
- Clean and Safe Orbits and Sustainable Satellite Constellations.

[2] see Lamy Report

Annex 1 - Recommended Space Technologies

Future Launching Concepts – Micro and Reusable

Micro launchers

I. **Key goals/Key technologies to be developed in timeframe 2018-2021**:

Identify, evaluate and compare candidate micro launcher concepts (reusable or low cost expendable);

Improve hybrid rocket engine, which is already studied in the hyprogeo programme, enhance liquid rocket engine, including ALM and fatigue analysis; explore a new disruptive technology as the continuous detonation wave engine (CDWE), up to TRL 3.

II. **Key Goals/Key technologies to developed in timeframe 2021-2025+**

In flight demonstration of upper stage based on demonstration on test bench of new propulsion system for upper stage.

III. **Key Goals/Key technologies to develop from 2025+ onwards**

In flight demonstration of innovative propulsion concept

Reusable launchers

Goal: Identification of the most promising reusable launcher concept(s), (e.g. ground launched vs. air-launched) with respect to overall lifecycle costs, reliability, robustness, flexibility and availability, and identification of required advanced key-technologies essential for the realization of the promising concept(s).

Key goals/Key technologies to be developed in timeframe 2018-2021:

Identify, evaluate and compare candidate reusable launcher concepts; identify the most promising concept(s). Demonstrate the interest of promising reusable launcher concepts compared to state-of-the-art expendable launchers.

Key activities to be undertaken:

- System design, analysis and optimization for identified launcher concepts, operations including ground infrastructure, overall lifecycle analysis with respect to costs, reliability, robustness and availability as well as flexibility to market change. Identification of the most promising concepts.
- Parallel work on critical RLV-technologies on system- and subsystem-level required for the promising concepts: e.g.
    - Reusable cryogenic tank insulation and integration with external thermal protection,
    - Avionics:
        - smart, reliable, automated and precise GNC for payload deployment and de-orbit/re-entry

        - HUMS for 1st stage re-entry including structure, insulation, TPS, propulsion
    - Increased robustness and lifetime of rocket engine regenerative cooling, valves, turbomachinery
      Propellant management systems, power and pressurisation systems etc.

Key Goals/Key technologies to be developed in timeframe 2021-2025+

- Continuation of work on critical RLV-technologies on system- and subsystem-level required for the promising concepts, in order to increase the TRL;
    - (inflatable) Materials for thermal shielding, cooling environmental protection,
- Perform technology development for potential break-through technologies with respect to cost effective reusable launchers ;
- Perform subscale (flight-) demonstration of selected critical system and subsystem technologies as for example:
    - advanced, efficient RLV-stage return technologies with high degree of autonomy like “in-air-capturing”/”mid-air-retrieval”

Key Goals/Key technologies to be developed in from 2025+ onwards

Flight demonstration of integrated subscale reusable launcher demonstrator under ESA, EU agency or industrial leadership.

Please find the corresponding roadmap in the Annex: Technology Roadmaps, Figure 1: A preliminary roadmap for future launching system development.

Optical Communications

Goal: Demonstrate feasibility and technological maturity (≥ TRL 7) of optical communications technology for the feeder links of very high throughput satellites in geostationary orbit.

I. **Key goals/Key technologies** to be developed in timeframe **2018-2021**:

Design and test of mitigation techniques to compensate the fading and distortion caused by the atmosphere and define the optical link format (framing, modulation, coding).

The objective would be to achieve a stable reception with reduce residual signal fluctuation not exceeding 3 dB.

II. **Key Goals/Key technologies** to be developed in timeframe **2021-2025+**

Development of a prototype for a bidirectional optical terminal and a ground station supporting Tbps and implementing the previously developed mitigation techniques.

The objective is to test and validate the prototype in the lab and with a terrestrial link emulating the propagation characteristics of a satellite link.

III. **Key Goals/Key technologies** to be developed in from **2025+ onwards**

In-Orbit Demonstration of bidirectional optical feeder links using a space qualified version of the previously developed space terminal prototype.

The final goal is to achieve TRL ≥ 7.

Time and Time Standards in GNSS-Systems

Goal: Establish a robust system time for Galileo. Advance the EU goal to provide a robust timing service for Galileo and EGNOS.

I. **Key goals/Key technologies** to be developed in timeframe **2018-2021**:

Design, test and development of a prototype (TRL>6) of a Galileo System Time based on Composite Clock algorithm using the Galileo ground clocks of Precise Time Facilities located in Fucino, Italy and Oberpfaffenhofen, Germany. For the communication between the two PTFs standard time transfer techniques like Common View over GNSS satellites or Two-way satellite time and frequency transfer (TWSTFT) will be used.

The objective is to achieve a stable and robust Galileo System Time, which can tolerate the outage of one or more clocks in one or both PTF.

Design, test and develop a prototype Galileo Timing receiver implementing upcoming EGNSS Robust Timing Service recommendations (TRAIM, dual-frequency, multi-constellation). The objective is to demonstrate the added value of the robust timing service and encourage adoption.

