ESRE

ASSOCIATION OF EUROPEAN
SPACE RESEARCH ESTABLISHMENTS

ESRE White Paper 2020

Selected Trends and Space Technologies Expected to Shape the Next Decade

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FOREWORD

In October 2016, the European Commission released its "Space Strategy for Europe". The main goals of the strategy include:

- Maximising the Benefits of Space for Society and the EU Economy, especially with regard to the needs to address global challenges such as climate change, environmental protection, migration, etc., and to establish services in support of transport and information flow in Europe and beyond, as well as
- Fostering a Globally Competitive and Innovative European Space Sector.
- Reinforcing Europe's autonomy in accessing and using space in a secure and safe environment.

The Space Strategy for Europe was welcomed and endorsed in 2017, both by the European Parliament and the EU Council. The main task ahead lies now in the successful implementation of the Space Strategy. On the EU side, the European Commission together with the future European Union Agency for the Space Programme will be responsible for this process. The key instruments for implementation will be the EU space programme (Galileo, Copernicus, SSA[1], GovSatCom) and the "space research" part in Horizon Europe.

While the definition of these activities within the EU's next Multi-Annual Financial Framework is presently under negotiation between the main EU institutions, the Association of European Space Research Establishments (ESRE) has updated its White Paper from November 2017, in order to provide a further contribution to the Space Strategy implementation process for the decade to come, this time with a more focused view on "space-related R&TD in Horizon Europe".

With regard to Horizon Europe, ESRE hopes that the contribution will prove to be helpful not only for the further Strategic Planning based on the recently approved Strategic Research and Innovation Agenda (SRIA) but also for the selection of possible topics for future collaborative R&D as well as for topics for future road-mapped-based R&D, with the latter possibly conducted under the framework of a Co-programmed European Partnership on Space.

[1] Space Situational Awareness

I. EXECUTIVE SUMMARY

The global space sector is undergoing rapid transformations. Due to the importance of its infrastructures and services for modern societies, new players from all parts of the world are entering the space sector challenging the European position in this domain. In order to remain one of the world's leading space actors, Europe has to react by reviewing its working methods, and to adapt by supporting, where needed, the inner-European cooperation between public and private players and to invest earlier into the most promising future technologies to generate the necessary breakthroughs.

With this document, the Association of European Space Research Establishments (ESRE) wants to provide a further contribution to the implementation of the "Space Strategy for Europe", this time with a more focused view on "Space-related R&TD in Horizon Europe". **The ESRE members CBK (Poland), CIRA (Italy), DLR (Germany), INCAS (Romania), INTA (Spain), NLR (The Netherlands), ONERA (France) and VZLU (Czech Republic) are key members in the European innovation chains. These renowned research organisations are major drivers of new knowledge, mature technologies and systems, and educate and train the future workforce.** All these are crucial elements that will strengthen the future competitiveness of the European space sector. Hence, this document prioritises the "research and technology development policy" and "global challenges" dimensions of the Space Strategy for Europe and provides the vision of the main public European space research organisations on future space research and technology development needs to help secure the European success of the space sector for the benefits of the European society and economy.

ESRE's main recommendations are:

- Technology roadmaps: make a stronger use of commonly agreed technology roadmaps, in particular in the context of the EU's upcoming Horizon Europe research programme, in order to guarantee the timely availability of technologies needed for competitiveness and for tackling global challenges.
- For future key system concepts, technologies and sub-technologies use more often, if possible, dual or multiple sourcing approaches, by awarding grants on strategic topics to more than one consortium and by implementing regular reviews and termination decisions in order to test different technological choices in a competitive way. Such a competitive approach should speed up innovation cycles also by improving the possibilities for REs/RTOs to bring in their substantial prototype development capabilities, in particular related to smaller scale systems.
- Re-focus R&TD on generic space technologies (not replaceable by COTS/adapted COTS components) and enhance total funding of R&TD, while also increasing the funding of related low-medium TRL R&TD in order to also secure the long-term competitiveness of the European space sector.
- Provide in public procurements more engineering freedom to industry and research organisations in order to foster innovation and competitiveness by focusing on high-level requirements and by adapting, relaxing or refraining from the stringent public ECSS standards where possible.

In line with the first two main recommendations, the annex contains a more detailed description of the recommended 19 selected proposals for larger-scale technology roadmaps/projects to be pursued in Horizon Europe that are deemed key to ensure future European competitiveness of the space sector. While the list of 19 technology roadmaps/projects is certainly non-exhaustive, it should help Europe to remain at the leading edge of space technology in several specific priority areas. Following one of their key mission objectives as public national research establishments, namely to provide R&TD support to industry, ESRE members are ready to implement these technology roadmaps/projects jointly with industrial partners.

II. INTRODUCTION – THE GLOBAL SPACE SECTOR IN TRANSFORMATION

Traditionally, in Europe and elsewhere strategic public activities have been the vehicle for innovation in the space sector. Public funding and R&TD support have been in particular provided by the governmental and space agencies' programmes, as well as research pursued by the corresponding national research establishments.

Not only did the public side cover its own demand related to

- national security,
- space-based services to help managing environment, transport and communication policies, as well as
- space science and human space exploration

with these actions, but it also supported industry in the development of their own commercial capabilities, space technologies and space systems. Even today, total institutional funding remains the largest source of revenues for European industry[2].

As a consequence of these efforts, space technologies and space-based data and services have become an integrated and indispensable part of modern economies and global society. The 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, space-based data and services play now a key role in the monitoring of the global climate, global natural disaster management as well as global security and defence activities. Nevertheless, a paradigm shift is taking place in the space sector both with regard to the intensity of private investments and technological innovations such as miniaturisation, digitalisation and reusable launchers. This paradigm shift originates from the US and takes place nowadays world-wide: 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, components and production methods from other mature terrestrial industries ("New Space"[3]).

These developments are 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 technologies. 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 methods, while maintaining appropriate levels of safety and reliability, will be one of the key factors of the future competitiveness of the European space sector. However, the above developments do not only represent a challenge for the European space industry. Complementarily, the European public stakeholders, i.e. the governments, space agencies and research centres 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 adaptations of the public side are twofold: not only would it 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 centres a key driving force in space-related innovation.

[2]The present ratio of institutional to commercial revenues in Europe is about 60 to 40.
[3] A comprehensive analysis of "New Space" and related recommendations for the European space sector have recently been published by the European Investment Bank (EIB) in its report "The future of the European space sector - How to leverage Europe's technological leadership and boost investments for space ventures", January 2019.

III. MAJOR TRENDS IN THE SPACE SECTOR AND ITS MAIN FIELDS OF ACTIVITY

1. Transversal Trends

It is mainly the combination of two major trends which are providing new opportunities across the whole portfolio of space activities:

The first one is the still ongoing miniaturisation in electronics. This allows for putting more and more capabilities in ever smaller satellites. The second one is the so-called Commercial-Off-The-Shelf (COTS) approach, strongly promoted by “New Space”, where space players procure, wherever possible, standard terrestrial commercial hardware for spaceflight or in order to modify it for spaceflight. This approach is often combined with mass production methods derived from other terrestrial industries.

As one important consequence of these two major developments, constellations of small satellites or of CubeSats become possible, in particular in LEO (due to the more radiation-friendly environment), which now possess a substantially more powerful feature set at much lower costs and much shorter development times. Here, very often the in general lower quality of commercial components is compensated by redundancy in satellites. The extent to which the space market embraces these opportunities can be inferred from the ongoing enhancements of existing LEO constellations or the buildup of new ones like OneWeb and Starlink (communication) or Planet’s CubeSats (Earth observation), to name a few prominent ones. These new constellations involve dozens, hundreds or sometimes even thousands of satellites, necessitating the rapid development of mitigation, avoidance and removal technologies with regard to space debris and even the organisation of a space traffic management system (STM). The sheer size of these constellations, combined with the fact that the satellites often interact or fly in formation, also poses new challenges with regard to the ground segment, where now a much higher degree of automation and autonomy will be needed in operations.

Satellite constellations can be used complementarily to High Altitude Pseudo Satellites (HAPS) and Remote Piloted Aerial Systems (RPAS) in collaborative missions. Indeed, while satellites can cover large areas, HAPS can be used for local scale applications, offering higher resolution due to the proximity to the Earth’s surface, thus enabling the detection of the phenomenon of interest, whose identification can be reached by means of RPAS. Furthermore, while constellations of satellites are generally used to reduce re-visit time, HAPS can hold station keeping or fly over a certain area during the mission. While it is clear that both the COTS approach and small satellites/CubeSats by themselves have their inherent limitations (e.g. very high resolutions necessitate big lenses/cameras (optical) or large active antennas (radar), deep space environment requires special electronics), it is as well obvious that also the public side, as a key procurer of space systems/services, can often profit from these and other “New Space” approaches.

It is against this background that, in particular in the US, more and more public institutions, including the Pentagon, have adapted or are trying to adapt their procurement and grant schemes in order to allow for more “New Space” (public anchor tenancy, procurement of services, etc.). The US is also accelerating the uptake of technologies being developed in research labs by the private sector. This goes beyond the simple maturation of technologies from mid to high TRLs but includes also the generation of new ideas and concepts focusing on low TRLs. These developments from ideas to proof of concepts are also accelerating in speed and are being emulated by China as well.

Key European industrial players have already successfully adopted “New Space”, where possible, as is e.g. demonstrated by the prominent involvement of Airbus and Thales in the buildup of the constellations OneWeb (Airbus), Blacksky and Iridium (Thales). National research centres have already applied these methods successfully for small science and Earth observation missions. However, adaptions on the public procurement side in Europe to “New Space” have been so far less impressive, as has also been noted by the recent EIB report[3].

One of the key hurdles in this context is given by the fact that in general European public procurements require compliance with the ECSS standards[4], which do not only prescribe key mechanical and electronic standards and procedures but also the management methods to be applied, thereby practically prohibiting “New Space” approaches. It is therefore pertinent that the ECSS standards[4] are regularly revisited and revised wherever possible. Stronger cooperation between research labs and industry in Europe should be encouraged on this issue. It should also be helpful for smaller commercial companies to provide a public inventory/set of recommendations with regard to the utilisation of COTS components in the commercial construction of small satellites and CubeSats.

Selected and recommended R&TD to be addressed in Europe, preferentially by collaborative research in Horizon Europe:

- Conceptual and subsystem-related R&TD related to space debris mitigation, avoidance and removal.
- R&TD on subsystems and standards for larger CubeSats.

Selected and recommended R&TD to be addressed in Europe, preferentially by large-scale projects in Horizon Europe (on the basis of a clear technology roadmap):

- Distributed payloads on-board clusters of small satellites.
- Elaboration of new concepts with regard to collaborative small satellite constellations.

2. Earth Observation

Nowadays, Earth observation satellites are equipped with a huge portfolio of different possible passive and active sensors, spanning the optical, infrared and radar regions of the electromagnetic spectrum. Further momentum in the field is expected to come from the development of new classes of sensors (e.g. vegetation fluorescence sensors, low-frequency Synthetic Aperture Radars, LIDAR trace gas detectors). In particular, the possibility to monitor Greenhouse Gases (GHG) from space, through active lidar sensors, promises to become another breakthrough for environmental monitoring applications and should be considered as a priority in the Copernicus roadmap.

The range of possibilities already provided by satellite-based Earth observations is 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.

[3] A comprehensive analysis of “New Space” and related recommendations for the European space sector have recently been published by the European Investment Bank (EIB) in its report “The future of the European space sector - How to leverage Europe’s technological leadership and boost investments for space ventures”, January 2019.
[4] European Cooperation Space Standardisation

Apart from the environmental global monitoring market that is mainly driven by national governments and international organisations, satellite-based observation also spurs a growing commercial and local government market, mainly by the provision of high-resolution optical and radar imagery, with short re-visit times that are suitable for local scale analyses.

In particular, just over the last few years, also Earth observation has started to profit from large constellations of small satellites which have enabled the provision of high-resolution imagery and short-time videos, at low costs and daily re-visiting time. Such information can play a vital role not only in security and defence activities, but also in civil and environmental protection applications in which typically local public agencies are interested and for which the development of effective downstreaming applications is needed. For such applications, the full potential of satellite Earth observations, in terms of spectral/spatial/temporal resolution, has not yet been unveiled, mainly due to a lack of integration among the free imagery data coming from the sophisticated instrumentation on board the space agencies' and governments' scientific satellites, and the high-resolution data coming from commercial satellite missions, aerial acquisition campaigns and on-ground sensor networks. An enhanced combined use of space-based data with locally measured data is a potential that also has to be better exploited in the context of the Copernicus programme and is expected to be a key driver for the development of the space Earth observation market in the next years.

Such a forecast is motivated also by the increasing development of environmental sensor networks, the exponential market growth of the small Remote Piloted Aerial Systems (RPAS) and the expected advent of the High Altitude Pseudo Satellites (HAPS), unmanned aerial vehicles flying in the stratosphere able to continuously monitor the Earth at a regional scale. It is also obvious that the whole sector will benefit from the new techniques provided by information technology in the areas of big data and data mining.

Selected and recommended R&TD to be addressed in Europe, preferentially by collaborative research in Horizon Europe:

- R&TD on radar sensors (including P-Band and L-Band SAR) and next generation of passive optical sensors (e.g. hyperspectral, fluorescence) and related image processing (for satellites, HAPS and RPAS).
- R&TD on subcomponents for very high-resolution optical and radar surveillance/observation sensors.
- Miniaturisation of all kinds of sensors for small satellite constellations, HAPS and RPAS.
- Utilisation of big data and artificial intelligence technologies for autonomous evaluation of huge Earth observation datasets.
- Real-time data processing of multi-source data from space, aerial (including stratosphere) and terrestrial sensors, developing both novel coordinated tasking approaches and data fusion technologies, e.g. in the areas crisis management and multi-mission planning.
- Development and validation of concepts and models for environmental bioindicators that can be monitored from space.
- Continuous data calibration between satellite-received data and simultaneous flight formation laboratories.

Selected and recommended R&TD to be addressed in Europe, preferentially by large-scale projects in Horizon Europe (on the basis of a clear technology roadmap):

- Pre-development of a lidar instrument for an active CO_2/GHG Copernicus precursor mission.
- Synergies among remote sensing platforms for improved spatial/temporal/spectral resolution.
- Calibration of satellite data with on-site gathered data.

3. Navigation

Our present society can no longer be imagined without the positioning and timing services provided by Global Navigation Satellite Systems (GNSS). The organisation and the management of today's mobility and global transport system more and more depend 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 synchronisation (for example in financial transactions, management of power plants and electrical grids and telecommunication networks). 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 rely on GNSS for their navigation function increases the demands for built-in security measures into GNSS systems. Both of these developments lead to an increasing demand for higher GNSS timing robustness and integrity.

As the dependence of our societies on GNSS will continue to grow in the near future, also the potential impact of threats to GNSS such as jamming and spoofing will be amplified.

For Galileo, the latter has led to the development of the concept of Open Service Navigation Message Authentication (OS-NMA) as a means to prevent signal spoofing. 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 used for aviation will become necessary 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 also support the envisaged facilitation of "autonomous driving" as well as UAV navigation.

Selected and recommended R&TD to be addressed in Europe, preferentially by collaborative research in Horizon Europe:

- R&TD on new highly stable clocks, including optical atomic clocks.
- R&TD on miniature high-performance quartz resonators to improve close-to-carrier phase noise at lower cost of atomic clock time references for GNSS emitters and receivers.

- Integrity measures, processing techniques such as A-RAIM and T-RAIM, R&TD on advanced receivers mitigating natural impairments (e.g. atmospheric delays, multipath of signals) and intentional disturbances such as jamming and spoofing.
- Coverage improvement, resistance to interference and spoofing.
- Inertial Navigation Systems and GNSS hybridisation and sensor fusion to improve the accuracy and integrity of positioning solutions.
- Novel architectures to develop GNSS beyond Galileo exploiting optical technologies to enhance navigation and time dissemination services.
- R&TD on a concept of a low-cost European space-based navigation information system providing current weather and forecast, areas with restricted permissions, air traffic, landing site conditions, etc., to be integrated with GNSS for precision (with integrity) and safe navigation of Personal Air Transport and Urban/Sub-Urban Mobility vehicles.

Selected and recommended R&TD to be addressed in Europe, preferentially by large-scale projects in Horizon Europe (on the basis of a clear technology roadmap):

- Design, test and development of a prototype Galileo System Time based on a Composite Clock algorithm.
- Design, test and development of a GNSS-based Emergency Warning System for dissemination of alert messages over diverse communication means.

4. Communications

Unrestricted 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 possibly 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. 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 conventional radio frequency bands are saturated and there is a need to go to higher frequency bands, that is Ka-band for user links and Q/V, W bands and optics for feeder links.

New RF frequency bands such as Q/V band and W band are currently envisaged for the feeder link only in order to increase total system capacity and to achieve a target capacity of 1 Terabyte per second. This can be done either with GEO satellites or with the new projects of mega-constellations. Another possibility could be to develop optical communications, 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. Europe has been at the forefront of this technology and should continue to be in that position in the foreseeable future. Optical communications can also be designed in such a way that they become quantum-safe, meaning that interception of the communication becomes impossible without being noticed.

