UK SPACE AGENCY

Space Exploration

TECHNOLOGY ROADMAP

Aurora Programme - artist's impression
Image Credit: ESA - AOES Medialab

The UK Space Agency plays a major role in delivering the government's National Space Strategy.

Our staff include scientists, engineers, commercial experts, project managers and policy officials who help to:

- **catalyse investment** to support projects that drive investment and generate contracts for the UK space sector

- **deliver missions and capabilities** that meet public needs and advance our understanding of the Universe

- **champion the power of space** to inspire people, offer greener, smarter solutions, and support a sustainable future

www.gov.uk/government/organisations/uk-space-agency

www.gov.uk/government/organisations/department-for-science-innovation-and-technology

Contents

Europe’s Rockets
Image Credit: ESA

Executive Summary

The growing global ambition for space exploration will be realised through critical technology evolutions and breakthroughs. The UK must decide its role in these ambitions and set out its areas of focus for national technology development to support future space exploration capabilities. The objective of the Space Exploration Technology Roadmap is therefore to identify areas of existing strength and under-developed technologies to be used in future space exploration missions. The identification of the technologies referenced in this document was founded on the requirements needed to meet the ambitions of ESA Exploration Missions, opportunities within NASA Exploration Missions and the wider global space sector, including upcoming commercial opportunities.

This roadmap will guide UK Space Agency decision-making by focusing on technologies where UK-based academia and industry are leading or well-placed to lead. The roadmap supports the aims of the National Space Strategy to grow and level-up the space sector and put the UK at the forefront of pioneering research and development, and fits within the framework of civil capabilities announced in July 2023 as part of the National Space Strategy in Action. The UK Space Agency has utilised and built upon information in various publications and through consultation with stakeholders in identifying the selected technologies which are the most appropriate for the UK to focus on developing for the purposes of space exploration. A simplified list of the recommended technologies can be found in Appendix II.

For the exploration technologies selected, the roadmap describes the overall role, benefits, current and planned national competence and support requirements. This document identifies a number of gaps that should be addressed for the UK to capitalise on the growing space economy: catalysing investment and positioning our space sector to continue to innovate and compete internationally.

The UK Space Agency encourages the UK space sector to review this document and incorporate its messages into their ambitions. We welcome feedback on the roadmap and will regularly review and revise the document as needed. Feedback can be provided via email to SpaceExploration@ukspaceagency.gov.uk.

The Rosalind Franklin Rover
Image Credit: ESA/Mlabspace

Commercial space services are helping to transform space science and exploration, as companies join with national space agencies, as well as working independently, to build space stations, and support humanity's return to the Moon and first steps on Mars.

UK Space Agency Corporate Plan 2022-25

Moon Rise
Image Credit: ESA - S.Cristoforetti

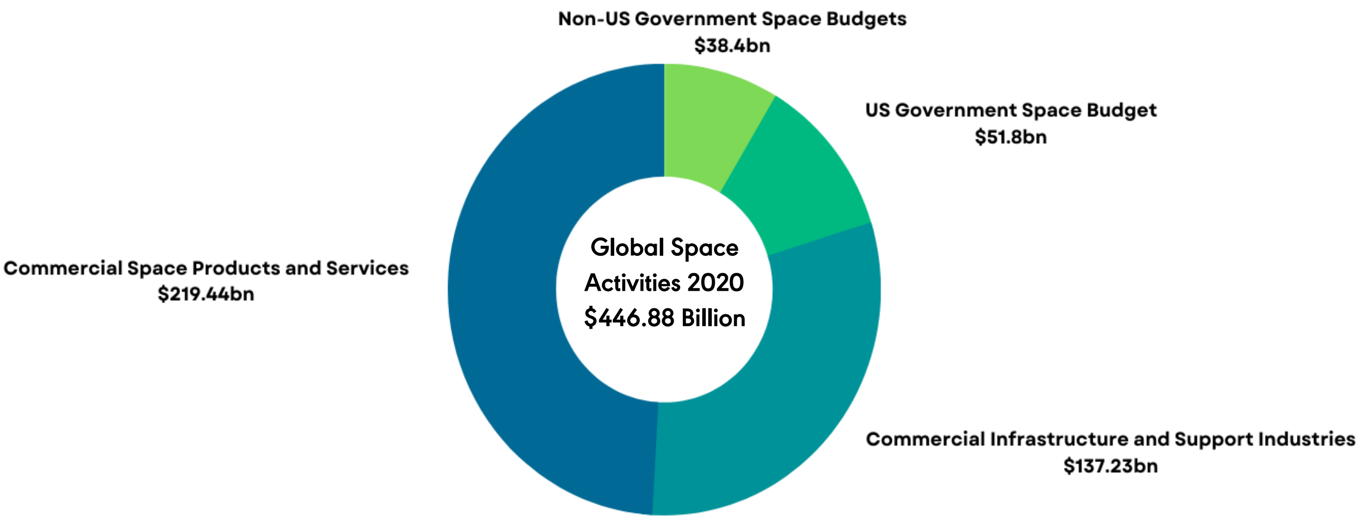
Context

Space Exploration

The UK plays an important part in the European Space Agency's (ESA) exploration programme as UK expertise and capabilities span across a large range of exploration activities. The Trace Gas Orbiter (TGO), launched in 2016 as part of the ExoMars programme, is equipped with UK built instrumentation used in the search for, and characterisation of, trace gasses in the Martian atmosphere. The TGO also acts as a communication satellite to the Rosalind Franklin Rover which will explore and take regolith samples from up to two metres below the surface of Mars - significantly, the Rosalind Franklin rover is Europe's first rover, and was built in the UK. In 2015, Tim Peake became the first British astronaut to visit the International Space Station (ISS).

In the next decade, opportunities in exploration will only increase: starting with Artemis I, the world is about to demonstrate that the return to the Moon is not a 'one off' mission but the start of a continued presence. Like on Earth, development requires a back-bone infrastructure that is reliable, sustainable, available, and affordable. By the mid-to-late 2020's the Lunar Gateway will be operational and provide a springboard for the development of a lunar base. The Gateway and base provide an unprecedented opportunity to develop and test technologies that facilitate off-Earth living and support humankind's first journeys to Mars. This is the catalyst behind the numerous missions underway and planned by space agencies and commercial ventures for exploration.

The UK's space exploration programme covers human and robotic missions to places where humans may one day live and work: this includes missions to the Moon, the lunar vicinity, and Mars; and related activities in Low Earth Orbit (LEO), though many technologies will inevitably transcend these boundaries. There are countless opportunities for the UK to capitalise on the growing global interest in discovery - but as one player in a large and growing international sector, the UK will need to focus its resources strategically.



Data from The Space Report 2021 Q2

The value of the global space economy is estimated to be worth around £490 billion by 2030[1] and $1 trillion by 2040.[2] Encouraging signs are already emerging that such heights may be achieved as revenue reached nearly $447 billion in 2020[3] and grew to $468 billion (approx. £385 billion) in 2021.[4] This growth is reflected in the UK with civil expenditure in space jumping from £300 million in 2014 to £700 million in 2019.[5] The UK Government is also investing in initiatives such as global internet provision through OneWeb and climate change monitoring via the TRUTHS mission in addition to continuing to support the launch of small satellites from UK soil through LaunchUK. The UK will continue to build on its pioneering attitude to space technology and excellent research and development facilities to make the most of the diverse and growing space economy.

Roadmap Purpose & Scope

The Space Exploration Technology Roadmap (SETR) is intended to signal key technology interests for exploration and the likely areas where support from the UK Space Agency will be concentrated. Through consultations with academia, industry, and institutions across the sector, we have reflected a clear array of synergies with other sectors and interested partners abroad.

This information should be of interest to the UK space sector, to investors, and to those not yet involved in the space sector. This roadmap will act like a brochure for the future: helping to catalyse investment and provide the international space industry with a guide to UK capabilities and ambitions. It should be read together with central government publications including the National Space Strategy, and National Space Strategy in Action, which together provide the strategic framework for our ambitions in space and the future of our strategic capability needs.

The roadmap reflects relevant national and international publications to provide the context of the space exploration umbrella the UK Space Agency and most of the UK space community operate within. The SETR is not intended to be a comprehensive list for every technology linked to space exploration. Instead, the roadmap provides an overall analysis of UK capabilities which are assessed against areas of opportunity in the global space economy and exploration missions. The result is a document which provides a solid grounding for why the identified technologies should be prioritised.

[1] National Space Strategy, HM Government, 2021
[2] Morgan Stanley, 2020, www.morganstanley.com/ideas/investing-in-space
[3] The Space Report, 2021, https://www.thespacereport.org/topics/economy/
[4] The Space Report, 2022, https://www.thespacereport.org/resources/2021-global-space-economy-grows-at-fastest-rate-in-7-years/
[5] National Space Strategy, HM Government, 2021

Size & Health of the UK Space Industry 2022

£17.5bn
Total space industry income in 2020/21

1,590
UK-based organisations with space-related activities

48,800
Direct employees in 2020/21

2.5x
UK average labour productivity

12% Space Manufacturing
9% Space Operations
75% Space Applications
4% Ancillary Services

5.1%
Income growth (y-o-y)

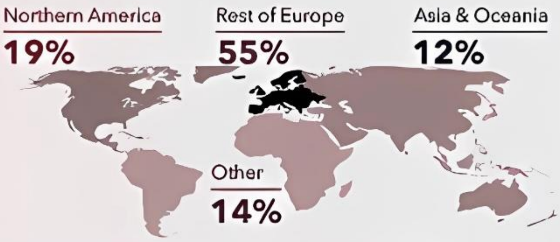
1 in 4
Employees are female

£788m
R&D expenditure in 2020/21

3 in 4
Employees with a primary degree or higher

Exports

£5.9bn
Income from exports in 2020/21



Employment by region

28% London
21% South East
18% Scotland
33% Other

Investment Monitor

Investments into UK-headquartered space companies

2022		2012-2022	
£635m	34	£11.7bn	293
Total funds invested	Investment deals	Total funds invested	Investment deals

GVA

£7.0bn
Direct contribution of the UK space industry to UK GDP

At least **£370bn** of UK GDP* is supported by satellite services

Earth Observation
Meteorology
Navigation
Communications

3 in 5
Organisations expect income growth over the next three years

know.space

know.space (2023) *Size & Health of the UK Space Industry 2022*
Based on analysis of 1,590 UK-based space-related organisations.
* UK non-financial business economy only.

UK SPACE AGENCY

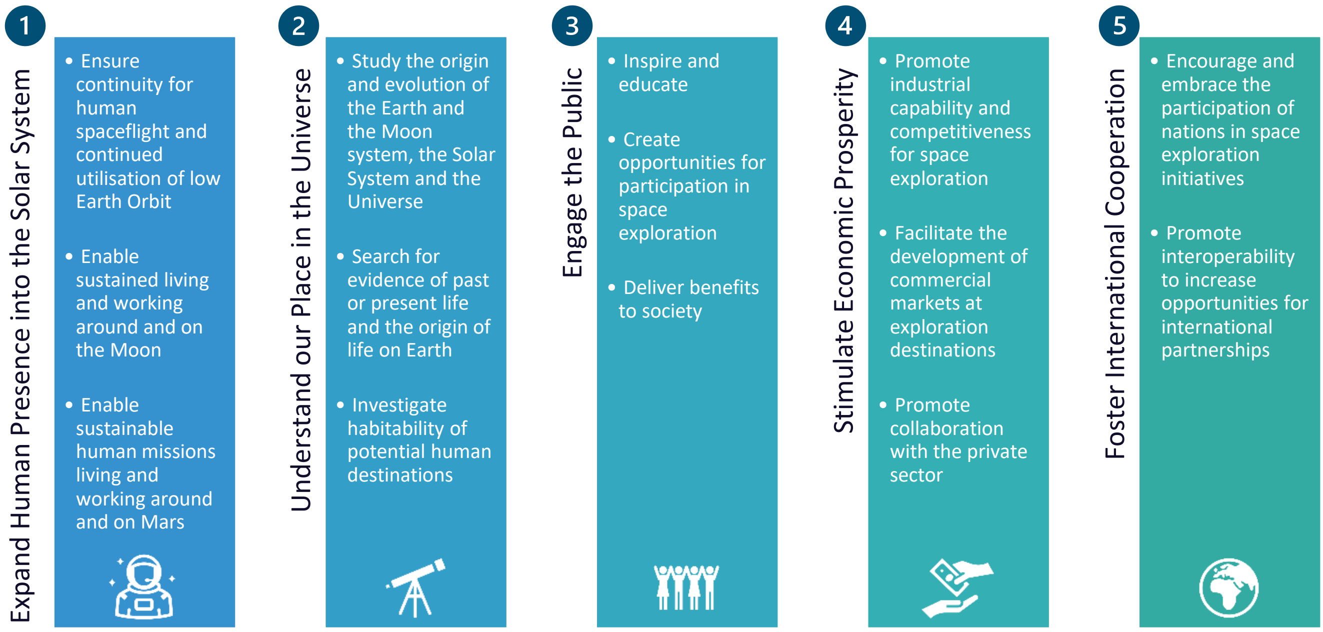
International Objectives

This section provides an overview of applicable international strategies and documents by which the UK Space Agency is guided due to our participation in such institutions or where future cooperation can be expected.

The International Space Exploration Coordination Group (ISECG)

The UK Space Agency is a member of ISECG alongside 26 other space agencies around the globe. The group was established in 2007 as a forum for agencies to discuss and strengthen their exploration ambitions, sharing information in the spirit of cooperation. A key product of this association is the Global Exploration Roadmap (GER) which provides a shared international vision for human and robotic space exploration, highlighting the challenges of space activities which need to be overcome to achieve the goals of the participating states.

The Global Exploration Roadmap (3rd Edition), published in 2018, (and additional supplements, published 2020 and 2022) is the flagship publication of the ISECG, to which the UK Space Agency contributes via inter-agency working groups. The GER outlines the need for humanity to explore space and the necessity for cooperation to achieve such ambitions while also explaining the five common space exploration goals which provide the overarching targets for the participating space agencies. The GER signals the member agencies' intent to develop such flagship missions as Lunar Gateway, Reusable Lunar Landers, Crewed Lunar Rovers, and various step-by-step advances to one day allow for humans on Mars. This is important for the roadmap as it provides a holistic picture of the technological innovations needed for the infrastructure, devices, and services that are required to make each mission a success – grounding our exploration technologies in tangible outcomes.



The five common space exploration goals of the Global Exploration Roadmap.

ISECG also produces a comprehensive **Critical Technology Portfolio** that specifies the innovations developed for the ISS. The portfolio then outlines additional improvements needed to enable greater lunar activity and, ultimately, a sustained presence on Mars. The portfolio catalogues each baseline technology based on why it is needed for exploration and the performance characteristics required to achieve its purpose while accommodating alternative technologies which can provide for redundancy in baseline missions. The items listed in the portfolio provide the end goal for the technologies required and are therefore a checklist for the UK Space Agency to reference against as we select and support certain exploration technologies.