II. **Key Goals/Key technologies** to be developed in timeframe **2021-2025+**

Design, test and development of a prototype (TRL>6) of a Galileo System Time based on Composite Clock algorithm using the Galileo system clocks , both on ground and in space.

Establishing a redundant optical time transfer connection of both PTFs to reduce errors based on satellite communications paths.

Design, test and development of a prototype implementation (TRL>6) of optical clocks in the Galileo PTFs to get a more accurate Galileo System Time.

Design, test and development of a prototype implementation (TRL>6) of an optical time transfer between two satellites in the MEO constellation equipped with optical clocks.

The objective would be to improve the stability and robustness of the Galileo System Time against clock outages.

III. **Key Goals/Key technologies** to be developed in from **2025+ onwards**

In-Orbit Demonstration of “Galileo system time space clock” using optical clocks and bidirectional optical links on each Galileo satellite.

The final goal is to achieve TRL ≥ 8.

CO2-Monitoring from Space

Goal: Pre-development of a LIDAR instrument with the target to allow for an active CO_2/GHG precursor mission to be launched around 2025, followed by a first operational mission in the timeframe 2030.

I. Key goals/Key technologies to be developed in timeframe **2018-2021**:

Identify candidate instrument and associated observational concepts, develop candidate instrument to TRL 6, and demonstrate its capabilities through airborne campaigns.

We would choose at least one technology at TRL 4 at the beginning of this study, which will be the main candidate for this TRL maturation and airborne measurement demonstration.

For risk mitigation and next phase preparation, we will choose one or two alternative technologies at TRL 3, that will be candidate for TRL 4/5 development and airborne technological validation.

Key activities to be undertaken with regard to instrument, in particular:

- Laser-related R&TD
- Noise-free detector related R&TD
- Spectral calibration related R&TD
- Aircraft-based measurements
- Alternative technologies review and maturation to TRL 4

Key activities to be undertaken with regard to observational concepts/validation

- In-situ-based measurements with low-cost meteorological instruments (ex. Ceilometers) for calibration and validation of aircraft/satellite data
- Sensor fusion of data products from Earth-based in-situ systems and passive and active CO2 sound systems in space
- Regional and city-scale modelling

Key action at end of first phase of technology plan (around 2021): Transfer of TRL 6 technology results and related concepts to ESA in order to allow for procurement of precursor mission (either funded via Copernicus programme or via ESA Member States)

II. Key Goals/Key technologies to develop in timeframe **2021-2025+**

- Develop next generation instrument H/W, e.g. new laser and detector subsystems or alternative technology instrument,
- continue further development, verification and validation of measurement concepts and performances via aircraft campaigns

III. Key Goals/Key technologies to develop in from **2025+ onwards**

- Verify and validate results of precursor mission via ground-based and airborne measurements

- Continue development of next-generation instrument H/W
- Contribute to system design phase for operational Sentinel mission

  Please find the corresponding roadmap in the Annex: Technology Roadmaps, Figure 4: A preliminary roadmap for CO2 Monitoring from Space.

Monitoring the Environment – Local Scale Matters

Goal: Develop tasking and data exploitation approaches to match the spatial/temporal/spectral resolution requirements from end users (*e.g.* environmental protection agencies, local governments, public bodies, *etc.*), typically exceeding the capabilities of the single Earth Observation (EO) system, through synergies among different space and non-space remote sensing platforms (e.g. HAPS).

Challenges:

- combined use of heterogeneous remote sensing platforms and sensors, to increase the spatial/temporal/spectral resolution of the observations;
- to develop capabilities of novel remote sensing platforms for persistent surveillance tasks;
- characterization and monitoring of living species through a set of advanced sensor.

Technologies: remote sensed (multispectral/hyperspectral/SAR) image processing, multi-temporal image processing, geo-information services development, remote sensed data fusion, ground systems for integrated EO task planning, software for unmanned aerial systems integrated mission planning, mission interoperability software.

Applications: *geo-information services* for environmental protection, pollution monitoring, nature health monitoring, forestry, agriculture and urban health monitoring**.**

I. **Key goals/Key technologies** to develop in the timeframe **2018-2021**:

- *Operational synergy among heterogeneous earth observation satellites*:
  - definition of paradigms for mission interoperability and development of basic information technologies (*i.e.,* operation data sharing) for integrated tasking;
  - improved algorithms (*i.e.,* cross-calibration, co-registration, multi-source classification) and workflows for image fusion among heterogeneous space borne sensors (*i.e.*, optical and synthetic aperture radar);
  - geo-information applications with improved spatial/temporal/spectral analysis resolution.
- *Synergy among space and aerial unmanned platforms*:
  - definition of mission interoperability paradigms;
  - improved algorithms (*e.g.*, cross-calibration, co-registration, multi-source classification) and workflows for image fusion;
  - geo-information paradigms with improved spatial/temporal/spectral analysis resolution.
- *Feasibility study on persistent surveillance applications*:

  - definition of mission concepts for EO small satellite constellations for the purpose;
  - improved algorithms and workflows for high frequency multi-temporal remote sensed image analysis,
- *Key methods for living species monitoring*:
  - formulation and validation of methods for living species monitoring (i.e. vegetation) using existing space borne and airborne sensors (*e.g.*, multispectral, hyperspectral, fluorescence, SAR ;
  - early applications for living species monitoring, using advanced sensors and concepts also based on physical models.

