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Science Advisory Council

European space exploration: strategic considerations of human versus robotic exploration

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building science into EU policy

EASAC

EASAC – the European Academies' Science Advisory Council – is formed by the national science academies of the EU Member States to enable them to collaborate with each other in giving advice to European policy-makers. It thus provides a means for the collective voice of European science to be heard.

Its mission reflects the view of academies that science is central to many aspects of modern life and that an appreciation of the scientific dimension is a pre-requisite to wise policy-making. This view already underpins the work of many academies at national level. With the growing importance of the European Union as an arena for policy, academies recognise that the scope of their advisory functions needs to extend beyond the national to cover also the European level. Here it is often the case that a trans-European grouping can be more effective than a body from a single country. The academies of Europe have therefore formed EASAC so that they can speak with a common voice with the goal of building science into policy at EU level.

Through EASAC, the academies work together to provide independent, expert, evidence-based advice about the scientific aspects of public policy to those who make or influence policy within the European institutions. Drawing on the memberships and networks of the academies, EASAC accesses the best of European science in carrying out its work. Its views are vigorously independent of commercial or political bias, and it is open and transparent in its processes. EASAC aims to deliver advice that is comprehensible, relevant and timely.

EASAC covers all scientific and technical disciplines, and its experts are drawn from all the countries of the European Union. It is funded by the member academies and by contracts with interested bodies. The expert members of EASAC's working groups give their time free of charge. EASAC has no commercial or business sponsors.

EASAC's activities include substantive studies of the scientific aspects of policy issues, reviews and advice about specific policy documents, workshops aimed at identifying current scientific thinking about major policy issues or at briefing policy-makers, and short, timely statements on topical subjects.

The EASAC Council has 29 individual members – highly experienced scientists nominated one each by the national science academies of EU Member States, by the Academia Europaea and by ALLEA. The national science academies of Norway and Switzerland are also represented. The Council is supported by a professional Secretariat based at the Leopoldina, the German National Academy of Sciences, in Halle (Saale) and by a Brussels Office at the Royal Academies for Science and the Arts of Belgium. The Council agrees the initiation of projects, appoints members of working groups, reviews drafts and approves reports for publication.

To find out more about EASAC, visit the website – www.easac.eu – or contact the EASAC Secretariat at secretariat@easac.eu

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Foreword

EASAC, the European Academies' Science Advisory Council, provides science-based evidence and advice to European decision makers. It does so very often by producing reports or statements that synthesise a subject in a form suitable for a wide audience and focused on questions that are relevant to policy-making. After over 50 reports and statements by EASAC on issues of the environment, energy and biosciences, the present report is the first dealing with a space-related subject.

The area of space science is, however, of great importance for European policy. For one thing, space science touches upon many areas that deeply influence our daily lives. At the same time, it deals with matters at the heart of modern science. And European decisions on investments in space science also have an impact on other EU activities in science, technology and innovation.

After two EASAC member academies suggested formulating a position on the direction of EU space science from the EU's national science academies, an EASAC working group was set up in 2013, to produce independent science-based analysis and recommendations on specific space-related issues.

In view of an important ministerial meeting of the European Space Agency (ESA) in late 2014, it was decided that the group of experts nominated by EASAC's member academies should look specifically at questions related to the human presence in space. This subject has been at the centre of numerous informal as well as formal discussions over the decades. It was thought that now is a good time to approach the question in an independent and objective way.

The present report represents the result of the work of these EASAC experts. It is hoped that it will prove useful in the present discussions, and that it will lead to further work on this important question for European policies and commitment to space science.

Professor Jos W.M. van der Meer
EASAC President

Composition of the Working Group

Following a scoping meeting to define the objectives of the current study, all EASAC member academies were invited to nominate representatives. The following lists the members, fields of competence, member academy, and current relevant responsibilities:

Wolfgang Baumjohann, Graz *space research*	Austrian Academy of Sciences (AT) *Director, Space Research Institute*
Paul Callanan, Cork *astrophysics*	Royal Irish Academy (IE) *Committee, Astronomy & Space Science*
Thierry Courvoisier (chair), Geneva *astrophysics*	Swiss Academies of Arts and Sciences (CH) *President, Swiss Academy of Sciences*
Michele Dougherty, London *planetary science*	Royal Society (UK) *Chair, UK Space Advisory Committee*
Ari-Matti Harri, Helsinki *planetary science*	Council of Finnish Academies *Head, Radar & Space Technology, Finnish Meteorological Institute*
Stamatios Krimigis, Athens *solar and planetary magnetospheres*	Academy of Athens (GR) *Emeritus Head, Space Department, Johns Hopkins*
Ernst Messerschmid, Stuttgart *astronautics and exploration*	German Academy of Sciences, Leopoldina/Acatech (DE) *Professor, University of Stuttgart*
José Pereira Osório, Porto *astronomy and space science*	Academy of Sciences of Lisbon (PT) *Professor, University of Porto*
Jean-Loup Puget, Paris *astrophysics and space science*	Académie des sciences *Head, Committee on Space Research, Académie des sciences*
Giancarlo Setti, Bologna *astrophysics*	Accademia Nazionale dei Lincei (IT) *Emeritus Professor, University of Bologna*
Karoly Szego, Budapest *particle and space physics*	Hungarian Academy of Sciences (HU) *Hungarian Space Research Board*
Sigmar Wittig, Karlsruhe *mechanical engineering*	German Academy of Sciences, Leopoldina (DE) *former chair, German Aerospace Center, DLR*

with the support of:

Michael Perryman (expert secretary) *astrophysics and space science*	Academia Europaea
Christiane Diehl	EASAC Executive Director

Abbreviations and acronyms

ASI	Agenzia Spaziale Italiana (Italian Space Agency)
COSPAR	Committee on Space Research
CSG	Centre Spatial Guyanais (Guiana Space Centre, Kourou)
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre)
EASAC	European Academies' Science Advisory Council
ELIPS	European Programme for Life and Physical Sciences in Space
ESA	European Space Agency
ESF	European Science Foundation
ESSC	European Space Sciences Committee (ESF)
EU	European Union
GLONASS	Global Navigation Satellite System (Russian satellite navigation system)
GNSS	Global Navigation Satellite System (generic)
GPS	Global Positioning System (US satellite navigation system)
IAA	International Academy of Astronautics
IAF	International Astronautical Federation
ILEWG	International Lunar Exploration Working Group
ISECG	International Space Exploration Coordination Group
ISEF	International Space Exploration Forum
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JUICE	Jupiter Icy Moons Explorer (ESA mission)
MSL	Mars Science Laboratory
NASA	National Aeronautics and Space Administration (USA)
NRC	National Research Council (USA)
OECD	Organisation for Economic Co-operation and Development
PLATO	Planetary Transits and Oscillations of Stars (ESA mission)
R&D	Research and development
RTG	Radioisotope Thermoelectric Generator

Summary

‘Application-oriented’ space programmes, such as telecommunications, navigation, and Earth observation, are fully served by ‘robotic’ (i.e. fully automated) satellites. The same is true of scientific programmes probing most areas of astronomy and cosmology, where a human presence would even jeopardise the demanding environmental requirements of these state-of-the-art instruments. Yet the exploration of the nearby solar system (for example, the Moon and Mars) may be conducted in principle by either robotic vehicles and/or a human presence.

Politicians, advisory bodies, and funding authorities may find it difficult to penetrate the various arguments put forward to justify future space exploration, especially in this area where robotic and human spaceflight capabilities overlap. To provide guidance, we examine some strategic aspects of this potentially powerful robot–human partnership.