Global Exploration Roadmap Critical Technologies (Summary Table)	Today ISS & Spaceflight Heritage	Near-Future Moon Vicinity/Surface	Future Mars Vicinity/Surface
Propulsion, Landing, Return			
In-Space Cryogenic Acquisition & Propellant Storage	Spacecraft: CPST/eCryo demo	u-G vapor free liquid tank to propulsion transfer, Efficient low-power LOx & H_2 storage >1 Yr (Mars)	
Liquid Oxygen/Methane Cryogenic Propulsion		Throttleable Regen Cooled Engine for Landing (Lunar Scale)	Throttleable Regen Cooled Engine for Landing (Mars Scale)
Mars Entry, Descent, and Landing (EDL)	Spacecraft: MSL class (~900 kg)	Demonstration of advanced technology in deep space environment	Large Robotics >1000 kg; Human ~40,000 kg
Precision Landing & Hazard Avoidance	Spacecraft: Lunar & Mars Landers State-of-the-Art	~100 m accuracy, 10's cm hazard recognition, Support all lighting conditions	
Electric Propulsion & Power Processing	Spacecraft: 2.5 kW thruster (Dawn)	~10 kW per thruster, High Isp (2000 s) (for some mission options)	~30-50 kW per thruster (for some mission options)
Autonomous Systems			
Autonomous Vehicle System Management	ISS: Limited On-Board Mgmt functions, < 5 s comm delay	On-Board Systems Mgmt functions (handles > 5 s comm delay)	On-Board Systems Mgmt functions (handles > 40 min comm delay)
AR&D, Proximity Operations, Target Relative Navigation	ISS: Autonomous docking	High-reliability, All-lighting conditions, Loiter w/ zero relative velocity	
Beyond-LEO Crew Autonomy	ISS: Limited Autonomy	Automate 90% of nominal ops Tools for crew real-time off-nom decisions	
Life Support			
Enhanced Reliability Life Support	ISS: MTBF <10 E-6, Monitored/operated by GC	More robust & reliable components (eliminate dependence on Earth supply logistics) Increased systems autonomy, failure detection capabilities, and in-flight repairability	
Closed-Loop Life Support	ISS: 42% O_2 Recovery from CO_2, 90% H_2O Recovery	Demonstration of advanced technology in deep space environment	O_2/CO_2 Loop closure; H_2O Recovery further closure; Solid Waste, reduce volume/storage
In-Flight Environmental Monitoring	ISS: Samples to Earth	On-Board Analysis for Air, Water, Contaminants	
Crew Health & Performance			
Long-Duration Spaceflight Medical Care	ISS: First Aid+, return home	Demonstration of advanced technology in deep space environment	Training (pre & in-flight) for medical aspects Continuous monitoring & decision support
Long-Duration Behavioral Health & Performance	ISS: Monitoring by Ground	Demonstration of advanced technology in deep space environment	Cognitive performance monitoring Behavioral health indicators & sensory stim.
Microgravity Counter-Measures	ISS: Large treadmills, other exercise equipment	Demonstration of advanced technology in deep space environment	Compact devices to assess/limit disorders Reduced weight/vol. aerobic & resistive eqpt.
Deep Space Mission Human Factors & Habitability	ISS: Large crew volume, food & consumables regular resupply	Demonstration of advanced technology in deep space environment	Assess human cognitive load, fatigue, health Optimized human systems factors/interfaces
Infrastructure & Support Systems			
High Data Rate (Forward & Return Links)	Ground (DSN): 256 kbs Forward, 10 Mbs Return Link	Demonstration of advanced technology in deep space environment	Forward: 10's Mbps; Return: Optical > 1Gb/s
Adaptive, Internetworked Proximity Communications	ISS: Limited capabilities	Demonstration of advanced technology in deep space environment	>10's of Mbps simultaneously between users Multiple Modes; Store, Forward & Relay
In-Space Timing & Navigation	ISS: Limited to GPS range Spacecraft: DSN Ranging	Demonstration of advanced technology in deep space environment	Provide high-spec Absolute & Relative pos'n Space-Qualified clocks 10x-100x beyond SOA
Low Temperature & Long-Life Batteries	ISS: Lithium-Ion (-156 C short duration), ~167 Wh/Kg	Lunar night temperatures and duration	
Comprehensive Dust Mitigation	Apollo: limited 3 day crew ops Rovers: limited mitigation	Multiple Active & Passive technologies required Significant advances in Life cycle	
Low-Temperature Mechatronics	ISS: +121 to -157 C	Operations to -230 C (cryo compatible); multi-year life	
ISRU: Mars In-Situ Resources		Potential Test-Bed for Mars Forward, and enhance lunar missions	O_2/CH_4 generation from atmosphere LOX/LH_2 generation from soil
Fission Power (Surface Missions)		Potential Test-Bed for Mars Forward, and enhance lunar missions	Fission Reactor (10's of kWe)
EVA/Mobility/Robotic			
Next Generation Surface Mobility	Spacecraft: Lunar and Mars Rovers State-of-the-Art	Autonomous & Crewed capability, less Ground Control Extended range, speed, payload; navigate soft/steep varying soils	
Tele-robotic Control of Robotic Systems with Time Delay	ISS: <1-10 Sec delay for GC Ops Spacecraft: Lunar/Mars Rovers	Few seconds to 10's of seconds Dynamic environments w/variable delays & LOC	Up to 40 Minutes
Robots working side-by-side w/ crew	ISS: Limited (Robotic support to EVA)	EVA control robots w/ no reliance on Ground Control International standard & protocols	

(ISECG) GER Extract: Technologies of interest for UK capabilities.

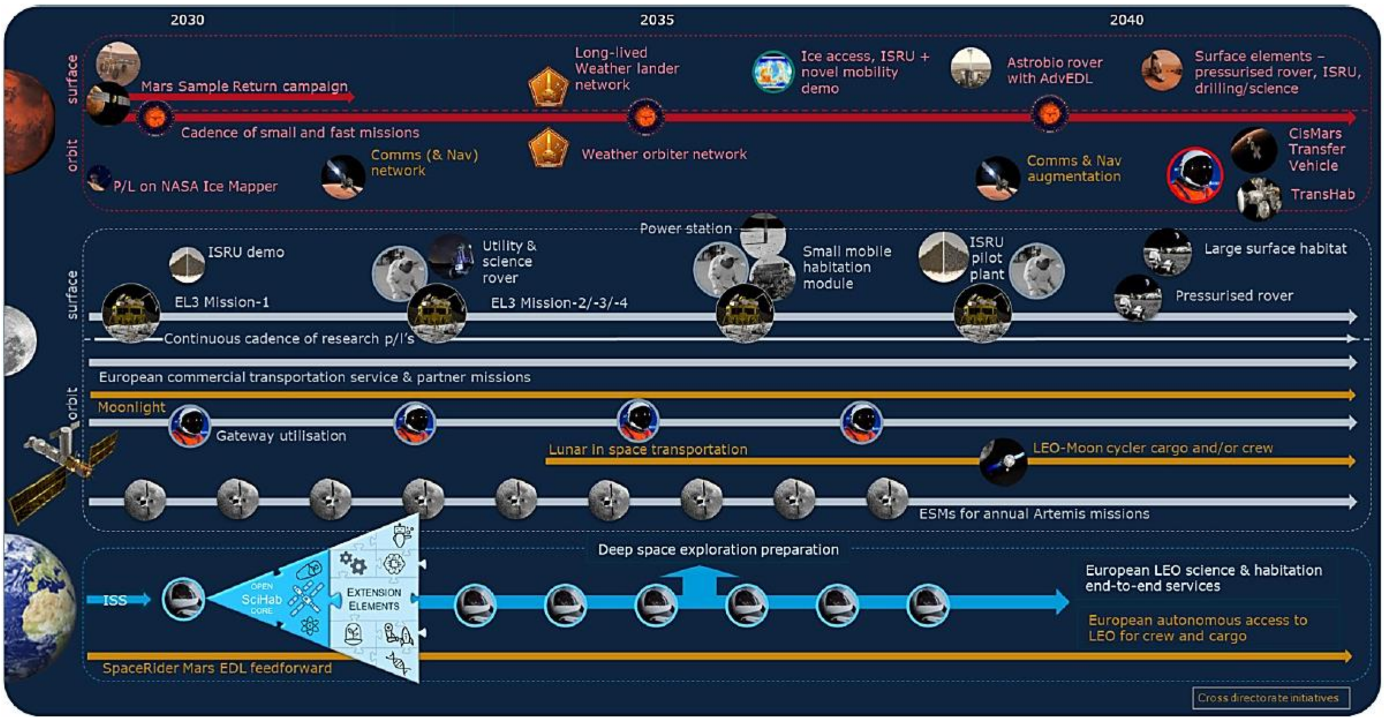
The European Space Agency (ESA)

As one of the 22 Member States of ESA, the UK plays an active role in determining and supporting key missions planned by European nations on a scale similar to those pursued by other major international players such as NASA and JAXA (Japan). In the spirit of cooperation between member states and to align to the international community of space agencies through ISECG, ESA's strategy for space exploration complements the long-term ambition for a human presence on Mars.

The European Exploration Envelope Programme (E3P) was created in 2016 to deliver Europe's space exploration strategy. The E3P brings together all of ESA's exploration activities into a single programme. The **Terrae Novae 2030+ Strategy Roadmap**, published in 2021, identifies the approach ESA will take towards space exploration, intending to make Europe (and by extension the UK) a commercial and science and technology enabler, an end-to-end capabilities provider, and a reliable partner.[6]

The principal exploration objectives of the strategy are to create new opportunities in Low Earth Orbit for a sustained European presence in and utilisation post-ISS, to enable a first European to explore the Moon's surface by 2029, to prepare for the first European to Mars by 2040, and all while delivering measurable benefits to society today.
[E3P] Terrae Novae 2030+ Strategy Roadmap

Terrae Novae 2030+ sets out the notional mission roadmap for ESA to which each member state can decide to contribute as an interested party. These missions are summarised by the diagram below and indicate potential areas for UK participation in the near and longer-term future.



(ESA) Terrae Novae 2030+ Strategy Roadmap: Notional Mission Roadmap

UK participation in, and financial contribution to, ESA's programmes is determined at the triennial ESA Council Ministerial Meeting. At the November 2022 meeting the UK committed £1.84bn to ESA over five years, of which, £217m accounted for ESA's Exploration Programme.[7] A further £71m was committed to the cross-cutting General Studies Technology Programme (GSTP) and £51m to the Moonlight initiative which is delivered through the Advanced Research in Telecommunications Systems (ARTES) programme.

[6] Terrae Novae 2030+ Strategy Roadmap, ESA, 2021
[7] HM Government, 2022, https://www.gov.uk/government/news/uk-secures-184-billion-investment-for-esa-programmes-with-support-for-earth-observation-sector

As a result, the UK has new or continuing roles in the following exploration-related activities:

- The Rosalind Franklin Rover
- Mars Sample Return
- Argonaut (European Large Logistics Lander)
- Lunar Gateway
- Moonlight (Lunar Communications Network) under the ARTES programme
- ENDURE (Radioisotope Heating & Power) under the GSTP programme

The technologies required for the realisation of these missions will guide UK Space Agency considerations in the near future and will be flagship examples of UK capabilities and expertise in space exploration.

The **Exploration Preparation, Research and Technology** (ExPeRT) is part of ESA's E3P. It integrates, coordinates, and manages the development of studies and technologies for future Exploration missions to LEO, Moon and Mars destinations. ExPeRT is crucial for this roadmap as it identifies the 'technology push' areas that are expected to result in a step-change or disruption to a field of technology which may subsequently facilitate exploration capabilities, aiding exploration missions. These broad categories provide a good basis for the roadmap to determine which technologies to develop in the UK as they are expected to generate breakthroughs for space exploration.

ESA's **Technology Compendium**, approved by member states each year, outlines the technology areas relevant for exploration activities which are either available or can be developed further. The development of the technologies noted are then supported through ESA funding pillars, which receive funding from UK subscriptions, allowing UK organisations to submit applications.

(ESA) Exploration Technology Compendium for 2022

> *Space is currently undergoing a revolutionary change, comparable to the internet economy 20 years ago, the consequences of which affect all domains of life. Europe cannot afford to miss a new potential golden age with high multiplier effects across the economy. Europe should translate its future autonomy in human and robotic space exploration into an offer of strong and reliable partnerships covering all world regions.*
> ***(ESA) Revolution Space: Europe's Mission for Space Exploration***

The National Aeronautics and Space Administration (NASA)

As the leading investor in space exploration, the United States, plays a crucial role in shaping the future of space exploration for the international community. NASA is, and will continue to be, an important partner for the UK Space Agency. It is necessary and important to take account of NASA's plans for space exploration regarding the lunar vicinity and surface, as well as missions to Mars, for areas of further cooperation for the UK space sector.

NASA's Strategic Plan details the goals for the Administration every four years. The latest, **Strategic Plan 2022,** provides the current vision for space exploration and missions underway, in preparation, and envisioned for the future. There are a range of synergies between the objectives and interests of NASA, the UK Space Agency, and the UK space sector, including:

- *Understand the Sun, solar system, and universe.*
- *Explore the surface of the Moon and deep space.*
- *Develop capabilities and perform research to safeguard explorers.*
- *Enhance space access and services.*
- *Innovate and advance transformational space technologies.*

The **Planetary Science and Astrobiology Decadal Survey** produced for NASA and the US Government by the USA's National Research Council has, since its first publication in 2002, become a staple of the space sector – outlining what various fields of research are currently achieving and where they are likely to see further study in the solar system. The study proposes a series of recommendations to NASA which reinforces their current objectives and provides a catalyst for future missions. Subsequently, this document provides a glimpse at some of the potential areas for cooperation with NASA for the UK Space Agency and the UK space sector supplying various instruments, devices, and expertise towards such operations.

There are too many technologies noted in the 2022 Decadal Survey (covering 2023-32) to be specifically noted in this strategic context. Some of the important technology areas for the UK to consider that are featured include, but are not limited to:

- *In-Situ Resource Utilisation (ISRU)*
- *Space Instrumentation*
- *Autonomy*
- *Challenging Environments*
- *Communication Systems*
- *Propulsion*
- *Radio-isotope Power Systems (RPS)*
- *Subsurface Access*

> *The committee strongly supports international efforts and encourages the expansion of international cooperation on planetary missions to accelerate technology maturation and share costs.*
> **Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032**

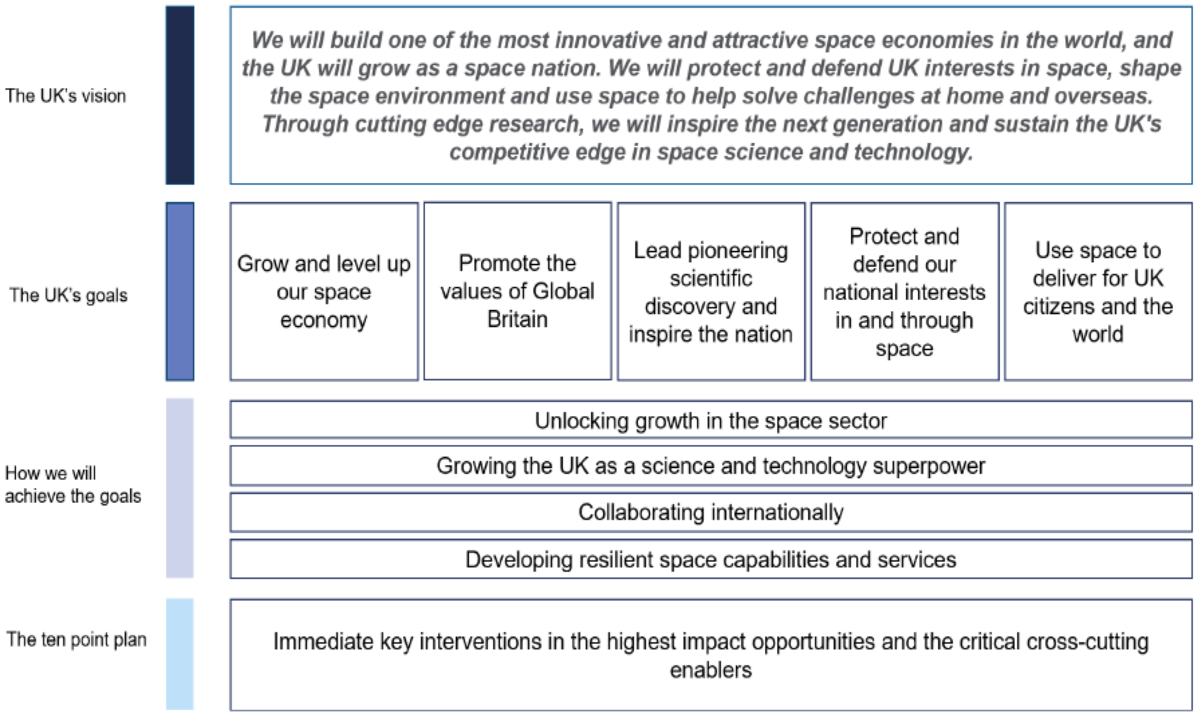
These areas already suit some of the capabilities of the UK space sector and where future growth is already beginning to take shape. NASA's strong heritage in these technologies alongside the world class knowledge and innovations of UK academia and industry provide unique opportunities for future collaboration. This is in line with the UK Government's priority to enhance our commercial and scientific endeavours with some of the world's most dynamic and emerging space economies as expressed in the National Space Strategy.