Whatever the technology (RF or optics), it is also necessary to overcome the signal attenuation caused by the lowest layers of the atmosphere, that is the troposphere. Predicting the data transmission performance along a given line of sight will make it possible to minimise the loss of data. To achieve this, predictive models of propagation conditions are of critical importance. 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).

In the field of RF links between satellites and ground, optical technologies can also be used, e.g. by the use of optical "beam-formers" "driving" passive phased array RF antennas via an optical laser feedback loop to enable them to track an RF beam. Space-based telecommunications represents the largest commercial activity of all space-related markets. 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) in LEO or MEO.

These constellations, some of which are presently being designed to work only on the basis of radio frequencies, could also benefit in the future from optical communications (including optical beamforming for RF links).

Selected and recommended R&TD to be addressed in Europe, preferentially by collaborative research in Horizon Europe:

- R&TD for the characterisation of the channel at high RF frequencies and in optics: temporally and spatially resolved statistics of optical links disturbing phenomena (transmission and turbulence).
- R&TD on physical models to anticipate channel perturbations (handover inputs), validated for both high-frequency radio links (Q, V and W) and optical frequencies.
- R&TD on channel disruption resilient schemes, including adaptive coding and modulation, smart gateway concepts and those exploiting the complementarity of RF and optical spectrum.
- R&TD on small-scale transmitters/receivers for optical inter-satellite links.
- R&TD on optical beamforming technologies.
- R&TD on optical wireless intra-spacecraft communications (OWLS) and optical technologies for the interior of the satellite, for the futuristic concept of the "all-optical satellite".

Selected and recommended R&TD to be addressed in Europe, preferentially by large-scale projects in Horizon Europe (on the basis of a clear technology roadmap):

- Demonstration of feasibility and technological maturity of optical feeder links for very high throughput satellites in geostationary orbit.
- R&TD on quantum-safe optical telecommunications.
- Design and demonstration of technological maturity of a CubeSat constellation optimised for IoT applications.

5. Defence

Space systems represent the only technology being capable of providing their owners with independence in regard to global positioning, surveillance and communications.

They are therefore indispensable for the defence activities of political and/or economic superpowers which command a large home territory and which possess the aspiration to be able to act globally. Prominent examples are the US, Russia, China and Europe. Like the US, Russia, and China also European member states have signed the Outer Space Treaty. Though this treaty only forbids the placing of weapons of mass destruction into orbit, Europe refuses any weaponisation of outer space and therefore does not pursue any such activities.

Consequently, most European defence-oriented space activities are inherently of dual use nature. Recently, EU member states came to the conclusion that in the future the European Union shall play a larger role in the coordination of European defence research and defence technology pre-development activities.

Therefore, Horizon Europe will be the first EU research framework programme to contain a defence-oriented research part. Furthermore, the EU after 2020 will possess a European Defence Fund, in the framework of which dedicated EU funds will be mixed with national funds and spent for the pre-development/prototype development of future defence equipment, which is to be later procured by member states. Because of the dual-use nature of the European defence-related space activities, see for more technological background the preceding chapters.

Selected and recommended R&TD to be addressed in Europe, preferentially by large-scale projects in Horizon Europe (on the basis of a clear technology roadmap) [here in the defence-oriented part of the programme]:

- R&TD on subcomponents for very high resolution optical and radar surveillance/observation sensors.
- Miniaturisation of all kinds of sensors for small satellite constellations, HAPS and RPAS.

6. Space Science, Space Exploration and Human Spaceflight

Space science, space exploration 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 the international space effort in the future.

Three important trends are expected to influence this area of space activities particularly strongly in the upcoming decades.

First, due to the progress in computational and robotic powers as well as in artificial intelligence, autonomous capabilities will become much more advanced, both with a view to automated missions and in support of human spaceflight.

Second, the cost for human spaceflight activities will be 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.) and by using robotic assembly in low Earth orbit. This will finally open up realistic possibilities for a permanent human presence beyond LEO, as is already in the planning of NASA, e.g. with its lunar gateway programme. Much of the technology developed within this programme will serve also as a first cornerstone towards a later human presence on Mars. Europe is expected to join this Moon initiative, and follow-up programmes, at a substantial, but still junior-partner level. Third, satellites might become the only, though indirect, measurement device for high-energy physics, as satellites can at least pick up the remnant signals of the very early universe, where energies were high enough for presently unknown physics.

Among European space science priorities apart from the universe, there is a clear scientific line that relates to exoplanet detection and characterisation focused on the direct imaging in both the visible and infrared range. The observation of exoplanets will not be restricted to their detection, next generation of instrumentation will try to identify their atmosphere and look for biosignatures for life detection. The detection of gamma and X-ray helps us to understand some energetic events and gamma-ray burst and black holes. Gravitational waves have opened multi-messenger physics to see different phenomena at different wavelengths.

The exploration of comets and asteroids had recently significant success, like the Rosetta and Hayabusa missions. Those bodies hold key information about the formation and evolution of our solar system and for sure small bodies will be targets for future missions. Mars and Moon are key targets in the exploration roadmaps agreed by many agencies. The establishment of water detection or mineral identification will play a main role in future Moon and Mars missions and require in the long-term outposts and habitat infrastructures. Mars Sample Return will be a multinational mission with a complexity that requires the development of many technologies, including the capabilities of sample handling by avoiding any kind of terrestrial contamination.

International planetary exploration will focus on Moon and Mars, nevertheless the space community has a large interest in the exploration of other bodies like in the outer solar system. The exterior planets and their moons (Europa, Ganymede, Titan, Triton, etc.) could hold clues for understanding the origin of life on Earth and possibly elsewhere.

Selected and recommended R&TD to be addressed in Europe, preferentially by collaborative research in Horizon Europe:

- Technological maturity and demonstration of freeform optics.
- Technological maturity and demonstration of efficient and compact spectrometric technologies.
- Efficient and reliable In Situ Resource Utilisation (ISRU) technology, to enable long-term planetary exploration.
- Autonomous systems with high reliability, and able to work in all lighting conditions (Automated Rendezvous and Docking – AR&D –, proximity operations, target-relative navigation).

- Environmental monitoring technology (on-board/on planetary surface analysis for air, water, contaminants, human health advanced detection & shielding).
- Mechatronic devices for subsurface sampling, drilling and excavation of planetary regolith in reduced gravity field.
- Robust rover technology for long-range exploration, including on-board autonomy, energy efficiency and thermal stability as well as manipulation and sample handling capabilities.

Selected and recommended R&TD to be addressed in Europe, preferentially by large-scale projects in Horizon Europe (on the basis of a clear technology roadmap):

- R&TD on compact and smart sensors for planetary exploration.
- Technological maturity and demonstration of very low temperature electronics for scientific exploration missions.

7. Research under Space Conditions and Robotics

Research under space conditions

Research under space conditions has been from the beginning intimately related with human spaceflight, as the understanding of the impact of microgravity and the cosmic radiation on the human body are a prerequisite for a sustainable human long-term presence in Low Earth Orbit and beyond. Apart from addressing flight medicine and biology (e.g. bio-hybrid life-support systems), the research uses the unique properties of space conditions also for the investigation of material physics (e.g. liquid properties, solidification). More recently, also the study of fundamental phenomena in condensed matter (e.g. complex plasma) has been incorporated in the research. Experiments are not only performed on the ISS but also on short-term flight opportunities like sounding rockets and zero-g parabolic aircraft flights. In the future, the aspects related to human spaceflight will focus more on the support of higher autonomy in preparation of human presence on Moon and Mars (e.g. food production).

Robotics

The utilisation of robotics in support of space operations started out prominently with human spaceflight, where e.g. the robotic arm of the ISS proved its usability for in-orbit assembly, as well as with space exploration, where e.g. rovers have allowed for scientific investigations which would have been impossible otherwise.

In the upcoming decades, due to the currently rapidly advancing developments in the field, robotics will become a much more central element in the day-to-day operations of a larger portfolio of space activities, embracing also the areas of on-orbit servicing of satellites and the removal of large space debris from Earth's orbit. In general, the field is expected to benefit greatly from the ongoing stronger integration of artificial intelligence technologies, endowing future space robotics with a substantially higher degree of autonomy. Examples of key major challenges for the future are the development of robust, multi-functional manipulators for Earth orbit servicing operations and the development of autonomous mobile robots with cognitive and probe handling capabilities for planetary exploration and sample return.

Selected and recommended R&TD to be addressed in Europe, preferentially by collaborative research in Horizon Europe:

- Support of experiments on short-term micro-gravity campaigns (similar to present IOV-approach).
- Next generation light-weight robotic arms and hands for various use cases.
- Exploration autonomous robots with different mobility capabilities (driving, walking, flying, etc.).
- Teleoperation and (semi-)autonomous operation concepts and S/W.
- Increased H/W and S/W modelling functionalities and simulation capacities (also in real-time).
- Compact, space qualified, high performance sensors for robotic sensing and operation: accelerometers, gyroscopes, magnetometers, gravimeters, seismometers and gas sensors.
- New and improved autonomous, self-aborting space docking and undocking systems/technologies.
- Robotic CubeSat missions for testing cooperative tasks, e.g. formation flying, infrastructure assembly in on-orbit conditions.
- Low cost, high performance digital processing systems, including AI solutions, for space applications.

Selected and recommended R&TD to be addressed in Europe, preferentially by large-scale projects in Horizon Europe (on the basis of a clear technology roadmap):

- Technologies for autonomous and cooperative swarm exploration.
- R&TD on new perception, reasoning and planning methods, based on Machine Learning and AI.

8. Access to Space

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

Recently, Space X and Blue Origin succeeded not only in recovering the first stages of their launchers, but also in successfully re-flying them. China, Russia, Japan, and India are also increasing their efforts in this domain since 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 and storage of the stages.
- Loss of economies of scale in production lines.

As a consequence, a key requirement for the successful introduction of reusability is a high 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 rapid development of capable small satellites and small satellite constellations, small launch vehicles are showing a promising commercial potential. At this moment more than 30 different companies are developing a micro-launcher. These companies are looking mostly towards low-cost expandable launch vehicles by using smart manufacturing technology, the use of COTS components and simpler logistics within the ground segment. The development of such small launchers may also be helpful for low-cost testing of a variety of technologies needed for reusability, be it for micro or for conventional launchers. Furthermore, air-launching can be a valuable alternative for small satellites reducing the cost and increasing flexibility and fast deployment of capabilities for both civil and defence applications.

Recommended key technologies to be addressed in Europe, preferentially by collaborative research in Horizon Europe:

- Execution of small-scale ground and flight experiments (including COTS components and high speed flights) to determine optimal system configuration for (partly) reusable launcher.
- Research and development of dedicated RLV Guidance Navigation and Control and Inertial Navigation Systems (GNC/GPS-INS), avionics and health monitoring systems, and hybrid navigation techniques.
- Basic research related to high temperature materials, lightweight structures, advanced propulsion, high speed aero(thermo)dynamics.
- Investigations on innovative lightweight structures and tanks and production technology, including research on propellant management based on sloshing experiments and further research on propellant management for non-metallic tanks.
- Redesign, investigations into improving ground segment infrastructure, operations and logistics for highly frequent launches of micro-launchers.
- Elaboration of concepts and research for low-cost reusable propulsion, including green propellant, throttleable engines, thrust vector control for application to small launchers, propulsion injector head technology and manufacturing approach (additive layer manufacturing, cross-feeding and thermal protection).
- R&TD in LO_x/CH_4 systems development (e.g. ignition, stability, modelling).
- Development of technologies strictly related to entry, descent, and landing.
- Fostering multiple individual small scale VTVLs demonstrator development in several European countries for increasing fast and incremental innovation steps, serving as alternative technological solutions for both access and planetary missions.

Selected and recommended R&TD to be addressed in Europe, preferentially by large-scale projects in Horizon Europe (on the basis of a clear technology roadmap):

- Identification and evaluation of micro launcher concepts, including subsystem prototype demonstration.
- Identification and evaluation of reusable launcher concepts; identification of the most promising concept(s). Partial demonstration of promising reusable launcher concepts compared to state-of-the-art expendable launchers.

9. Synergies with Other Sectors

Satellite constellations and other parts of the space segment 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, and safety & security services heavily rely on space-based systems.

Space security and cybersecurity together are referred to as “cyberspace” and constitute a unique technological domain that is becoming a prominent focus for international strategic, political, and economic competition. Clearly, also the space sector can benefit from the related technology developments in this field.

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 also directly profit from scientific and technological progress achieved on Earth in the fields of big data, data mining, machine learning and artificial intelligence in general. Equally, the space sector will soon be able to benefit from the emerging quantum technologies, both with regard to new powerful sensors and with regard to the possibility of quantum-safe telecommunication.

The fast transformation of the space sector will result in an increase of satellites on low orbits and a need for promoting a safe access into outer space as well as secured on-orbit operations. In this context, automated space traffic control system will become crucial, in the same way ATM/ATC systems have become essential when aviation started to emerge as an economic sector. Therefore, techniques borrowed from aviation will be considered to design STM/STC systems from both technical and regulatory perspectives (e.g. mandatory use of a standardised transponder for satellites above a certain size).

Finally, the space sector will continue to profit from spinning-in manufacturing technologies as well as project management methods from other industries, in particular with a view to mass production.

Selected and recommended R&TD to be addressed in Europe, which have not already been mentioned in the chapters above, here possibly addressed with the help of other parts of Horizon Europe than “Space”, preferentially by large-scale projects in Horizon Europe (on the basis of a clear technology roadmap):

- Autonomous (cyber) event detection, containment and recovery, e.g. through data mining, machine learning, artificial intelligence/neural networks, quantum measurements, etc.
- Concepts of Space Traffic Control (STC)/Space Traffic Management in terms of technologies and regulation aspects.
- Pre-identified structural optimised parts designed for Additive Layer Manufacturing (ALM) to improve ongoing or new missions.

IV. RECOMMENDATIONS FOR HORIZON EUROPE

A paradigm shift is taking place in the space sector and Europe needs to adapt by adopting reforms to reinforce and enable innovation throughout the space sector that encourages investment in technology and in knowledge-based capital (e.g. by allowing to experiment with new ideas, technologies and business models).

In order to meet the above challenges and support industry and research centres as the main engine for innovation in the space sector in Europe, it is recommended that the public side in Europe commits itself to foster European competitiveness via the following measures that should be implemented in particular by Horizon Europe:

- Increase the funding for medium/long-term oriented R&TD (over-next generation) in order to secure the long-term competitiveness of the European space sector; with a view to Horizon Europe increase the total funding for "space research" while keeping collaborative research as the main instrument (as is both presently also targeted by the EU Council).
- Foster earlier cooperation (in terms of TRLs) between European space research organisations and industry, preferably via commonly agreed technology roadmaps, which set the goals via high-level requirements for vital subsystems.
- Explore the possibilities to conduct such roadmap-based R&D under the framework of a co-programmed European partnership.
- Provide also in the Horizon Europe "space research" part funding for essentially unprescribed calls in order to foster ideas of disruptive nature.
- Maintain in Horizon Europe "space research" substantial possibilities to foster space science related R&D.
- Fund some innovation directly via the EU's space programmes, here in particular Galileo and Copernicus, e.g. through the procurement of experimental/test satellites and experimental/test payloads, in order to secure the possibility of a rapid take-up of specifically required next/over-next generation technology by those programmes.
- 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 Space" approaches.
- Implement policies that encourage in particular innovation and entrepreneurial activity promoted by start-ups engaging in the "New Space" approach, e.g. by strengthening existing public risk capital provision instruments like the InnovFin Space Equity Pilot (ISEP) (funded by Horizon 2020) and other instruments like the ones of the European Fund for Strategic Investment (EFSI) or new instruments under the European Innovation Council EIC of Horizon Europe.
- Execute first smaller scale public procurements without the obligation of compliance to the ECSS standards (leaving more engineering and management freedom to the contractor).
- Last but not least, resort in public procurements as much as possible to high-level requirements, thereby leaving more engineering freedom to the contractor in order to foster innovation and competitiveness.

Transversal Trends

DISTRIBUTED PAYLOADS ON-BOARD CLUSTERS OF SMALL SATELLITES

1. Objectives

The objective of the project is the development of technologies allowing the use of fragmented and distributed instrumentation on board several small platforms which will work as coordinated elements within clusters and satellite formations.

2. Challenges

The customers generally want to improve space missions by means of lower costs, lower development times, technology edge positioning, flexibility and versatility. To achieve these goals, the use of fragmented and/or distributed instrumentation on board several small platforms is proposed. The main challenges of this approach are formation flying precise enough for Earth observation applications, highly accurate attitude determination and control system, multi-node inter-satellite link equipment and distributed miniaturised payload for Earth observation. The solutions of such challenges shall take advantage of contemporary and future results from fields such as nanotechnology, artificial intelligence, 3D printing, robotics and image sensor technology.

3. State-of-the-art assessment and proposed innovations

Today, most of the space segment data are provided by the fleet of large satellites. Due to the technology advance in recent years, following a sunrise of the "New Space" companies and their risk–tolerant approaches, the cluster of small satellites is now foreseen as capable of delivering comparable or better mission results than with a monolithic large satellite. Also, formations of small satellites which perform their tasks in cooperation seem to open a wide field of opportunities.