This report looks at some general aspects of space exploration, and opens a dialogue into the type of questions that are likely to be best satisfied by robotic vehicles, and those that may be best served by a programme of human space flight. Driving the latter are scientific enquiry (including life and engineering sciences), broader considerations of technology and economy, as well as more philosophical and political aspects such as curiosity, national prestige and international cooperation, along with the collective benefits of an increasing public and political awareness of space exploration.

The case for the augmented *scientific* exploration of the solar system is very strong. Specifically, there are numerous bodies whose more detailed investigation would substantially advance scientific enquiry, ranging from the inner and outer planets and their moons, to asteroids and comets. Their further exploration will be central to understanding many details of the formation and evolution of our solar system, as well as insight into questions of the origin and presence of life both here and elsewhere in the Universe.

We reiterate some of the well-known arguments for the economic and societal benefits of funding *pure science* and, specifically in this context, of space science missions. We argue that from the standpoint of advancing the astronomical sciences most effectively (within which we include fields ranging from the solar system to cosmology), human presence is not easy to justify, especially since evidence indicates that European funding in robotic exploration is already stretched compared with scientific aspirations.

A number of general recommendations related to the future European space exploration programme are presented. Indeed, a strategic plan for the cost share between robotic and manned missions in European space exploration, capitalising on technological advance and international cooperation, but without negatively impacting the future of pure scientific research, would be highly desirable.

The current considerations may be of interest to various broad audiences, including the European Space Agency (ESA); national governments in their role of funders of research and as funders and members of ESA; the European Parliament and European Commission; as well as for the media, general public, and younger generations, where interest and excitement in questions of space and space exploration is intense and broad ranging.

1 Introduction

1.1 Background to the present report

Space activities belong to three main categories, all with strong societal and cultural implications (for an alternative functional classification, see Appendix B). Moving progressively outwards from the Earth, these categories are the following:

- scientific, political and commercial activities dealing with the Earth, e.g. meteorology, climate, resources, communications, navigation, military and surveillance;
- activities related to the exploration of the solar system, typically scientific, and which may be either robotic or manned;
- astronomical research beyond the solar system, where all telescopes and associated operations are currently (and preferentially) automated (or 'robotic').

European policies and activities are reasonably well focused and organised on the first and last of these three categories, with the selections of missions in each of the areas being determined by evolving scientific developments and commercial priorities.

But after more than 50 years of space missions, with new countries such as China and India entering the field, and with scientific, commercial, political, and popular interest all on the rise, the category related to solar system exploration is in a more ill-defined state.

The reason for this present uncertainty and potential controversy is tied to the fact that, while deep space activities are restricted to purely 'robotic' (i.e. automated) observatories, the future exploration of the *inner* solar system may develop via robotic or manned missions, the latter coming with substantial financial and technological challenges.

In an atmosphere of competition for prestige, and industrial interests, there are substantial financial stakes. Politicians, advisory bodies, and funding authorities may find it difficult to distinguish between the various arguments put forward to justify future space exploration.

The goal of this EASAC report is to consider Europe's role in advancing scientific knowledge based on the balance and partnership of robotic and human space flight missions.

This report aims to provide guidance mainly from the perspective of the astronomical and solar system sciences, although the viewpoints of the more exploration-related members, as well as those of peer reviewers, have been incorporated. Different perspectives might be given by those looking at space with greater emphasis on human and life sciences, for engineering and materials science, or from the perspectives of industrial development, international collaboration, or political prestige.

1.2 Intended audience

The current considerations may be of interest to various broad audiences, including the following:

- the European Space Agency (ESA), notably for the directorates of Science and Robotic Exploration and Human Spaceflight and Operations;
- national governments in their role as funders of research, and as funders and members of ESA. An independent European-wide policy view should be of value, as well as further engaging individual EASAC member academies in the future;
- the European Parliament, the European Commission, the individual Commission Directorates General (specifically for Research, and for Enterprise and Industry), and the Commission's President and Chief Scientific Adviser;
- the media, general public, and younger generations, where interest and excitement in questions of space and space exploration is intense and broad ranging.

In all of these areas, an objective and strategic consideration of some aspects of the future of solar system exploration might begin a process with a significant impact on long-term European ambitions and policies.

The timing of this report takes account of the next ESA Ministerial Meeting (of national representatives) due to take place in December 2014.

2 Considerations in developing a strategic view

2.1 What is meant by space exploration?

The term ‘space exploration’ is used in different communities with rather different meanings, ranging from the purely scientific to the more philosophical. We will adopt, as an operational definition, that ‘*Space exploration represents the extension of human reach beyond the Earth’s atmosphere using spacecraft to access unknown terrains and environments, and to acquire knowledge about space, planets, stars, or other celestial bodies by human and robotic means.*’ Across the world, space exploration is carried out by more than 14 space agencies, which in addition to NASA and ESA, include those of Russia (Roscosmos), Japan (JAXA), China, and India[1].

From a *purely scientific perspective*, the exploration of the solar system has developed into an essential undertaking for understanding the formation of the solar system and of the Earth, and questions of planetology more generally. It also addresses questions related to the beginning of life on Earth, and the search for evidence for (past) life and biological activity elsewhere in the solar system and beyond[2].

From a *human space flight perspective*, space exploration represents the outward continuation of Earth-based exploration, which has advanced over many centuries. These activities, ranging from the Apollo programme, the current International Space Station activities, and future plans for manned missions to Mars, have a strong impact on the public. At the same time, associated costs are very large.

2.2 Motivations for space exploration

Various arguments can be put forward for space exploration in general:

- scientific: to increase our understanding of the solar system and of the Universe as a whole. Scientists frequently argue that the search for the underlying laws of physics, and for a deeper understanding of the Universe are, for a civilised and advanced society, powerful arguments for capital investment and research;

- unexpected spin-offs: as an extension of the pursuit of ‘pure research’, entirely unexpected and unpredictable spin-offs can eventually deliver substantial benefits to society, and related economic dividends[3];

- applied spin-offs: more calculated approaches to exploiting potential spin-offs arising from space research are being increasingly well coordinated. ESA’s Technology Transfer Programme (and its associated Business Incubations Centre), for example, has been set up to share the benefits of its research and development, making space sector technologies available to European industry;

- technology development: more immediately, space exploration provides new and inspiring challenges, requiring the direct development of new technologies;

- economic: these technological developments create new possibilities for innovation and economic growth (see Appendix C), spanning business opportunities for industry as well as access to new resources. This provides the strong motivation both for politicians and tax-payers to commit to their very high costs;

- industrial: related to both technology and economic return is the strong industrial interest to develop large-scale facilities and capabilities for space exploration;

- political: space exploration has the capability of spectacularly demonstrating national and international capabilities, and has the potential of fostering international cooperation in ambitious projects on an unprecedented scale, underpinning the ‘peaceful’ aspects of international collaboration. At the same time, individual countries, and Europe as a whole, do not want to be left behind in the commercial aspects of space exploration, but rather want to be considered as viable collaborative partners by other spacefaring countries and organisations. For Europe, this means maintaining a level of space exploration know-how such that other key players (USA, Japan, China, Russia, as well as emerging investors like India and Brazil) consider that it provides

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[1] The Space Data Coordination Group (www.ceos.org) provides a more complete compilation.

[2] As illustrations of these scientific quests, the particular case of Mars is widely considered as central to these investigations, but the moons of Jupiter and Saturn are important also: Europe built the Huygens probe which landed on Titan, Saturn’s largest moon, as part of the NASA–ESA–ASI Cassini mission, while JUICE was selected by ESA in 2012 to characterise three of Jupiter’s moons (Ganymede, Callisto, and Europa), all thought to have significant bodies of liquid water beneath their surfaces, as potentially habitable environments. The Rosetta mission, as part of a much broader scientific programme, is on track to place a lander on a comet, thus demonstrating Europe’s leadership in this field of robotic exploration.