UK Objectives

The National Space Strategy (NSS), published in 2021, is the UK's first-ever dedicated strategy and vision for space. The strategy sets a clear rationale for the importance of space for the UK politically, economically, scientifically, and for defence. In July 2023, the **National Space Strategy in Action** provided further direction on the UK's priorities and set out the strategic goals for civil space capabilities. The UK Space Agency is dedicated to ensuring that the ambitions set out in this strategy are factored into our work, they are therefore the essential criteria for selecting the exploration technologies for this roadmap. These essential principles are:

1. *Growing Existing Strengths*
2. *Leadership in High Growth Areas*
3. *Leadership in Emerging Sectors*

The roadmap also reflects wider UK Government ambitions such as *Levelling Up* and *Promoting Global Britain*. A central tenet of the NSS is to grow the UK as a science and technology superpower. In collaboration with other partners the UK will seek to set long-term space science and exploration goals that maximise societal benefits, continuing to support NASA-led Artemis programme for returning humans to the Moon.[8] The UK Space Agency will therefore invest in technology development in relation to UK supported missions and where there are longer term UK ambitions, while closed-loop life support systems and regenerative technologies that can be deployed across international missions will also be a vital component to a successful and sustainable space industry.



(HM Government) National Space Strategy 2021

The strategy allows the UK Space Agency to develop its international collaboration to boost access to missions, scientific data, and technology development through new partners such as NASA and the Japanese Space Agency (JAXA). The Agency's new Bilateral Programme highlights our desire to do more activity beyond the work we do through ESA providing new avenues for technology development. The UK Space Agency is working through a renewed international plan which focuses more heavily on bilateral collaboration, and which will effectively prioritise our engagements; establishing stronger bilateral relationships with like-minded countries sits

[8] National Space Strategy, HM Government, 2021

at the top of our international agenda. In time, the programme will allow for funding directed towards new partners to enhance our commercial capabilities in emerging space economies.[9] An example of such intentions is the **UK-Canada Space Agencies MOU on Joining Activities and Information Sharing** signed in 2021, providing a clear impetus for collaboration by pooling research and development resources to benefit both nations' space sectors. Similarly, the UK Space Agency will look to take full advantage of the **UK-Australia Space Bridge** signed in 2021. The space bridge improves access to trade, investment, and research opportunities.

The UK Innovation Strategy, published in 2021, sets out how the UK Government intends to make the UK a global hub for innovation by 2035. The strategy acknowledges the importance of innovation and technology development for the benefit of science, the economy, and society. It notes seven key technology 'families' where it sees particular strength and opportunity for the UK, namely:

- Advanced Materials and Manufacturing
- AI, Digital and Advanced Computing
- Bioinformatics and Genomics
- Engineering Biology
- Electronics, Photonics and Quantum
- Energy and Environment Technologies
- Robotics and Smart Machines

Domestically, facilitating collaboration between industry, researchers and government will strengthen the broader technological ecosystem, not least as government is a crucial customer for transformative technology. Internationally we should not hesitate to remind the world that the UK is a technological powerhouse that offers enormous value to collaborators and investors.
UK Innovation Strategy 2021

With strong synergies between these families and space exploration technologies, the roadmap will therefore bolster areas already identified as UK assets and opportunities.

The Integrated Review, published in 2021, puts science and technology at the centre of the UK's overarching national and international strategy with the Government's vision for the UK to be recognised as a Science and Tech Superpower by 2030.[10] The roadmap will complement the Integrated Review's 'own-collaborate-access framework' through its similar approach in identifying areas of exploration technology. Furthermore, **The UK Science and Technology Framework**, published in 2023, sets out the strategic approach to identified critical technologies to 2030. These technologies (Artificial Intelligence, Engineering Biology, Future Telecommunications, Semiconductors, Quantum) can be enabled by space activity as well as supporting space exploration missions themselves.

In 2020 the UK signed the **Artemis Accords**, a shared international vision of human activity on the Moon and Mars. The Artemis Accords, grounded in the Outer Space Treaty 1967 (of which the UK is also a signatory), will play a crucial role in the development of exploration technology due to the internationalisation of standards and need for interoperability of equipment in space. The UK is intent on taking a leading global role in civil space as demonstrated by signing the Accords,[11] as such the roadmap will take account of this by integrating the Accords' principles as standard.

The Devolved Administrations

A Strategy for Space in Scotland and **The Northern Ireland Space Strategy**, both published in 2021, and **Wales: A Sustainable Space Nation**, published in 2022, are the devolved administrations' strategic plans for their respective space sectors. These strategies outline a concentrated view of the UK's space sector alongside the aims and ambitions of each country of the United Kingdom. Scotland, Wales and Northern Ireland each have distinct goals for their sectors over the coming decades which the UK Space Agency will look to support and to also benefit from the skills, expertise, and technological advances that will grow in each country.

[9] National Space Strategy, HM Government, 2021
[10] Integrated Review, HM Government, 2021
[11] HM Government, 2020, https://www.gov.uk/government/news/uk-and-nasa-sign-international-agreement-ahead-of-mission-to-the-moon

Commercial Space

Over the past decade, there has been a step-change in commercial activity in outer-space, with a significantly increased and growing role for commercial activities. Commercialisation is less advanced in exploration compared to other space domains (such as telecommunications, Earth observation, or launch) but will become increasingly significant.

UK approach to commercialisation in exploration

There are different types and degrees of commercialisation in space exploration. For practical purposes, the UK Space Agency recognises three broad categories of exploration commercialisation in which it may play a role:

- **Commercial delivery of institutional missions:** using services provided on a commercial basis for the delivery of institutional missions, i.e., space agency mission requirements delivered through procurement of commercial services.
- **Capitalising on institutional investment:** enabling and encouraging the commercial exploitation of legacy assets of exploration programmes, i.e., enabling industrial R&D on the ISS or other microgravity facilities.
- **Enabling 'purely' commercial activities:** enabling commercially driven exploration in which government or institutions are not the principal stakeholders or customers, i.e., companies exploring space for commercial goals. The UK government role here is mostly currently limited to policy, legislation, and regulation (see the Outer Space Act 1986; the Space Industry Act 2018; the Space Industry Regulations 2021). We may consider some targeted investment where there is broader public (socio-economic or strategic) benefit as well as a commercial motive.

The SETR identifies technologies which can serve *all* space exploration efforts, regardless of whether they are commercially or institutionally driven. If, for example, a specific technology opens commercial opportunities for UK companies, that will be taken into account as well as its utility on institutional science missions.

Low Earth Orbit

A greater role for private enterprise in LEO has been cemented in recent years. In 2020, NASA awarded Axiom Space docking access to the ISS, allowing the company to develop the first commercial module (Axiom Orbital Segment) for the ISS. In 2021, the administration went further by awarding contracts to three U.S. companies to design new space stations/commercial destinations in LEO, these include *Orbital Reef* (Blue Origin & Sierra Space), *Starlab* (Voyager Space), and an as yet unnamed concept by Northrop Grumman.[12] NASA's statement on the scheduled termination of the ISS (in its current institutionally led form) by the early 2030s is a decisive pronouncement of LEO becoming a primarily commercial realm. After 21 years of scientific discovery and technological advancements, the ISS has provided humanity with the necessary knowledge to set up bases beyond LEO. This step-change in the makeup of the space economy provides three main opportunities for the UK:

- the ability to develop and provide technology for new space infrastructure;
- new bases for further experimentation and innovation when they are functional; and,
- greater institutional activity beyond LEO – demanding even greater technological advances to overcome the challenges of living in the lunar vicinity and putting a human on Mars.

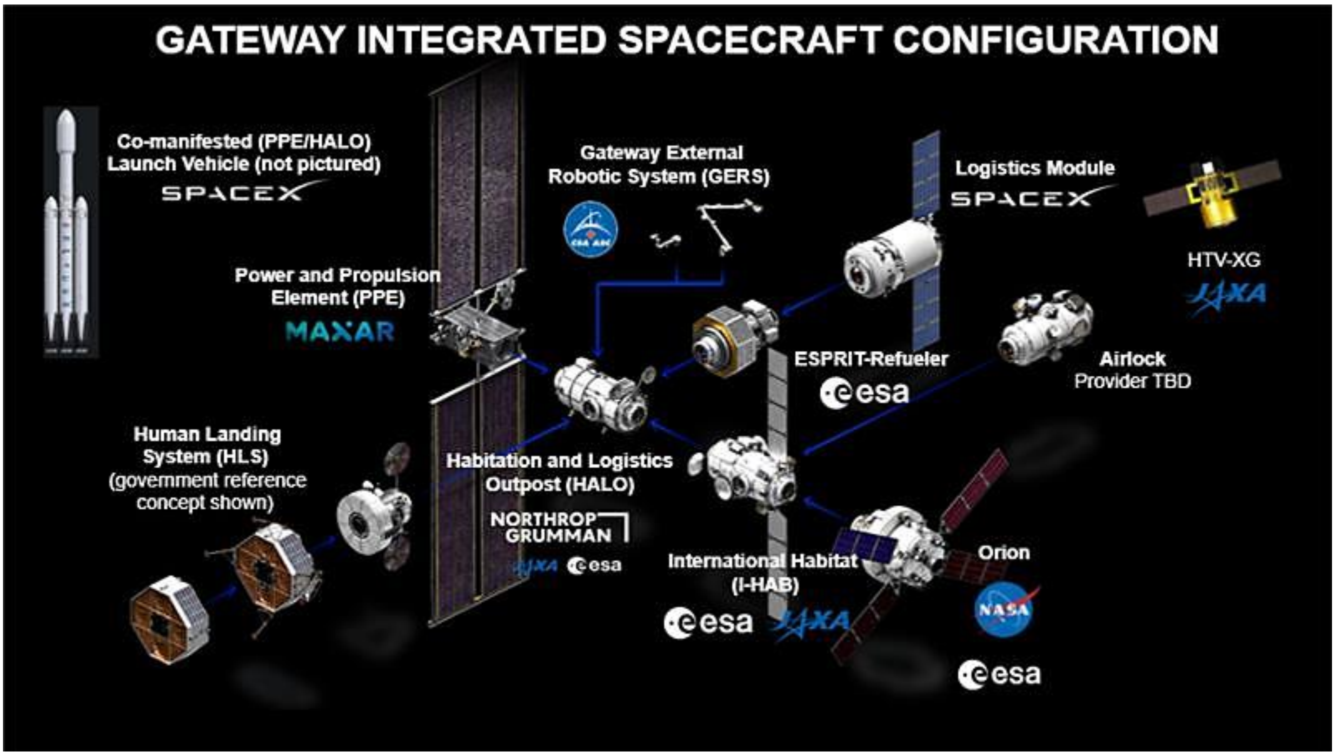
[12] NASA, 2021, https://www.nasa.gov/press-release/nasa-selects-companies-to-develop-commercial-destinations-in-space

The Moon

The next phase of human activity in the solar system will be returning to, and establishing a human presence on, the Moon. The *Gateway* will provide many of the research benefits provided by the ISS today for the lunar vicinity in addition to facilitating further exploration to the polar regions of the Moon and into deep space. In 2021, NASA awarded *SpaceX* a contract to develop the first commercial human lander to the lunar surface, following their success as the first private spacecraft to deliver astronauts to the ISS in 2020.[13] NASA continued to demonstrate the role of the commercial sector by a second subsequent award to Blue Origin and their partners.[14] Commercial providers have continually contributed crucial services for institutional missions, such programmes are only likely to increase over the coming decades as lunar infrastructure is established and undoubtedly grown.

The Gateway will provide the base for lunar surface activity where UK organisations are already developing cutting-edge research and technology for a range of uses. The UK, through ESA, is supporting the development of the proposed Argonaut (formerly EL3), which will provide a payload landing system for the Moon – boosting UK capabilities in this area as well as access to the lunar surface. The UK Space Agency has also invested in the ESA Moonlight initiative, building a satellite constellation for the Moon to allow for the necessary navigation and communication services required for lunar exploration. Missions such as these will require a robust supply chain that can provide the equipment and services needed to maintain their purpose and offer opportunities for upgrade and additional uses.

With 250 or more missions to the Moon likely over the next 10 years, it is estimated that a significant proportion of those missions will be crewed, while other missions will be robotics active in reconnaissance, support, and build-up of the lunar ecosystem. The scale of this ambition illustrates why permanent lunar infrastructure is necessary as the core backbone of a sustainable return to the Moon.



(NASA) A full view of Gateway that includes elements from international partners.

[13] NASA, 2022, https://www.nasa.gov/press-release/nasa-provides-update-to-astronaut-moon-lander-plans-under-artemis
[14] NASA, 2023, https://www.nasa.gov/press-release/nasa-selects-blue-origin-as-second-artemis-lunar-lander-provider

Lunar Pathfinder

The Lunar Pathfinder spacecraft is an important step in humanity's return to the Moon. In this project, ESA, and by extension the UK, is the anchor customer for services from Lunar Pathfinder while NASA would also receive services in exchange for launching and delivering the spacecraft to lunar orbit. Further prospective customers can determine their requirements in consultation with SSTL. The Lunar Pathfinder is also the first step towards achieving ESA's Moonlight project to create a network of communications and data relay satellites which could also provide navigation services for lunar exploration.

Designed, owned and operated by Surrey Satellite Technology Ltd (SSTL), the spacecraft will offer commercial communication services to lunar orbiters and surface assets such as rovers and instruments, as well as a lunar navigation services demonstrator and scientific experiments. This project is a direct example of the growing commercial realm of space exploration and the role of institutions in facilitating and cooperating with commercial entities to achieve shared ambitions.