II. **Key Goals/Key technologies** to develop in timeframe **2021-2025+:**

- *Technological synergy (interoperability / collaboration / integration) among heterogeneous EO satellites*:
  - geo-information paradigms for which synergy among heterogeneous EO satellites is strongly required and is based on interoperability.
  - advanced information technologies for integrated tasking (common tasking interface).
- *Technological synergy between space and aerial unmanned platforms*:
  - geo-information applications for which synergy among EO satellites and RPAS is strongly required and is based on interoperability;
  - basic information technologies (*e.g.*, real-time availability of satellite operation data) for integrated tasking among heterogeneous platforms (EO satellites/RPAS).
- *Persistent surveillance applications and further concepts*:
  - geo-information paradigms through EO small satellite constellations;
  - definition of mission interoperability paradigms among EO satellites and high altitude pseudo satellites (HAPS)
- *Living species monitoring based on the available novel technologies*:
  - formulation and validation of methods for living species monitoring using both high resolution space-borne hyperspectral sensors or fluorescence sensors and heterogeneous sensors and platforms (*e.g.*, accurate calibration);
  - consolidated geo-information paradigms for living species monitoring, based on advanced sensors (*e.g.,* fluorescence sensors) and concepts (*e.g.,* physical models).

III. **Key Goals/Key technologies** to develop from **2025+ onwards:**

- *Active collaboration among heterogeneous earth observation satellites*:
  - multisensory/multiplatform collaborative tasking (*e.g.,* in tandem configuration);
  - geo-information applications for witch integrated multisensory/multiplatform collaborative tasking is an enabling technology.
- *Integrated tasking between space and aerial unmanned platforms*:
  - multisensory/multiplatform collaborative tasking (i.e. among satellites and RPAS) ;
  - geo-information applications for witch integrated multisensory/multiplatform collaborative tasking is an enabling technology.
- *Multiplatform collaboration for persistent surveillance*:
  - information technologies for active collaboration among EO satellites and HAPS;
  - multiplatform geo-information applications .

- *Living species monitoring based on heterogeneous platforms*:
  - multiscale approach to living species monitoring , also based on physical considerations;
  - multiplatform geo-information applications.

Please find the corresponding roadmap in the Annex: Technology Roadmaps, Figure 5: A preliminary roadmap for Monitoring Environment at a Local Scale.

Small Satellites – Collaborative Constellations

Goal: Accelerate the EU competitiveness by building challenging and innovative collaborative EU demonstrator missions ("learning by doing") in the timeframe of H2020 and FP9, and develop in parallel the enabling technologies that allow for proof-of-concept based on in-orbit (and/or on-ground) demonstration of selected technologies. This approach is envisioned to stimulate EU industrial competitiveness and independence, whilst also resulting in new EU made services from Space that are kick-started by EU stimulus.

The research is proposed along three lines:

- *Leading by doing*: working towards "NewSpace" European Constellation as a very strong instrument to develop European technology and services and put it to the test
- *Bringing best industrial practices to the space domain*: large series production like in automotive become key
- *Developing key enabling technology*: using a "NewSpace" style to start technology development urgently with the ambition to close the gap with the US and develop new unique technologies, payloads, and services

I. Key goals/Key technologies to be developed in timeframe 2018-2021:

Define a concept demonstration mission for a Collaborative Small Satellite Constellation.

Key activities to be undertaken for the mission definition are:

- Market analysis & end-user requirements definition. Targets markets include Food Security, Climate Action, Secure Energy, Secure Societies, Smart Green Transport, Excellent Science
- Mission selection, mission concept elaboration, identification of key elements (incl. mass production concepts), requirements and architecture definition

Key activities to be undertaken for technology development are needed in the following areas:

- Secure inter-satellite communication, essential for "cluster" and "formation" constellations
- Constellation positioning and orbit control, including electrical propulsion
- Distributed on-board data handling, processing, and analysis
- Sensor fusion, distributed sensors and multi-sensors development

Key action at end of first phase of technology plan (in 2020): Preparation of an EU program beyond H2020; the next framework program (FP 9) should be the vehicle to support mission implementation.

II. Key Goals/Key technologies to developed in timeframe 2021-2025+

In-orbit validation of the demonstration mission and selected technologies.

Key activities to be undertaken for the mission are:

- Future markets development
- New manufacturing process (smart materials and multi-material 3D-printing)
- In-orbit assembly, test and integration

Key activities to be undertaken for technology development are needed in the following areas:

- Secure autonomous operations
- Integrated networked capability with a/o RPAS and HAPS
- High accuracy attitude and orbit determination and control
- On-orbit big data (pre-)processing

III. Key Goals/Key technologies to be developed in from 2025+ onwards

Mission and technology demonstration of an operational collaborative small satellite constellation.