To be able to fulfil such promises, the small satellites shall have precise formation flying capability with sub-centimetre tracking error accuracy and low change in relative velocity in a frame of formation members, which allows maintaining the desired formation in space. Capability of autonomous navigation in a frame of formation has been already demonstrated in several space missions, e.g. CanX 4-5 (Canadian SFL), Spheres (MIT) and others. Missions which consider utilisation of formation flight are also in the scope of ESA, e.g. PROBA-3 is currently in phase C of development. The distributed system is not dependent on formation flying only. Earth observation and scientific payloads also need a high pointing accuracy to be able to deliver the desired results. However, such pointing shall be performed by each satellite in formation in a coordinated manner which allows to reach the required resolution. This cannot be achieved without multi-node inter-satellite link equipment, which will assure the control and coordination among the cluster's nanosatellites.

All the above-mentioned technologies are necessary for enabling the usage of distributed payloads. Such distributed payloads need a new generation of miniaturised equipment for all kinds of missions (Earth Observation, Science, Telecommunications) together with the appropriate software for this purpose which allows control of such a distributed system.

The key technologies are:
- Formation flying control system.
- Attitude Determination and Control System (ADCS).
- Inter-Satellite Link (ISL) equipment.
- Miniaturised payloads.

4. Added value and impacts for Europe

To ensure the leading role of European companies in the development of next-generation Earth observation, communications and science systems, Europe shall reflect the current trend of small satellite applications. The clusters of small satellites implementing fractionated systems and instrumentation, which can deliver comparable or better mission capabilities compared to large monolithic satellites are answers to the demand for more flexible and robust systems. The demonstrated new technologies will greatly strengthen the competitiveness and growth of European companies in the global satellite market. This approach will develop technologies for innovative fractionated Earth observation systems. It will demonstrate innovative enabling technologies in distributed sensing, formation flying, and pointing.

5. Key goals/technologies to be developed in the timeframe 2021–2023

The key goal for the first period is to achieve reliable technologies which allow usage of the distributed system for Earth Observation purposes. The technologies to be developed are:
- Efficient and stable formation flying control system for nanosatellites compatible with Earth observation requirements.
- Highly accurate Attitude Determination and Control System (ADCS) for nanosatellites which enables coordinated pointing of the fractionated instrument constrained by formation flying and which paves the way to reach high spatial resolution on the ground.
- Multi-node Inter-Satellite Link (ISL) equipment for nanosatellites control and coordination.
- Fractionated instrumentation based on miniaturised payloads for Earth observation.

6. Key goals/technologies to be developed in the timeframe 2024–2026

The key goals for the second period are to further improve the technologies necessary for precise formation flying. Such technologies are:
- Artificial intelligence technology for close-loop formation flying control.
- Micro-propulsion systems to extend the operational lifetime of the cluster working below 500 km.
- Communication methods for high-capacity ISL.
- Accommodation of communication standards for multi-node information exchange in a frame of satellite formations.
- Development of constellations of small satellite clusters.

7. Key goals/technologies to be developed in the timeframe from 2027 onwards

In-orbit demonstration of the small satellite cluster for Earth Observation. The final goal is to achieve TRL ≥ 8.

ELABORATION OF NEW CONCEPTS WITH REGARD TO COLLABORATIVE SMALL SATELLITE CONSTELLATIONS

1. Objectives

The development of small satellite constellation concepts – not limited by region or orbit – to provide new services or improve upon existing ones. These concepts are to be collaboratively investigated and shall yield an overview of the scientific, economic or other benefits in the form of a concept list of feasible and challenging opportunities.

2. Challenges

Within the concepts to be developed, challenges to be encountered vary from technical to operational. There will be an incentive to eventually make use of COTS products, which could necessitate a technology push or revision to ensure the required quality. Several of these challenges are (but are not limited to) satellite positioning, pointing accuracy, orbital control, power density/distance, in-orbit replacement (upgrades), operations/constellation management (scheduling), on-board autonomy (AI/Machine Learning), EOL procedure, debris mitigation (STM).

3. State-of-the-art assessment and proposed innovations

Currently few satellite constellations are in operation. The most notable applications for which satellite constellations have been established are in the domains of navigation and communications. GNSS systems require continuous global coverage, which is only possible through the usage of constellations. Similarly, for large coverage applications within the communications field, constellations are employed. Constellation design within these fields are therefore, and have been for some time, quite well understood. However, there are still a large number of applications for which satellite constellations could be beneficial. Examples of such applications – though not exclusively – that would benefit from innovative small satellite constellation concepts are:

- Modular constellation design, whereby each satellite having dedicated functionalities (e.g. space-based solar power).
- On-orbit servicing of satellites.
- Space debris removal systems (i.e. pick-up sats + main disposable unit).
- Combined fabrication systems (split factory functions over multiple small sats).
- Lunar orbiting systems (GPS/LO).
- Mars orbiting system (GPS/MO/Meteo).
- Lagrange point swarms.

4. Added value and impacts for Europe

With regard to small satellite constellations, it is important that Europe is not dependent on international partners who have their own advancement in mind but is able to investigate and develop the technologies which matter the most to Europe. The focus could be more on reusable resources, cost-effective solutions or a more dedicated mission profile.

Finally, working on concepts within Europe will create a positive view of the future, in which all members can contribute and return the technological advances into their own economy.

5. Key goals/technologies to be developed in the timeframe 2021–2023

As a first step, it is necessary to list possible concepts, agree on the most promising ones and perform a feasibility study for each concept. The concepts which promise to be the most interesting ones will then be investigated and discussed regarding timeline, development and benefits. The first year of this timeframe could be used for concept agreements, trade-offs and selections, while the second year can be used for a more in-depth research of the selected concepts to create a priority list with a set of requirements as outcome. This timeframe will yield the Phase 0 (mission analysis and identification) and Phase A (feasibility) studies.

6. Key goals/technologies to be developed in the timeframe 2024–2026

Having the selected concepts and requirements of the concepts, the most promising one(s) can be taken into further detail. At this time, technological trade-offs can be done within the concept(s) to have a better understanding of which technologies are (close to being) ready for usage in the small satellite constellation concept, and in which areas a development is necessary, with an indication of expected maturity. This is where the Phase B (preliminary definition) and Phase C (detailed definition) studies are performed.

7. Key goals/technologies to be developed in the timeframe from 2027 onwards

Having the areas of technology development, the various (sub)systems can be investigated further in detail and a development can be started according to the set requirements. This can, depending on the selected concept, include COTS products which are (nearly) suitable or induce new development as well. A verification and validation concept needs to be set up not only for the mission design as a whole, but also for the individual subsystems. This is where hardware is developed, most likely in an EBB-EM-EQM-FM fashion, to get ready to deployment. Moreover, the End-Of-Life (EOL) phase should be included in the overall mission design. With this, the lifetime cycle is completed by having the Phase D (qualification and production), Phase E (utilisation) and Phase F (disposal) steps.

Earth Observation

PRE-DEVELOPMENT OF A LIDAR INSTRUMENT FOR AN ACTIVE CO_2/GHG COPERNICUS PRECURSOR MISSION

1. Objectives

The general goal of this strategic initiative is the development of a greenhouse gas Integrated Path Differential Absorption lidar (IPDA) instrument, to leverage this photonic technology for Earth observation, and to allow for a CO_2 precursor satellite mission, measuring CO_2 columns from space and inferring global and regional CO_2 fluxes, to be launched around 2027, with the vision of a first operational mission in the timeframe > 2030.

2. Challenges

In comparison to passive remote sensing, lidar is a relatively new technology in Earth observation. The key goals are therefore to prospect, promote, demonstrate, and qualify subsystem technologies required for the key building blocks of greenhouse gas lidar instruments. The objective is to achieve both a technology and scientific readiness level that enables a breakthrough for greenhouse gas monitoring using lidars and foster the industrial competitiveness on this field in Europe.

3. State-of-the-art assessment and proposed innovations

Currently, the lacking technology readiness level of lidar sub-systems still impedes the use of active remote sensing technologies using lasers for greenhouse gas monitoring from space – despite their huge potential. The upcoming Franco-German MERLIN mission for CH_4 (to be launched around 2024), will pave the way towards such capabilities. However, significant improvements are required for CO_2 monitoring. Thus, innovative approaches in the fields of transmitter technologies, infrared detector development, frequency references and frequency measurement optical devices, optics, and photonics shall be studied to overcome these shortcomings targeted at realising an operational active greenhouse gas monitoring mission within the Copernicus programme. The added value of synergistic sensor deployment and the use of HAPS and other aerial platforms as well as terrestrial stations to support airborne campaigns and provide validation capabilities shall be investigated, and observational concepts/validation addressed. This also includes the link between satellite products and user requirements by scientific algorithm development.

4. Added value and impacts for Europe

For the foreseeable future, carbon dioxide (CO_2) will remain the major greenhouse gas contributing to global warming and the climate crisis. Therefore, there is an urgent societal and scientific need to monitor the exchanges of carbon between the atmosphere and both the ocean and the land surfaces. As a spaceborne technology that shows a huge potential for fulfilling the stringent observational requirements, the Integrated Path Differential Absorption (IPDA) lidar technique has been identified. IPDA uses hard target reflection of near-IR laser light to measure the column averaged dry air CO_2 mixing ratio and derive regional carbon exchange rates. The specific advantages of an active remote sensing mission using lidar are that it does not require the sun as a light source and can therefore provide measurements at both day and night, all-seasons and all latitudes with high accuracy and low bias.

However, up to now, proposed CO_2 lidar missions (such as ESA's A-SCOPE and NASA's ASCENDS mission) did not yet advance beyond feasibility studies. Although the scientific merit is generally acknowledged, the main reason for this is the lacking technology readiness level on several important fields such as laser transmitters, infrared detectors or laser frequency stabilisation.

By promoting technologies related to all lidar subsystems, Europe will have the possibility to take over and expand its expertise in spaceborne lidar systems building up on the Aeolus wind lidar mission launched by ESA in 2018. With a successful precursor, and, moreover, an operational active remote sensing greenhouse gas mission, Europe will invest in a knowledge-based society combining remote sensing technology and Earth observation to monitor, understand, and devise means to mitigate climate change.

5. Key goals/technologies to be developed in the timeframe 2021–2023

In the beginning of this strategic initiative, a general roadmap will be established through identifying candidate instruments and associated observational concepts. Considering the most promising and alternative subsystems, active lidar sensors shall be brought to TRL 6 through technology research and development. This shall be demonstrated through environmental (radiation, vibration, etc.) testing campaigns at both component and sub-system level, and airborne campaigns which will present a major step forward not only with regard to future space missions but also for using this technology onboard of high altitude stratospheric platforms or aerial platforms (such as aircraft and/or balloons) to monitor local scales. To do so, eligible flight laboratories throughout Europe and test sites for airborne campaigns have to be identified.

For risk mitigation and next phase preparation, the plan is to choose also alternative technologies at lower readiness level (e.g. TRL 3) that show potential to be candidate for TRL 4/5 development and airborne technological validation in the subsequent phase. Innovations of the commercial (e.g. photonic) industry shall be identified with the goal to consolidate spin-in technologies for the advancement of active remote sensing using lidars in space.

Key activities to be undertaken with regard to instruments will be concentrated on the following fields:

- Transmitter technologies: solid state lasers, laser amplifiers, non-linear optics (e.g. optical parametric oscillator and amplifier concepts), fibre lasers, hybrid lasers (fibre/solid-state), frequency combs, coatings.
- Detector technologies: development and testing of noise-free infrared detectors.
- Frequency reference and diagnostic equipment: development of spaceborne frequency combs as generic devices from frequency monitoring and control.
- Telescope technologies: large lightweight and deployable telescopes.
- Optical system engineering and optoelectronics (e.g. optical filters and onboard diagnostic equipment).
- Airborne demonstrators and ground support equipment.

The technology-related work packages will be accompanied and supported by scientific studies related to:

- Model performance and measurement concepts (e.g. multi-wavelengths concepts).
- Calibration and validation of satellite and airborne instruments (e.g. by in-situ sensors).
- Exploitation of sensor fusion and synergies with other active and passive remote sensing and in-situ instruments.
- Model studies related to regional and city-scale modelling and GHG budgeting.

6. Key goals/technologies to be developed in the timeframe 2024–2026

The second phase of the strategic initiative will focus on the development of next-generation instrument hardware, e.g. new and improved laser and detector subsystems, telescopes, or alternative technology instrument development as well as risk reduction and mitigation studies based on airborne demonstration. In parallel, further developments, and verification of the measurement concepts via aircraft campaigns will be executed and scientific algorithms tested and validated. The scientific community will be gathered behind the project and international cooperation fostered (e.g. with the USA, Japan, and China).

7. Key goals/technologies to be developed in the timeframe from 2027 onwards

In the timeframe from 2027 onwards, the strategic initiative will focus on the continuation of the development of the third generation of instrument hardware and contribute to the system design phase for an operational Sentinel mission. This includes both space and ground segments as well as launching requirements. Furthermore, the exploitation of system synergies of various space sensors and their data fusion will be expedited. This includes wind and GHG lidars for the direct measurement of greenhouse gas fluxes, the synergy of active and passive remote sensing as well as the monitoring of multiple species.

SYNERGIES AMONG REMOTE SENSING PLATFORMS FOR IMPROVED SPATIAL/TEMPORAL/SPECTRAL RESOLUTION

1. Objectives

The objective of the project is to match the increasing 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.

2. Challenges

The spatial/temporal/spectral resolution required by applications (environmental protection, citizens' safety, security, etc.), can be achieved in two ways: developing satellite platforms with increased performance or implementing synergies among space (and also non-space) remote sensing platforms. The challenge considered by this project is to reach improved resolution performance through new synergies. Such synergies can be developed through two complementary challenges. The first is to make available data from different platforms within limited time and spatial windows, in order to gather comparable data. The second is to use in synergy different data sources, developing approaches and tools able to overcome the gap in terms of different spatial resolution, acquisition time, and types of sensors.

3. State-of-the-art assessment and proposed innovations

Earth Observation (EO) satellites provide a large set of free/low-cost remote-sensed images that cover large areas, but such data suffer from many limitations in terms of: 1) spatial resolution; 2) update frequency; 3) waiting time for availability; 4) spectral coverage; 5) time and weather conditions. These limitations can discourage end users from using satellite technologies because they might be unsuited for their application needs.

Such limitations can be successfully overcome using a synergic approach, making available methods and tools to end-users in order to design successful applications. Considering the available and the planned EO platforms, higher spatial, temporal and spectral performance can be achieved by using them complementarily for the same purpose. Such synergy can be implemented by planning the mission tasks in order to facilitate the multi-scale/multi-temporal/multi-sensor fusion of the acquired images. Also, satellite data can be integrated together with that provided by other low-cost airborne remote sensing platforms, in particular small Remotely Piloted Aerial Vehicles (RPAS). The use of such platforms in synergy can be obtained by planning the RPAS acquisitions within specific time windows and fusing satellite and airborne data. Cross-calibration among sensors may be needed. Considering emerging technologies for new remote sensing platforms, low-cost micro-satellite constellations and High Altitude Pseudo-Satellites (HAPS) should be considered to increase the temporal frequency of the acquisitions.

In order to improve spatial, temporal and spectral resolution of the analysis to successfully respond to increasing requirements from end users, the project aims at investigating two complementary strategies, based on technologies for environmental applications that shall be further developed and improved with respect to their current readiness level:

- Synergy among heterogeneous satellite missions.
- Synergy among aerial platforms and Earth Observation satellites.

These two strategies are mainly based on the following methodology and technology developments:

- Acquisition planning approaches and software tools for satellite management able to make available different satellite data sources to the requiring end users in order to be used together for the same needs.
- Data fusion approaches and data processing tools enabling applications to use different satellite sources together within the same analysis.
- Acquisition planning approaches and software tools for unmanned aerial vehicles (including RPAS and HAPS) enabling end users to design missions to gather aerial data that can be used together with satellite data.
- Aerial payload requirements, data fusion approaches and data processing tools enabling the applications to use satellite and aerial sources together to perform the same analysis task.

The effectiveness of such approaches and technologies shall be tested and validated by including them in downstream applications based on geographical information systems.

4. Added value and impacts for Europe

Increasing the capabilities of the future Earth Observation (EO) system, in terms of spatial/temporal/ spectral resolution, in order to satisfy end-user needs (environmental agencies, civil protection, local administrations, agriculture industry actors, etc.) that are interested not only in global-scale but also in local-scale phenomena is nowadays an urgent need to satisfy.

This can be achieved through: the improvement of synergies among heterogeneous (optical and radar) satellites, in order to include the capability of radars to collect data in all-time and all-weather conditions; the improvement of synergies among satellite platforms and small RPAS, in order to gain advantages of the broad diffusion of small RPAS and to exploit their potential role in validation of satellite low-spatial-resolution data; but also improving synergies among satellite platforms and HAPS, with the aim to combine the capability of HAPS of implementing persistent surveillance with the large coverage of satellites.

Also considering that the Copernicus programme is probably the most important one among the existing free EO data sources and the DIAS technology (Data and Information Access Services) will tremendously boost the development of downstream applications, an improved synergy among free data sources (i.e. the Copernicus programme) and commercial data sources, with the aim to enhance free images with the better spatial and/or temporal resolution of the commercial missions would be also highly beneficial both for the Copernicus programme and the improvement of Earth Observation.