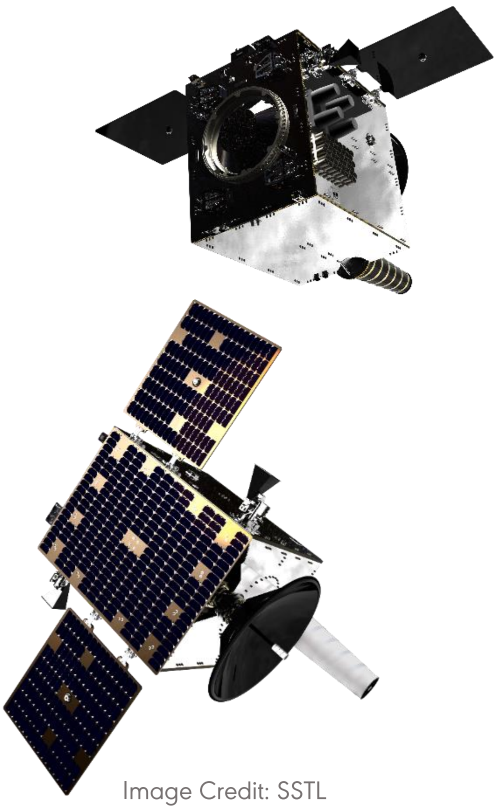


Image Credit: SSTL
The Lunar Pathfinder Spacecraft

CLPS Missions

NASA's Commercial Lunar Payload Services (CLPS) missions will greatly increase the opportunities for delivering payloads to the Moon and will open up access to a greater range of actors. The UK has unique technical capabilities to offer such missions – for example the Open University with RAL Space are providing the Exospheric Mass Spectrometer for the PITMS instrument which will be delivered to the Lunar surface on the first mission of US company *Astrobotic*. Besides UK entities acting as supplier to larger missions, the UK Space Agency is considering how to leverage the new opportunities afforded by regular, lower cost access to the Moon for scientific and commercial gain.

Reflecting on deep space
Image Credit: Nathanial Bradford / Goonhilly Earth Station

Consultations

A series of dialogues were undertaken in the development of the roadmap. It was necessary to engage with various stakeholders during the drafting of the document to ensure that the UK Space Agency has reflected the ambitions and latest high-level technological understanding of representatives of the UK space community.

The 20th June 2022 saw the opening of the community survey (20th June – 31st August 2022) which requested associated technology information. Respondents were asked to submit information on technologies that they believed were vital to enabling future space exploration missions and would require further investment and support for their development. The survey also asked for supporting information, including:

- How the technology relates to other technology areas and UK priorities;
- The ability of the UK to develop and produce such technologies; and
- How it will help keep the UK at the forefront of science.

Not all of the suggested technologies are referenced in this document, however, all the submitted information was reviewed and helped to inform the outcomes noted. On 7th July 2022 a free open access webinar was held to further explain the intention of the UK Space Agency to develop the roadmap and how to complete the community questionnaire to multiple representatives of the UK space sector.

Various teams across the UK Space Agency were continually involved in reviewing the roadmap as it developed so as to pool all internal expertise and sector knowledge in the development of this document. The Department of Science, Innovation and Technology (DSIT) was consulted due to its responsibilities for UK space policy and their wider interests in the fields of energy technology. Other public bodies were given the opportunity to input including the UK Research and Innovation (UKRI) Councils, the Satellite Applications Catapult, and the High Value Manufacturing Catapult. The Space Academics Network (SPAN) and Space Science and Exploration Committee (SSEC) were also presented with a draft roadmap for comment.

The Space Exploration Advisory Committee (SEAC) performed an appraiser role during the drafting process and were prominent in the outcome of the roadmap design. The SEAC is responsible for advising the Agency on matters relating to human and robotic space exploration programmes. Membership of the SEAC consists of representatives of the academic and industrial communities from across the breadth of relevant subject areas, including biomedicine, fundamental physics, robotics and autonomy, and space science. More information on SEAC and active members can be found on the UK Space Agency website.

The UK Space Agency would like to thank all parties that submitted information and engaged with the roadmap during its development for their time and participation in this exercise.

The Roadmap

As detailed in the context chapter, there are a number of factors for the UK Space Agency to take into account when determining the right exploration technologies to prioritise. To bring these elements together the roadmap has taken a sequential approach which is summarised in the schematic below:

Limitations

The roadmap cannot, and does not, show every opportunity that may exist for exploration technologies – only those where a strong UK capability is demonstrated. The roadmap also does not go into granular detail as its purpose is to outline and influence later decisions on prioritisation and support for the listed technologies. Further supplementary roadmaps may provide greater granularity specific to the technology.

Technology Criteria

For any particular technology to be viable for the roadmap it must first meet the criteria of having a valid use in space exploration either through specific missions or likely scenarios for its use in future. The technologies must also be an area where the UK can meet the *Essential Principles* of the National Space Strategy.

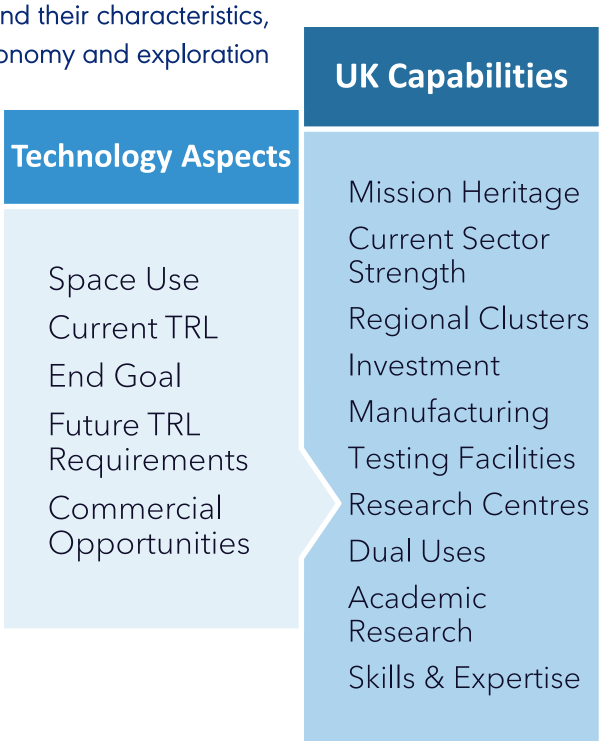
All the technologies assessed in this roadmap can be attributed back to elements of the Technology Criteria.

Technology Assessment

Technologies captured by the criteria are outlined to understand their characteristics, status, and role in space exploration to meet global space economy and exploration ambitions to the 2030s and beyond.

Their presence in the UK is understood at a high-level and used to consider the current capabilities of UK organisations as well as what may be necessary to develop the technology further. Some technologies have specific characteristics that lend themselves well to UK capabilities or unlock further technologies. However, all the selected technologies in the roadmap are of equal consideration, there is no implied hierarchy or preference to one technology over another in the roadmap.

The areas identified are where the UK Space Agency believes the UK can maintain, grow, or achieve a position of leadership based on its capabilities. Supplementary roadmaps will explore these Technology Aspects and UK Capabilities further.



Definitions

As a member of ESA, and to reduce the risk of duplication and confusion, the UK Space Agency will identify technology subdomains (and, if necessary, groups) based on those found in ESA's Technology Tree. As of the time of writing, the roadmap refers to Version 4.0 (STM-277), published in 2020. The ESA references and definition for each subdomain and group selected have been given within each *Technology Theme*.

Reading the Roadmap

The following pages will examine the exploration technologies. To integrate UK priorities, the roadmap will select an overarching 'Technology Theme' followed by the appropriate space exploration technology subdomain(s) which correspond, although they are not intended to be exhaustive. Technology groups may also be identified to further breakdown key components of a particular exploration field. The UK Space Agency has determine which Technology Theme is the most appropriate for each of the noted ESA subdomains and groups.

Due to the multifaceted nature of exploration missions and the interconnectedness of such technologies, many of the technologies noted in this document have more than one home in the definitions and indeed the Technology Themes. The UK Space Agency has therefore chosen the applicable technology theme for each subdomain based on where there is a particular UK capability, but this should not be understood as disregarding their applicability to other areas.

Cloud-free Europe
Image Credit: ESA (contains modified Copernicus Sentinel data (2017), processed by Sinergise/ESA)

Technologies

Advanced Manufacturing

Novel Materials and Materials Technology [24.A]

Materials not yet used in space but presenting potential interest.

Materials Processes [24.B]

Materials manufacturing processes and fabrication techniques.

Modelling of Materials Behaviour and Properties [24.E]

Modelling, characterisation, analysis and testing of materials behaviour and properties.

Advanced Manufacturing Technologies [24.I]

Manufacturing technologies that bring added value compared to traditional manufacturing such as lead-time reduction, cost reduction, performance improvement, design freedom, or enable new capabilities.

Advanced manufacturing is a broad term covering a range of aspects. Ultimately, this technology will facilitate the production of materials and structures for and in space to enable a diverse range of applications and services including the construction of space stations and energy systems, in addition to human habitability beyond LEO and eventually a base on the Moon.

The manufacturing of advanced component parts such as crucibles, ceramics, and coatings, particularly those that are durable and dust mitigating, will be necessary for adding redundancy to structures and devices. The UK has strong capabilities in component parts and extensive supply chains supporting sectors such as aerospace, automotive, and defence. Taking these skills to space exploration is supported by the High Value Manufacturing Catapult terrestrially and the Satellite Applications Catapult for applications off-Earth.

Novel materials, alloys, and manufacturing processes are of particular interest to the UK Space Agency. For instance, the additive manufacturing process (3D printing of material, layer upon layer) allows the production of precision and complex structures without the dependency on extensive production facilities. When combined with recycle/reuse techniques such technologies aid the development of a closed-loop system in space. Several UK groups are already involved in additive manufacturing in low/microgravity environments which will add efficiency of material use, a minimized human footprint where installed (removing the need for direct involvement in manufacturing) and reduce the risk of debris. This technology will be applicable to multiple uses and missions across the spectrum and has a strong commercial application to space.

With key strengths in material science and metallurgy, the UK has specific niche strengths in certain technologies such as the *Cambridge FFC* process which are attractive to partners across the international community. In temperatures low compared to traditional methods and through only a handful of steps, the process enables the purification of metal oxides into metals. This can be applied to the Moon and Mars where materials in regolith can be used to generate outputs for use in the building blocks of living off-Earth. This technology overlaps many of the themes in this roadmap and can be an excellent catalyst for developments in novel materials, robotics, autonomy, ISRU, and space nuclear power.

The UK Space Agency will continue to work with our partners in the Advanced Manufacturing Research Centre (UK AMRC) and Nuclear AMRC, the Satellite Applications Catapult, the Research Councils, and their respective networks in the wider manufacturing sector to support the development of technologies in this theme and their varied applications to the global space economy.

Autonomy & Artificial Intelligence

Machine Learning and Artificial Intelligence for On-board Data Subsystems [1.D]

Developments, characterisation, and evaluation techniques for On-board Data Subsystems.

Software Technologies [2.A]

Advanced software development (requirements, design, verification, validation, maintenance, and qualification) methods/tools. Advanced functions to be implemented in software. Both ground and space application included. Development of related standards.

Software Autonomy and Artificial Intelligence [2.A.I]

Autonomy aspects of software and implementation of artificial intelligence. It also covers system-level avionics aspects of on-board autonomy.

For space exploration and wider commercial activities, autonomy and AI are important for enhancing the capability and efficiency of missions.

Autonomous navigation enables exploration of other planetary bodies without the need for direct control by crew on Earth or in orbit, reducing resource pressures and mitigating the impact of latency. Such software can also aid scientists through its ability to scan large celestial surface areas for objects of interest thereby slim-lining data caches for review. Machine learning and AI have already proven useful through automated algorithms for 'crater counting' which has been used as valuable base data to estimate the age of planetary bodies. Furthermore, autonomous systems can compensate for regions in space with few or no fixed references for spacecraft to position themselves through various 'localisation' efforts.

Autonomous activity allows spacecraft to undertake their purpose or a range of objectives with minimal or no direction from Earth or orbiting facilities. Planetary rovers and other spacecraft and solutions will continue to need such autonomy to initiate the right sequence of steps and mitigate/correct processes as needed. Equally commercial operations in LEO will depend heavily on the ability for AI and autonomous activities to support robotic tasks. They are a clear requirement for all activity in space in the future, with humans both present and absent.

The UK has a strong heritage in this field and is now ranked third in the world for private investment in AI companies in 2020. AI is further supported by the AI Sector Deal, the AI Council, and the National AI Strategy to continue to maintain and grow skills in this field and invest nearly £1bn.[15] There is a clear opportunity for the UK to lead in this area when applied to space exploration, exploiting this capability to maximise outputs where human access is limited. Exploration technology development for autonomy and AI will mean applying existing learning and capabilities to spacecraft and missions.

[15] HM Government, National AI Strategy, 2021

Communications & Mission Operations

Telecommunication Subsystems [6.A]

Telecommunication techniques and algorithms (coding, modulation, access, synchronisation, networking, security etc.), subsystem tools and telecommunication equipment.

Mission Operations [9.B]

Aspects related to operation processes and mission control concepts, including automation, autonomy at various levels and distribution/decentralisation, operations support processes (such as operation training) and associated tools, dependability and security of operation systems and processes.

The UK has a world leading communications sector covering a vast range of capabilities. The customer demand for increasingly flexible satellites in LEO and GEO and beyond is growing, opening further opportunities for new technologies, services, and business models. Communications covers a vast range of technical areas therefore any associated technologies that correlate to space exploration in this outline can be considered of interest.

The UK has a healthy heritage of space communication with Cornwall's Goonhilly Satellite Earth Station once being the largest of its kind in the world, while continuing to provide commercial services and deep space communications today. Present infrastructure initiatives such as the Internet of Things, autonomous vehicles, transport, remote health, and network orchestration are growing UK capabilities. Subsequently, the throughput and congestion in the RF spectrum with ever increasing demand for greater capacity, is leading a drive to develop technologies that operate at higher and optical frequencies, including inter-satellite links. There is significant experience, and thus opportunity, for the UK in developing next-generation technologies and mitigating the impact of congestion from growing space access.

The establishment of lunar communications infrastructure and the relays required to encompass the entire celestial body will be a crucial step in living and working on the Moon. The UK, through its membership of ESA, is supporting the creation of this system through its subscription of £206m for telecommunications programmes, which includes £51m for ESA's Moonlight Programme. Reducing the cost and complexity of developing multiple bespoke systems, the Moonlight Programme will be developed for both institutional and private customers, increasing access to the Moon, and will be Europe's first non-terrestrial telecoms system. This could also serve as a proving ground for deep space and Mars missions. Lunar and deep space communication technologies should have delay tolerant networking integrated and be able to support multiple missions.

The UK Space Agency unveiled a new £15m fund for UK businesses to revolutionise satellite communications technology in October 2022. The competition supports the development of ambitious technologies across the satellite communications ecosystem funded through the UK Space Agency's leading role in ESA's ARTES programme.[16] This support enables the continued strength of the communications satellite sector and provides the opportunity to develop technologies one step further for space exploration needs. Beyond the support for LEO and GEO communications, the UK Space Agency will look to support technologies with a clear benefit for, and use in space exploration, particularly those that may have additional benefit to the wider communications sector.