Key activities to be undertaken for the mission are:

- "Mass" production, including assembly, test and integration
- In-orbit commissioning

Key activities to be undertaken for technology development are needed in the following areas:

- Reliable and simple de-orbit system
- Satellite virtualisation & constellation operating system
- Sensor fusion on-board high level processing

The final goal is to achieve TRL ≥ 7.

Please find the corresponding roadmap in the Annex: Technology Roadmaps, Figure 3: A preliminary roadmap for Collaborative Small Satellite Constellations development.

Satellite Sub-systems – COTS Components

Goal: To establish a roadmap to promote the massive use of COTS in space.

I. Key goals to be developed in timeframe 2018-2020:

Key activities to be undertaken with regard to the roadmap:

We can consider three levels:

Programmatic level:

- *ESRE Agreements on common lines to proceed.*
- *Prepare an ESRE SWOT analysis to motivate this roadmap.*
- *Involvement of EU, ESA and Member States.*

- **Key action at end of first milestone** (**around 2018**): *<u>Agreement in common lines</u> to proceed inside ESRE (consensus) previously to the involvement of industry and test houses*.

Technical level:

- *Identification of the candidate components to invest on. To study different cases to analyse if investment on COTS is worthy (i.e. perform* COTS Components *business cases).*
- *Study of the critical aspects of different applications, and analyse if the use of COTS* Components *is appropriate.*
- *Cross-fertilization of non-space components (COTS* Components) to be used in space applications*.*
- *Contact with the COTS* Components *manufacturers, to know more about the construction and processes behind the COTS* Components*.*
- *Involvement of test houses (commercial) from the beginning, with knowledge in the field.*
- *Looking for COTS standards at space level, Survey similar initiatives at EU level and overseas (NASA, JAXA)…*

  Key action at end of second milestone (**around 2019**): *Design of strategies to work on COTS* Components *testing/qualification*.
- *Disseminate this pan-European initiative.*
- *Explore the European added value of an initiative like this (i.e. COTS* Components *roadmap).*
- *Funding proposals preparation.*

Output level:

- *A preparatory action based of a Coordinated and Support Action (CSA) of 1 year is proposed to be included in the WP 2019.*

II. Key goals to be developed in timeframe 2020-2030:

Key activities to be undertaken concerning the roadmap:

- COTS components Data Base. The Joint European Database of COTS components for space is an initiative that requires of research effort in the strategies to identify, screen and test potential candidates to be used in several operational space scenarios. After the 2019 CSA, a topic in the range of 10 M€ for the WP 2020 is proposed. The target is to produce major advances in the identification of COTS to populate the European COTS database. Expected projects between 1-2 M€ will be launched to survey among the last generation commercial parts of different families: passive components; diodes; transistors (e.g. MOSFET, FET, bipolar, etc.); high power components; integrated circuits (e.g. operational amplifiers; voltage regulators; DC/DC converters, etc.); memories; microprocessors; FPGA's, optoelectronic emitter and detectors; batteries; etc. This topic will consist of several Research and Innovation Actions (RIA´s) to identify suitable candidates from the different components families.

- The projects will be devoted to identify candidates for the database scavenging in high reliability industrial civil sectors as automotive.

In the WP 2019 a CSA and for the WP 2020 several RIA´s are recommended.

Please find the corresponding roadmap in the Annex: Technology Roadmaps, Figure 2: A preliminary roadmap to promote the massive use of COTS in space.

Technologies for Compact Sensors – Smart Sensors for New Space and Planetary Exploration

Goal: increasing EU miniaturization capabilities and developing and qualifying complete instruments based on them. The development of specific technologies would end into the construction of miniaturized payloads or satellite-borne instruments devoted to very specific duties to be allocated in small satellite constellations which could act as distributed instruments.

I. Key technologies to be developed in timeframe 2018-2020 (and on the medium term):

- *RHBD mixed signal ASIC building blocks for Front-Ends*
  - *Low Speed, high-precision (e.g. <1MHz GBP, low noise, low offset amplifiers, 18-20 bit ADC, 100ksps)*
  - *High bandwidth, medium-precision (e.g. 1GHz GBP amplifiers, 16-bit ADC, 20Msps)*
  - *Same, <90um technology*
- *Selection, Qualification and Screening of COTS (Electronics, OE & Detectors). Intensive, cooperative and somehow "public" research on qualification of state-of-the-art COTS. This comprises activities at the physics level, selection and testing. This activity would include not only electronic parts, but also and very especially state-of-the art detectors of different kinds, being optoelectronics one of the maximum interest given their huge range of applications.*
- *Die level integration techniques (System-in-Package enabling capabilities). One way of boosting miniaturization and high-performance would be the integration of complete circuits based on existing de-capsulated parts.*
- *Spot shielding techniques. Advances in spot-shielding technologies would be needed to provide increased radiation protection to the resulting circuits, where specially needed.*
- *Design of protective circuitry (SEL supervisors, SET filtering, etc.). A part that is identified as robust to space environment in some aspects (e.g. TID, SEU) but not some other (e.g. SEL) can be protected by decapsulating it, integrating some protective circuitry with it, and re-capsulating.*
- *Processing resources (IP-cores for Logic / S/W libraries for Microcontrollers). Identification of main (recurrent) needs in the fields of signal processing, statistical analysis, spectral analysis, communication protocols, etc., and development of IP-core and/or S/W libraries as building blocks to be used within the instruments.*
- *Alternative power supply systems. Research on alternative power supply methods for low-power, low-duty-cycle sensors (e.g. betavoltaics radio-active power-supplies).*