In this new scenario of connected EO systems with different characteristics, European industries, which are already leaders in Synthetic Aperture Radar (SAR) satellite constellations, could get the leadership in the emerging HAPS market.

Moreover, European satellite assets would be strongly valorised if they could provide data useful to complete analyses performed with widely used remote sensing tools such as small RPAS.

5. Key goals/technologies to be developed in the timeframe 2021–2023

The roadmap for this strategic initiative will start with the consolidation of the awareness of end users' needs and the definition of a synergic approach. This goal will be achieved through the definition of end users' needs and their spatial/temporal/spectral requirements as well as the definition of applications for which a synergic approach can help to match end users' requirements.

Moreover, interoperability among different EO missions will be enabled through the definition of best practices for mission interoperability among different satellite missions and the development of software tools for integrated tasking among homogeneous (similar payload) and heterogeneous (different payload) EO missions. This goal will be achieved by improving workflows for high frequency multi-temporal remote sensed image analysis and the development of algorithms (i.e. cross-calibration, co-registration, multi-source classification) and data processing workflows for image fusion among heterogeneous spaceborne sensors (i.e. optical and synthetic aperture radar). Furthermore, the development of downstream applications i) for improved time resolution analyses based on small satellite constellations and other better spatial/spectral resolution satellites and ii) applications based on heterogeneous sensor data will be fostered.

With respect to the interoperability between EO missions and RPAS, the following key goals/technologies should be developed:

- Definition of mission planning tools for RPAS that include and use, in advance, information on Earth Observation satellites' orbits and swaths.
- Improved algorithms (e.g. cross-calibration, co-registration, multi-source classification) and data processing workflows for image fusion among satellite and aerial remote sensed data.
- Mission paradigms (e.g. application-oriented detection-recognition-identification paradigms) and data processing best practices (e.g. use of ground truth based on RPAS surveys) for improved spatial/temporal/spectral resolution analyses.

And for a future scenario in which HAPSs work together with EO satellites to monitor the Earth:

- Definition of mission interoperability paradigms among EO satellites and future HAPS fleets.
- HAPS payload development and data processing technologies.

6. Key goals/technologies to be developed in the timeframe 2024–2026

In a second step, applications that easily and naturally use in synergy multi-mission satellite data sources should be developed. In particular, the development of software technologies for integrated tasking (e.g. common tasking interface) and of downstream applications for which synergy among different EO satellite missions is strongly required in order to achieve the required spatial/temporal/spectral resolution and is based on mission interoperability.

Moreover, applications that easily and naturally use in synergy satellite and aerial data sources with the development of sensor payloads designed to be used in combination with satellite acquisitions and of software technologies (e.g. web services for real-time availability of satellite operation data) for integrated tasking among heterogeneous platforms (EO satellites/RPAS), together with the development of downstream applications for which synergy among EO satellites and RPAS is strongly required and is based on mission interoperability.

With respect to HAPS that should work together with EO satellites, the definition of mission interoperability specifications for combined data acquisition from EO satellites and HAPS.

7. Key goals/technologies to be developed in the timeframe from 2027 onwards

In the timeframe from 2027 onwards, the strategic initiative will focus on the continuation of an active collaboration among heterogeneous Earth Observation satellites. In particular, a multi-sensor and multi-platform satellite collaborative tasking (e.g. in tandem configuration) with the development of downstream applications for which multi-mission satellite collaborative tasking is an enabling technology.

A set of available technologies for integrated tasking among space and aerial unmanned platforms will rely on the development of web services for RPAS in order to implement multi-sensor and multi-platform collaborative tasking and of downstream applications for which satellite and aerial collaborative tasking is an enabling technology.

For the satellite-HAPS active collaboration for persistent surveillance, the design of ground control stations that implement active collaboration among EO satellites and HAPS as well as of downstream applications that use both satellite and HAPS data will be developed.

Moreover, the development of platforms for integrated data access, including further data sources (e.g. coming from HAPS) other than Sentinel data, extending the capabilities of the DIAS technology developed within the Copernicus programme will be investigated.

CALIBRATION OF SATELLITE DATA WITH ON-SITE GATHERED DATA

1. Objectives

Coordinated European effort through scientific and technical development in order to provide state-of-the-art calibration of satellite data with on-site and in-situ gathered data.

2. Challenges

Aerosols, air pollutants and greenhouse gases represent one of the principal topics in atmospheric science and are of high political interest due to their significant effects on climate, but also on human health, visibility and ecosystems. Information on aerosols' distribution in the atmosphere as well as on their interactions with other atmospheric components like gaseous precursors, water vapour and ozone are necessary to highlight the air quality processes and climate-related parameters. This knowledge can only be obtained by combining all available information using state-of-the-art experimental techniques from ground-based, airborne or space measurements. This is a challenging task considering that particular techniques are specific to each of the measurement parameters and the difficulty to homogenise and compare their retrievals.

3. State-of-the-art assessment and proposed innovations

On a yearly basis, more than 15 dedicated calibration and validation (cal/val) campaigns are taking place in Europe and probably several more unknown campaigns that can provide relevant input to the satellite cal/val activities are taking place. The main challenge of this proposal is to unify and offer to the scientific community the tools and context to collaborate efficiently in the context of cal/val missions in order to ensure efficient usage of funding and higher scientific relevance.

ESA is developing the Earth Observation Envelope Programme 4 (EOEP-4), including Earth Explorer missions and GMES (Global Monitoring for Environment and Security) Sentinels, included in the Copernicus programme. Out of these, ADM-Aeolus, EarthCARE, Sentinel-4, Sentinel-5 precursor (S5P) & Sentinel-5 focus on different aspects of the atmosphere. The products related to the atmospheric composition data products include clouds, aerosols, greenhouse gases and water vapour.

The development and testing of the retrieval methods, as well as the calibration and validation of the missions' products rely on combined ground-based and airborne measurements, which can provide:

Ground-based facilities

- Quasi-continuous and highly accurate measurements of various parameters for the atmospheric species at the local scale, when in fixed position.
- Cost-effective medium to long-term measurements of various parameters for the atmospheric species, with high temporal resolution, during campaigns.

Airborne facilities

- Short-term intensive measurements of various parameters for the atmospheric species, with high temporal and spatial resolution, during campaigns.
- Test bed for new techniques, instruments, and technologies.

Ground-based combined with airborne facilities

- Synergy between various measurement techniques, inter-comparison, cross-validation of the data products.
- High temporal and spatial resolution, regional to local variability.
- Extended vertical range of the observations.

4. Added value and impacts for Europe

The expected added value is related to the following aspects:

From a scientific point of view, supporting co-located campaigns and scientific international collaboration, it is expected that the number of scientific publications will increase, the development of improved methods and technologies will be encouraged, the project proposal with a highly international relevance will be developed favoured by the international collaboration. Open access data principles will apply.

From the education perspective, children, young people and students will be encouraged and supported with dedicated activities to enter this scientific domain by actively participating in all activities, thus solving the European-level lack of trained personnel on the labour market. With respect to society, the quality of life of European citizens will be improved by providing information to environmental agencies, civil protection, local administrations, etc., state-of-the-art, harmonised and high-quality data that will feed the forecast models across Europe.

5. Key goals/technologies to be developed in the timeframe 2021–2023

The short-term objectives and technologies proposed are the following ones:

- Landscape analysis of all research infrastructures and entities at European level in the field of cal/val activities, identifying gaps and strengths of the community.
- Creating an online platform for connecting all the identified entities.
- Creating a working group formed by representatives of each entity led by ESRE.

- Elaborating, adapting and harmonising good practices and guidelines to be applied for data, data processing and others, based on past experience (see ESA, ESFRI projects and RI, ENVRI FAIR results and guidelines).
- Developing a plan for common cal/val activities in collaboration with ESA.
- Development of new technologies for measurements of aerosol, trace gases and clouds adapted to the development envisaged by ESA, NASA.
- Execution of an inter-comparison campaign.
- Elaborating a common training framework for students and young scientists.

6. Key goals/technologies to be developed in the timeframe 2024–2026

The medium-term objectives and technologies proposed are the following ones:

- Development of new technologies for measurements of aerosol, trace gases and clouds adapted to the development envisaged by ESA, NASA.
- Execution of periodic common cal/val missions in accordance with the needs expressed by the scientific community and ESA. At least one dedicated campaign per year.
- Monitoring of cal/val activities across Europe.
- Continuous updating of the landscape analysis and training plan.
- Starting a long-term campaign.

7. Key goals/technologies to be developed in the timeframe from 2027 onwards

- Improvement of the developed technologies within the frame of this large project.
- Planning and implementation of a long-term campaign throughout Europe.

Navigation

DESIGN, TEST AND DEVELOPMENT OF A PROTOTYPE OF A GALILEO SYSTEM TIME BASED ON A COMPOSITE CLOCK ALGORITHM

1. Objectives

The objective of this proposal is to establish a robust system time for Galileo and to promote the provision of a reliable timing service for Galileo and EGNOS.

2. Challenges

The Galileo System Time (GST) is a main element within the Galileo system. In case of interruption of GST the Galileo system can run out of service for a while. When defining new approaches like distributed clocks or distributed system time generation, the interruption or failure of one element of the new Galileo System Time does not lead to the complete outage of the Galileo service.

3. State-of-the-art assessment and proposed innovations

The Galileo System Time is currently operated by two hot redundant Precise Timing Facilities (PTF). The generation of the GST is based on a PTF master clock principle. This generated GST is used for synchronising the whole Galileo system elements. Therefore, the two PTFs have a central role in Galileo operation. In case of a failure of the active system, the backup system takes over the action. If there is an error in the backup system (e.g. a single additional failure), the operation of the whole Galileo system is interrupted. This interruption of service can also happen when one PTF is in maintenance and an error occurs at the active PTF chain. Using the approach for distributed clocks in a common way (Composite Clock algorithm) the aforementioned errors do not lead to the failure of the Galileo service. The distributed clocks can consist of clocks of the Galileo Control Centre, the clocks of the Galileo Sensors Stations (GSS) and the clocks on the Galileo satellites as well as of clocks of well-established National Metrology Institutes (NMIs).

4. Added value and impacts for Europe

The timing capability offered by satellite navigation systems is at the core of most vital infrastructures: telecom networks operation, energy distribution, financial transactions, and TV broadcast are some examples of areas where GNSS is used for timing and synchronisation (T&S) purposes. GNSS provides a unique offering to the timing and synchronisation user communities by delivering a free, stable and very accurate time and frequency source available worldwide. The expansion of telecom networks (e.g. Small Cells, 4G) makes GNSS more and more essential, driving future developments and the T&S community is facing many challenges linked to an increased need for resilience, reliability and security, supported by an evolution of the regulation.

For all these aspects a highly available and robust time signal coming from Galileo or EGNOS for world-wide users is indispensable in many ways for the high degree of industrialisation of Europe.
The new concept meets the requirements of the telecommunications, energy and finance sectors in terms of accuracy, authentication, robustness, resiliency, and traceability.

5. Key goals/technologies to be developed in the timeframe 2021–2023

The key goals are to achieve a stable and robust Galileo System Time, which can tolerate the outage of one or more clocks, and to demonstrate the added value of the robust timing service and encourage adoption. The technologies to be developed are:

- Design, test and development of a prototype (TLR > 6) of a Galileo System Time based on a Composite Clock algorithm using the Galileo ground clocks of the Precise Time Facilities located in Fucino, Italy, or Oberpfaffenhofen, Germany.
- Design, test and development of an optical link between one PTF and an NMI demonstrating the usage of the distributed clocks with highly accurate measurements.
- Design, test and development of a prototype Galileo Timing receiver implementing upcoming EGNSS Robust Timing Service recommendations (TRAIM, dual-frequency, multi-constellation).

6. Key goals/technologies to be developed in the timeframe 2024–2026

The key goal is to improve the stability and robustness of the Galileo System Time against clock outages. The technologies to be developed are:

- 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 and/or Two-Way Satellite Time and Frequency Transfer (TWSTFT) will be used.
- Design, test and development of a prototype (TLR > 6) of a Galileo System Time based on Composite Clock algorithm using the Galileo system clocks, both on the 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.

7. Key goals/technologies to be developed in the timeframe from 2027 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.

DESIGN, TEST AND DEVELOPMENT OF A GNSS-BASED EMERGENCY WARNING SYSTEM FOR DISSEMINATION OF ALERT MESSAGES OVER DIVERSE COMMUNICATIONS MEANS

1. Objectives

The objective of this proposal is to develop a GNSS-based Early Warning System aimed at providing warning information to the population at risk as well as the needed operational support to first responders on the field. As such, the main goals of the developed system will be to enable anytime-anywhere penetration of warning messages, owing to the large coverage of GNSS systems as well as the forwarding of messages throughout the available terrestrial infrastructure.

2. Challenges

In order to achieve the aforementioned objectives, the project work plan will have to address the integration of the GNSS system with 1) existing early warning systems and 2) terrestrial systems for what concerns both the actual network integration and the service convergence concept. To this end, upgrade of the existing GNSS architecture functionalities and related services will have to be carried out along with the extension of the network interfaces exposed by the terrestrial network. In this respect, the evolution of the 5G network architecture as well as the support of big data will have to be properly taken into account in order to enable an optimised GNSS-based warning service.

3. State-of-the-art assessment and proposed innovations

The EU programme within the framework of the past FP7 and concluding H2020 has dedicated quite some attention to the development of early warning systems based on a multi-channel approach (e.g. Alert4All, PHAROS) and integrated with other external facilities like sensors and Copernicus data images (e.g. HEIMDALL). Nevertheless, the capabilities offered by the integration of navigation systems (i.e. GNSS-based) have received limited attention, mostly focused on the integration of EGNOS and Galileo from an architecture (e.g. Alert4All and PHAROS) viewpoint or in terms of real data exploitation through the EDAS platform (I-REACT). Only recently, the GRALLE project has shown the potentials of an actual integration of warning systems and GNSS, by demonstrating the reception of warning messages in dedicated pilots in Europe and in Asia. In spite of the great achievements therein recorded, the roadmap towards an actual operation service still requires a deeper investigation and a more complete demonstration.

In particular, the innovation brought in by this proposal mostly consists in showing the integration of GNSS services in very different end devices (i.e. smartphones/tablets, driving-aided systems, wearables for first responders) and providing data fusion with the other information sources, hence necessitating a rework of the overall data distribution network architecture. The overall proposal will then aim at demonstrating the effectiveness of the developed concept in a variety of use cases, embracing both natural and man-made disasters. Moreover, the case of cascading effects as well as cross-border situations will be addressed as well. A key element in the success of the project will be a large participation from first responders as active players of the project, in order to get the final service and system definition aligned with their actual needs.

4. Added value and impacts for Europe

The added value of this activity will be the exploitation of GNSS systems in the current version (EGNOS and Galileo) and their future evolution so as to provide the necessary support in every kind of disaster management situation, meeting the first responders requirements and also matching the institutional constraints that may vary from country to country across entire Europe. The overall impact will be considerable for entire Europe not only in terms of a unique platform for authorities and population at risk but also in terms of new market opening, given the highly multi-disciplinary nature of the considered system to be developed (e.g. big data, telecommunication integration, GNSS integration, data fusion, etc.).

5. Key goals/technologies to be developed in the timeframe 2021–2023

The key goals expected from the first period will consist in the overall system definition based on the users' requirements and the consequent system development, which will be considered as subdivided in consecutive releases owing to the modular system architecture, so that incrementally new modules and functionalities will be integrated throughout the entire duration of the project. The main achievement in this timeframe will be the capability to transport warning messages over the existing GNSS systems, integrated with candidates warning systems. The messages will then be distributed to the population at risk, by digital and traditional means (i.e. sirens). The demonstration will consider specific use cases.

6. Key goals/technologies to be developed in the timeframe 2024–2026

The second increment of the project will consist in the consolidation of the overall system, by enabling the integration of other information sources, to be fused with those available from GNSS systems. Moreover, the integration with the terrestrial infrastructure will also be carried out, on the basis of the characteristics of the specific use cases.

7. Key goals/technologies to be developed in the timeframe from 2027 onwards

The last increment of the activity will consist in integrating first responders in terms of "standard" devices (e.g. smartphones, etc.), forwarding of GNSS signals through TETRA/5G+ infrastructure, and the use of smart wearables. The end of the project will then culminate in a finalised fully integrated warning system, capable of addressing very different use cases under diverse operational frameworks (i.e. cross-border, cooperation between multiple agencies, etc.). The fully integrated system will in turn be demonstrated in different scenarios. The final objective is to have a fully operational system, operated and maintained by different actors (institutions and enterprises) in order to financially support the system consolidation and evolution through the commercialisation of its components. As such, the expected target is to reach TRL 8–9 at the conclusion of the project.

Communications

DEMONSTRATION OF FEASIBILITY AND TECHNOLOGICAL MATURITY OF OPTICAL FEEDER LINKS FOR VERY HIGH THROUGHPUT SATELLITES IN GEOSTATIONARY ORBIT

1. Objectives

Demonstration of feasibility and technological maturity (up to TRL 7 – at least for specific subsystems) of optical communications technology for the feeder links of very high throughput satellites in geostationary orbit.