[16] UK Space Agency, £15 million investment in satellite communications from UK Space Agency, https://www.gov.uk/government/news/15-million-investment-in-satellite-communications-from-uk-space-agency

In Situ Resource Utilisation

In Situ Resource Utilisation [22.B]

Technological aspects related to the use of indigenous materials at the site of an interplanetary mission for the production of resources such as propellants (e.g. methane, oxygen), reactants for fuel cells (e.g. carbon monoxide, oxygen) or fluids/gases for life support.

In Situ Resource Utilisation (ISRU) is a broad and still growing area of exploration technology. There are multiple roles for ISRU devices that can serve a variety of uses for activity on the lunar surface, the lunar vicinity, and Mars. These include fuel for spacecraft, construction of parts for bases, and the oxygen and water needed for human habitation. The generation of consumables from resources found on celestial bodies is crucial for the feasibility, and ultimately cost effectiveness, of the future of exploration.

International exploration efforts are currently at the early stage of development and testing of these technologies with NASA's Mars 2020 Perseverance Rove proving the generation of oxygen from carbon dioxide via a solid oxide electrolyser cell was possible in 2021 through its 'MOXIE' instrument.[17] Similar opportunities for technology demonstrations and future instrument development are on the horizon for the Moon as CLPS and Argonaut catalyse access to lunar resources.

The UK has a strong capability in this area through its cutting-edge industrial science and chemical sectors, as well as the strong skillset in fuel cells, batteries, and chemical crucibles – vital elements of ISRU devices. In addition, analysis of mission data from previous and current orbital spacecraft and rovers, as well as the integration of machine learning to future spacecraft will aid global efforts in lunar surface prospecting. UK scientists will continue to play a crucial end-to-end role in this process; identifying where the required lunar resources for ISRU activity can be found, the methods for efficient exploitation and future material uses and monitoring. Furthermore, the supplementary evolution and integration of ISRU technologies to achieve closed-loop systems and interoperability will also need to be developed to ensure efficient and sensible use and re-use of resources off-Earth.

The UK will build upon international work to identify end products and processes, utilising existing assets to contribute to the global effort of creating mechanisms deployable to a range of scenarios and an array of ISRU applications. The UK Space Agency will also look to support organisations to cooperate and share ISRU expertise with other UK and global partners through both project funding opportunities and access to international symposiums related to such technologies.

[17] NASA, MOXIE, https://mars.nasa.gov/mars2020/spacecraft/instruments/moxie/

Life Support & Crew Performance

Environmental Control & Life Support (ECLS) [22.A]

All technologies for controlling, maintaining, and supporting human presence in non-terrestrial environments, such as regenerative (recycling) technologies for air, water and waste, food production and preparation, environmental monitoring, and control, including habitability issues.

Applied Life Science Technology [14.C]

Application of advanced and new technologies of the life sciences to specific problems of planetary exploration, planetary protection and human long-term presence in space.

Application of Human Physiology Technologies [14.C.I]

Application of human physiology technologies to human health monitoring/care and countermeasures for long duration spaceflight and includes radiation monitoring.

Software Technologies [2.A]

Advanced software development (requirements, design, verification, validation, maintenance, and qualification) methods/tools. Advanced functions to be implemented in software. Both ground and space application included. Development of related standards.

Space accessibility is increasing at an unprecedented rate, and, in a relatively short time, it is expected that humans will be living and working off-Earth in ever greater numbers. Consequently, technologies that specifically address the negative impacts of sustained periods off-Earth will be a necessity. There are many proficient UK organisations active in this broad field which can apply their expertise in extreme physiology, health, and medicine to develop life support systems and counter measures: exercise, medication, and nutrition.

Technologies that mitigate the effects of microgravity on the musculoskeletal system will be required for numerous settings from space stations to eventual lunar and Martian bases. These technologies will need to be designed with interoperability, multifunctionality, and consolidation in mind. Telemedicine will likely be the only option for crews to access health services in space for the considerable future, so, technologies that monitor vital signs will prolong crewed exploration missions while technologies that integrate such considerations will add value to other devices and benefit their astronaut patients. Miniaturised devices, particularly those usable by non-specialists, will also be necessary to extend and de-risk crewed exploration missions.

In addition, isolation and communication latency will predictably have psychological impacts and will require sophisticated mitigation techniques through technologies that enable greater crew toleration of exploration conditions, such as delay-tolerant-networking and device interfaces. This area will work closely together with communications and have multiple terrestrial benefits for communities in remote areas of the world and groups such as the British Antarctic Survey teams.

The UK's medical and sporting sectors are at the forefront of global innovation supporting their multi-billion-pound industries and have exceptional capabilities to apply their aptitudes to new ventures of research and development in space. The UK Space Agency, in collaboration with UKRI, will prioritise the development of these technologies where they can also provide benefits on Earth to maximise the societal and commercial gains.

Navigation & Sensing

Radio Navigation Subsystems [6.B]

Radio navigation techniques and technologies, subsystems capable of generating, receiving, exploiting and analysing the signals from current and upcoming radio navigation subsystems (GPS, Glonass, EGNOS, Galileo), including subsystem tools and navigation equipment.

Optical Equipment and Instrument Technology [16.C]

All techniques and technologies for the design, manufacture and test of optical equipment and instruments for imaging, spectroscopy, radiometry, sounding, remote sensing, metrology, ranging, illumination, free-space optical communications for applications in Earth observation, science and planetary research, telecommunication, and navigation.

This theme has many interlinks with other technology themes in this roadmap. Advances made in multiple fields may converge to enable the creation of novel navigation and sensing technologies. The UK has a strong history and capability in science and Earth observation programmes and the subsequent development of associated instruments to advance science and commercial activity.

For exploration, there will inevitably be a strong need for systems that provide autonomous navigation capabilities in areas where there are no satellite constellations and limited orbital infrastructure as more activity on the Moon and Mars takes place. The further we travel in space; the more refined sensing abilities are also needed for efficient autonomous decision making as communication latency will impact ground operation controls.

One such example of UK capabilities in this theme is Light Detection and Ranging (LIDAR), a method of determining the distance of an object by measuring the time of travel of a laser source to reflect from a target. LIDAR instruments are an important optical sensing tool in exploration and are also capable of analysing chemical and physical composition of a targeted area. The UK has heritage in the development of these systems for a range of uses, the data collected from which can be further utilised for scientific study, adding value to missions.

UK abilities in this field can be applied to various missions, providing UK involvement and development for exploration as well as terrestrial improvements. Furthermore, advancements in this theme enhance capabilities elsewhere as they adapt to suit the need required of them - enabling further learning and development opportunities.

Propulsion

Chemical Propulsion Technologies [19.A]

Wide range of technologies for propulsion subsystems, based on the use of chemical energy, relevant to the following major applications: (1) spacecraft on-board propulsion (including micro-propulsion); (2) reusable or expendable launch vehicles/upper stage/space tugs propulsion; (3) re-entry manoeuvring propulsion subsystems.

Electric Propulsion Technologies [19.B]

Propulsion subsystems that use electrical energy (solar or nuclear), classified according to the following major applications: (1) spacecraft on-board propulsion (including micro-propulsion); (2) orbital stages/tugs propulsion.

Other Propulsion Technologies [19.C]

Wide range of non-classical propulsion subsystems, for both spacecraft and launchers/upper-stages, and the technology field of breakthrough propulsion physics.

Nuclear Propulsion Subsystems [19.C.II]

Technologies and techniques related to the use of nuclear engines to produce thrust such as Nuclear Thermal Rocket (NTR), that uses a working fluid that is heated to a high temperature in a nuclear reactor, or Nuclear Electrical Rocket (NER), that uses the thermal energy from a nuclear reactor converted into electrical energy to drive an electrical thruster.

Supporting Propulsion Technologies and Tools [19.D]

Technologies and tools that are used in support of the development, qualification, integration, and monitoring of propulsion subsystems. These tools and technologies, although similar in scope and classification, might differ substantially depending on their use for chemical, electrical or other propulsion.

From launch to orbit to interplanetary travel, propulsion is a crucial component. The UK developed, built, and launched its own space rocket propulsion system, *Black Arrow*, in the last century. In recent years British innovations from the UK's respected aviation sector and engine expertise, have delivered a range of novel and disruptive capabilities ranging from Synergetic Air Breathing Rocket Engine (SABRE) to the LEROS 2b rocket engine used on the Israeli Beresheet Lunar Lander.

In-space propulsion provides momentum, control, and positioning for spacecraft in addition to breaking for landing craft. The UK is taking these capabilities to space exploration by enhancing existing UK facilities and investing in ESA missions where propulsion systems will be required. For example, the UK National Space Propulsion Test Facility based at Westcott Venture Park, Buckinghamshire was opened in 2021 as one of only three such sites in the world. The facility provides high altitude pumped test cells, for engines up to 3N, 22N, and a sea-level (un-pumped) test facility for engines up to 30kN.[18] The UK built Rosalind Franklin rover and ESA's Argonaut mission both require landing propulsion systems and are areas of ESA's Exploration Programme that the UK is significantly subscribed. The UK Space Agency will continue to promote and facilitate UK expertise and development of these systems within ESA programmes and other exploration missions where it is applicable to the wider space industry.

[18] STFC, UK Space Facilities, https://www.ukspacefacilities.stfc.ac.uk/Pages/Nammo-UK---Westcott---Facilities-at-Westcott.aspx

Robotics

Robotic Applications and Concepts [13.A]

System aspects of innovative robotic concepts for missions.

Automation & Robotics Systems and Subsystems [13.B]

Detailed definition of robotic systems and subsystems, including technology developments dedicated to specific applications.

Automation & Robotics Components and Technologies [13.C]

General purpose and specific Automation & Robotics (A&R) components and methods.

Launchers, Re-entry Vehicles, Planetary Vehicles [20.G]

Includes all related technologies for the development of vehicle primary and secondary structures, control surfaces, shields, etc.

Mechanism Core Technologies [15.A]

Building-block technologies used individually or in combination to provide a mechanism function.

Robotics is a distinctive term that contains many elements from digital concepts to component mechanisms and extending through to full planetary rovers, spacecraft, and other systems. The UK has skills in developing and integrating a varied range of robotic facets terrestrially and in both low gravity and microgravity for space exploration, as demonstrated with the recent fully UK built Rosalind Franklin Rover.

Component level items and broader enabling technologies are both important to the wider development of robotic systems. These technologies are a valuable asset for the future of space exploration as new vehicles, modules, and space stations are developed and for enabling in-space servicing, assembly, and manufacturing (ISAM) to become more mainstream. ISAM facilities will rely heavily on robotic systems for the various processes that occur during the manufacturing of materials for space exploration or commercial ventures back to Earth.

The design and build of the Rosalind Franklin Rover was UK-led, the first of its kind to be built in Europe. As the Rosalind Franklin mission gets underway, UK organisations will be able to better understand the performance of the subsystems and look towards next generation technologies. The legacy of this mission will be the development of the UK robotics sector yet further. Moreover, the need for re-entry systems will only grow as the return of ISAM material or resources from other bodies and experiments to Earth as Artemis Missions complete and the commercial space sector grows. The UK Space Agency will look to support technologies related in this area in partnership with the developments needed for ESA's Argonaut mission.

The UK Space Agency will focus development of robotic technologies where they can enhance humanity's ability to generate products off-Earth for use in further exploration, particularly those technologies with clear commercial opportunities. In addition, robotic elements of planetary and re-entry vehicles development will continue to be supported where possible through our participation in ESA missions.

The UK Space Agency does not currently recognise *Launchers* to be a direct area of interest for UK activity regarding exploration, however, elements of this technology will continue to apply to other themes such as propulsion and will continue to be indirectly considered.

Sample Curation

Reliability and Reusability Aspects of Materials [24.J]

Development of test and methods for materials characterisation and verification, addressing reliability and reusability.

Advanced Physical & Chemical Characterisation and Analysis of Materials [24.J.I]

Advanced technologies and methods to characterise and analyse materials: electron microscopy, X-ray diffraction, Raman spectroscopy etc.

Life & Physical Sciences [14]

All technological aspects related to instrumentation in support of life and physical sciences, and for ensuring delivery of a complete instrument technology. The objective is an optimised scientific return, the emphasis being rather on a consistent system philosophy than on the development of component technologies. All technologies and techniques relating to planetary protection, both sterilisation methods and technologies, and also technologies needed to monitor contaminants.

At the time of writing there have been six successfully operated rovers on Mars. The international community has learned a lot from these missions, but remote science instrumentation can only tell us so much, to understand the complexities of Mars (and other celestial bodies) we must be able to analyse samples on Earth. NASA and ESA are currently planning ways to bring the first samples back to Earth under the Mars Sample Return (MSR) mission with the *Perseverance Rover* already gathering and depositing samples to be collected. It is envisaged that by the early 2030s the first samples will be returned to Earth, creating an unprecedented opportunity for science.

The principles of planetary protection apply to Earth as well as other celestial bodies and humanity must ensure the proper containment of all materials that are obtained off-Earth, samples are thus treated as extreme biohazards. The Science and Technology Facilities Council (STFC) has overall responsibility for Earth-based sample curation in the UK, including the development of associated science instruments.

UK organisations are already involved in developing the Double Walled Isolator (DWI) for ESA which is required for the safe handling of Mars samples in laboratories. To ensure materials are kept pristine the development of the DWI will include working cooperatively with the robotics sector to keep contamination at safe and minimal levels. Developing these devices in the UK will extend our already fantastic laboratory capabilities and astrobiology sector while also likely to have multiple terrestrial uses in sectors such as electronics, pharmaceuticals, and defence.

Development of the retriever system and curation facility(s) is shared between STFC and the UK Space Agency and is being taken forward through our membership of ESA due to the bilateral relationship with NASA that already exists in this area. Currently there are plans for a NASA Mars Sample-Return Receiving Facility and an ESA European Sample Curation Facility within which UK organisations will have access to conduct science through the UK Space Agency's subscription to the ESA programme.

The UK Space Agency will continue to work closely with our sister organisations in the UK and internationally to position the UK to be involved in the return of samples from space and their subsequent analysis.

Science Instrumentation

Instrumentation in Support of Life Sciences [14.A]

Aspects of human physiology, biology, biotechnology, exobiology/planetary exploration.

Instrumentation in Support of Physical Sciences [14.B]

Aspects of fluid science, material science, crystal growth, applied physics, planetary exploration.

Applied Life Science Technology [14.C]

Application of advanced and new technologies of the life sciences to specific problems of planetary exploration, planetary protection and human long-term presence in space.

UK scientists are amongst the highest regarded experts in the world. The skills and capabilities of the scientific community lend themselves well to the development of new and next-generation instrumentation for exploration activity. Science instrumentation is a broad theme that encompasses many devices, each device performs a specific function which generates the scientific data that is the purpose of most exploration missions.

The UK has robust experience in science and EO programmes and has heritage in the development of instruments for exploration missions. UK supplied Magnetometers can be found in numerous spacecraft across missions such as *Cassini*, *Bepi-Columbo*, and *Solar Orbiter*[19]. The UK, in partnership with other ESA member states, developed the Seismometer "SEIS-SP" used to detect 'Marsquakes' down to atom sized tremors in NASA's *InSights* mission.[20] Furthermore, the UK led the European consortium involved in building the Mid-Infrared Instrument "MIRI" for the James Webb Space Telescope, providing the scientific leadership, instrument design, and overall project management in addition to being responsible for the overall construction and quality control.[21] The UK has further examples of involvement in Panoramic Cameras, Mass Spectrometers, and Infra-red devices as well as various other instruments.