II. Key technologies to be developed in timeframe 2020-2025:

- *Development of "general purpose" mixed signal ASICs. We refer to selected schemes such as a multiplexed front-end capable of conditioning signals from a number of types of sensors, performing a high-precision digital conversion and offering fully digital interface and configurable capabilities. This kind of development could be used in a big number of applications and can be easily manufactured in Europe:*
  - *Multi-purpose Compact Front-End (F.E.) ASIC, Low Speed.*
  - *Multi-purpose Compact Front-End (F.E.) ASIC, High Speed.*
  - *Multi-purpose Compact Instrument Control Unit (F.E. Low Speed / High Speed + Computer).*

- *Development of compact low-power Instrument Control Units for serving a range of instruments:*
  - *Autonomous Multipurpose Compact ICU (F.E. Low Speed / High Speed + Computer + Power).*

  Key goal at the end of this timeframe: development of particular sensors / instruments for Planetary Exploration, Earth Observation, Telecommunications, etc. as demonstrators of the previous technologies.

III. Key goals to be achieved in timeframe 2025-2030:

- *Development of particular sensors / instruments for Planetary Exploration, Earth Observation, Telecommunications, etc. flight qualified and proven.*

New Optical technologies – Improving detecting and sensing capabilities

Goal: Establish a roadmap to promote the use of freeform optics and ultra-stable materials in space optics instrumentation.

I. Key goals to be developed in timeframe 2018-2020:

Key activities to be undertaken with regard to the roadmap:

- *Identify proposals where freeform optics is applicable, trade-offs of classical versus freeform concepts in any space instrument.*
- *Promote interaction between centres/companies with a clear interest in developing such a technology: workshops, conferences, etc.*
- *Establish a development plan for manufacturing and testing ultra-stable materials susceptible to be used as mirrors substrate and mechanical structure.*
- *Explore coatings properties on ultra-stable materials: define test campaigns for measuring spectral reflectance, adherence, survival, etc.*
- *Establish, in general, a roadmap for analysing the potential uses at theoretical level of both freeform optics and ultra-stable materials creating the proper network of interested centres and companies.*

II. Key goals/technologies to be developed in timeframe 2020-2025:

Key activities to be undertaken with regard to the roadmap:

- *Test facilities conditioning for carrying out freeform optics verification.*
- *Stand-alone freeform optics verification.*
- *Development of optical systems using freeform surfaces: integration and testing.*
- *Manufacturing of ultra-stable samples: environmental tests including cryogenic conditions (a few Kelvins).*

III. Key goals/technologies to be developed in timeframe 2025-2030:

Key activities to be undertaken with regard to the roadmap:

- *Consolidate the freeform technology up to get a maturity level compatible with its use in space. Provide the means to transfer this technology to the industry.*
- *Consolidate the use of ultra-stable materials as mirror substrates for space applications up to get a maturity level compatible with its use in space. Provide the means to transfer this technology to the industry.*

Manufacturing for space applications

Goal: Establish a roadmap to develop 3D multi-material and multi-functional micro and macro for extra-terrestrial fabrication

I. **Key goals to be developed in timeframe 2018-2020:**

- Develop a multi-material and multi-functional topological optimization tools
- Determine individual voxels or parts, which can be made very precisely using microfabrication

II. **Key goals/technologies to be developed in timeframe 2020-2025:**

- Develop a hierarchical architecture for the design of mechanisms, actuation, and electronic
- Develop a fully recyclable and reusable multi-material process

Onboard Processing for Very High Throughput Satellites

Goal: Demonstrate feasibility and technological maturity (≥ TRL 7) of an hybrid transponder for very high throughput satellites in geostationary orbit capable of handling the conversion from optical feeder links to RF user links and vice versa.

I. Key goals/Key technologies to be developed in timeframe **2018-2021**:

Design of on-board processing techniques to handle the conversion from optical feeder links to RF user links and vice versa and development of a first prototype for a bidirectional hybrid transponder.

The objective would be to support a throughput as high as 200 Gbps as initial technology demonstration.

II. Key Goals/Key technologies to be developed in timeframe **2021-2025+**

First in-Orbit demonstrator targeting 200 Gbps and using exiting optical terminal technology (e.g. LCT from Tesat).

The goal is to achieve TRL ≥ 7, although with limited throughput.

III. Key Goals/Key technologies to be developed in from **2025+ onwards**

In-Orbit Demonstration of hybrid transponder for very high throughput satellites in geostationary orbit with bidirectional optical feeder links.

The final goal is to achieve TRL ≥ 7 and to support an aggregate throughput in range of Tbps.

Technologies for Autonomous and Cooperative Swarm Exploration

Goal: Demonstrate the use of robotic swarms for future extra-terrestrial in-situ exploration missions.