[3] Among countless examples, Michael Faraday’s experimental work over several decades in the early 1800s established the observational basis of electromagnetism. James Clerk Maxwell turned this into his unified electromagnetic field theory, conclusively confirmed by Heinrich Hertz, which subsequently facilitated the technological developments of Edison, Bell, and Marconi in the latter part of the nineteenth century, and subsequently to the extensive foundations of modern society; (2) Einstein’s development of special and general relativity in the early 1900s, long considered to be of only theoretical interest, today forms a central and crucial base of all satellite navigation systems. Without its development over many decades, satellite navigation would not exist.

state-of-the-art science and technology, and is therefore a good partner to cooperate with.

- societal and cultural: space exploration offers extraordinary appeal to the public worldwide[4]. It raises public interest, inspires and develops scientific culture to new levels, and attracts young people toward scientific and technical careers.

We may conclude that the drivers are a complex mix of science, technology, economic development, geopolitics, and national image. Indeed, 'adventure' and even the simple aspect of the human experience of space flight are essential motivating ingredients to any long-term programme of space exploration.

2.3 The International Space Station

Bridging the scientific exploration of the solar system, and the long-term goals of human space flight, is the International Space Station (ISS). The ISS carries out experiments in human health and materials science which, at present, cannot be done easily on other space platforms, along with experiments in fundamental physics and Earth observation.[5]

In the area of human health, ISS research is providing advances in the understanding of ageing, trauma, disease and the environment. Biological and human investigations have provided an improved understanding of basic physiological processes normally masked by gravity, and the development of new medical technology and protocols driven by the need to support astronaut health, including telemedicine, disease models, psychological stress response systems, nutrition, cell behaviour and environmental health.

In the area of Earth observation and disaster response, the ISS allows observation of the Earth's ecosystems, with the possible advantages of human intervention and assistance which robotic Earth observation facilities are unable to provide.

In the area of micro-gravity science, the ISS has been central to the understanding of many phenomena in life sciences and technology.

Today, the ISS is the only human flight element of the European space programme. It has become a reliable facility, with experiments that can be planned with some confidence of execution. Fields now covered include micro-gravity research, medical and engineering sciences, chemistry, material developments, and fluid physics, with the number of experiments carried out having increased substantially over recent years. ESA's European Programme for Life and Physical Sciences (ELIPS) has produced many advances in a variety of scientific disciplines since its inception in 2001. Since the bulk of the substantial infrastructure costs for building and operating the facility are now in the past, its use for science, which has been greatly improved in recent years, should continue to be optimised.

Looking back to the origins of the ISS, the scientific community was not involved in the decision to build it. Rather, a substantial fraction of the scientific community was opposed to it, with concerns that its sheer magnitude would compete for funds with more immediately scientifically-justifiable projects. But while not primarily funded for science, this large-scale experiment now exists, and science is making good use of it. Such a situation is very likely to recur as space exploration develops.

Looking to the future, the USA is considering an extension in the operations of the ISS to around 2024. Meanwhile Russia, China, and Europe are considering their own prospects for future collaborations in this or new space station initiatives.

2.4 The ESA space science programme

In addition to its various national space programmes, European space exploration is underpinned by the highly successful ESA space science programme. Encompassing a broad range of medium and large astronomy and solar system missions, this programme builds on an advanced and diversified European science and technology expertise. It has provided an ambitious vision and strategic framework for European leadership in space science over the past two decades, and has been continuously re-assessed to do so over the coming 20–30 years.

Technical complexity frequently means that the lead times of pioneering solar system and astronomy missions are intrinsically very long, although it is important to distinguish between the longer timescales over which a particular vision or framework programme is constructed (e.g., the recent selection of the 'medium-class' exoplanet mission PLATO with a nominal launch date of 2022, and of the 'large-class' gravitational wave mission with a planned launch date of 2034), and the shorter 8- to 10-year implementation timescales which are targetted once a specific design concept has been approved. Combined with a pressing demand for flight opportunities dictated by scientific advance and international competition,

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[4] See, for example, the EC's 2014 Enterprise and Industry Eurobarometer survey 403 on Europeans' awareness and expectations of space-based activities and services (ec.europa.eu/enterprise/index_ en.htm).

[5] Further details can be found in the joint agency publication '*International Space Station Benefits for Humanity*' (NP–2012–02–003–JSC), and in the 2010 DLR report '*Forschung unter Weltraumbedingungen – Strategie 2025*' (Science under Space Conditions).

with some delays inevitably arising from unforeseeen technical complexities, launcher-induced delays, revised partnership agreements, or simply knock-on effects from other programmes, there is the general perception that ESA's robotic space exploration programme is financially restricted compared with Europe's ambitious scientific vision and leadership potential.

The fact that ESA's robotic missions come largely from a mandatory programme which has a fixed envelope agreed by Member States, whereas its human spaceflight programme operates more on an 'a la carte' principle, suggests that ESA's successful robotic programme should not suffer even if the appetite for human space flight programmes should expand in the future. But we nevertheless stress, given Europe's high aspirations and advanced technical and scientific capabilities, and the intrinsically long implementation timescales for today's state-of-the-art space missions, that European space science would probably suffer should existing funding be diverted from robotic missions to the intrinsically even more expensive human space exploration programmes.

2.5 Space exploration: the importance of a long-term strategy

Development of more advanced robotic missions, followed by manned missions to the Moon and Mars, are natural next steps in advancing our understanding of the solar system, and to explore the conditions for the origin of life. These are extraordinarily ambitious endeavours, with challenging technical and organisational requirements.

But more immediately, space exploration is confronted by problems and uncertainties in two major areas: the future of the ISS; and whether astronauts will return to the Moon or set foot on Mars.

The USA exercises historical leadership in this domain, but various changes in their policy (such as terminating the Apollo programme, withdrawing the Space Shuttle, cancelling the Moon return programme initiated by President George W. Bush, and more recent uncertainties in the context of their Decadal Surveys[6]) show the consequences of an absence of a long-term strategy demanded by such ambitious aspirations. Newcomers in the exploitation of space, such as Japan, India, and China, all want to acquire the status of a technological power of first order by following the tracks pioneered by the USA and Soviet Union in the 1960s.

European thinking, planning and implementation in the domain of space exploration is perhaps at a cross-roads. Ministerial declarations have stated that Europe wants to participate in space exploration, but the areas of focus have not been clearly and realistically articulated. The planning effort originally initiated in the framework of ESA's Aurora programme, for example, now appears to have been overly ambitious, and has since been reduced to the ExoMars mission (with an orbiter due for launch in 2016, and a lander in 2018). And the historical evolution of the ExoMars mission within ESA has delivered important lessons that indicate that the agency decision-making structures have found it difficult to organise the funding of a mission with objectives based in two Directorates.

While scientific considerations alone may not drive human space flight, wider considerations may imply that ambitious space exploration programmes, including human spaceflight, will happen sooner or later, perhaps (for example) under either American, Russian or even Chinese leadership: China has announced plans to send its own 'taikonauts' to the Moon within the next decade, while Russia has announced similar intentions. If it were argued, politically, that Europe could not be absent from such initiatives without a major loss of status, then it cannot realistically act only by passively following the lead of other spacefaring nations. Hence a clear European vision on the balance between robotic and manned space exploration is needed.

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[6] Kennel & Dressler (2014, Science, Vol. 343, pp140–141) quote the National Research Council's 2012 report '*NASA's Strategic Direction and the Need for a National Consensus*' which concluded that: '*There is no national consensus on strategic goals and objectives for NASA. Absent such consensus, NASA cannot reasonably be expected to develop enduring strategic priorities for the purpose of resource allocation and planning.*' They drew attention to the fact that key recommendations from the 2010–12 decadal surveys could not be implemented because of significant differences between expected resources and reality.