The UK is a dependable partner for numerous payloads on various missions and this will continue as commercial operations come online alongside institutional exploration activity, providing additional opportunities for growth. Terrestrial science instrumentation development will be necessary to find commercial avenues for end-products both on Earth and when applied to space exploration, for example, devices will be needed for monitoring and testing of the inputs and outputs of ISRU devices. Future science instruments and experiments will likewise need to be designed for experiments on limited and/or uncrewed stations, minimising the need for human operation and monitoring as commercial stations transition to a different operating model. Retaining and advancing the UK's leading position in this technology theme will require the continued development of payloads for microgravity life science experiments and planetary exploration missions.

[19] STFC, Space Magnetometer Calibration Facility, https://www.ukspacefacilities.stfc.ac.uk/Pages/Imperial-College---London---Space-Magnetometer-Calibration-Facility.aspx
[20] UK Space Agency, Marsquakes' mission successfully lands on Red Planet, https://www.gov.uk/government/news/marsquakes-mission-successfully-lands-on-red-planet
[21] UK Space Agency, James Webb Space Telescope/MIRI, https://www.gov.uk/government/case-studies/james-webb-space-telescope-jwst#:~:text=The%20UK%20led%20the%20European,newly%20forming%20stars%20and%20planets.

Space Nuclear Power

Power Generation Technologies [3.B]

Methods for generating power from different sources (e.g. solar, chemical, nuclear) as well as energy harvesting.

Nuclear Fission Reaction Technologies [3.B.III]

Power generation subsystems using fission reactors adapted for space use.

Radioisotope Power Technologies [3.B.IV]

Power generation subsystems using the natural decay heat of radioisotopes, either for thermal control (Radioisotopes [Heater] Units) or converted into electricity (Radioisotopes Thermo-electric Generators).

Energy Storage Technologies [3.C]

Technologies and methods of energy storage after generation from solar, chemical, or nuclear sources.

Electro-Chemical Technologies for Energy Storage [3.C.I]

Technologies converting chemical energy to electricity for storage purposes (e.g. batteries, fuel cells).

Space Nuclear Power is a vital asset to any exploration mission as it provides a long durability for its user that is not dependent on sunlight and thus missions beyond LEO, and where the Sun's light is intermittent, will likely require a high-density energy source such as nuclear power. A reliable and lasting source of energy for construction, power, heating etc., nuclear power is a necessity for an end-goal of human habitability on the Moon and for the infrastructure required to travel on to Mars. The UK has strong capabilities in this field and is at the forefront of the technology terrestrially and has an evolving capability in space exploration. Although space nuclear power has limited mission heritage, such technologies have been understood terrestrially since the mid-twentieth century, with the UK taking a lead role.

The world's first full-scale commercial nuclear power station, Calder Hall, opened in 1956 at Sellafield, Cumbria and was the precursor to a further 19 stations across the UK over time. Nuclear power currently constitutes around 15% of the UK's power supply and is intended to reach 25% by 2050.[22] As part of this ambition, the UK Government is supporting the development of Advanced Nuclear Technologies:

- *Small Modular Reactors* which are reduced in size and allow for off-site manufacturing for flexible deployment; and,
- *Advanced Modular Reactors* which take advantage of novel fuels and other technological innovations while using Small Modular Reactor principles.

The UK currently has a strong heritage of very small nuclear reactors thanks to their use in Royal Navy submarines since the 1960s and a number of UK based businesses have invested in this technology in recent years as part of the UK Government Small Modular Reactor Programme. Terrestrially, this Programme will unlock technologies for more localised power generation while retaining and growing vital essential skills in this domain – both of which can be applied to developing similar capabilities for space. A UK developed Micro Reactor will provide a significant contribution to global Artemis ambitions and provide a valuable avenue for growth for the associated UK supply chain.

Radioisotope Power Systems (RPS) are essential for planetary deep space exploration where solar energy is limited or intermittent. RPS are used to maintain operating temperatures for spacecraft instruments in the extreme cold of space in the case of Radioisotope Heater Units (RHUs) while they may also provide electrical power in the case of Radioisotope Thermo-electric Generators (RTGs). RPS are essential for future space exploration and important both as a stand-alone technology and as the power source for numerous other technologies. The Perseverance Rover, currently exploring Mars, is fitted with an RTG capable of producing 110W of electricity at beginning of life and is expected to provide a power supply for 14 years.[23] Similar variations of this RTG have been used for many

[22] HM Government, Nuclear energy: What you need to know, 2022, https://www.gov.uk/government/news/nuclear-energy-what-you-need-to-know
[23] NASA, 2020, https://mars.nasa.gov/mars2020/spacecraft/rover/electrical-power/

other NASA missions. Meanwhile, the solar-powered Rosalind Franklin Rover for ESA's Rosalind Franklin mission will have an RHU component to maintain instrument temperatures during the Martian night.

Most RPS use Plutonium-238 as the fuel source, however, since the 1980s, production has slowed and all but ceased globally, this lack of fuel supply is driving a global push for alternative fuels. Americium-241 (^{241}Am) is understood to be a viable fuel source for future RPS with a significantly longer half-life (around 430 years compared to 90 years). The UK has proved the capability of ^{241}Am by powering a lightbulb from heat generated by a small amount of the fuel during a 2019 research project and has a large stockpile of ^{241}Am as a by-product of the nuclear energy industry, overseen by the Nuclear Decommissioning Authority.[24] There is over 15 years' worth of research on this concept with UK institutions owning their own RPS patents. The combination of expertise in understanding, developing, and manufacturing such devices alongside a healthy supply of a compatible fuel, provides the UK with a unique capability to lead in this field.

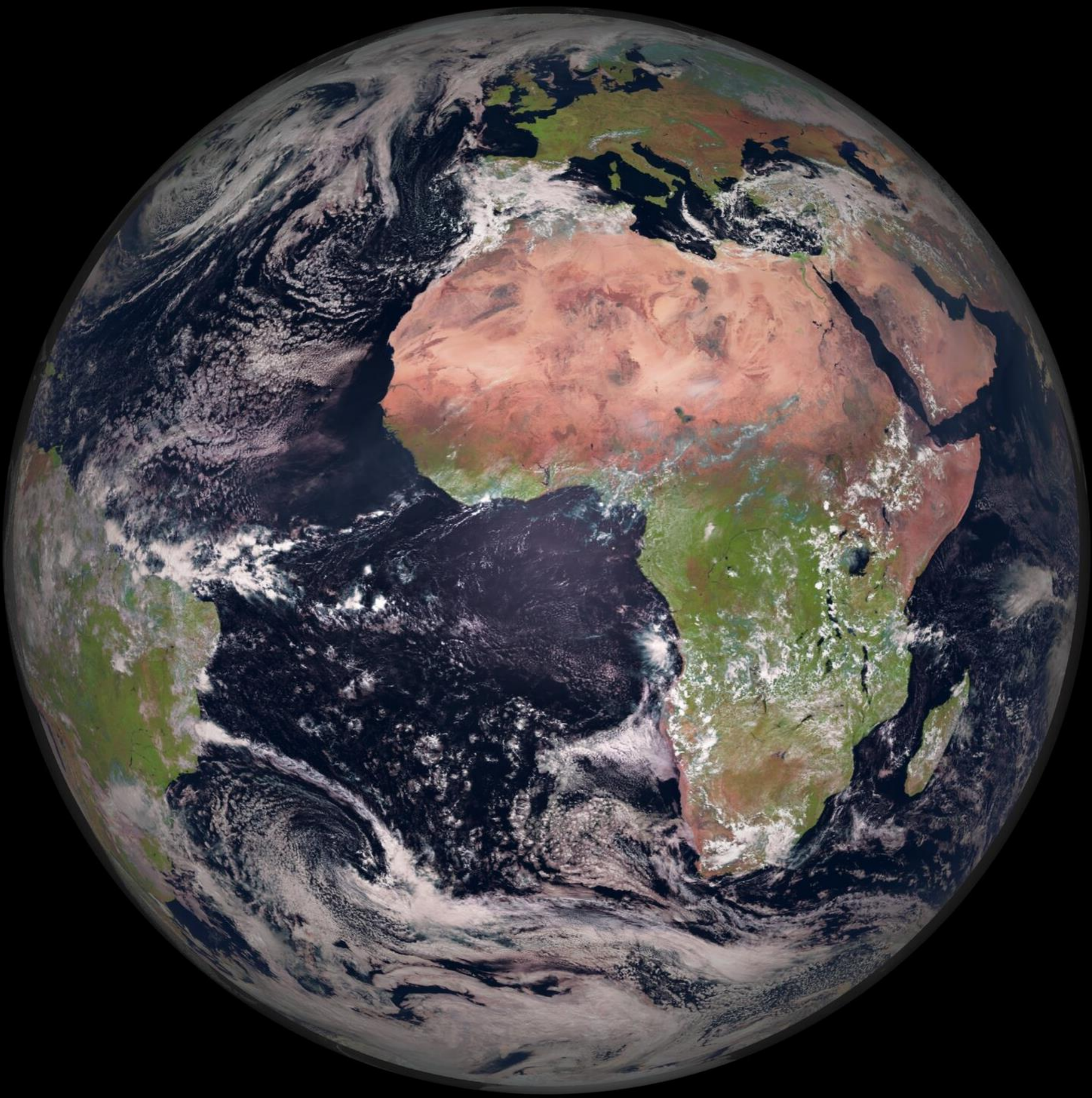
In December 2022, the UK Space Agency and National Nuclear Laboratory announced the development of a new £19m laboratory in Cumbria to extend the UK's capabilities in this area and provide a scalable production of the fuel.[25] Furthermore, the UK subscribed £22m to ESA's ENDURE programme at CMin22, which seeks to develop European RPS. The UK Space Agency will look to support the development of RPS in the UK and the further understanding and development of ^{241}Am fuel source to provide a strategic advantage for UK participation in global exploration efforts.

Fuel cell technologies are an important component of any power generation activity, including Space Nuclear Power and ISRU. Fuel cells convert the energy of a chemical reaction into electrical power and provide a steady supply of power compared to systems relying on solar energy which are time or orbitally/geographically constrained. The creation of power from an input fuel, as opposed to storing and recharging, also provides more durability and less decay compared to a battery. As part of terrestrial and space nuclear power and of ISRU capabilities, the UK has valuable skills and knowledge in fuel cell technologies.

[24] NNL, 2019, https://www.nnl.co.uk/2019/05/uk-scientists-generate-electricity-from-rare-element-to-power-future-space-missions/

[25] UK Space Agency, UK Space Agency and NNL work on world's first space battery powered by British fuel, https://www.gov.uk/government/news/uk-space-agency-and-nnl-work-on-worlds-first-space-battery

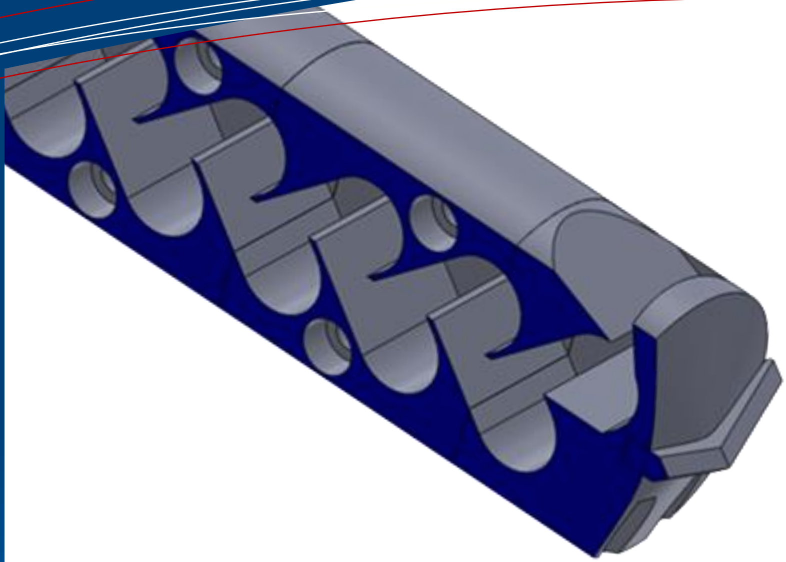
Case Studies



Earth
Image Credit: EUMETSAT/ESA

PULSE ELEVATOR

The University of Glasgow



A simple device that has an extremely small footprint, which does not exploit friction, and which does create heavy torque requirements, is an attractive new technology option.

PROVEN CAPABILITIES

The technology has already proven that it can uplift granular materials in both drilling and bulk transport contexts. Although it is a simple architecture, it appears to be entirely novel, and a patent has been applied for.

An industrial PhD, supported by Schenck Process UK, is currently getting underway.

The Problem

Subsurface exploration or ISRU requires the transport of granular materials, either as drilling spoil or as regolith for further processing. For tasks like this, the auger has been the key technology option for many thousands of years: a rotating scroll which exploits frictional forces to drive the material upwards against gravity.

When drilling, however, this creates a requirement for a rotating drillstring. The power required to auger the spoil out of the hole can far exceed the power required to break the material itself, and the torque applied must be reacted to the planetary surface. This is challenging, particularly for smaller landers and when moving larger quantities of material, for ISRU, the power requirements may rise still further.

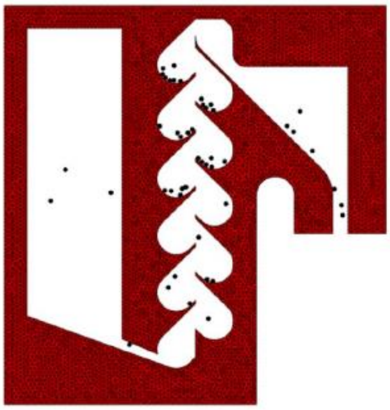
The differential friction technique creates an unavoidable loss of energy while also resulting in heating of the material. In a terrestrial industrial setting this task might be tackled using vibratory conveyors or bucket systems, which are usually complex and bulky pieces of equipment that would require considerable additional cost and time to translate into space applications.

UK Space Agency Support

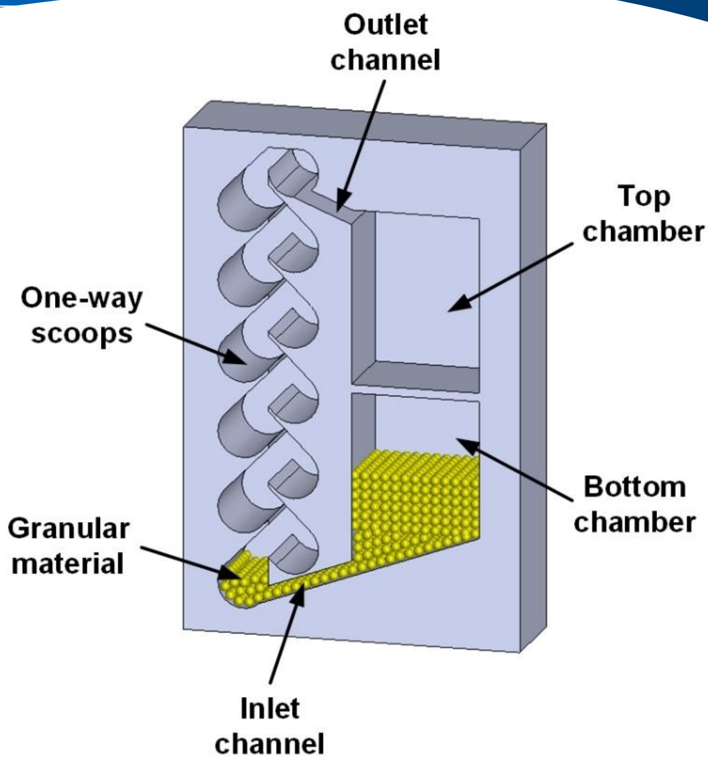
The UK Space Agency supported the development of this concept through the 'augers not included' project. The £85,000 grant allowed the University of Glasgow to build a drillbit that, instead of an auger, had an internal pulse elevator. This smooth-walled drillbit was able to penetrate to its full design depth, more than five-bit diameters, in rocky materials while the spoil was for the first time ejected through, rather than around, the drillbit.