I. Key goals/Key technologies to be developed in timeframe **2018-2021**:

The general goal here is to develop demonstrators that can be used to validate the components required for swarm technologies.

The emphasis is placed on the development and testing of three key components:

1. Prototyping of a robust high-rate data communication system for swarm applications. The system should be able to support a high number of autonomous users, be robust against network perturbations, and support real-time control and cooperative data processing applications. The targeted data rate is 10-50 Mbit/s.
2. Development of a swarm-based navigation system that is able to localize all individual robots, external devices, drop boxes and the like. The system should support continuous operation and provide sub-meter localization accuracy.
3. Demonstration of the principle of swarm exploration and navigation based on sensor data (e.g., magnetometers, gas sensors, seismic sensors), and decentralized modelling and mapping of the observed phenomena. A set of possible sensors for a swarm mission will to be selected in cooperation with planetary scientists.

II. Key Goals/Key technologies to be developed in timeframe **2021-2025+**

Development of a prototype swarm system up to TRL 6 that validates the concept of swarm exploration and can be used as a platform for further system optimization.

In particular, a prototype swarm platform for more extensive testing is to be developed. The latter integrates several robotic vehicles, communication, localization and exploration functionality, and a selected sensor package. Using this prototype swarm further testing of exploration algorithms for the selected sensor package is carried out. Different exploration scenarios/swarm missions are tested, supporting up to 10 agents in environments on Earth, such as those mimicking Martian terrain or caves. The goal is to evaluate the system performance with respect to autonomy, speed of exploration, network perturbations, and algorithms robustness.

III. Key Goals/Key technologies to be developed in from **2025+ onwards**

Deep involvement of industrial partners and space agencies in testing of swarm technology. Preparation of a possible mission. Extension of demonstrations with respect to drop boxes, environmental diversity and mission tasks.

The final goal is to achieve TRL ≥ 7.