3 Possible component missions

3.1 Development of existing capabilities

With the next ESA Ministerial Meeting in December 2014 to be significantly focused on launchers (Ariane 5/6), there is the opportunity to consider Europe's strategic requirements. It is unrealistic to think that Europe's launcher policy will be influenced either by the continuation of the ISS activities or by large interplanetary missions, and it is likely (and financially desirable) that it should remain determined by non-scientific considerations for the foreseeable future. We nonetheless emphasize that a solid European-led exploration programme will require appropriate lift capabilities.

The next decade could also herald a major effort devoted to the development of astronautics: the techniques for providing mobility in planetary space. Whilst the financial burden of the construction of a very heavy man-rated launcher would be a major (and perhaps premature) step, Europe could nevertheless take part in a worldwide R&D programme on orbital operations, including automatic rendezvous, docking, assembly, fuel management, use of ionic engines, and manoeuvres in low-Earth orbit.

Today, human spaceflight, constrained to low-Earth orbit, presents somewhat limited public interest, but the preparation of the next development phases (such as long-duration flights) should include in-orbit manipulation of very large spacecraft in view of assembling large-scale transport options to the Moon and, in due course, to Mars.

Another important question is how to propel future outer planetary missions (at large distances from the Sun, where solar cells are impractical), as well as manned missions to Mars (where required durations are too long for fuel cells or batteries). RTGs (radioisotope thermoelectric generators) satisfy many of the requirements for missions that demand modest power. While there are issues with (plutonium) RTGs in the USA, their availability since the 1960s has helped make the USA the leaders of long-distance planetary exploration, and exploration much beyond Mars is widely considered to be unfeasible without them. Europe does not have RTGs, although it possesses the technical capabilities for making them (using the isotope americium 241).

3.2 The International Space Station

In this programme, the International Space Station (ISS; with an extension of its operational lifetime to 2024 currently under consideration by NASA) could play a central role which has not been particularly clearly formulated to date. Options might include the following:

- defining the infrastructure priorities for servicing and cargo transportation, whether by Ariane 5, by Soyuz launched from Centre Spatial Guyanais (CSG), or by other commercial vehicles;
- strategically maintaining the options for human access to low-Earth orbit;
- more effective exploitation of the ISS for the physical, life, and engineering sciences, and by the scientific community more generally (for example, involving explicit 'Announcements of Opportunity' for engineering sciences);
- articulating the role of the ISS in terms of human biology, especially in the context of future missions to the Moon or Mars;
- defining more specifically what the ISS can contribute to the long-term development of human space flight (such as transportation systems, robot–human interfaces, and advanced life-support systems);
- expanding and enhancing its capabilities for education, which the astronauts on board have undertaken with great success, and further publicising its scientific work and potential.

3.3 Human-assisted robotics

A simple trade-off on the advantages and disadvantages of humans in space science missions risks leaving out what may be a likely scenario of the future: that of human-assisted robotics, in which the emphasis is more on collaboration and mutual interaction, rather than on competition. Examples may be human habitation of low-Earth orbit structures, like the ISS, which can provide substantial platforms for the assembly and launch of larger robotic planetary missions, or by using humans in a Mars orbit to operate sample return robots without the long control delays implied by the Earth–Mars signal transit. There may be other ways in which astronomy and planetary science could secure and develop benefits from manned programmes (along the lines of the five repair and maintenance missions to the HST). Since the 1960s, NASA and then the Russians, Europeans and Chinese have all found it politically viable to fund, at huge costs, manned spaceflight. It seems likely that scientists will have to benefit where and when they can from a manned space programme funded for a range of reasons, perhaps few if any being scientific.

3.4 Targets of solar system exploration

There are large numbers of bodies (planets, moons, asteroids, and comets) and various 'locations' (such as low-Earth orbit, geostationary orbit, the Sun–Earth 'Lagrange' point L2, etc.) that command considerable scientific interest. The intention of this report is not to attempt a detailed scientific prioritisation, but to give some *examples* of the focus of exploration targets in the solar system. But a little background should help with orientation.

Mercury is considered to be a cornerstone for understanding some aspects of the formation and evolution of the solar system, although the scientific questions that will be outstanding following the ESA–JAXA BepiColombo mission and the NASA Messenger mission remain to be seen. Jupiter is another such 'cornerstone' planet, and it is orbited by the highly interesting moon Europa. Comet and asteroid missions are also scientifically crucial to advancing our understanding of the formation of the solar system.

To this extent, the panorama is wide open for follow-on missions to Mercury (after BepiColombo), to Venus (after Venus Express), to Jupiter, Saturn and their moons (after Cassini and JUICE), and to comets and asteroids (after Rosetta). All are likely to have valid scientific goals, with potential impacts on questions of habitability and the ongoing debates on the origins of life.

The Moon, however, figures particularly prominently in discussions of the development of future robotic and human missions, aided by its relative proximity.

The exploration of Mars, whilst immensely challenging, is still easier than for Mercury or the Jovian system. At the same time, its scientific importance includes the fact that it has similar (if not so complex) atmospheric dynamics as the Earth, being of central relevance for determining how common and diverse life may be in the Universe (an important question for scientists and tax payers alike), while offering the potential of sample return missions that are probably central to understanding potential biological activity, past or present.

We intentionally do not expand on the ongoing debate on the commercial exploitation ('mining') of solar system bodies (such as tritium mining on the Moon, or platinum-group mineral mining from passing asteroids), since the possibilities are still somewhat too premature and contentious for further consideration here.

Finally, we emphasize that notwithstanding the importance of advancing our knowledge and understanding of solar system bodies, these studies also provide the crucial foundations for corresponding research into the wider nature of the Universe beyond.

3.5 Exploration of the Moon

3.5.1 Scientific justification

Arguments for the continued scientific investigation and exploration of the Moon, whether by remote or *in situ* observations, are numerous[7]. Objectives, ranging from purely scientific to more applied include the following:

- understanding the origin of the Earth–Moon system;
- understanding the detailed origin of the Moon;
- understanding the (internal and surface) mineralogical composition;
- appreciating its economic value (e.g. for surface exploitation or mining);
- understanding cratering implications for formation, and (Earth) impacting bodies;
- understanding the dynamical evolution of the solar system bodies;
- understanding the effects on long-term climate change;
- its relevance in understanding the origin of life on Earth;
- consideration of an astronomical observatory on the lunar far side.

In summary, lunar investigation and exploration currently appear as an important component of future space exploration programmes. Nevertheless, most if not all of the above can be fully conducted by robotic remote-sensing orbiters or landers.

3.5.2 Robotic exploration of the Moon

Pilot studies. Various studies have been made of lunar bases over the past 10–20 years. Among these, the ESA considered a lunar base for astronomical observations, but this generated relatively little scientific interest, especially considering the practical environmental restrictions such as surface dust and seismology[8]. Similar conclusions related to sample return studies performed in France, while a comparable study was performed in Germany around 2010, but was discontinued due to insufficient funding.

The Robotic Village. Elaborated and studied by the International Lunar Exploration Working Group (ILEWG), the Robotic Village has been conceived as an umbrella coordinating the various national robotic missions to the Moon. Specifically, the ILEWG community has

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[7] Broad and extensive reviews of the scientific justification for the exploration of the Moon include '*Mission to the Moon*', ESA SP–1150 (1992), and '*Why the Moon?*', proceedings of the International Lunar Workshop, ESA SP–1170 (1994).