2. Challenges

Optical communication offers almost unlimited bandwidth availability, thus the capability to provide ultra-high throughput without the need to apply frequency reuse on the feeder links (which results in a dramatic increase of the required number of ground stations if a conventional approach in the radio frequency domain is pursued). However, achieving a stable and reliable transmission through the atmosphere is far from trivial due to blockage caused by clouds and to the turbulent behaviour of the atmosphere causing severe impairments to the optical signal. While the first issue can be addressed by operating a suitable number of optical ground stations, the second one requires more advanced countermeasures (especially in the uplink) like e.g. pre-distortion based on adaptive optics, a technology successfully employed in astronomy but still requiring significant R&D effort for its usage in the telecom domain. Appropriate interleaving and coding strategies shall also be considered (at least in the design phase), at the price of complex interfaces with other components of the network. The design of a payload operating the conversion from optical to electrical signal and vice versa according to acceptable power, mass and heat dissipation requirements is another major R&D challenge.

3. State-of-the-art assessment and proposed innovations

Free-space optical communication is today successfully employed in Earth Observation for the links between the LEO satellites called "Sentinels" and a GEO relay within the European Data Relay System (EDRS). This proves that optical technology is suitable for operational usage. However, the aforementioned LEO-GEO links are not impaired by any atmospheric turbulence. Moreover, the supported data rate in EDRS is limited to few Gbps, whereas Very High Throughput Satellites shall support throughput in the order of several Tbps. Extending this technology to achieve reliable transmission through the atmosphere at data rates in the order of several Tbps represents a major breakthrough for the telecom domain.

To achieve such dramatic performance improvement, technologies from the fibre network domain shall be brought to space. Dense Wavelength Division Multiplexing and higher order modulations with coherent reception are examples of possible game changers. Considering atmospheric transmission windows and space environment constraints on wavelength separation, the data rate per wavelength shall be maximised and reach several tens of Gbps per channel, with a required power on board per channel that shall exceed ten watts to cope with distance and atmospheric losses. On the ground, uplink power per channel will have to be close to a hundred watts, unless major improvements on turbulent channel mitigation are made (such as those expected from the S^2 concept exposed below).

Feasibility of a bi-directional long-range data transmission on a dense wavelength grid (the Consultative Committee for Space Data Systems currently works on a 100 GHz spacing grid) at optical power compatible with expected data rates still needs to be demonstrated in a relevant environment.

Atmospheric turbulence is the biggest challenge in ground-to-satellite links. In downlink, state-of-the-art adaptive optics are required for fibre coupling, and in uplink it can contribute to minimising signal fluctuations by pre-distorting the laser beam. In this last case, however, the performance is limited by the point-ahead-angle, i.e. the angle between up- and downlink.

Several incremental developments may contribute to mitigate this risk, each of them bringing its own challenges:

- Adaptive optics and other alternative systems for turbulence mitigation shall be developed to guarantee high reliability, particularly in anisoplanatism configurations.
- Appropriate interleaving and error correction techniques shall be identified and developed for the atmospheric turbulent channel.
- Optical amplification handling multiple hundreds shall be developed, keeping in mind specific optical architectures for the optical ground segment.
- On-board payload designs to increase the link budget margin, including development of large telescopes and low-noise pre-amplifiers.

4. Added value and impacts for Europe

European industry is at the forefront of commercially based optical communication technology developments and most space-borne experiments have been launched by European industry. However, when it comes to space-to-ground communication through Earth's atmosphere, Europe is lagging behind North America and Asia, who are rising quickly in new initiatives in this field.

Therefore, it is necessary to potentiate joint activities for non-dependence in Europe in this field. 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. Optical feeder links are an essential technological enabler to allow space technologies to bring billions of people into the global economy by allowing broadband connectivity to otherwise unserved or underserved areas.

Thanks to its directivity, the optical bandwidth provides an intrinsically secured, hard to intercept means to exchange a huge amount of data contributing to strengthen Europe's sovereignty in its access to space.

5. Key goals/technologies to be developed in the timeframe 2021–2023

Design and test of mitigation techniques (adaptive optics, coherent beam combining or other alternative approaches) to compensate the fading and distortion caused by the atmosphere in both link directions (e.g. phase correction for fibre coupling and pre-distortion).

Defining the optical link format (framing, modulation, coding) and 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 500 Gbps as initial technology demonstration.

Extensive characterisation of atmospheric parameters (transmission and turbulence) to assess the expected availability and consolidate the link budget margins.

Optical amplifiers, demonstrating of 10-watts-class space-qualified booster amplifiers and in-lab-demonstration of high optical power amplifiers (typ. 100 W/channel) compatible with phase modulation format.

6. Key goals/technologies to be developed in the timeframe 2024–2026

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. First in-orbit demonstrator targeting 500 Gbps and using existing optical terminal technology with appropriate adaptations. The goal is to achieve TRL ≥ 7, although with limited throughput.

7. Key goals/technologies to be developed in the timeframe from 2027 onwards

In-orbit demonstration of bidirectional optical feeder links for very high throughput satellites in geostationary orbit for using a space qualified version of the previously developed space terminal prototype, including S^2 concept if demonstrated worthwhile and economically viable.

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

R&TD ON QUANTUM-SAFE OPTICAL TELECOMMUNICATIONS

1. Objectives

A huge amount of data is exchanged every day around the world, especially via the Internet, between stakeholders and critical infrastructures. This data can be related to finance, health, business, national defence, etc., which is the reason why securing the communication channel is fundamental. Standard cryptographic algorithms ensuring communication security are based on a secret encryption key exchange between the communicating parties. Nowadays, this key exchange confidentiality is based on computational assumptions. The development of a quantum computer, theoretically possible and currently the subject of intensive research, would definitely jeopardise the current secure communication system. For this reason, the investigation of quantum-safe optical telecommunication technologies, based on a coding of information on the quantum states of light, is necessary to enable the development of a European large-scale network of information-theoretic secure communications.

The next ten years should be marked by demonstrations of feasibility and technological maturity (up to TRL 7) of optical quantum communication technologies, including the exchange of secret keys implementing quantum key distribution (QKD).

2. Challenges

As introduced above, quantum key distribution (QKD) offers inherently secure means for exchanging secret encryption keys among communication partners. QKD is the most technologically mature quantum communication application. QKD systems may be set up based on continuous variable (CV-QKD), discrete variable (DV-QKD) and/or entanglement-based schemes. Together with quantum-resilient (or post-quantum) coding schemes, encryption keys distributed via QKD can be used to communicate securely via traditional networks, as e.g. the Internet. This combination enables secure communications that are resistant against potential quantum computing attacks.

However, the range of quantum secret key exchange based on standard fibre QKD systems undergoes fibre losses and is limited to 150 km. One way of extending the distance would be the use of quantum repeaters, but this technology, which also requires quantum memories, is currently not mature enough to be deployed. For these reasons, satellite-based QKD appears as a necessary and complementary technology to enable quantum-safe communications on a European or even intercontinental scale.

Using satellites as relays for exchanging secure keys between optical ground stations on Earth, however, raises the issue of free-space propagation of the quantum signal through the atmosphere. The consequences of propagation through atmospheric turbulence (turbulent index-of-refraction, diffraction, diffusion, absorption, etc.) must be estimated and taken into account in the system design to be compensated. Moreover, both satellite- and user-terminals on the ground (quantum sources and detectors, information processing nodes, etc.) must be efficient, cost-effective and robust to enable QKD for a larger market.

3. State-of-the-art assessment and proposed innovations

Free-space optical communication systems are nowadays successfully employed for Earth Observation, with links between the LEO satellites called “Sentinels” and a GEO relay within the European Data Relay System (EDRS). This shows that the state-of-the art European classical optical technologies are suitable for operational usage in space and on the ground and could thus be extended to QKD implementations. In the highly competitive framework of quantum-secure space communication systems development, a QKD protocol and an entanglement-based QKD (both using single-photon sources) between a satellite and the ground was experimentally demonstrated recently with the Chinese MICIUS satellite. Extending the optical technologies available in Europe to enable QKD in satellite-to-ground applications represents a major breakthrough for secure communications.

4. Added value and impacts for Europe

The deployment of secure communication means is a prerequisite for economic stability and development and a healthy transition towards a secured information society. Furthermore, it is necessary for national defence in the current context of space militarisation. Especially the potential economic impact for Europe is huge, which is the reason why several industries are investing in quantum security technologies: telecommunications and optoelectronics devices companies, telecommunication network providers, information technology firms, internet/cloud secure services, security and defence companies.

5. Key goals/technologies to be developed in the timeframe 2021–2023

Within four years, it seems reasonable to target a TRL 6 level of development. As a first step, the communication channel should be modelled by performing and assessing classical as well as quantum-limited measurements using optical communication systems available in space today. Then, demonstrator missions should be designed and realised, along with the development of space and ground segments suitable for QKD: design of satellite-systems compatible with QKD (and choice of QKD protocol), tests with satellites, further development of QKD sources and quantum-limited detectors, and design of optical ground stations equipped with QKD-compatible technologies. In addition, an optimisation and trade-off between QKD protocols for the satellite-ground channel shall be investigated.

6. Key goals/technologies to be developed in the timeframe 2024–2026

Within seven years, a TRL 7 may be targeted, with the development of an operational quantum key distribution system including space and ground segments. QKD-compatible satellites should be launched (GEO and/or LEO). Optical ground stations suitable for QKD should be deployed on the scale of Europe. Satellite QKD systems shall be connected to existing terrestrial infrastructure.

7. Key goals/technologies to be developed in the timeframe from 2027 onwards

In the long run, TRL 7+ may be targeted, with worldwide deployment of functional QKD (satellites constellation and optical ground stations network), and the development of next-generation quantum key distribution systems: optimisation of the available space-ground systems to bring them to higher QKD key rates, implementation of quantum teleportation, quantum memories, and quantum information processing nodes on the ground.

DESIGN AND DEMONSTRATION OF TECHNOLOGICAL MATURITY OF A CUBESAT CONSTELLATION OPTIMISED FOR IOT APPLICATIONS

1. Objectives

Design and demonstrate technological maturity (≥ TRL 6) of a cubesat constellation optimised for IoT applications and capable of serving billions of devices. Main technological innovations are optical inter-satellite links and RF user links using advanced random access protocols.

2. Challenges

The Internet-of-Things (IoT) market is growing exponentially. Suppliers are struggling to keep up with the increasing demand for ubiquitous connectivity. This gap could be filled using a constellation of LEO nanosatellites to serve terminals with omni antennas and very low power requirements (battery-powered). The important advantages of LEO satellites (e.g. favourable link budget and short round-trip time) have typically been overruled by the high upfront costs required to deploy a full constellation: approaches based on GEO satellites and/or terrestrial connectivity (e.g. LPWAN) have thus been considered more appealing up to now. However, new technologies are deemed to radically change this situation. The increasing use of nanosatellites (such as cubesats) drastically decreases the cost of the space segment, as well as the use of commercial hardware onboard satellites based on SDR (Software Defined Radio) technology, instead of expensive dedicated hardware.

Another key aspect that needs to be addressed is the design of a communication waveform capable of maximising the number of devices that can be served in the allocated bandwidth in order to maximise the revenue per bandwidth unit and reduce the power consumption of the IoT devices. Last but not least, optical technology can significantly increase the bandwidth available for inter-satellite links and for feeder links. Moreover, use of optical spectrum, as well as of unlicenced frequency bands for the RF up- and downlinks can reduce the barrier to entry due to regulatory constraints.

3. State-of-the-art assessment and proposed innovations

Free-space optical communication is today successfully employed in Earth Observation for the links between the LEO satellites called “Sentinels” and a GEO relay within the European Data Relay System (EDRS). This proves that optical technology is suitable for operational use. The next logical step is to adapt this technology to serve also inter-satellite links (ISLs) of constellations made of small satellites. This adaptation is, however, far from trivial and requires a substantial redesign of the optical terminal in order to meet the much tighter size, weight and power constraints of nanonsatellites.

As far as the RF links to/from the IoT devices are concerned, most of the existing/upcoming IoT systems employ very simple waveforms, originally developed for terrestrial IoT systems (such as LoRa), which rely on very sub-optimal medium access control protocols and forward error correction: this yields a poor exploitation of bandwidth and power which is not acceptable for a satellite-based system.

4. Added value and impacts for Europe

The rapidly increasing demand of solutions for IoT services is pushing for the development of energy-and-bandwidth-efficient and ubiquitous IoT wireless systems. It is foreseen that by 2025 the number of connected devices will be close to 100 billion, with a large share of devices located in remote areas: this is the case of sensors used to aid agriculture, to monitor the oil and gas extraction plants, to meter water consumption/availability, and to track containers (e.g. on ships). This market can be hardly served by cellular mobile networks, and points to the need of an economically viable world-wide wireless network for IoT services.

5. Key goals/technologies to be developed in the timeframe 2021–2023

Design of an optical terminal suitable for ISLs between nanosatellites in low Earth orbit targeting a data rate in the order of 100 Mbps. Design, implementation and test of dedicated waveforms and protocols for the RF user links from/to the IoT devices with data rates per IoT terminal between 128 bps and 2 kbps and aggregate throughput in the order of hundreds Mbps. Early in-orbit tests could rely on a store-and-forward concept.

6. Key goals/technologies to be developed in the timeframe 2024–2026

Development of a prototype for a bidirectional optical terminal for ISL links and first in-orbit demonstrator with at least two nanosatellites integrating both technological developments. The payload shall support sampling and storing of the RF user links' waveforms.

7. Key goals/technologies to be developed in the timeframe from 2027 onwards

Design of a full constellation with (near) real time capability and extending the payload capability to perform on-board decoding and demodulation of the RF user links.

Defence

R&TD ON SUBCOMPONENTS FOR VERY HIGH RESOLUTION OPTICAL AND RADAR SURVEILLANCE/OBSERVATION SENSORS

1. Objectives

The objective of the project is to address the resolution requirements from end users (in security and defence but also in other fields) by fostering sensor technology and the corresponding assembly, integration and verification/testing facilities. This project is therefore complementary to other topics within this document aiming at the same goal through operational (e.g. tasking, telecommunications) and/or data processing technologies. Following the European Defence Agency, high resolution is intended here as a general term that applies not only to the spatial domain but also to the spectral and radiometric ones.

Temporal resolution, which is critical for emergency and security applications, is not related to sensor technology and will not be addressed. Likewise, technologies not strictly related to sensors but those that are required for high resolution imaging (on-board data handling capabilities in terms of communication bandwidth, processing performance and on-board storage) are not considered within this project.

2. Challenges

The high spatial/temporal/spectral resolution required by many users of Earth Observation data, including security and defence applications, can be achieved in two ways: developing sensors with increased performance or implementing processing algorithms or operational solutions. The challenge considered by this project is to reach improved resolution through increasing sensor performance.

A second challenge is to reduce the European dependence from external suppliers for the basic materials/ subcomponents/subsystems (or even technologies) required to build Very High Resolution (VHR) sensors. Finally, the sensor performance has to be verified before launch using specific facilities and methodologies. Such facilities are sometimes difficult to find for new technologies, and the potential of advanced sensors is not correctly realised. Therefore, suitable AIT (Assembly, Integration and Testing) technologies could also be considered for improving VHR sensors.

3. State-of-the-art assessment and proposed innovations

The current technological edge in spatial resolution of optical panchromatic data is close to one foot, and visible and near-infrared (VNIR) multispectral data is only slightly worse. State-of-the-art short-wave infrared (SWIR) and thermal infrared (TIR) sensors used for remote sensing have increasing ground pixel sizes, with the thermal imaging sensors currently limited to 100 m/pixel. If high spectral resolution is required in the VNIR, the spatial resolution is reduced, and pixel sizes around 30 m are targeted for current or near future hyperspectral sensors (e.g. PRISMA, EnMAP, HyperScout). In the microwave range, submetre resolution is possible in the X band, although improvements in bandwidth are needed to go down to the foot level and to improve the image quality. Quad polarisation is common, although at the cost of electronics and operational complexity.

Summarising, the current state of the art shows that improving sensor spatial resolution is mainly needed in hyperspectral, SWIR and TIR sensors, and to a lesser extent in SAR systems. In the VNIR range, the demand is to achieve the current resolution with compact, low-cost sensors that could be suited for large constellations of satellites.

A wide range of technologies could produce improvements in VHR imaging. A preliminary list of fields where research is requested is shown below; although of course unexpected, disruptive ideas and technologies could also benefit this topic.

- Advances in SWIR (1–2.5 microns), MIR (3–5 microns), and TIR (8–13 microns) detectors.
- New concepts for hyperspectral sensors.
- Optics and structures for compact, stable and lightweight optical sensors.
- Phased array antenna distributed across platforms.
- Reconfigurable antennas – smart antennas.
- Very high bandwidth components (both for RF & baseband SAR subsystems).

4. Added value and impacts for Europe

The trend in the use of Earth Observation data shows that the number of potential users of VHR images through Europe is huge. Such users cover a very wide range of applications and societal challenges: secure societies, urban climate, resource efficiency or sustainable agriculture, to name but a few. Providing these users with the improved VHR images they need (in optical, thermal and microwave ranges) would necessarily help in the response to those challenges. From the technological point of view, Europe is already competent in some of the fields outlined here. But in others, Europe is lagging behind other economic areas. The research promoted by this project might help in closing the gap. Achieving a European capacity in all technologies related to VHR sensors, helping European strategic non-dependence in this field, would be a very important impact on its own.