Annex-2 Technology Roadmaps

Future Launching Concepts

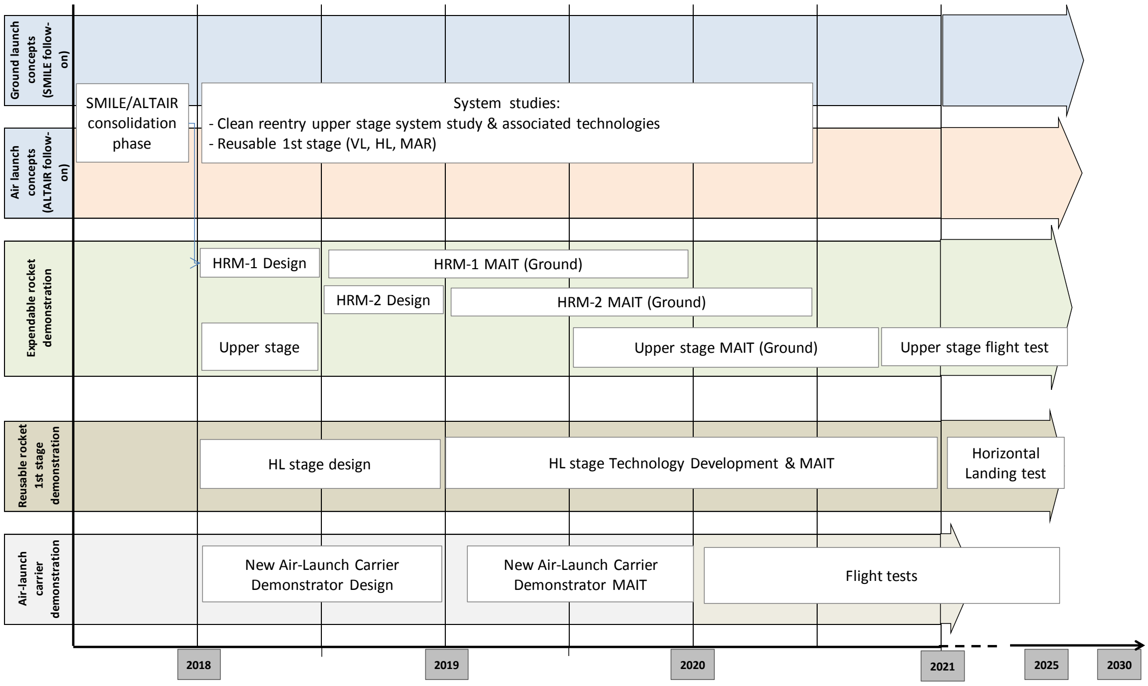

Figure 1: A preliminary roadmap for future launching system development

Satellite Sub-systems – COTS Components

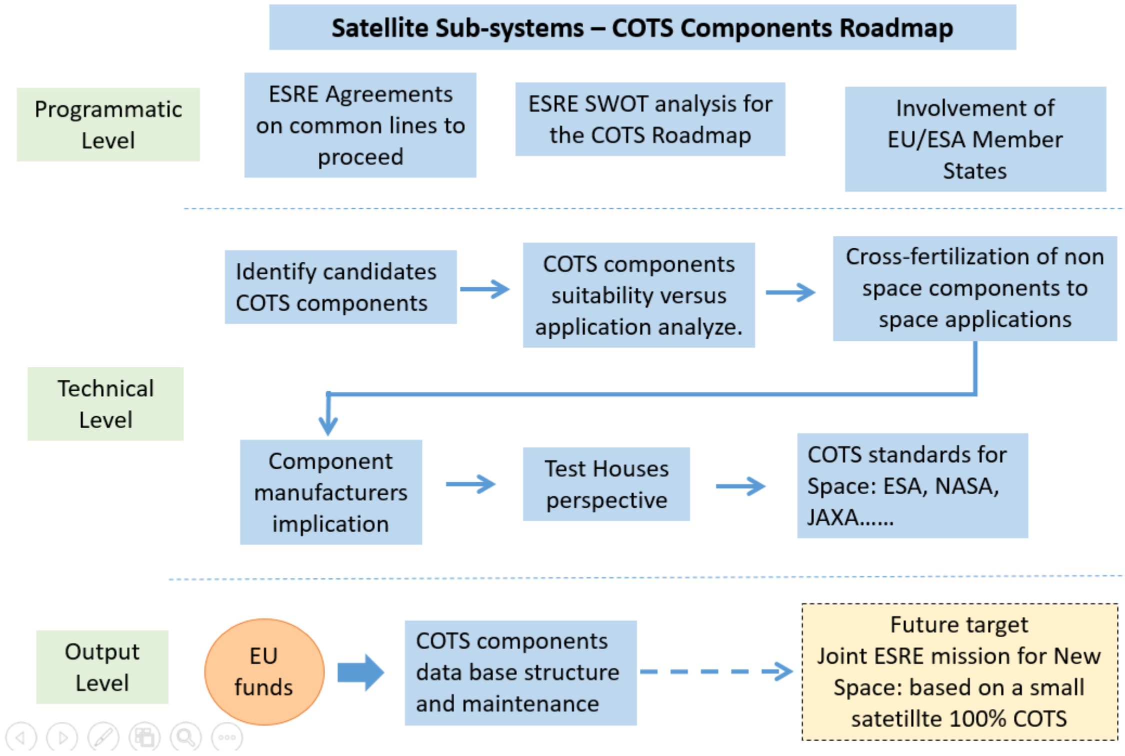

Figure 2: A preliminary roadmap to promote the massive use of COTS in space

Small Satellites – Collaborative Constellations

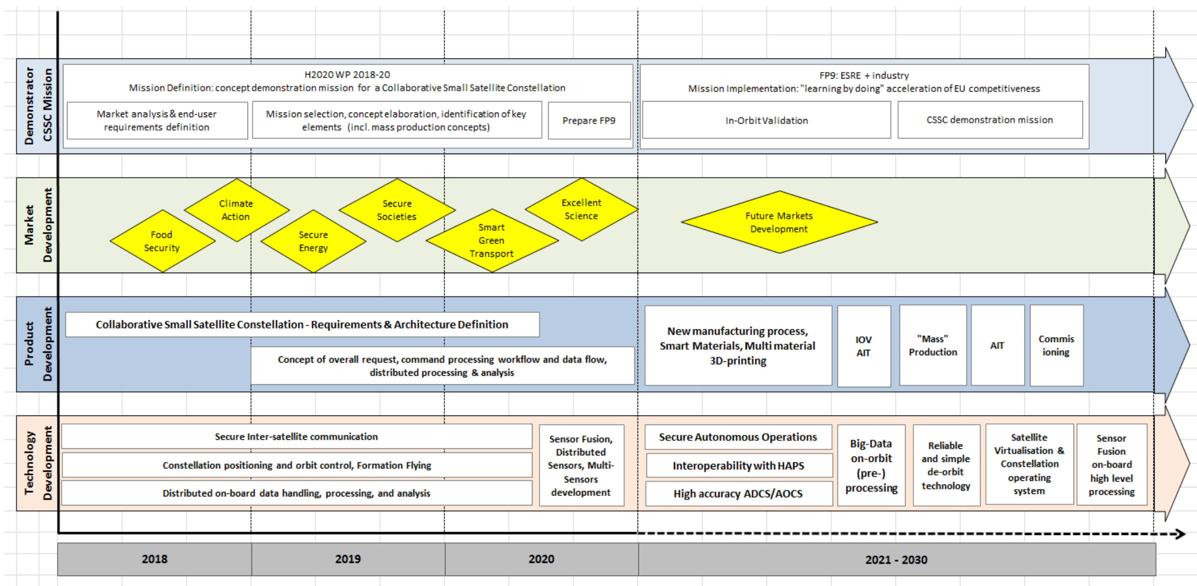

Figure 3: A preliminary roadmap for Collaborative Small Satellite Constellations development