[8] *A proposed medium-term strategy for optical interferometry in space*. Report to the ESA astronomy working group by the ESA Space Interferometry Study Team (SIST). J. Noordam et al., ESA, 1990.

recommended a sequence of technology, exploration and commercial missions on the path to human Moon presence. This includes a phased approach with orbital reconnaissance, small landers, a lander network for science and exploration, advanced robotic missions with the deployment of large infrastructures and demonstrating resource utilisation, followed at some unspecified point by human arrival.

Such a programme is intended to initiate and enhance international collaboration, as well as scientific, commercial and public engagement opportunities. Various infrastructure assets such as telecommunications and power generation could be shared by the international partners. Notwithstanding its flaws, the ISS has shown that a major cooperative joint venture in space is feasible. A Global Lunar Robotic Village could further encourage and stimulate peaceful and progressive exploration, and foster cooperation between nations, space agencies and private companies.

The European Lunar Lander. Alongside these ambitious ideas, a European Lunar Lander was proposed to the last ESA ministerial meeting. Its consideration illustrates the type of problems that ESA may encounter when looking at lunar exploration in the future. The funding request to the optional programme was €650 million, for a stationary, technology demonstration mission, with almost no science, and taking some 6 years to build. Yet if robotic exploration of the Moon in a European context is to be successful, it must presumably occur quickly and cheaply. Even acceptance of a European Lunar Lander today would lead to a static lander on the lunar surface at least 7 years after China's Jade Rabbit. Furthermore, ESA's lunar mission Smart-1 failed to initiate a revival of lunar science in Europe. Concerted action would presumably be necessary to change this situation.

3.5.3 Human exploration of the Moon

From a purely *scientific* standpoint, a lunar human base is far harder to justify, and the scientific case for it would need to be carefully examined. The drive for human presence on the Moon may be argued from the point of view of pioneering exploration, technological development, inspiration of our citizens (especially our younger minds), and national prestige. But for most of the scientifically-driven investigations, robotic missions are likely to provide all of the technical capabilities required for the foreseeable future.

We note that the added value of human lunar landings or bases may be re-evaluated if rather higher personal risks (and therefore significantly reduced costs as well as timescales) for the astronauts could be accepted (see section 4.4), thus making more optimum use of the flexibility that the brain provides. Investments in human space flight being substantial, the advantages if such investments were instead made in automatic/robotic technology development would also need to be considered.

We recognise, again, that manned missions can generate considerable public interest, although human flights to and from the International Space Station (ISS) today generate much reduced interest among the general public. They may increase the popularity of space exploration among politicians and tax payers, although they also have their critics.

In summary, while current *scientific* exploration requirements do not demand a human presence on the Moon, history (in the form of the Apollo and the ISS programmes) has shown that space science can take advantage from human as well as robotic space flight. At the same time, if, in the future, goals are identified that cannot be achieved using current technology, then these should first be used as a driver for greater technological and robotic innovation, rather than as an immediate motivation for manned missions. As well as being more cost effective, this approach is likely to yield more immediate economic dividends.

3.6 Exploration of Mars

3.6.1 Scientific justification

Scientific drivers for the exploration of Mars include establishing the following:

- whether life ever started on Mars, and whether conditions for long-term life sustainability were ever attained;
- how Mars has evolved over time, characterising the origin and evolution of its atmosphere, hydrosphere, cryosphere, lithosphere, magnetosphere and deep interior;
- to what extent the present surface conditions of Mars are supportive or hazardous to life, both to putative indigenous or terrestrial life forms (including humans).

3.6.2 Robotic exploration of Mars

There are two distinct drivers inspiring robotic missions to Mars. The first is science-driven (section 3.6.1): that is, pursuing specific goals that will help to understand the possible origin of life beyond Earth, and the evolution of a rocky planet. The second driver involves the preparation, in terms of technology development and demonstration, for the human exploration of the planet.

Various nations and organisations have plans to develop advanced robotic missions to Mars, with some long-term intentions to send humans. These include the following:

- the USA has a number of robotic missions currently exploring Mars;

- ESA has sent robotic probes, with ExoMars planned for 2016 and 2018;
- Russia/Soviet Union has sent numerous probes;
- Japan has sent one robotic mission, Nozomi;
- China's Yinghuo-1 was lost with Russia's Phobos sample return mission, Fobos-Grunt;
- India launched an unmanned Mars orbiter (Mangalyaan) in November 2013.

Mars Sample Return is a challenging series of missions which gathers several key technologies, and has been studied both in the USA and in Europe (e.g. the i-Mars scenario in the framework of the International Mars Exploration Working Group, comprising separate launchers for an orbiter and lander, and considered for the early 2030s).

Developing a *coherent suite* of progressively enhanced robotic missions for Mars would allow a progressive refinement in our understanding of the planet's detailed nature, whilst facilitating the development of a manned mission at some time in the future. Should it be that some specific *scientific* goal cannot be carried out by robotic missions as currently conceived, this would also motivate the development of innovative technologies.

3.6.3 Human exploration of Mars

The next foreseeable steps in the *scientific* exploration of Mars neither require nor obviously benefit from a manned mission. Nevertheless, manned missions have been the subject of engineering and scientific proposals since the 1950s, including plans to land, settle on and terraform its surface, and even to exploit its moons Phobos and Deimos.

With typical Mars missions having round-trip flights of 400–450 days, and overall durations of 1000 days including a 500-day stay (dictated by synodic alignment), several key challenges for a human mission to Mars (some of which also apply to robotic missions) have been identified.[9] In addition to substantial costs, these include the following:

- the development of a suitable launch vehicle;
- the health threat from exposure to solar and higher-energy Galactic cosmic rays;
- the effects of low gravity on muscle and bone growth;
- the psychological effects of isolation from Earth[10];
- the social effects of living under crowded conditions for more than a year;
- the inaccessibility of terrestrial medical facilities;
- the reliability of life-support systems for the interplanetary travel phase;
- the efficiency and reliability of associated recycling systems;
- the development of suitable (supersonic retro-propulsion) landing systems;
- the reliability of life-support systems for a 500-day stay on Mars;
- the physical and psychological effects of extended (many months) surface dust storms;
- the energetics of escaping from the Martian surface;
- the availability of fuel, particularly challenging for the return trip;
- avoiding forward-contamination of potential habitable zones;
- avoiding back-contamination of Earth with possible Martian microbes.

For these reasons, a human mission to the Martian surface is generally considered to be implausible in the near future. Nevertheless, ESA's Aurora programme (of which ExoMars is part), established in 2001, was set up with the objective of implementing a long-term European plan for robotic and human exploration of the solar system.

Again, notwithstanding their scientific relevance, manned missions have the potential to generate significant public interest and inspiration, and could increase the popularity of space exploration among both politicians and tax payers. But, as in the case of human missions to the Moon (section 3.5.3), careful consideration should be given to contrasting the advantages of such human exploration developments, with the returns expected if such investments would be invested in robotic technology developments.

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[9] Examples from the substantial literature include a review of the political, economic and cost–benefit aspects, as well as technological and biological feasibility, by Ehlmann et al. (2005, Acta Astronautica 56, pp851–858), and an analysis of the health issues by Horneck & Comet (2006, ASR 37, pp100–108).

[10] See, for example, the Mars-500 psychosocial isolation experiment (en.wikipedia.org/wiki/ MARS-500) conducted between 2007–2011 by Russia, ESA and China.

3.6.4 Costs of a human mission to Mars

Estimating the cost of a human mission to Mars is itself challenging, with many issues still unknown, and the technological challenges necessarily based on a wide-range of assumptions. Indicative estimates for a round-trip mission, including a presence at the Martian surface for a few months, range from $10 billion to $500 billion.