The Solution

The pulse-elevator is a simple concept whereby vertical oscillation is used to transport granular material along the device. The pulse-elevator has a series of alternating and opposing scoops, developed from the fluidic Tesla valve, such that any material inside the device can only easily move in one direction.



Particle distribution, at 0.9 s after initialisation at 5 g.



A simple pulse-elevator architecture, when shaken, will quickly move all the particles in the bottom chamber into the top chamber.

The oscillation, combined with the inertia of the material, tends to move the contents along (and usually up) the device with each excitation cycle. Because this cyclic movement is a simple-harmonic, the torque is eliminated and careful damping can help to manage any loads that need to be reacted externally.

Benefits

The auger has been used in every single drill-based exploration mission ever flown, having been deployed to planets, the Moon, and comets. An alternative that can reduce the electromechanical footprint of the devices required to meet these most challenging requirements has the potential to deliver impactful change to future mission architectures.

More Information

Research Paper (IAA): *Acta Astronautica*, Volume 200, November 2022
Operating Principles YouTube Video: youtube.com/shorts/tezBop_xufc

TERRESTRIAL APPLICATIONS

After bulk liquids, granular materials are the world's second most traded commodity. This includes:

- Mined Materials
- Foodstuffs
- Industrial Feedstocks

They are also encountered in process engineering, particularly in fields such as pharmaceuticals, where the pulsed nature of the pulse-elevator delivery lends itself to new applications in metering. Each of these need to be moved between shipping holds, silos, and delivery vehicles.

A novel, low-footprint device has considerable opportunity in which to find new applications on Earth.

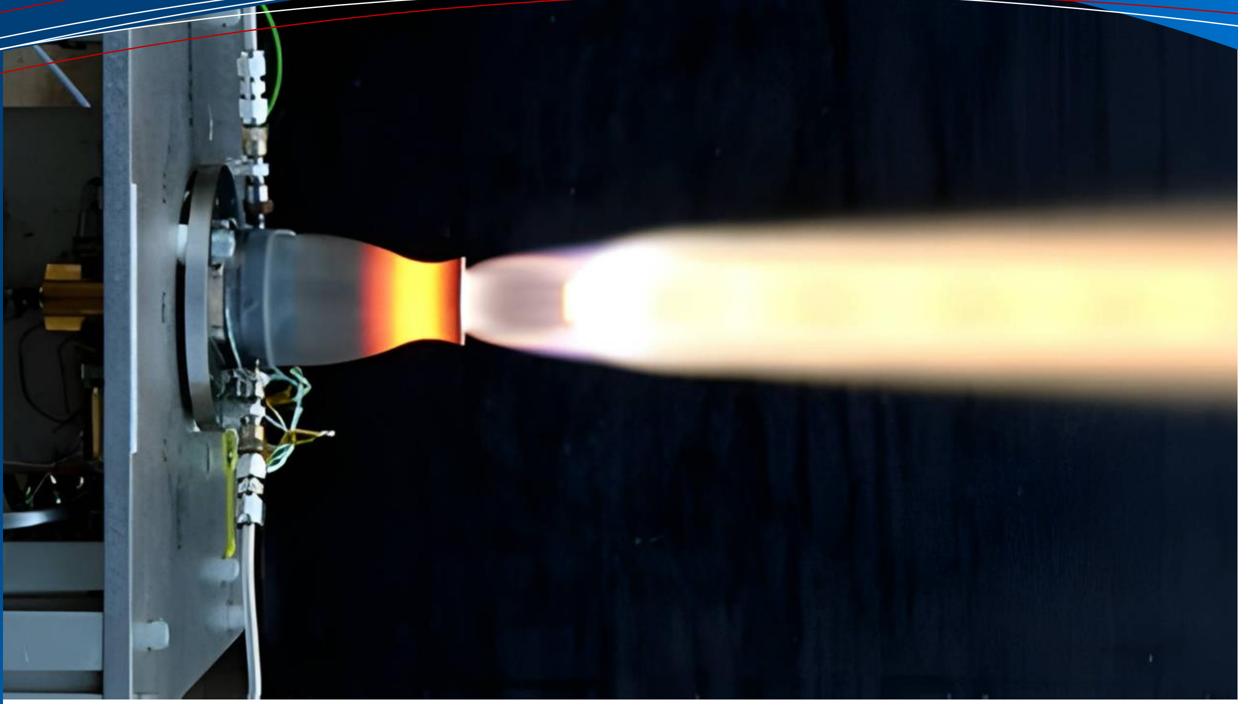
Contact

James Watt (S) Building,
University of Glasgow
University Avenue
Glasgow, G12 8QQ
-
Patrick.Harkness
@glasgow.ac.uk

LEROS 4 MON/MMH 1kN Engine

Nammo (U.K.) Ltd.

This 'Apogee Class' rocket provides over 1000 Newtons of thrust which makes it ideal for moving significant amounts of equipment and supplies to the surface of the Moon and, in future missions, to Mars and beyond.



The LEROS 4 thrust chamber concept being tested.

SECTOR WIDE APPLICATIONS

The spacecraft propulsion experts at Nammo UK have a long history of producing rocket engines for both Earth orbit duties and deep space missions.

Nammo UK's LEROS family of engines and thrusters have provided the motive power for large numbers of spacecraft. They have literally hundreds of engines and thrusters on Earth satellites that supply us all with communications, satellite navigation, weather and tidal information, global warming data, and television services.

The Problem

In order to carry out deep space missions to far planets such as Jupiter, Venus and Mars, the main spacecraft engine needs to be able to accelerate the vehicle to speeds up to ¼ million miles per hour when it leaves Earth orbit. In addition to this early mission acceleration, the engine also has to slow down the vehicle very rapidly to enable orbit insertion around the target planet.

Spacecraft engines at the 1 kN and throttleable 7kN thrust class have not previously been available. Such engines are now being considered for commercial missions of various outputs shows that high efficiency (lower propellant mass needed on board) and high thrust are the way forward for many future missions.

The recent developments at Nammo for main satellite/spacecraft engines at higher thrust levels than have previously been the norm, have been driven by ESA requirements for propellant efficiency on orbit insertion (in the case of the 1 kN engine) and for Lunar landers with greater mission manouevring capability with higher payload capacity.

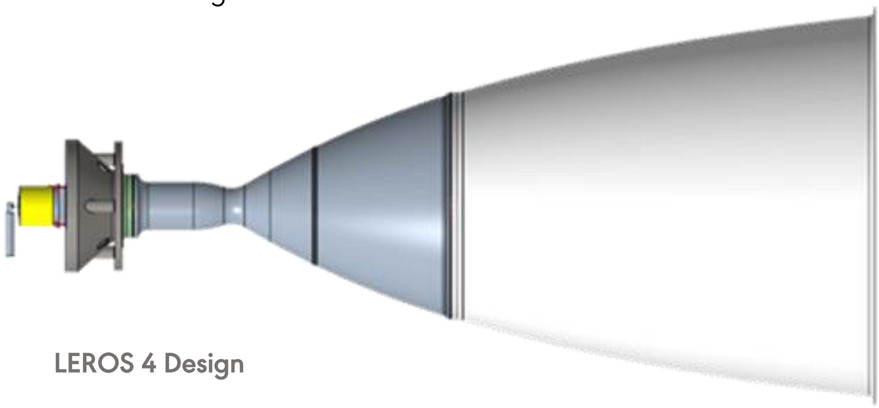
UK Space Agency Support

All Nammo apogee engines are hot-fire tested in the UK National Space Propulsion Test Facility at Nammo Westcott. The UK Space Agency invested £4 million in 2016 to develop the Buckinghamshire site to provide testing facilities that allows UK companies and academics to fire up and test state-of-the-art space propulsion engines at up to 1.5kN in high-altitude vacuum, an equivalent test altitude of 140,000ft. The site opened to users in 2021.

Nammo

The Solution

The LEROS 4 high thrust rocket engine has been developed by Nammo UK, the UK space propulsion company based near Aylesbury, specifically for Moon and inter-planetary missions. The engine has a thrust range between 900N and 1100N.



LEROS 4 Design

The LEROS 4 engine has been developed using the proven Nammo UK apogee-class engine design methodology. The materials used and the injector configuration are largely an extension of those used on lower thrust class LEROS engines. The head-end which is the interface between the flow control valves, injector, and spacecraft mounting points uses similar principles as the heritage LEROS main engine designs but state-of-the-art methods of manufacture of key components together with Nammo's own high flow Apogee Engine Valves (AEVs) have been included in the design to optimise heat dissipation from the injector zone whilst keeping the head-end at low temperatures which is vital for preservation of the integrity of the valve seats.

Even though Nammo have taken heritage LEROS technology as the basis for the LEROS 4, every part of this new engine is unique and has been optimised for the LEROS 4.

Benefits

This engine is a true mission enabler. The LEROS 4 provides twice the thrust of standard apogee class engines and can therefore carry out the deceleration much more efficiently in terms of burn time and propellant consumption.

In the case of Jupiter, the JUNO spacecraft had to decelerate from 235,000 mph to 16,000 mph in one continuous burn – in this case the burn was 31 minutes to achieve successful orbit insertion. LEROS 4 will enable higher mass spacecraft to perform similar planetary or Moon orbit-insertion burns with even more efficiency due to its ability to carry out the complete manouevre faster. Proto-flight and Qualification testing is due 2024 while LEROS 4 can be ordered now.

More Information

LEROS 4: https://www.nammo.com/product/leros-4
Westcott Space Cluster: https://westcottspacecluster.org.uk

FURTHER INNOVATION

The Nammo test and development teams are applying their extensive expertise and experience to the new RELIANCE throttleable and high thrust engine, currently under intense development.

The engine has internal liquid cooled channels throughout the expansion cone and combustion chamber to ensure temperature stability during its operational lifetime. It has a unique moveable pintle injector to maintain the fuel to oxidiser mixture ratio at whatever thrust it is commanded to produce. The engine also carries its own propellant pumps and controller on board to enable multiple engines to be run side-by-side from the same shared propellant tanks.

Contact

Nammo (U.K.) Limited
Building 47
Westcott Venture Park
Westcott, Buckinghamshire
HP18 0XB
-
Adam.Watts
@nammo.com

RF ROVER: AUTONOMOUS NAVIGATION

Airbus Defence and Space Ltd.

Rosalind Franklin being integrated in the Bio-Clean Facility at Airbus in Stevenage

The primary purpose of the Rosalind Franklin mission is to explore a Martian terrain where there is strong orbital data indicating a warm and wet past, in order to acquire and examine sub-surface samples for evidence of past or extant life.

Adaptability

The mobility system can be modified to function on any solid planetary body, such as the Moon. Although naturally illuminated stereo cameras are the primary sensors for Rosalind Franklin, the mobility architecture is such that it can be adapted to use alternative primary sensing solutions such as artificially illuminated cameras, LIDAR or RADAR.

The Problem

The large distance to Mars leads to a round trip communication latency between 10 and 40 minutes depending on the relative orbital positions of Earth and Mars. Such latency, in combination with limited line of sight visibility between Earth and the Rover, mean that real time driving under operator control is not feasible.

Furthermore, orbital mapping resolution is insufficient to allow route planning below a strategic scale of many 10s of metres, yet, mobility system constraints arising from the limited mass and volume that can be landed necessitate a terrain knowledge resolution of just a few centimeters to safely negotiate the topologically complex Martian terrain.

Thermally the Martian environment is extremely harsh and highly variable. The atmosphere is very thin causing dramatic temperature variations, yet, it is thick enough to allow dust storms that greatly reduce the power that can be harvest by solar arrays.

UK Space Agency Support

The Rosalind Franklin Rover is an ESA programme to which the UK is a major contributor via the UK Space Agency. The UK sector provided the Rover design and assembly but also the landing platform which will safely carry it to the surface of Mars.

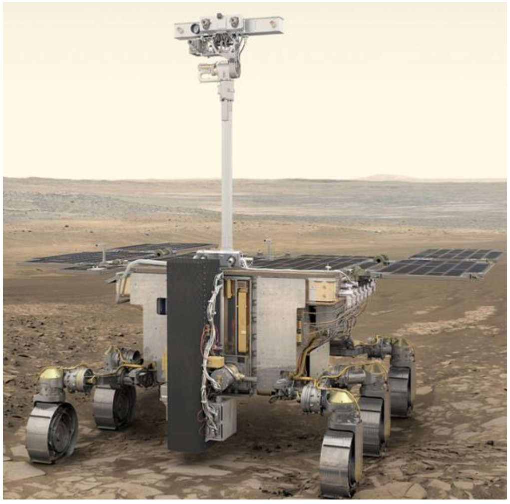
The UK Space Agency continues to champion and support the Rosalind Franklin mission now due for launch in 2028.

AIRBUS

The Solution

Airbus in the UK has developed an autonomous mobility system that assesses the local terrain topology from within a few metres of the Rover down to centimetre level resolution. The system plans and drives a safe traverse through local hazards (large rocks, deep hollows, and steep slopes) towards a specified strategic target that can be up to 100 metres away. This is accomplished by two broadly independent functions, Navigation (Nav) for terrain assessment and Relative Localisation (RelLoc) for determining the position and heading of the Rover relative to its starting position and heading.

Nav is performed at regular drive distance intervals. A mast mounted stereo camera takes terrain image pairs to the front and to each side of the Rover. Each of these image pairs is processed and stitched together to produce a map of the arc of terrain a few metres ahead. This map is stitched to the previously mapped arcs and processed to identify non-traversable areas and to apply traverse costs to the traversable areas. Using this data, the path planner identifies the best path towards the target destination over this mapped terrain arc.



The Rosalind Franklin Rover
Credit: Airbus

RelLoc provides regular estimates of the Rover position and heading using a fusion of high frequency inertial measurement data and wheel odometry data, and lower frequency visual localisation data. This allows progress along the planned path and wheel slippage in the drive direction and lateral deviations from the target path to be determined. This can be corrected through adjustment of the individual wheel steering angles and drive speeds. The inertial measurement unit is provided by TAS-UK and visual localisation SW is provided by CGI using algorithms developed by Oxbotica.

Benefits

The autonomous mobility concept and integrated thermal design concepts implemented in the Rosalind Franklin Rover are adaptable to lunar use in support of exploration and utilisation. The mobility concept allows for exploration in unmapped areas with complex unknown terrain while lending itself to detailed mapping and characterisation of terrain considered for ISRU or scientific instrumentation placement as well as autonomous conduct of those missions. The integrated thermal design concept, in particular the use of radioisotope heaters in conjunction with a well thermally isolated warm box, is essential for achieving lunar night survival and reliable exploration of permanently shadowed regions.