5. Key goals/technologies to be developed in the timeframe 2021–2023

In the short term, those technologies with a higher TRL should be consolidated, while the foundations of the less mature technologies shall be established.

I. Next-generation sensors

- Improving radiation hardness of new developments performed by the European industry to potentiate joint activities for non-dependence actions for space and defence.
- Low-cost elements for multispectral imaging.
- Advances in free-form optics design for compact instrumentation for future spaceborne Earth Observation systems.
- Smart/higher bandwidth antennas.
- Large format arrays with high radiometric performance in the VNIR and SWIR.
- Research in TIR concepts allowing very high resolution (optics and detectors).

II. Improved AIT facilities and metrology

- Design tools and algorithms for optimisation of designs containing free forms.
- Manufacturability of new materials in free-form way.

6. Key goals/technologies to be developed in the timeframe 2024–2026

The medium-term goals/technologies focus on lower-TRL subsystems, and should consider the transition from design to prototyping, including airborne demonstrators, and the development of ground support equipment for testing and validation at system level.

I. Next-generation sensors

- Novel dispersive elements for multispectral imaging.
- Prototyping full, compact, VHR multispectral imagers using free-form optics.
- Low-cost components for smart/higher bandwidth antennas.
- Large-format arrays with high radiometric performance in the VNIR and SWIR.
- Development of TIR concepts allowing very high resolution.

II. Improved AIV facilities and metrology

- Designing AIV and metrology techniques for AIV for segmented mirror telescopes (TIR) and antennas (SAR).

7. Key goals/technologies to be developed in the timeframe from 2027 onwards

Technologies which currently correspond to a very low TRL, as well as innovative and disruptive technologies are expected for 2027 onwards. Sample goals could be:

- Development of curved focal planes.
- Manufacturing improved TIR optics and detectors.
- Prototyping full, compact, hyperspectral and TIR imagers.
- Research in segmented mirror telescopes for TIR.
- Technologies for distributed SAR systems.

MINIATURISATION OF ALL KINDS OF SENSORS FOR SMALL SATELLITE CONSTELLATIONS, HAPS AND RPAS

1. Objectives

To enable the miniaturisation of a broad range of sensors that are currently used in HAPS, RPAS and satellite systems. This includes, among other things, sensors in the infrared domain (NIR, SWIR, MIR, TIR), hyperspectral sensors, visible light sensors, antennas (phased array, reconfigurable, smart), SAR sensors and attitude sensors (IMUs, magnetometers, star trackers, Earth and Sun sensors). The focus of this project is to look at key enablers for reducing the dimensions, power output and mass of sensors and the systems that are related to their performance or with which the sensors are integrated.

2. Challenges

Miniaturisation comes with many challenges, especially when the scope of the main objective is broad and encompasses many different types of sensors. Among the main challenges that are generally applicable to all sensor types, there is the effect miniaturisation has on performance, material requirements, thermal design, manufacturability and ultimately cost. Reduced power consumption is another driving requirement that must come along with miniaturisation, for any sensor to be easily accommodated in a small satellite. Many systems are difficult to scale. In some cases, the performance is directly related to the dimensions, as one can see in, for instance, optical systems. In other systems, material properties are a bottleneck or the lack of sufficient research into alternative materials hinders the development of smaller and smaller sensors. Heat dissipation is largely related to size as well as causing further difficulties for the design of small sensors. Demanding the same performance on a smaller volume often means an increase in the system's relative complexity as well, causing the manufacturability to be further challenged, demanding higher and higher precision of the machines used to create the sensors and the people who operate them. The same applies to the associated electronics and signal processing: increased capabilities are desirable to produce smart sensors, increase performance and autonomy, reduce data transmission or storage needs, etc. All these challenges may result in increased costs, at least during the development phase.

We may divide the target sensors into two categories: platform and scientific (payload) ones. Main platform sensors are those related to AOCS subsystems, of very special relevance for Earth Observation missions, or multi-satellite missions (clusters). However, within the cubesat market most of the needs are already covered with flight-proven sensors offering adequate performances within good mass and power constraints.

Focus should then be put on payload sensors. However, the number of different sensors is as large as the number of mission applications: From passive optical sensors in different ranges of the spectrum, to compact lidars or radio sounders. Due to this, during a first stage it will be more practical to work on Key Enabling Technologies needed for the development of a number of sensors, rather than targeting very particular sensors themselves. Of course, the rough definition of the technology needs should be linked to particular target applications. Initially, the following areas are identified:

- Deployable structures for optical systems, thermal control (deployable radiators) and antennas.
- Free-form optics for compact optical designs for Earth Observation applications.
- Mixed-signal microelectronics (ASICs) development for sensors' front-ends.
- Die-level integration and packaging technologies for the creation of System-on-Chips based on existing COTS (detectors plus front-ends).
- Particular detectors (e.g. CMOS APS, Silicon Photo-Multipliers, etc.).
- Ultra-stable materials with minimum thermal expansion coefficient for the construction of precision supporting structures.

3. State-of-the-art assessment and proposed innovations

Looking at the current state of sensors used in space, many sensors themselves have already reached quite an advanced step of miniaturisation. For instance, star trackers are currently available at a size of around 10 cubic centimetres. Since many of the actual sensors themselves are already quite compact, the project will mainly focus on aspects that reduce the overall size of the system the sensor is integrated in.

As stated before, most of the needs for AOCS systems are already covered by existing sensors. Some examples of this are the ST-200 Star Tracker from BST (40 grammes, digital, 10 arcsec accuracy), the New Space NFSS-411 Fine Sun Sensor (35 grammes, 0.1 deg., digital), or Horizon Sensors such as MAI-SES from Maryland Aerospace (33 grammes, digital, 0.25deg. accuracy within fine field of view), just to mention a few.

In mixed signal ASICs, there are European groups that have developed different technologies or design techniques, for their use in space. For example, the Institute of Microelectronics in Seville (Spain) has developed a complete library of resources for low-frequency, precision, front-end developments, based on AMS 0.35 μm technology. The Norwegian company IDEAS (Integrated Detector Electronics AS) offers a number of ASICs specially for optoelectronic detectors, based on the same technology. Some technologies exist for increased bandwidths, such as DARE library from IMEC, Belgium. But in general, there is still a wide field for improvement in high-precision (needed for scientific sensors), high-speed (applications such as lidar) or high-voltage (needed to bias some detectors) solutions.

In the field of System-on-Chip integration, only a few companies are offering such services. In Europe, 3D-Plus offers integration services to transform a discrete-components PCB into an integrated circuit up to some level. Of course, the cost is not negligible. In the US, some other companies offer similar capabilities and other added-value strategies (e.g. the integration of single-event latch-up protection circuitry and a COTS component into a unique package). Nevertheless, the offer is really limited. Many COTS could be more safely employed in small satellites with the incorporation of some protective/mitigation circuitry, TID-reducing packages, etc.

4. Added value and impacts for Europe

With respect to the space sector, smaller sensors translate to smaller satellite systems. With much of a satellite system's cost coming from the launch segment, the smaller the satellite the lower the cost. Many of the New Space opportunities arise from creating global coverage through the deployment of constellations of smaller satellites. As such, lowering the cost of each satellite greatly lowers the threshold for creating a constellation of satellites. This enables the possibility of greater space economic activity. Alternatively, smaller sensors can mean the usage of more sensors on board the same system, which can be used to create safer systems through redundancy or greater performance through sensor fusion. All enabling technologies related to electronics, optoelectronics and microelectronics integration and/or qualification for space perfectly fit within the so-called "Strategy for the Non-Dependence" of Europe. A huge market (given the increasing number of cubesats being launched) would open to any stakeholder capable of offering reliable components, detectors, or complete subsystems or sensors for the small satellites market.

5. Key goals/technologies to be developed in the timeframe 2021–2023

Perform a survey on currently used sensors on board HAPS, RPAS and satellite systems. Identify and evaluate the most likely and effective candidates for miniaturisation. Propose the first conceptual designs for miniaturised alternatives to the existing sensors. Develop key enabling technologies.

6. Key goals/technologies to be developed in the timeframe 2024–2026

Further develop the designs for the miniaturised sensors. Create prototypes and perform extensive laboratory tests.

7. Key goals/technologies to be developed in the timeframe from 2027 onwards

Perform on-board tests for the most mature miniaturised sensors.

Space Science, Space Exploration and Human Spaceflight

R&TD ON COMPACT AND SMART SENSORS FOR PLANETARY EXPLORATION

1. Objectives

The idea is to increase competitiveness of European entities in the field of miniaturisation and development of compact measuring instruments that can be implemented in planetary exploration missions. In the proposed solution we would like to present:

- The possibility of extending the capabilities of planetary penetrators treated as a platform equipped with a sensor with extended capabilities. It would be possible to demonstrate TRL > 6 of the technology based on the fact that the penetrators already possess TRL 9 which reduces the risk of developing too many new solutions.
- The possibility for the increased miniaturisation of active spectroscopy solutions (laser-induced breakdown spectroscopy, Raman) to make them suitable for small robotic exploration systems starting at roughly 20 kg in (thermally) challenging environments (Moon, asteroids, comets).

2. Challenges

The main challenge for the proposed activity is the necessity to identify miniaturised technological solutions that are acceptable in the course of a qualification based on ECSS standards or similar processes used in science missions worldwide.

It will be critical to develop electronics sub-units that can be integrated into systems very limited in power, mass and size. Yet the systems will have to function with immense precision in rough environments with strong day-night temperature changes, a challenging radiation environment and sometimes even only roughly known environment conditions pre-flight.

For the penetrators only thermal sensors and accelerometers were implemented in an in-situ flight experiment. Therefore, different possible sensor technologies need to be assessed for their applicability.
The entire development of all systems and subsystems must then be validated by a test campaign in order to prove the appropriate level of performance and technology readiness on Earth before proposing them as a part of a space project.

3. State-of-the-art assessment and proposed innovations

Planetary penetrators have been successfully being developed for many years as important instruments during space missions (Rosetta, InSight). We believe that by extending their functionality by implementing more advanced sensors they can become even more valuable tools in planetary exploration.

A miniature Raman spectrometer is currently developed for the DLR/CNES rover for the JAXA MMX mission. Heavier systems like the MSL Rover "Curiosity" (ChemCam) or the Mars2020 rover (SuperCam) carry such systems, or the RLS for ExoMars mission leaded by INTA, all with mass of about 10 kg.

4. Added value and impacts for Europe

The ongoing analysis of organic molecules, biosignatures and the search for life in the Solar System as well as the understanding of the evolution of our direct cosmic neighbourhood are major focus points of Europe's science community. In-situ measurements and proposed sample return missions have generated a lot of buzz in the science community as well as in the general public. This has been picked up by ESA and the national agencies.

Furthermore, the increased interest in space mining means that instruments allowing autonomous investigation of the regolith properties on celestial bodies like moons and asteroids are going to be a crucial source of useful information on potential targets for larger-scale endeavours like, for example, excavation for ISRU.

5. Key goals/technologies to be developed in the timeframe 2021–2023

In principle, all of the key aspects to be addressed in the indicated timeframe are more concerned with the identification of possibly already existing technologies to be used or refurbished to be space applied than to be developed from scratch. This task requires a systematic approach and is to be run by entities with broad experience in working with both industry and academia.

Each identified technology needs to be paired with an appropriate testing and verification approach that would prove its usefulness and reliability. Apart from standard testing against space environment loads, dedicated functional and life test methodologies need to be developed to support this endeavour. Once the previous steps are finalised, possible technological missions should be selected and proposals made aiming for a demonstrator of technology. This also includes assuring funding and building a consortium, but this task should be delegated to space agencies (European and national level). The ultimate goal is to present technology functionality in a space mission, which needs to be preceded by TRL increase first in representative conditions and finally in a real space environment.

Key activities to be undertaken in this timeframe are:
- Identification of possible technologies to be used.
- Testing of the technology and testing methodology development.
- Identification of possible missions that could benefit from the proposed technology development.

6. Key goals/technologies to be developed in the timeframe 2024–2026

- Present functioning prototypes.
- Test prototypes in representative space-like conditions and include them in science proposals for the in-situ exploration of the Solar System.
- Increase the maturity of the full system TRL > 6.

7. Key goals/technologies to be developed in the timeframe from 2027 onwards

- Achieve TRL 9 of a proposed solution during a dedicated space mission.

TECHNOLOGICAL MATURITY AND DEMONSTRATION OF VERY LOW TEMPERATURE ELECTRONICS FOR SCIENTIFIC EXPLORATION MISSIONS

1. Objectives

The exploration of Ocean Worlds like Europa, Ganymede, Enceladus or Titan are key scientific targets for the coming years. Even the exploration of the northern and southern land of Mars, far from the equatorial zone, are also relevant to study the planet's evolution and search for possible existence of extinct life. What all those bodies have in common is that their environment is quite extreme, in terms of radiation but also in terms of ambient temperature. Mean surface temperature at Europa is 102 K, at Titan 90 K and at Enceladus 75 K. In addition, the power resources are very low due to their distance to the Sun. Also considering Moon exploration, one challenging task is surviving night periods when temperature drops to 80 K.

Typically, rovers, landers and long-distance probes are equipped with so-called warm boxes dedicated for subsystems' electronics and components which have to operate continuously. Other elements of spacecraft (e.g. robotic arms, reaction wheels, detectors located outside, etc.) due to their dimensions will require some electronics like control boards or data processing systems that should survive in a harsh environment. In some cases, if it is required to operate under low-temperature ambient conditions, systems are warmed up before which requires time and power. All those solutions overcome the problem of low-temperature ambient conditions. In this activity, we propose research for technologies which may allow for wide, direct operation of electronics under low-temperature conditions. Progress in this technology will impact space systems by making them more efficient and performing.

2. Challenges

Low-temperature conditions are very common in space. Advantages of having solutions which work directly under such conditions in space are significant. It might save the power needed for warming up of electronics, limit mass if 'warm boxes' are not needed, simplify a Thermal Control System (TCS), etc. Moreover, there exists a number of situations where direct operation under cryogenic conditions is required and results in an increase of performance of the equipment. For example, in a case of detectors front-end electronics, direct operation at low temperatures is profitable due to low noise levels. It also makes the utilisation of superconductors possible, which may result in additional efficiency and performance increase.

In the case of space applications, the main challenges for low-temperature electronics are: (i) keeping confirmed reliability and predictability of the equipment for a given operational time, (ii) assurance of repeatability of properties under certain low temperature in this case conditions, (ii) operation under high to very high radiation levels (e.g. for Europa missions).

3. State-of-the-art assessment and proposed innovations

While relevant work and bibliography exist at R&D level with regard to the operation and modelling of different electronic technologies at low/cryogenic temperatures, we lack a systematised work and a common database in this field. Moreover, the availability of high-integration circuits able to operate under low temperatures or dedicated for cryogenics is very limited. The situation is even more difficult if radiation specification of such circuits is needed.

It is known that many FET devices can operate almost all the way down to cryogenic temperatures, whereas JFETs get limited by freeze-out to around 40 K. Different MOSFET and CMOS devices may work beyond this limit. Bipolar technologies are limited to a smaller range (100 K) as their gain rapidly decreases with decreasing temperatures. Still, this is more than enough for low-temperature (non-cryogenic) applications such as Mars, although a fine characterisation is needed to account for thermal variations of main parameters in the design. Nevertheless, the behaviour is improved by variants such as HBTs. In all cases, we are talking about silicon devices, but others based on other materials (Germanium) may show different behaviours.

Nevertheless, what does not exist is a real low-temperature electronics market. If the space-grade market is reduced, the low-temperature one is even more. A strategy based on solely designing, validating, packaging and qualifying integrated circuits, independent of the level (from single analog amplifiers to complex digital devices), capable of withstanding both the radiation and low/cryo-temp environments, would be very limited as well as expensive. While that line of work may exist, a systematic work in testing space-grade devices for low/cryo-temp applications, maintaining and sharing a common database, must also be established. One result from this work will be the identification of needs, i.e. types of components for which no existing devices meet the low-temp requirement, to feed the parallel activity of design and development of dedicated ICs for low-temp.

Thus, at least four parallel lines of work should be defined:

- Systematic selection and characterisation of existing space-grade devices for operation at low/cryogenic temperatures.
- Microelectronic design of low-temp, rad-hard (level TBD) devices. In this field, Radiation Hardened By Design (RHBD) techniques are preferred, to ease the manufacturing in European foundries. Work may be started at building blocks level, so as to develop a library of proven design blocks that may be used to build the complete circuits, both analog and digital. After initial results from previous lines of work, main needs (complete circuits) would be identified.
- Development of packaging techniques for low/cryo-temperatures and intensive thermal cycling (not only absolute temperature, but also large thermal variations). Packaging is a critical aspect of ICs' development. Work should be started in parallel to guarantee that it does not become a bottleneck in the end.
- Standardisation of the methodology of determination and/or verification of low-temperature electronics reliability.

Three different ranges should be considered: low temperature, meaning down to 133 K (-140 °C, extreme qualification temperature for Martian missions), and semi-cryogenic ones, reaching the 70 K needed for Ocean Worlds' exploration, and finally a cryogenic one down to the Kelvin range.