The lowest estimates are based on optimistic costings, for example for the MarsOne mission, with no return option for the crew[11]. The higher-end estimate is based on the actual cost of the ISS as a yardstick, which was about €100 billion[12]. A manned Mars mission requires launching roughly the same mass as the International Space Station (ISS) from Earth, with about one-tenth of that mass (40 tonnes) deployed on the Martian surface[13]. Since the largest unit deployed to the Martian surface to date has been the Mars Science Laboratory, of the order of one metric tonne, some loose extrapolation suggests an upper cost envelope of around $500 billion for a human mission to Mars. Even so, many of the challenges in such complex and pioneering ventures are frequently under-estimated, with the final cost and development time of the International Space Station (ISS), for example, both originally underestimated by a factor of 10.

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[11] www.mars-one.com/faq/finance-and-feasibility/how-much-does-the-mission-cost

[12] www.esa.int/Our_Activities/Human_Spaceflight/International_Space_Station

[13] www.space.com/20999-nasa-manned-mars-missions.html

4 Elements of a coherent European vision

4.1 Determining scientific priorities

The position of the European Commission, and others, provides a clear framework for a focus on space activities across Europe, but leaves open the questions of how best to decide scientific and strategic priorities. Various considerations are relevant, not necessarily in fixing priorities, but in reflecting on how to decide them:

- considerable financial resources are required for any pursuit of space use;
- continued and future investment in space research, exploration, and utilisation is considered crucial for future European development;
- mastering space technologies is crucial in ensuring, in strategic areas, the leadership of Europe, not to say independence, on the world scene;
- a long-term, ambitious vision of the future direction of space exploration would assist the choices facing national and international bodies;
- at the European level, scientific guidance as an aid to decision-making should be, as far as feasible, independent of national priorities and industrial interests, while recognising that many wider considerations enter the final debate (such as national priorities, industrial return, security, and prestige);
- one essential ingredient of these discussions is the appropriate balance in the potentially powerful robot–human space flight partnership;
- a requirement for proactive space law, which assesses initiatives that may come from space organisations beyond Europe (USA, Russia, Japan, India, China, etc.).

4.2 International cooperation

Numerous factors, some rather self-evident, enter into any considerations of international collaboration. Among these are the following:

- it should be considered mandatory that Europe retains an independent and authoritative space capability;
- precursors to the consideration of possible collaborations should include a clear definition of the scientific and technological objectives, and a robust estimate of development, infrastructure, and operational costs of any facilities;
- the reliability of potential partners should be carefully assessed before embarking on capital-intensive and long-term collaborations;
- given that space activities, especially the ambitious activities involved in any long-term vision, are so expensive, it seems inevitable that a European space policy should be based on a broad cooperation;
- within the coherent programme, there should be a clear separation between fully autonomous European components, activities where Europe can take a leadership role, and activities where it can be only a participating partner;
- international cooperation will be mandatory for Europe to benefit from the experience of other spacefaring nations and organisations and, conversely, to provide benefit to others;
- somewhat idealistically, stronger worldwide governance, at something like the level of a UN space agency, might assist the development of a long-term programme.

4.3 Relevant timescales

As a guide to the timescales of relevance to the future of space exploration, and its associated decision-making, we make the following observations:

- accumulated expertise (scientific, technical, and managerial) should not be allowed to lapse or disappear, since deep technical expertise requires considerable overhead in time and resources to regenerate. This consideration requires and drives a coherent programme with well-defined development continuity;
- individual components in any long-term plan should have associated execution timescales of not much more than 10 years: this is a conclusion arising from studies and experiences of large-scale projects dictated by considerations including individual and collective motivation, management milestones, and progress tracking;
- certain critical timescales are related to the development of our societies, where limits to growth, and the more sustainable use of resources, drive development timescales of 20–30 years. Certain global issues faced by humanity today will presumably look to science for their resolution. Among these are climate change, energy availability and reliability, and medical advances. Further, and probably continuous, scientific and technological breakthroughs are needed, and the basic and applied research stimulated and catalysed by space research and exploration may provide some of these advances;

- on even longer timescales of hundreds or thousands of years, 'outward migration' may be driven by issues such as human conflict or resource depletion. On timescales of millions of years or more, this could conceivably be driven by natural if very rare or distant-in-time calamities such as near-Earth object impacts or changes in the energy output of the Sun. On these far distant horizons, more ambitious space flight goals to secure the destiny of humanity may be perceived as mandatory, but they have no impact on the present considerations.

4.4 Risk

As soon as human space flight is considered, the currently accepted wisdom is that risk to human life (in terms of launchers, survival systems, space travel, and return to Earth) must be suppressed to extremely low levels of probability.

Yet it is important to emphasise that significant reductions in risk come with enormous, and potentially prohibitive, technical penalties and financial costs. While it is difficult to quantify the trade-off between risk and cost, it is perhaps plausible to suggest that each factor-of-10 improvement in failure probability might come with a factor 10 increase in cost. Thus lowering the probability of failure from 10% to 1% might increase the cost by a factor-of-10 or more. Lowering the formal chance of failure to 1 part in 1000 might cost 100 times that of a system with a failure probability of 10%. But whatever the formal probability estimates, significant advances in space exploration will always carry some risk to human life.

Quantifying these risks will always be difficult, but a comparison with the historical levels of risk as commercial aviation developed might provide a useful guide. Another real example is the US Space Shuttle programme, with its 134 flights and two complete losses. If this level of risk seems to have been acceptable to funding agencies, then using cost information parametrically based on the Space Shuttle programme could give a more realistic picture for the future.

It may be that the next steps in the human exploration of space can only be considered, at least at realistic funding levels, if much higher risks to human life are considered acceptable. Such risk acceptability is an issue not only for the astronauts themselves, but also for the societies that sponsor them.

To take a specific and relevant example: there are no known means of delivering humans to Mars while avoiding radiation doses that would be illegal on Earth, and it is far from clear that publicly funded organisations could undertake to do so.

In a very real sense, space exploration is analogous to the discovery and settlement of the New World. Hence the term 'pioneering the space frontier' is most appropriate, and it may be that risk and sacrifice must be seen as inherent. In the face of this heritage and the realities, it could even be argued that today we face another very real danger: that the flame of adventure may flicker as society becomes more averse to taking chances. If the public, and politics, demand only perfection, and if we can accept only success, we cannot take chances, and advances may falter.

It may indeed be that human passage to Mars, the establishment of a Martian base, or habitable stations at the Sun–Earth Lagrange point L2 (the next 'space location of interest' beyond the low-Earth orbiting ISS orbit) will only be feasible on foreseeable timescales if accompanied by some changes in society's perception and approach to risk.

5 Conclusions

The future offers enormous possibilities for space exploration on many fronts. History assures us that this progress will be exciting and highly rewarding, but at the same time somewhat unpredictable, and with occasional setbacks.

But we also emphasise that continued investment in these various areas, including basic research, brings diverse contributions to society, ranging from technological development with new knowledge, innovative services and economic growth, to education and inspiration, and even international stability.

Europe has demonstrated a remarkable potential for innovation and leadership in the past, and has the opportunity to continue to do so into the future. There are many ingredients, and there will be many viewpoints and perspectives on how this should best be achieved.

The goal of this contribution has been to identify, from the perspective of scientific advance, some of the possibilities for the future directions and balance of the powerful and exciting robot–human space flight partnership.

The recommendations that follow aim to distill some of the many considerations entering this complex debate.

We hope and expect that the present report will help in shaping European views in the context of ESA's future ministerial meetings, and that it will also provide a useful starting point for the development of further, possibly more concrete, European perspectives in space.

6 Recommendations

Based on the arguments developed here, we make the following recommendations.