TERRESTRIAL APPLICATIONS

The autonomous mobility concepts implemented on Rosalind Franklin are adaptable to terrestrial applications in which robotic access is desired but communication maybe infrequent or unreliable or autonomy is beneficial, such as:

- Agricultural soil sampling surveys
- Pipeline and sewer inspection
- Disused mine workings exploration
- Ocean floor exploration
- Undersea infrastructure inspection
- Disaster site exploration and inspection

Contact

Airbus Defence and Space Ltd
Gunnels Wood Road
Stevenage
SG1 2AS

Bridging the Gaps

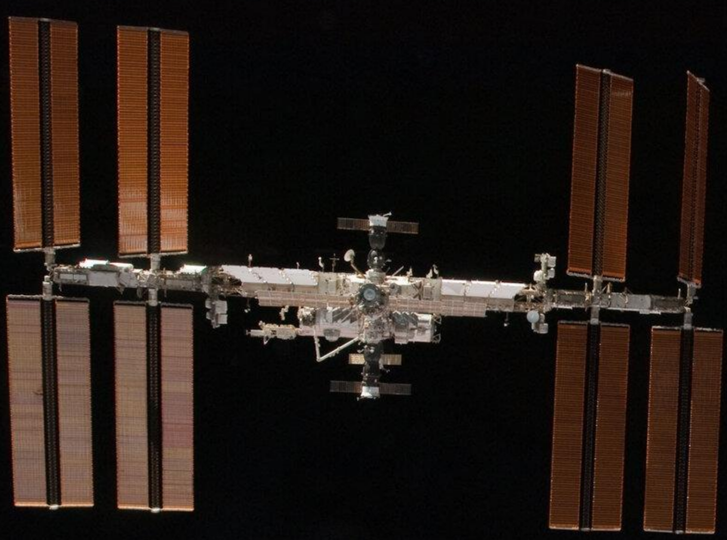
Achieving the development of the technologies in this Roadmap will not happen instantly, instead, it will take collaboration, dedication, and support from all organisations with an interest in this field. This section details some of the assistance available at present and where the UK Space Agency will seek to build-on current relationships to unlock further opportunities.

UK Space Agency

The overall remit for the development of these technologies sits with the UK Space Agency. The Agency routinely represents the interests of the UK space and space exploration sector at various international committees including through **ISECG**, the **International Mars Exploration Working Group** (IMEWG), ESA's **Programme Board for Human Spaceflight, Microgravity and Exploration** (PB-HME) and **European Utilisation Board** (EUB) as well as nationally through our collaboration and representations to other government departments.

The Exploration team also runs dedicated funding calls for the advancement of exploration technology, providing UK based organisations the ability to conduct feasibility studies, industrial research, and technology demonstrations through grant funding. Further information on the types of projects funded through this avenue can be found on the gov.uk website. The team will continue to provide such opportunities for the space exploration sector and seek out new opportunities with other funding providers to maximise UK Space Agency resources for the benefit of technology development.

The Exploration team also runs the Exploration Community Development Fund designed to aid organisations to participate and formulate activities that are of benefit to the wider UK exploration community with grants up to £50,000, subject to budget availability. This support helps foster connections between organisations so that expertise can be shared, and collaboration opportunities promoted.



Following the NSS' desire to do more bilateral activity beyond that which is done through ESA, the UK Space Agency has put appropriate funding in place to support joint activities with like-minded countries. The UK Space Agency is committed to maximising opportunities of working with new partners and will seek to support exploration collaborations where possible.

The UK Space Agency will continue to cooperate and align with DSIT and other government departments involved in the strategic planning that supports the UK's space sector.

Further information about UK Space Agency funding opportunities can be found on our website.

ISS backdropped by a blue and white part of Earth
Image Credit: NASA

UK Research and Innovation (UKRI)

UKRI brings together the seven Research Councils in England and Innovate UK to invest in innovation across a broad range of sectors. UKRI is an important facilitator in the development of space and space exploration technologies, particularly through the work of the **Science and Technology Facilities Council** (STFC) and the **Engineering and Physical Sciences Research Council** (EPSRC) which specialise in areas applicable to this field. For example, STFC are responsible for the **Rutherford Appleton Laboratory** (RAL), **UK Astronomy Technology Centre**, and **Boulby Underground Laboratory**, facilities where cutting-edge space science takes place.

UKRI is a catalyst for helping businesses to access technology expertise and facilities in the research base, supporting early-stage translation and scale-up, and formulating academic-business partnership models that leverage private investment through their expertise and grant funding opportunities.[26] UKRI will therefore be an important partner to the UK Space Agency, to whom we will continue to collaborate and seek to expand funding opportunities for the development of these technologies.

European Space Agency (ESA)

In addition to the exploration missions and funding agreed at the Council of Ministers, the UK and ESA support the development of technology through the **General Support Technology Programme** (GSTP). The GSTP provides funding to organisations across the UK in developing innovative technologies to grow UK capability; taking leading-edge technologies that are not ready to be sent into space and developing them to be used in future missions.[27] This funding is an additional mechanism that the UK Space Agency encourages the exploration community to utilise. The UK committed a further **£71m** to this programme at ESA CMin 2022.

Through the UK's membership of ESA, British organisations also have access to various ESA centres around Europe including **Spaceship ECSAT** (the European Centre for Space Applications and Telecommunications), the **VULCAN Analogue Facility** and **ESA Business Incubation Centre UK** which are all located at the Harwell Space Cluster, Oxfordshire.

Moon – Western Near Side
Image Credit: NASA/JPL

[26] UKRI Strategy 2022 to 2027, UKRI, 2022
[27] ESA, About the General Support Technology Programme (GSTP), https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Shaping_the_Future/About_the_General_Support_Technology_Programme_GSTP

Next Steps

This roadmap identifies the key exploration technology areas where the UK Space Agency believes the UK has strong capabilities. These areas will be a focus for development to allow the associated sectors to capitalise on future missions and other uses in space.

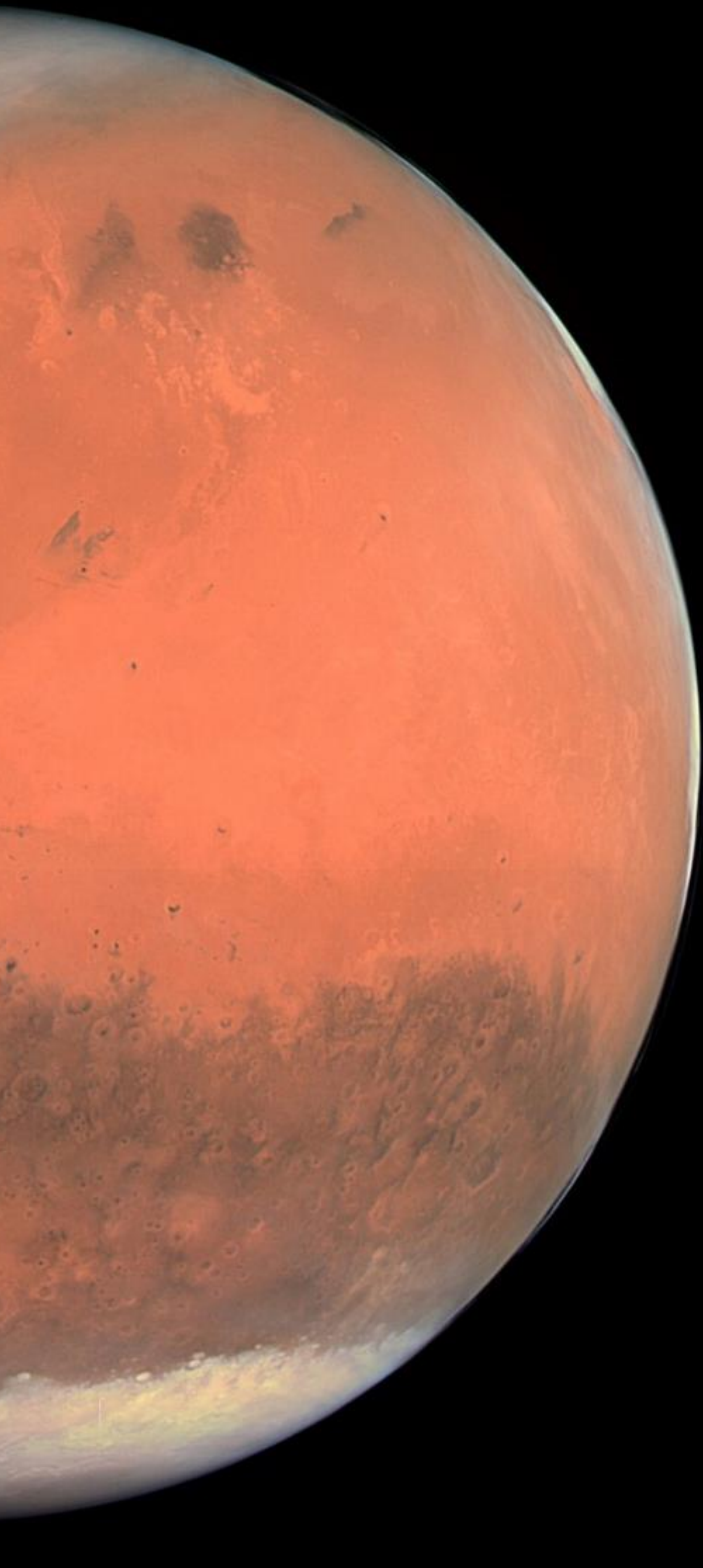
The SETR will inform the future work of the UK Space Agency over the next decade in seeking to achieve the goal of maintaining and growing UK capabilities in exploration technologies. It serves as a brochure for the UK space sector, highlighting technologies where the UK has a high aptitude and therefore areas for growth and investment.

The UK Space Agency will champion and refer to the roadmap at sector events, in conversations with strategic partners, to international and UK organisations, and throughout wider UK Space Agency considerations and planning.

To provide further analysis on each specific technology area, the UK Space Agency intends to publish supplementary roadmaps. These additional publications will provide greater granularity and will outline key information for the technologies. The UK Space Agency will continue to consult UK industry and academia about such capabilities in producing these additional roadmaps.

To ensure the document remains appropriate for these aims, it is the intention of the UK Space Agency that this roadmap will be reviewed and revised as necessary.

The UK Space Agency will continue to welcome feedback on the roadmap, if you wish to provide a comment on any aspect of the document then contact us at SpaceExploration@ukspaceagency.gov.uk



True-colour image of Mars seen by OSIRIS
Image Credit: ESA & MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA,

Appendix

Appendix I: Glossary

AI	Artificial Intelligence	**UKRI**	UK Research and Innovation
CLPS	Commercial Lunar Payload Services (NASA)	**LEO**	Low Earth Orbit
CMin	Council of Ministers (ESA)	**LIDAR**	Light Detection and Ranging
DSIT	Department of Science, Innovation and Technology	**JAXA**	Japan Aerospace Exploration Agency
DWI	Double Walled Isolator	**MSR**	Mars Sample Return
E3P	European Exploration Envelope Programme (ESA)	**NASA**	National Aeronautics and Space Administration (USA)
EL3	European Large Logistics Lander (Argonaut)	**NSS**	National Space Strategy
EPSRC	Engineering and Physical Sciences Research Council	**PB-HME**	Programme Board for Human Spaceflight, Microgravity and Exploration (ESA)
ESA	European Space Agency	**R&D**	Research & Development
EUB	European Utilisation Board (ESA)	**RAL**	Rutherford Appleton Laboratory
ExPeRT	Exploration Preparation, Research and Technology	**RHU**	Radioisotope Heater Unit
GER	Global Exploration Roadmap	**RPS**	Radioisotope Power Systems
GSTP	General Support Technology Programme	**RTG**	Radioisotope Thermo-electric Generator
IMEWG	International Mars Exploration Working Group	**SEAC**	Space Exploration Advisory Committee
ISAM	In-Space Servicing, Assembly, and Manufacturing	**SETR**	Space Exploration Technology Roadmap
ISECG	International Space Exploration Coordination Group	**STFC**	Science and Technology Facilities Council
ISRU	In-Situ Resource Utilisation	**TGO**	Trace Gas Orbiter
ISS	International Space Station		

Appendix II: Roadmap Technologies

A simplified list of the exploration technologies featured in this roadmap, designated by overall UK Space Agency *Technology Theme* and the relevant ESA defined technology subdomains and groups where necessary.

Advanced Manufacturing

Novel Materials and Materials Technology
Materials Processes
Modelling of Materials Behaviour and Properties
Advanced Manufacturing Technologies

Autonomy & Artificial Intelligence

Machine Learning and Artificial Intelligence for On-board Data Subsystems
Software Technologies

- Software Autonomy and Artificial Intelligence

Communications & Mission Operations

Telecommunication Subsystems
Mission Operations

In Situ Resource Utilisation

Life Support & Crew Performance

Environmental Control & Life Support (ECLS)

- Habitability Technologies

Applied Life Science Technology

- Application of Human Physiology Technologies

Software Technologies

Navigation & Sensing

Radio Navigation Subsystems
Optical Equipment and Instrument Technology

Propulsion

Chemical Propulsion Technologies
Electric Propulsion Technologies
Other Propulsions Technologies

- Nuclear Propulsions Subsystems

Supporting Propulsion Technologies and Tools

Robotics

Robotic Applications and Concepts
Automation & Robotics Systems and Subsystems
Automation & Robotics Components and Technologies
Launchers, Re-entry Vehicles, Planetary Vehicles
Mechanism Core Technologies

Sample Curation

Reliability and Reusability Aspects of Materials

- Advanced Physical & Chemical Characterisation and Analysis of Materials

Life & Physical Sciences

Science Instrumentation

Instrumentation in Support of Life Sciences
Instrumentation in Support of Physical Sciences
Applied Life Science Technology

Space Nuclear Power

Power Generation Technologies

- Nuclear Fission Reaction Technologies
- Radioisotope Power Technologies (RPS)

Energy Storage Technologies

- Electro-Chemical Technologies for Energy Storage

Appendix III: Further Information

National Space Strategy
www.gov.uk/government/publications/national-space-strategy

Size & Health of the UK Space Industry 2022
www.gov.uk/government/publications/the-size-and-health-of-the-uk-space-industry-2022

UK Space Facilities
www.ukspacefacilities.stfc.ac.uk/Pages/home.aspx

ESA | Terrae Novae 2030+ Strategy Roadmap
www.youbenefit.spaceflight.esa.int/terrae-novae-2030-exploration-strategy-roadmap/
ESA | Revolution Space: Europe's Mission for Space Exploration
www.esa.int/ESA_Multimedia/Images/2023/03/Revolution_Space_Europe_s_Mission_for_Space_Exploration
ESA | Technology Tree (V4.0, STM-277), 2020
www.esa.int/About_Us/ESA_Publications/STM-277_ESA_Technology_Tree
ESA | About the General Support Technology Programme (GSTP)
www.esa.int/Enabling_Support/Space_Engineering_Technology/Shaping_the_Future/About_the_General_Support_Technology_Programme_GSTP

ISECG | Global Exploration Roadmap
www.globalspaceexploration.org/

NASA | Artemis Accords
www.nasa.gov/specials/artemis-accords/index.html
NASA | Commercial Space Stations
www.nasa.gov/press-release/nasa-selects-companies-to-develop-commercial-destinations-in-space

UKSA | Corporate Plan 2022-2025
www.gov.uk/government/publications/uk-space-agency-corporate-plan-2022-25
UKSA | Exploration Programme
www.gov.uk/government/collections/space-exploration-programme

UK SPACE AGENCY