ESRE

ASSOCIATION OF EUROPEAN SPACE RESEARCH ESTABLISHMENTS

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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, an extended version of this document (available online at **www.esre-space.org/publications**) contains an annex with 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.

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[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.

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.

www.esre-space.org