1. Europe should intensify its efforts to advance at the forefront of scientific and technological capability in space, aiming to ensure technical non-dependence while maintaining the highest scientific quality.
2. Long-term European space exploration programme should be based on a well-identified and autonomous component within a global cooperation framework, exploiting Europe's highly-developed and advanced scientific and technological capabilities.
3. Future *scientific* exploration of the Moon through robotic vehicles may eventually clarify whether subsequent steps could benefit from robotic or human presence.
4. Plans for a *scientific* exploration programme of Mars, perhaps even over the next 20–30 years, should be consolidated, but need not explicitly include a human presence, for which no compelling scientific arguments have so far been advanced.
5. ESA, in dialogue with its stakeholders, should consider how it could be better structured to discuss, formulate, and agree on a more effective strategy for planetary exploration using whatever assets (robotic, human-assisted robotic, or human) that might exist.
6. Strictly scientific considerations should not necessarily rule out a European participation in a broadly-based international human presence in deep space (including asteroids, the libration points, the Moon or Mars), which may bring other advantages (including socio-economic or technological).
7. If the operational phase of the International Space Station is extended, Europe should aim to exploit its capabilities fully. Appropriate assessments of its productivity should be made as thoroughly as for other disciplines.
8. The future development of European space facilities and infrastructure (for example, heavy-lift vehicles, deep-space telecommunication relays, and power supplies for missions beyond Mars) should be capable of supporting the target exploration programme.
9. Given that the highly successful European space science programme is already heavily constrained financially in delivering its full potential in a timely manner, existing resources should not be diverted from robotic to human exploration components with the justification of addressing fundamental scientific questions.
10. A wider dialogue should be initiated between agencies and stakeholders on acceptable levels of risk in space exploration.

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Notwithstanding these very useful comments, the Working Group emphasises that responsibility for the content rests exclusively with those named on page vii.

Appendix 1 The context of EASAC advice

Various advisory committees are associated with Europe's national space programmes, European-level activities (most notably, ESA), and European industries. Beyond Europe, both national programmes (in the USA, Japan, China, and India) and international bodies (including the IAA and IAF) have their own advisory structures and priorities.

On such a costly but strategic issue as space exploration at the European or multi-national level, scientific advice should be objective and, as far as practically feasible, decoupled from national priorities and industrial interests. To assist defining priorities, scientific guidance at a European level is clearly desirable.

The European Academies' Science Advisory Council (www.easac.eu) is an umbrella organisation comprising the national science academies of the EU Member States, Norway and Switzerland. EASAC enables these various academies to collaborate, and to provide independent advice to European policy-makers. Accordingly EASAC can call upon extensive academic knowledge and authority, and can aim to bring a degree of independent and objective advice even beyond that of its representative academies.

As stated in its mandate, '*EASAC provides a means for the collective voice of European science to be heard. Its mission reflects the view of academies that science is central to many aspects of modern life and that an appreciation of the scientific dimension is a pre-requisite to wise policy-making. This view already underpins the work of many academies at national level. With the growing importance of the European Union as an arena for policy, academies recognise that the scope of their advisory functions needs to extend beyond the national to cover also the European level. Here it is often the case that a trans-European grouping can be more effective than a body from a single country.*'

Because many experts in the field are inevitably affiliated to particular international organisations, research programmes or missions, the composition of any EASAC working group, and the topics that it tackles, must be carefully structured. This EASAC study specifically aims to be focused on strategic questions of policy, science and more general impacts on European society. In contrast, issues of implementation and detail rightly belong to the individual institutions and their (scientific) advisory groups.

The present working group covers a broad range of scientific expertise, predominantly in the areas of astrophysics and planetary science, with incomplete or marginal coverage in other important areas such as life and material sciences. This reflects the perspectives emphasised in section 1.1.

Appendix 2 Functional overview of space activities

As an alternative to classifying space activities by 'operational location' (section 1.1), they can be divided loosely into different – and partly overlapping – functional categories. This classification is included here for reference, with possible future applications indicated in italics:

- scientific investigation
  - low-Earth orbit observatories (namely ISS and MIR, partly scientific)
  - Earth-focused (e.g. probing the radiation belts, gravity field, etc.)
  - solar system research, ranging from the Sun, to planets and asteroids
  - astrophysics and cosmology, over a wide range of wavelengths and objectives
- exploration
  - lunar exploration and landing, including bases for scientific observation
  - solar system exploration, including flybys, orbiters, and landers
  - *lunar and Martian bases*
- civilisation well-being and improvement
  - meteorology, telecommunications, microgravity (including life sciences research)
  - Earth observation, including resource management
  - global navigation satellite systems (GNSS): GPS, GLONASS, Galileo, etc.
  - their role as a technology driver for engineering, material science, etc.
  - *space debris removal*
  - *long-term human survival in the face of human-made and natural disasters*
- catastrophe mitigation
  - space weather: potentially affecting power distribution and communications
  - volcanic risk monitoring
  - *near-Earth asteroid detection and avoidance*
  - *earthquake prediction*
- military
  - communications, navigation and surveillance
- more speculative future economic possibilities, such as
  - *space solar power*
  - *lunar, planetary, or asteroid mining*

Appendix 3 Economic considerations

Economic considerations, including affordability and effects on growth, are central to any discussions of space science and space exploration, whether in the context of basic or applied research, and whether related to robotic or manned exploration. Naturally, even basic scientific research (such as solar system exploration, astronomy and astrophysics, and cosmology) cannot be decoupled from questions of affordability, value for society, and industrial development and return.

Space is now universally recognised as an essential tool of our civilisation, providing key services for telecommunications, GNSS-satellite positioning, environmental surveillance, meteorology, crisis management, and science. Accordingly, it is widely supported by governments and private operators.

In very broad terms, figures for 2013 (from www.euroconsult-ec.com) suggest an expenditure of some €200 billion worldwide, with US government spending being about $40 billion. Across Europe, the space sector has been estimated to generate civil and military annual sales of some €5.5 billion, and to employ around 33 000 people.

Direct economic return

The investments in space programmes are often justified by the scientific, technological, industrial and security capabilities they bring. But these investments can also provide interesting socio-economic returns such as increased industrial activity, and bring cost efficiencies and productivity gains to other fields (e.g. weather forecasting, telemedicine, environmental monitoring and agriculture previsions).

In most European countries, space programmes are contracted out to national industries. Although detailed economic impacts vary, documentation of positive industrial returns from institutional investments are growing[14].

Analysis by the OECD Space Forum (www.oecd.org/futures/space) provides estimates of the economic return on investments in space across Europe. As examples, they give the following figures for 2009: in Norway, an investment of NOK1 million provided a return of some NOK4.7 million. In Denmark, €1 million of Danish contributions to ESA generated a turnover of €3.7 million. In the UK, the space industry's value-added multiplier is estimated to be 1.91. In the US commercial space transportation industry, the factor is 4.9. At the upper end of the scale, NASA claims a 7:1 return for every US dollar spent in the space programme.

The link between basic research and prosperity

The distinction between basic research and applied R&D is essentially a distinction between discovering the laws of nature, and harnessing them for practical purposes.[15] These categories of knowledge production are linked, and are interdependent. Quoting the out-going President of the Max Planck Society, Peter Gruss[16]: '*80% of economic growth in the industrialised countries results from the development of new technologies. And it is research, after all, that contributes vital ideas for new technologies*'.

Although more classic economic theories largely ignore the role of investment in basic research in economic prosperity, various attempts have been made more recently to quantify their link. In the class of economic theories characterised by 'endogenous growth', technological progress is generated by accumulation of knowledge. An important result of these models is that growth is strongly dependent on spending on basic research, and indeed ceases without it[17].