4. Added value and impacts for Europe

Currently, for many applications there are no low-temperature solutions in the form of electronic circuits which might be utilised for space especially in the EU market. For example, in the case of the ARIEL (ESA) mission so-called 'sidecar' electronics which is a part of the telescope's front-end have to operate under cryogenic conditions to reach mission requirements postulated by scientists. Such a solution does currently not exist in the European market.

The increase of skills of European entities in the area of low-temperature electronics for space will increase the competitiveness of the EU and strengthen its position as a world-leading region in the space exploration area.

Research in the proposed area will significantly gain activities in electronics dedicated for low temperatures. It will also enable to utilise current achievements in cryogenic technology (e.g. high superconductors, extremely low-noise amplifiers, etc.) for space. Establishing a new area of development will impact the progress in satellite subsystems' parameters like efficiency of DC/DC converters and drivers, detectors' sensitivities and others.

Except utilisation in space exploration and exploitation, we believe that this activity will elevate EU capabilities and generate growth in such areas as low-noise electronics, ASICs design modelling and synthesis, cryo-technologies, etc.

5. Key goals/technologies to be developed in the timeframe 2021–2023

In the timeframe 2021–2023, two phases could be identified: the first one, screening of existing space-grade devices in order to know their performances at low/cryogenic temperatures, developing at the same time standard methodology for evaluation/validation under these extreme conditions; in a second phase and once having identified the areas where special developments are needed, work on the improvement of packaging techniques and on design tools to be used in low-temperature/cryogenic microelectronics systems.

- Selection and characterisation of existing space-grade devices for operation at low/cryogenic temperatures.
- Development of a standardisation methodology for validation of devices at low/cryogenic temperatures.
- Development of packaging techniques.
- Development of libraries for design blocks to be used in complete circuits to be used in low-temperature/cryogenic microelectronics.

6. Key goals/technologies to be developed in the timeframe 2024–2026

- Selection and characterisation of existing space-grade devices for operation at low/cryogenic temperatures.
- Development of components and intensive tests at low/cryogenic temperatures.

7. Key goals/technologies to be developed in the timeframe from 2027 onwards

- Test in a technology demonstration mission.

Research under Space Conditions and Robotics

TECHNOLOGIES FOR AUTONOMOUS AND COOPERATIVE SWARM EXPLORATION

1. Objectives

Demonstrate the use of robotic swarms for future extra-terrestrial in-situ exploration missions. Demonstrate the use of small satellite swarms for single telescope formation. Demonstrate the use of small satellite swarms for Earth Observation.

2. Challenges

Considering economy aspects of launching a spacecraft into space, the size of a single object of a swarm needs to be very limited. Hence, many engineering challenges arise. Within the main issues is miniaturisation of electronic and mechanical subsystems, e.g. computers, communication antennas, sensors and actuators. One of the problems when the system is small is maintenance of temperature in a range of electronics operation, another is radiation protection.

3. State-of-the-art assessment and proposed innovations

Due to the trends of advances in computational and robotic technologies, autonomous capabilities are expected to become much more pervasive for space applications, e.g. to support unmanned missions, to assembly infrastructures in human spaceflight, etc. These trends also include technologies about multi-robot cooperative systems, and distributed artificial intelligence and swarm computing. Indeed, the general intent is to develop multi-component (or multi-agent) space systems, which shall be low-cost and able to autonomously run for years in a harsh environment. For example, such intent is tangible for:

- In-orbit operation and satellite formations – different multi-satellite applications are already envisaged. The main focus is the automated consensus agreement of the flying formation for the constellations (e.g. by optimising the power consumption) or the automated support for the assembly of in-orbit structures (e.g. by optimising suitable efficiency indexes).
- Surface and planetary exploration – the goal is to use cooperative multi-robot teams in space explorations, by using heterogeneous, reconfigurable, intelligent and interoperable robots to enhance the application areas, the duration and the operational distance of future missions.

The previous categories exhibit some implemented or designed applications, such as XEUS, CLUSTER II, DARWIN and other ESA missions. However, all these missions do not employ the key features of swarm intelligence, such as decentralised and local cooperation and emergent behaviour. Some swarm-based concepts have been investigated also in NASA's ANTS project, which has proposed different mission profiles employing swarm technologies for both spacecraft and surface-based rovers.

The reference project shall advance space applications by applying and innovating technologies about distributed artificial intelligence and swarm computing to ensure autonomic properties (i.e. self-managing, self-configuration, self-optimising, self-healing and self-protecting) for the agents involved in space missions.

This will also require the introduction of learning capabilities for the agents, which shall dynamically adapt to the unknown features of the harsh and unstructured environments (e.g. swarms of rovers shall learn the characteristics of unknown surfaces). Some protocols shall be designed to provide interoperable systems, allowing collaboration among agents specialised in different tasks.

Furthermore, swarm-based missions will pose new challenges regarding their complexity and their verification. Indeed, a new operational model shall be defined to take into account the autonomy and the autonomicity of the cooperative multi-robot system, and some form of human supervision shall be detailed at swarm level. Verification shall be especially analysed since one of the most challenging aspects of swarm technology is determining how to verify that the emergent system behaviour will be proper and that no undesirable behaviour will occur. Verifying intelligent swarms (i.e. swarms with individual autonomic properties) is even more difficult because of the several interacting intelligent elements. To deal with such challenge, new techniques for intelligent swarm verification (e.g. applying formal methods, safety monitoring based on learning assurance, runtime verification, explainable artificial intelligence, rare event simulation, etc.) shall be implemented.

4. Added value and impacts for Europe

The need of miniaturisation of spacecraft will stimulate the research branch of the European industry to develop a technology of small devices operating in hostile environments. Eventually, the technology will be applicable for on-Earth applications such as medicine, lifesaving, monitoring, environmental protection, etc.

5. Key goals/technologies to be developed in the timeframe 2021–2023

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 key components:

- 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.
- Development of a swarm-based navigation system that is able to localise all individual robots, external devices, drop boxes, and the like. The system should support continuous operation and provide submetre localisation accuracy.
- Demonstration of the principle of swarm exploration and navigation based on sensor data (e.g. magnetometers, gas sensors, seismic sensors), and decentralised modelling and mapping of the observed phenomena. A set of possible sensors for a swarm mission is to be selected in cooperation with planetary scientists.
- Development of suitable verification methodologies for the validation and certification of highly autonomous and cooperative space applications based on swarm intelligence. Such methodologies shall provide evidence for the "trustiness in autonomy", especially for the development of intelligent and swarm-based software systems in space applications.

6. Key goals/technologies to be developed in the timeframe 2024–2026

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 optimisation.

In particular, a prototype swarm platform for more extensive testing is to be developed. The latter integrates several robotic vehicles, communication, localisation and exploration functionality, and a selected sensor package. Using this prototype testing of exploration algorithms for 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 algorithm robustness.

7. Key goals/technologies to be developed in the timeframe from 2027 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.

R&TD ON NEW PERCEPTION, REASONING AND PLANNING METHODS, BASED ON MACHINE LEARNING AND AI

1. Objectives

To advance existing methods and develop new methods in the field of machine learning and artificial intelligence in order to improve the performance of autonomous space-based systems such as satellites and rovers.

2. Challenges

One of the major challenges in developing artificial intelligence and machine learning for space applications will be to bridge the different fields of expertise. Since the usage of such algorithms in the space field is to date still quite limited, the building up of expertise and creating sufficient understanding of machine learning/AI among space engineers and creating sufficient understanding of space engineering to machine learning/AI experts will be an important challenge.

Another important aspect will be the interpretability and explainability. Interpretability deals with the extent to which a system's cause and effect can be observed and understood, while explainability concerns the ability for human agents to understand the inner workings of the system, once given some form of autonomy. In space-based systems, which are no longer "fixable" once launched into orbit and which are also incredibly expensive, requirements on the interpretability and explainability are expected to be prevalent.

3. State-of-the-art assessment and proposed innovations

On the satellite front, 2020 will see the launch of the first European satellite to demonstrate an instance of on-board artificial intelligence: PhiSat. The satellite will filter the images taken by the hyperspectral camera for cloud cover. Since this is the first demonstration of using machine learning/ artificial intelligence algorithms on board a satellite, the field itself is still a frontier. NASA has used machine learning/artificial intelligence in its EO-1 satellite previously, wherein it was trained to detect several features such as cloud cover but also volcanic eruptions.

With respect to rovers thus far, in particular the Mars rovers run some of their tasks autonomously, mainly for scientific tasks such as the AEGIS software used on board the Mars Curiosity rover, which identifies targets for rock and soil analysis by looking at images from the ChemCam system. Considering the incredible potential for further autonomy in space systems, while at the same time still being rarely utilised in the field today, there's a lot of room for further innovations.

Further advancements in the field of vision-based navigation can aid rovers in traversing rough terrain, especially in places such as Mars whereby the signal delays are too great to directly pilot the vehicle. Such algorithms can also be trained for in-orbit conditions whereby they can serve to enable autonomous docking, which will become more and more relevant with the advent of on-orbit satellite servicing. The active removal of uncooperative debris also requires the satellite's capability to "learn" the debris' spin rate in order to determine the best method to collect it.

Algorithms should be developed for satellites to have the on-board capability to perform constellation management based on telemetry received from other satellites within the constellation through inter-satellite links. With constellations currently planned to exceed, in some cases, thousands of satellites, it will not be cost-efficient anymore to manage the satellite operations solely with human operators. Satellites must become capable to auto-correct their orbit in order to cover potential blind spots that can occur when one of the satellite malfunctions, or when demand in a particular area temporarily increases. Another important aspect is for satellites to learn to autonomously respond adequately to collision risks.

On the Earth observation front, we're seeing a greater utilisation of low Earth orbit, in particular by small satellites. Lower orbits translate to a higher resolution for the same instruments, but simultaneously decrease the communication time with the ground. This puts greater strain on the number of images that can be transmitted to the ground with each pass. Smarter image processing algorithms should therefore be developed in order to send down the images with the greatest value, both through selection of images with the most information and post-processing the images in order to reduce the amount of data required to be sent down for analysis on the ground.

4. Added value and impacts for Europe

With the upcoming launch of the first European satellite to make use of machine learning/artificial intelligence algorithms on-board, and the relatively limited number of overall spacecraft to make use of this technology to date, Europe is well positioned to stay competitive in the field of space-based autonomous systems. Creating further expertise in the field of machine learning/artificial intelligence would improve many existing systems and enable many others.

These improvements would benefit the entire range of European space infrastructure, including but not limited to Earth Observation, navigation, communications, defence, (cyber)security, space safety, and many others. The further development of autonomous space systems can also act as an enabler in the economic sphere, whereby more autonomy on-board can free up businesses from having to have every type of expertise in-house, lowering the threshold for new businesses to be created in the space field.

5. Key goals/technologies to be developed in the timeframe 2021–2023

The process will start off with a broad investigation of the current state of the art in machine learning and artificial intelligence methods and an analysis of how these relate to the existing space hardware and applications. After creating this overview, for each of the above capabilities a team will be formed that will work on the design of different algorithms that would enable each of those capabilities.

6. Key goals/technologies to be developed in the timeframe 2024–2026

After having designed several algorithms, a selection of the most promising methods will be made so that at least one method per capability can be developed. Throughout the rest of this period, the aim is to bring each of these methods to technological maturity through rigorous simulation and testing.

7. Key goals/technologies to be developed in the timeframe from 2027 onwards

Once a method has matured, the goal should be to provide a means to perform an on-orbit demonstration. Industrial partners should be sought out that would be interested to exploit the developed methods and would be willing to host an experiment on board future space systems.

Access to Space

IDENTIFICATION AND EVALUATION OF MICRO LAUNCHER CONCEPTS, INCLUDING SUBSYSTEM PROTOTYPE DEMONSTRATION

1. Objectives

The objective of this large-scale project is to identify and evaluate the most promising concept for a microlauncher (ML) and to define a set of high-level requirements, to define a roadmap for the maturation of key technologies enabling the development of such system, to realise both ground and in-flight demonstrators for the validation of key technologies, as well as integrated flight demonstrators at system level.

2. Challenges

An economically viable and commercially self-sustaining microlauncher can meet the growing need of dedicated launch services for small satellites, however, this is not easy to be achieved. On the technical side, one of the biggest challenges in the design and development of a microlauncher is the fact that the reduction of the launcher size does not simply imply a decrease in the launcher cost and/or complexity.

Therefore, the microlauncher design has to incorporate disruptive low-cost technologies, digitalisation, standardisation and automatisation to be able to fulfil the market need for this class of satellites.

The biggest financial challenge with respect to the microlauncher development is the fact that the system requires considerable funding and several initiatives have been cancelled due to the lack of financial resources.

3. State-of-the-art assessment and proposed innovations

At this moment, worldwide, the need to have a dedicated launch opportunity for small satellites is increasing as launch opportunities become scarce due to the increase of small satellites. Another factor is that many of the small satellites need dedicated orbits to set up their constellations. Therefore, the piggy-back ride is at a disadvantage as the primary payload decides the final target orbit.

Microlaunchers are an alternative to conventional launchers and are not new to satellite operators. However, although the market for small satellites is expected to increase substantially in the coming years, despite some progress in the field, developing a robust and cost-effective microlauncher is not yet straightforward. There are limited opportunities to launch them affordably and no operational dedicated launcher for small satellites exists today in Europe. Some initiatives are being run in Europe within the frame of ESA-FLPP and H2020, but their TRL and feasibility are still falling short. ESRE's proposal for a large-scale development approach to innovate in the sector is:

- Targeting of 100 kg payload market through proposing an optimal design for the launch vehicle.
- R&D on new technologies in the fields of propulsion, avionics, structures, mechanisms, GNC and thermal control in order to ensure reduction of environmental impacts, complexity, cost and time of integration and operation.
- Integration of or further maturing subsystems and technologies already available throughout the European market in a demonstrator for the selected optimal launch vehicle design.
- Development of a European-based launching site dedicated to microlaunchers based on an innovative ConOps that can accommodate a high launch rate- per year.
- Support future industry developments by TRL advancement and bottom-up research initiatives through unbiased technology selection from the available technology market.

4. Added value and impacts for Europe

The development and operation of a commercial microlauncher in Europe can meet the growing need for dedicated launch services required by companies manufacturing small satellites. A European-based launch capability for small launchers, based on the innovative ConOps approaches, will ensure European operators much more launch opportunities and strategic independence in Access to Space for this class of satellites. Furthermore, the newborn critical technologies for low-cost European launchers might be exploited also for the heavy launchers as well as for other non-space applications. In terms of contributions made by Research and Technology Organisations (RTOs) contribution to the above sector, the assurance is that through the development of a demonstrator at least key technologies validations shall be done which can be used in future industrialisation of such concepts.

5. Key goals/technologies to be developed in the timeframe 2021–2023

The short-term objective of the proposed large-scale microlaunch vehicle development roadmap will include research into and selection of an optimal launcher, modular key technologies selection for further maturation and development of a breadboard for demonstration purposes.

The key technologies will in turn be developed not as stand-alone initiatives, but rather framed by the target of a final system demonstrator but not limited to the demonstrator. This method will provide future accessibility of interested stakeholders into the technologies. Breadboards and ground demonstrators should be developed through which the targeted TRL 4/5 shall be achieved.

A. Definition of an optimal microlauncher system and development roadmap.

The first objective aims to assess and select an optimal launch vehicle (ground-based or airborne) for the 100 kg payload class to LEO/SSO and mission requirements which shall properly feed into technology developments.

During the selection of the optimal concept, critical technologies such as propulsion shall be assessed in terms of solutions available, or which need and could be adapted, or the need to research and develop them from low TRL. Moreover, an important factor would be the impact of adapting such systems for the small-scale demonstrator and the respective feasibility. Furthermore, an assessment in terms of one vs multiple-engine configuration per stage shall be done and then evaluate the cost vs system complexity problem. At the end of this phase, it shall be required that a selection of the critical technologies would be done from the key technologies' maturation pool.

B. Modular key technology selection and maturation.

In particular, the approach that shall be taken is to select and address common technologies that could be deployed modularily on multiple concepts, in order to not limit subsystem technologies advancement. First phase targeted key technologies that shall not limit further integration are:

- Maturation of anisogrid or CFRP structure technologies for launcher stages, inter-stages and tanks.
- Development of ALM processes for engine components.
- Development of key components for propulsion systems such as CMC for hybrid engine components, closed and open cycles, injectors, TC cooling, nozzle flow, turbopump and GG system, electropump.
- Development of a low-cost TVC system and breadboard testing.
- Development of a robust GNC system for microlauncher vehicles.
- Maturation of hybrid navigation technology including sensor fusion data logic.
- Maturation of batteries, including Li-Ion with disturbed topology and power management system.
- Maturation of smart structures together with smart manufacturing techniques.

C. Development of ConOps with available technologies.

In parallel, the non-conventional ConOps will be elaborated, designed and sized according to the selected microlauncher concept.

Flight demonstrations will be defined in order to validate the ConOps including ground and flight operations, logistics and safety aspects, as well as availability and slight adaptation of existing alternative launch sites (e.g. in Europe).

The development of numerical tools is also included in this target as simulation environment (flight simulator) to support the design and analysis of the trajectory. Wind tunnel test campaigns are also envisaged to study the multi-body and single-body (microlauncher) aspects as well as single vs multiple engine configurations.