CO2-Monitoring from Space

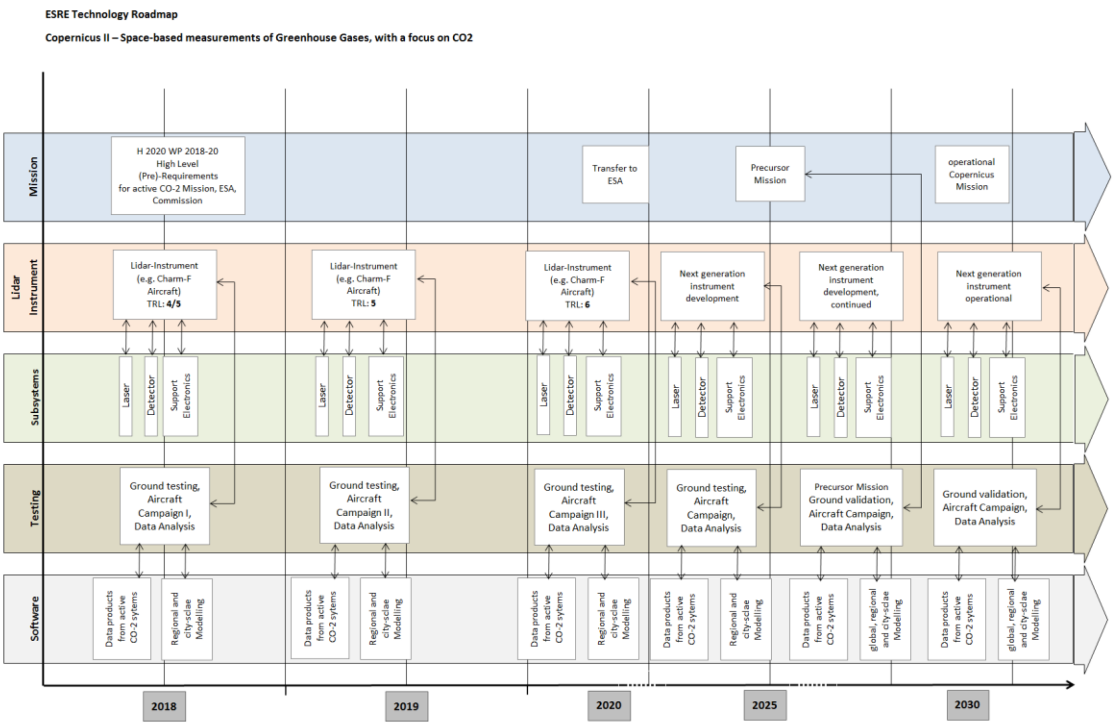

Figure 4: A preliminary roadmap for CO2 Monitoring from Space

Monitoring Environment at a Local Scale

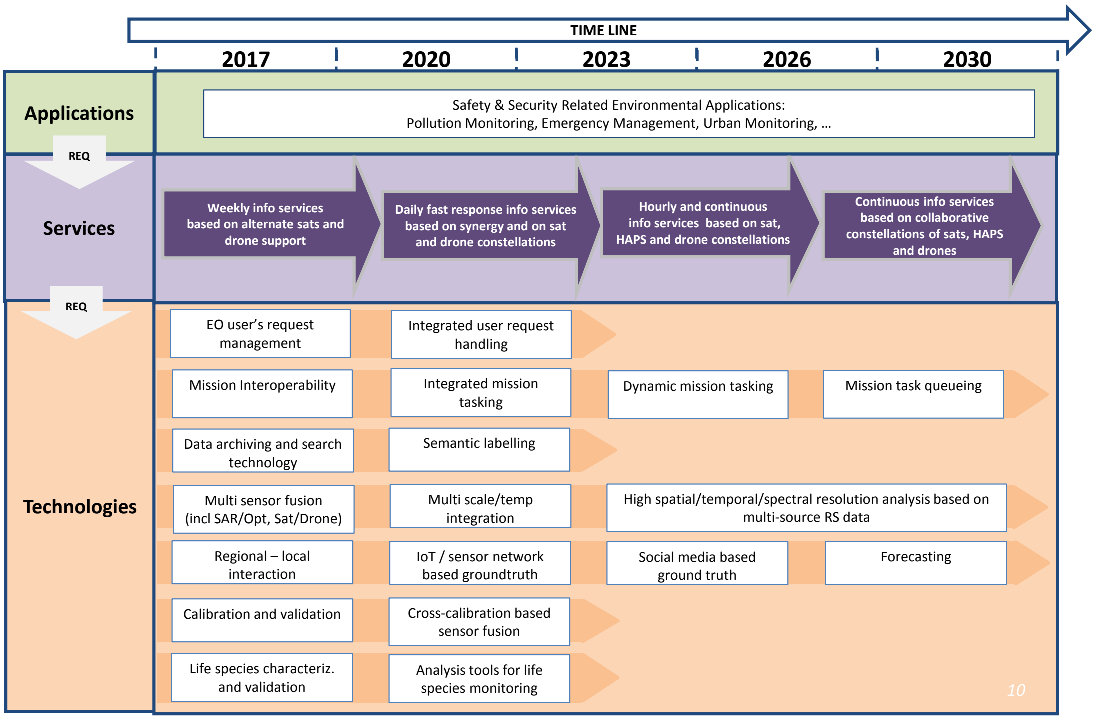

Figure 5: A preliminary roadmap for Monitoring Environment at a Local Scale