The fact that there is no clear consensus on this question is probably reflected in the varying percentage of gross national product that is spent on space R&D by each country, and their contribution to ESA. Estimates by www.euroconsult-ec.com indicate that the current annual expenditure on space per capita ranges from $12 (0.03% of GNP) in the UK, $17 (0.05%) in Italy, $19 (0.04%) in Germany, $44 (0.10%) in France, and $150 (0.32%) in the USA.

That basic research is likely to be indispensable as a catalyst for wealth improvement and societal advance endorses the precepts and goals of the Lisbon Strategy[18].

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[14] See, for example, www.oecd.org/sti/inno/1822844.pdf for an assessment of the ESA programmes.

[15] A more considered definition is given in the OECD's *Frascati Manual for Research and Development Statistics* (2002, p30). There, basic research is defined as '*experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundation of phenomena and observable facts, without any particular application or use in view*'. In contrast, applied research is '*directed primarily towards a specific practical aim or objective*', while experimental development is defined as '*systematic work drawing on existing knowledge gained from research and/or experience which is directed to production*'.

[16] *Max Planck Magazine* 2012, issue 4, p6.

[17] See, for example, 'Basic Research and Prosperity: Sampling and Selection of Technological Possibilities and of Scientific Hypotheses as an Alternative Engine of Endogenous Growth', C.A. van Bochove (CWTS–WP–2012–003, 2012).

[18] The Lisbon Strategy (or Agenda) was an action and development plan, set out by the European Council in Lisbon in March 2000, for the economy of the EU between 2000–2010. It was intended to deal with low productivity and stagnation of economic growth through various policy initiatives. Its aim was to make the EU '*the most competitive and dynamic knowledge-based economy in the world capable of sustainable economic growth with more and better jobs and greater social cohesion*'. Concrete measures included the extension of the Framework Programmes for Research and Technological Development into FP7, and the Joint Technology Initiatives. By 2010, most of its goals were considered not to have been achieved.

Appendix 4 Other considerations on space exploration

A Viewpoint of the European Commission

In 2011 the European Commission published a communication: '*Towards a space strategy for the European Union that benefits its Citizens*' (Brussels, COM(2011)152).

They argued that: '*Space activities and applications are vital to our society's growth and development. They often have a direct impact on citizens' daily lives. In this context, space policy is an instrument serving the Union's policies and responds to three types of need:*

- *social: the citizens' well-being depends on space policy in areas such as the environment, combating climate change, public and civil security, humanitarian and development aid, transport and the information society;*
- *economic: space generates knowledge, new products and new forms of industrial co-operation, it is therefore a driving force for innovation and contributes to competitiveness, growth and job creation;*
- *strategic: space serves to consolidate the EU's position as a major player on the international stage, and contributes to its economic and political independence.*'

While science as such is conspicuously absent in this formulation, it plays a central role in all three areas. Accordingly, we do urge that science should become a more identifiable element of future European space strategies.

B Other perspectives

There are numerous national and international inputs to planning in the physical sciences, in astronomy, and in space science. Generally focused on implementation options, they are particularly important for programme development, rather than long-term strategic visions. Among these structures, we note specifically the following:

- ESA: ESA has programmes across various 'directorates', including science and robotic exploration, Earth observation, telecommunications, navigation, human space flight, and launchers. Within each directorate (and at Council level), advisory boards establish priorities and plans, across mandatory and optional programmes, and taking into account both scientific advice and programme balance;
- COSPAR: the Committee on Space Research, has as its objectives the promotion of scientific research in space at an international level. It undertakes international 'road maps' in space exploration, as well as in astronomy, space weather, etc.;
- EC: the European Commission has, on various occasions and through various structures, highlighted the importance of space exploration and its direct benefit to society. As one example, its 2011 conference, co-organised by the EC and ESA, led to representatives formulating the 'Lucca declaration': a commitment to begin open, high-level policy dialogue on space exploration at government-level for the benefit of humankind (esamultimedia.esa.int/HSO/DeclarationLucca.pdf);
- ESF: the European Science Foundation has a standing committee on space science, the European Space Sciences Committee (ESSC), which provides its own guidance on issues of European space policy, for example providing inputs and commentary on the relevant programmes of ESA;
- IAA: the International Academy of Astronautics has issued various strategic reports on space exploration, including *The Next Steps in Exploring Deep Space* (2004). In January 2014, 32 heads of space agencies met in Washington DC to discuss planetary robotic and human spaceflight exploration, and the summit declaration proposes specific activities enhancing global cooperation in space exploration;
- ISECG: the International Space Exploration Coordination Group is an association of 14 space agencies. They published a '*Vision for Peaceful Robotic and Human Space Exploration*' in 2006, and documents setting out a '*Global Exploration Roadmap*' and '*Benefits Stemming from Space Exploration*' in 2013;
- ISEF: on the political side, the International Space Exploration Forum convened, in January 2014, government representatives from 35 nations, featuring high-level policy discussions about the future of space exploration, developments in robotic space exploration, extending humanity's reach beyond low-Earth orbit, and the importance of international cooperation;
- NASA: the National Research Council's Space Studies Board develops 10-year strategies for each major space science discipline. Between 2010 and 2012 the SSB carried out decadal surveys in astronomy and astrophysics, planetary science, solar and space physics, and in life and physical sciences in space. Each aims to identify the most important science goals for the coming decade through extensive consultation. NASA generally implements the priority recommendations of such NRC studies.

C Other studies related to human exploration

Various previous studies have presented arguments and obstacles for human exploration. These include the following:

- the IAA 2004 study '*The Next Steps in Exploring Deep Space*', which presents various pros and cons for human space flight;

- an extensive NRC report '*Pathways to Exploration–Rationales and Approaches for a US Program of Human Space Exploration*' (available at www.nap.edu/catalog.php?record_id=18801) had the objectives of reviewing '*the goals, core capabilities, and direction of human space flight*'. Although not endorsed by NASA, the assessment was motivated by concerns that, without an independent basis for the establishment of long-term goals, political cycles and other factors would continue to drive instability in the human spaceflight programme.

  The committee considered that the arguments supporting human spaceflight divide into two sets: pragmatic rationales (economic benefits; contributions to national security; contributions to national stature and international relations; inspiration for students and citizens to further their science and engineering education; and contributions to science), and aspirational rationales (the eventual survival of the human species through off-Earth settlement, and shared human destiny and the aspiration to explore).

  The committee identified no single practical rationale that is uniquely compelling to justify such investment and risk. Rather, they argue, '*human space exploration must be done for inspirational and aspirational reasons that appeal to a broad range of US citizens and policy makers and that identify and align the United States with technical achievement and sophistication while demonstrating its capability to lead and/or work within an international coalition for peaceful purposes*'.

  The technical analysis completed for that study showed that for the foreseeable future, the only feasible destinations for human exploration are the Moon, asteroids, Mars, and the moons of Mars. Among this small set of plausible goals for human space exploration, the most distant and difficult is a landing by humans on the surface of Mars, requiring overcoming unprecedented technical risk, fiscal risk, and programmatic challenges. They concluded that the horizon goal for human space exploration is Mars, with all long-range space programmes for human space exploration converging on it.

  The report includes considerations of international collaboration (including specifically the ESA and China), recommendations for a 'pathways approach' beyond the ISS, and recommendations for implementing a sustainable programme.

- the ISECG Global Exploration Roadmap (August 2013) argues that for Mars, nine out of 10 technical obstacles to safe human exploration are coded 'red' in the traffic light system, meaning they are 'show stoppers' with no available solution. According to this assessment, the unprecedented technical risks identified in the NRC study would currently be judged as insurmountable.

EASAC, the European Academies' Science Advisory Council, consists of representatives of the following European national academies and academic bodies who have issued this report:

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