6. Key goals/technologies to be developed in the timeframe 2024–2026

The mid-term objective of the selected microlauncher development will include:

A. Further maturation of key technologies up to TRL 7.

In this timeframe, the key technologies selected and developed in the short term will be further matured in order to reach TRL 6/7. A ground demonstrator with increased level of complexity will be designed, manufactured and tested in representative conditions. Among those there will be the following:

On top of the technologies that have been started in phase 1 and which have been selected for further maturation in this phase, additional technology maturation shall be started for the following subsystems:

- Avionics complete solution including OBC, sensors, antennas, transponders in C and X bands, including breadboard testing.
- Pyrotechnic or pneumatic separation selection and further maturation including breadboard testing.
- TT&C solution selection and breadboard testing.
- Extensive CFD and wind tunnel campaign.
- Sizing and breadboard testing of RCS system.
- TPS system, reusable cryogenic insulation (if applicable).

B. Development of a flight demonstrator with on-board TRL 4/5 technologies.

In parallel, a scale version demonstrator of the microlauncher will be designed and developed based on the TRL 4/5 technologies previously developed in order to perform a first demonstration of the system, of the mission concept as well as of the operations.

The flight demonstrations will take place by exploiting the most promising launch approach down-selected in the previous phase in representative operative conditions. The flight demonstrations will take place by using simulations of the reference microlauncher with increasing difficulty levels in terms of launch platform operative envelope and test-vehicle capacity (e.g. mock-up of a microlauncher first stage, equipped with test avionics, then again equipped with a conventional propulsion module) which shall demonstrate the functionality of the ready key technologies selected, as well as for example the RCS system.

7. Key goals/technologies to be developed in the timeframe from 2027 onwards

The long-term objective of the ESRE microlauncher development roadmap will include:

A. Development of a pre-operative flight demonstrator with the matured technologies on-board.

The full-scale flight demonstrator of the selected optimal launch vehicle from previous phases development will be integrated based on the TRL 6/7 technologies previously developed in order to perform a pre-operative demonstration of the system, of the mission concept as well as of the operations.

Moreover, in this phase extensive research shall be done in terms of developing and improving existing tools for real-time trajectory computation and optimisation, development of a 6-DOF flight simulator, as well as improving and maturing specific GNC algorithms.

IDENTIFICATION AND EVALUATION OF REUSABLE LAUNCHER CONCEPTS; IDENTIFICATION OF THE MOST PROMISING CONCEPT(S). PARTIAL DEMONSTRATION OF PROMISING REUSABLE LAUNCHER CONCEPTS COMPARED TO STATE-OF-THE-ART EXPENDABLE LAUNCHERS

1. Objectives

The multi-fold objective of the project is to identify the most promising concept for a reusable launcher; to define and put in place the plan for maturation of the key technologies enabling the reusability; to realise ground and flight demonstrators of the technologies; and, finally, to realise a pre-operative demonstrator integrating the matured technologies to be flight-tested in a significant environment.

2. Challenges

Launcher stages recovery and reuse is very challenging because it implies new capabilities to be developed at mission, system and subsystem level.

Indeed, the reusable stages will be designed, adapted, first to the return flight where stages will undergo a “working environment” very different in terms of aerothermal and mechanical loads from the one that expendable launchers encounter nowadays and then to the reusability where the design must rely on new rules, in all systems and subsystems.

Moreover, a new paradigm is also necessary for what concerns the ground and flight operations. In fact, the ground segment and launcher segment will need to be extended to cover not only the mission part of entry-descent-landing but also the post-landing phase with a wider envelope of actions to be defined and matured to cover the need of a reliable and affordable cycle of recovery, refurbishment/reconditioning and reuse. Last but not least: the great challenge will be to acquire all the new capabilities in an affordable and low-cost way in order to prove a commercially valid solution. The launch system reusability solutions shall be demonstrated in flight within five years, including forecast of investment needed.

3. State-of-the-art assessment and proposed innovations

In parallel to US Space Shuttle exploitation, several configurations of reusable launching systems (TSTO, SSTO, winged configuration, airborne, etc.) have been extensively studied for several decades. Nevertheless, during the latest decade, several players in the USA were developing reusable launchers, including SpaceX and BlueOrigin. China and Russia are also engaged in this subject on their own.

Europe has recently demonstrated the capability to manage a re-entry mission of a non-winged system with IXV and work is ongoing to develop a new reusable re-entry system (e.g. Space Rider system) and some efforts have been funded through international projects to develop reusable launchers in the medium and long term (for instance, a 1 MN class, partly 3D-printed low-cost reusable engine, called Prometheus, reusable stage demonstrators, dubbed Callisto, and Themis).

The innovations proposed within the ESRE roadmap will be framed as building blocks of a unique final target and are related to the following main aspects:

- Innovative restartable engine with modular thrust including high Isp, low-thrust engine.
- CMC engine nozzle.
- Guidance, Navigation and Control algorithms for re-entry, decent and landing of stages.
- 3D printing/ALM components for engines.
- Descent and landing devices for descent and landing of stages.
- Ground segment (recovery, refurbishing).

For each of the technologies involved, the activity shall identify and prototype the key equipment and components at all levels (subequipment, equipment and subsystems) which would enable a step forward in reusability. The activities shall include an assessment of the cost effectiveness of the proposed new technologies expected for the exploitation phase (flight and ground operations). TRL 5/6 should be sought at completion of the short-mid-term period in view of a possible IOD/IOV in-flight demonstration, in agile mode as much as possible, as a next step. An estimation of the necessary investments and time schedule needed to reach TRL 8/9 will also be covered.

4. Added value and impacts for Europe

The proposed development roadmap can allow Europe to reduce the gap in reusable launch systems availability and enable a reduction in the launch cost and also decrease the cost of the European autonomy concerning “Access to Space”.

In a long-term perspective, mastering reusability on Earth would enable more feasibility in approaching inter-planetary missions, as the technology would then need only slight adjustments, the core being validated through repeatability of Earth-to-orbit missions.

Mastering reusability for every stage of a launcher would be a great achievement which could not only reduce launch cost of heavy-medium launchers, lead time from order to launch, and increase flexibility in launch date, flexibility in launch destination but also mitigate space debris. It would mitigate risk and increase opportunities for flying new technologies, new services and applications.

5. Key goals/technologies to be developed in the timeframe 2021–2023

The short-term objective of the ESRE Reusable Launcher development roadmap will include:

A. Definition of a reference RL system and development of key technologies up to TRL 4/5 including BBs.

The first objectives aim at identifying the reference system and mission requirements to properly feed the technology developments. The key technologies will in turn be developed not as stand-alone initiatives but rather framed by the target of a unique final system. Breadboards will be realised and the final TRL reached will be 4/5. In particular, the following targets are planned to be reached:

- Development of reference concepts for a reusable launcher.
- Development of thermal protection solutions able to withstand temperatures as high as 1700 °C (e.g. based on CMC materials) to be applied to exposed structures of different shapes. Material samples and breadboards will be realised and ground-tested in relevant environment.
- Development of Descent & Landing solutions for autonomous guided flight and precision landing through small-scale platforms via low-altitude drop-tests.
- Development of a low-cost reusable propulsion, with innovative components including green propellant, throttling capacity, thrust vector control, with realisation of a ground BB.
- Development of structures for launcher stages and inter-stages able to withstand cyclic loads and realisation of structural BB to be tested in relevant environment.
- Development of GN&C logic and algorithms for entry-decent-landing and testing on the ground in simulated environment.
- Development of health monitoring systems for structures and engines. Prototypes solutions will be tested in laboratory.
- Redesign, investigations into improving ground segment infrastructure, operations and logistics for highly frequent launches of RLVs.

B. Development and demonstration of ConOps.

In parallel, the ConOps of the Reusable Launcher re-entry flight until precision landing will be elaborated and designed. Development of numerical tools is also included in this target as simulation environment (flight simulator) to support the design and analysis of the trajectory during re-entry, descent, and landing phases.

6. Key goals/technologies to be developed in the timeframe 2024–2026

The mid-term objective of the ESRE Reusable Launcher development roadmap will include:

A. Maturation of the reference RL system and further maturation of most promising key technologies up to TRL 6/7 including flight demonstrators of technologies.

For instance:

- Realisation and testing of TPS demonstrators with increased representativeness and ground-testing in qualification environment.
- Realisation and flight testing of prototypes for descent & landing solutions with increased representa-tiveness.
- Further development of entry-decent-landing GN&C algorithms for testing on the ground in simulated environment and flight test on board flight demonstrators of parafoil-based platforms and vertical landing platforms.
- Development of a re-ignitable engine with development of a prototype demonstrator integrating all the components.
- Development of 1:1-scale structure demonstrators for launcher stages and inter-stages to be tested in qualification environment.

B. Development and demonstration of ConOps.

In parallel, the ConOps of the Reusable Launcher re-entry flight until precision landing will be matured via flight demonstrations by using the flight platforms with increased complexity (parafoil-based, winged-based) to replicate descent and landing phases both horizontal and vertical.

7. Key goals/technologies to be developed in the timeframe from 2027 onwards

The long-term objective of the ESRE Reusable Launcher development roadmap will include:

Development and flight demonstration of a prototype Reusable Launcher incorporating all the key technologies which have been raised previously at TRL 6/7 and replication of all the critical phases of the re-entry-descent-landing leg.

Synergies with Other Sectors

PRE-IDENTIFIED STRUCTURAL OPTIMISED PARTS DESIGNED FOR ADDITIVE LAYER MANUFACTURING (ALM) TO IMPROVE ONGOING OR NEW MISSIONS

1. Objectives

The general objective is to identify opportunities and necessities for specific S/C & launcher missions related to the development of structurally optimised ALM parts/components. The goal is to obtain better structural components with lower mass and the same or better structural properties than the traditionally manufactured concept. The mass reduction is considered as the main goal given the fact that every extra kilogramme of payload implicates significant costs to the missions.

2. Challenges

Even though ALM manufacturing is not a new technology, it is hard to get it accepted as an agreed manufacturing method for space components because of repeatability issues, powder manufacturing (which may provide contamination if not cleaned and checked thoroughly) even though there are a lot of concepts and studies that prove the benefits. The result may prove to be a step forward in considering ALM as an accepted manufacturing method. According to the available public research, a part made through structural optimisation and designed for ALM provides an impressive mass difference compared to a part made through traditional manufacturing.

3. State-of-the-art assessment and proposed innovations

There are already entities, which made progress in the ALM concepts for S/C or launchers, possibly in ESA projects and published part of their work.

The proposed innovations through the research done with respect to the technology addressed are applicable as follows:

- Develop and standardise an end-to-end process for space applications ALM manufacturing.
- Incentivise adoption of the technology at the industry level and offering the framework for ALM equipment improvements in terms of printing envelope, precision and tolerances.
- Increase of automation level in the manufacturing process, rendering the possibility of the complete production of parts allowing to minimise complex assemblies and to reduce the quality assurance processes.
- Enable in-situ process monitoring/control for further improvement of the process consistency and the ALM products' quality.

4. Added value and impacts for Europe

Europe will further improve its authority in the space sector by benefitting from cutting-edge technologies and methods, and identifying and enabling entities which will provide an end-to-end process for structurally optimised parts designed for ALM manufacturing.

By identifying additional opportunities in ongoing strategic missions or in new ones, the benefits will be represented by minimising the mass and the number of different parts enabling a simpler overall design and a lower mass as well as faster production time and cycles.

5. Key goals/technologies to be developed in the timeframe 2021–2023

Develop a structurally optimised part or component, designed for ALM manufacturing with respect to the identified opportunity or for the given necessity which shall be taken, given the initial inputs, from concept level to detailed design, having made in between structural analysis. The structural analysis shall be compared with a part designed to be manufactured through conventional manufacturing but keeping in mind also a list of pros and cons (i.e. manufacturing and post-processing cost, mass, ETA, structural properties. Manufacture a batch of identic parts by using methods to prove that the printed material has similar structural and microstructural properties on the entire outside volume of the targeted part which is intended to be manufactured.

Identify appropriate nondestructive testing/nondestructive inspection methods to verify potential criticalities like structural integrity, fusion, and loose powder. Qualify the batch of parts:

- Substantiating (a) stable & repeatable AM production process(es) and demonstrate the required material quality level and its consistency in order to qualify for space applications.
- Making a set of checks (mass, dimensions, etc.) and mechanical tests to verify the similarity between the ALM parts.
- Using the test results of each ALM part to compare them with the structural analysis.
- Using the test results of each ALM part to compare them with conventionally manufactured test results.

6. Key goals/technologies to be developed in the timeframe 2024–2026

In-flight validation of structurally optimised parts/components designed for ALM by using the learned knowledge and applying it for real missions.

Recurrent structural components of S/C and launchers that are currently manufactured through conventional methods and can be subjected to improvements by using structurally optimised parts/components designed for ALM to be re-designed and introduced in the manufacturing work-flow of space application suppliers.

7. Key goals/technologies to be developed in the timeframe from 2027 onwards

To achieve a high percentage of ALM technology usage in space applications in order to reduce mass, to integrate functions, to reduce assembly steps, in conjunction with faster production time and lowered cost through automation.

ABBREVIATIONS

Abbreviation	Explanation
AI	Artificial Intelligence
ALM	Additive Layer Manufacturing
AOCS	Attitude and Orbit Control System
A-RAIM	Advanced Receiver Autonomous Integrity Monitoring
ASIC	Application Specific Integrated Circuit
ATC	Air Traffic Control
ATM	Air Traffic Management
BB	Breadboard
Cal/val	Calibration and Validation
CFD	Computational Fluid Dynamics
CFRP	Carbon Fibre Reinforced Plastic
CMC	Ceramic Matrix Composite
CMOS	Complementary Metal Oxide Semiconductor
ConOps	Concept of Operations
COTS	Commercial off-the-shelf
DC	Direct Current
DIAS	Copernicus Data and Information Access Service
DOF	Degree of Freedom
EBB	Engineering Bread Board
ECSS	European Cooperation for Space Standardization
EDRS	European Data Relay Satellite
EGNOS	European Geostationary Navigation Overlay Service
EM	Engineering Model
EO	Earth Observation
EOL	End of Life
EQM	Engineering Qualification Model
ESFRI	European Strategy Forum on Research Infrastructures
ESRE	Association of European Space Research Establishments
FAIR	Findable, Accessible, Interoperable, Reusable
FET	Field Effect Transistor
FM	Flight Model
Gbps	Gigabit per second
GEO	Geostationary Orbit
GG	Gas Generator
GHG	Greenhouse Gases
GNC	Guidance Navigation and Control
GNSS	Global Navigation Satellite Systems
GovSatCom	Governmental Satellite Communications
GPS-INS	Global Positioning System - Intertial Navigation System
GST	Galileo System Time
HAPS	High Altitude Pseudo Satellite
HBT	Heterojunction Bipolar Transistor
IMU	Inertial Measurement Unit
IOD	In-orbit Demonstration
IoT	Internet of Things

ABBREVIATIONS

Abbreviation	Explanation
IOV	In-orbit Validation
IPCC	Intergovernmental Panel for Climate Change
IPDA	Integrated Path Differential Absorption
ISL	Inter-Satellite Link
Isp	Specific impulse
IXV	Intermediate eXperimental Vehicle
JFET	Junction Field Effect Transistor
LEO	Low Earth Orbit
LIDAR	Light Detection and Ranging
LoRa	Long Range
MEO	Medium Earth Orbit
MIR	Mid-Infrared
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NMI	National Metrology Institute
OS-NMA	Open Service Navigation Message Authentication
PTF	Precise Timing Facility
QKD	Quantum Key Distribution
R&TD	Research and Technology Development
RCS	Reaction Control Systems
RF	Radio Frequency
RI	Research Infrastructure
RLV	Reusable Launch Vehicle
RPAS	Remote Piloted Aerial System
RTO	Research and Technology Organisation
SAR	Synthetic Aperture Radar
SSA	Space Situational Awareness
SSO	Sun-synchronous orbit
SSTO	Single-stage-to-orbit
STC	Space Traffic Control
STM	Space Traffic Management
SWIR	Short Wave Infrared
Tbps	Terabit per second
TC	Thrust Chamber
TIR	Thermal Infrared
TPS	Thermal Protection System
T-RAIM	Time-Receiver Autonomous Integrity Monitoring
TRL	Technology Readiness Level
T&S	Timing and Synchronisation
TSTO	Two-stage-to-orbit
TT&C	Telemetry, Tracking and Command
TVC	Thrust Vector Control
UAV	Unmanned Aerial Vehicle
VHR	Very High Resolution
VNIR	Visible and Near Infrared
VTVL	Vertical Take-off and Vertical Landing

ESRE

The Association of the European Space Research Establishments – ESRE – was formally established in March 2016 as an international non-profit organisation. Present member organisations of ESRE are the national space research centres CBK (Poland), CIRA (Italy), DLR (Germany), INCAS (Romania), INTA (Spain), NLR (Netherlands), ONERA (France) and VZLU (Czech Republic).

Through ESRE, these national research centres strengthen their cooperation and propose European Research and Development (R&D) actions to advance science and technology both to support the competitiveness of the European space sector and to address the grand societal challenges.

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