Access to the Space environment and Low Earth Orbit: What are the Opportunities?

For many years, scientists have been utilising platforms both in orbit and on Earth to conduct fundamental research. The ESA Erasmus archives[16], contain a database of more than 4100 funded and/or co-founded R&D experiments related to the space sector, from advanced metallurgical processes in microgravity to how biofilms form.

As of September 2023, there are already a number of existing incumbents involved in active flight operations, including Arianne Space, Blue Origin, Boeing, Northrop Grumman, Rocket Lab, SpaceX and Virgin (Galactic) to name a few. There are also a number of active access providers supporting customers to fly R&D payloads in space including organisations like Airbus (Bartolomeo), Axiom Space, Ice Cubes, Space Forge (Forge Star), Kayser Space, Open Cosmos and Sierra Space, again to name a few. These capabilities are augmented through access to analogue platforms on Earth, including Drop Towers (e.g. Zarm Drop Tower), Parabolic flights (e.g. Novespace), Sounding rockets (e.g. Swedish Space Consortium) and centrifuges (e.g. ESA ESTEX Long Arm Centrifuge) allowing researchers to understand the effects of variable gravity on material processes on Earth (examples of research on these platforms is discussed later in this section).

Importantly and in the context of this paper, this capability for space/microgravity access is growing in both scale and diversity. This is coming from both existing and new players developing capabilities to provide and/or support greater access to the space environment for customers including Gravitlabs, Orbex, Skyrora, the Exploration Company, the aforementioned Space Forge and Sierra Space and many more globally. It is important to stress at this point, that whilst this paper has being open to and included several contributions from across the globe, it is more focussed on the UK R&D system. It is therefore recommended if you are not based in the UK to contact your local space agency (or organisation in charge of national R&D strategy) to enhance awareness of local capabilities and intelligence.

At a UK level, there are a number of mechanisms that have been developed to support both understanding and access to opportunities to conduct R&D research with the space environment (some more focused on commercial and others academic). At the early career stage for example, the European Space Agency runs dedicated education initiatives which provide student led research groups with the ability to design and run Space related experiments. These include the Spin, Drop, Fly and Orbit your thesis programmes, where many UK teams have applied and run experiments on (N.B. UK based teams can apply to receive additional support from the UK Space Agency[17]). ESA also runs a number of open call processes for the wider R&D community, including Announcement of Opportunities[18], to support R&D access to space-related platforms.

It can however be challenging to support the connection between existing space sector actors and non-space actors (both academic and commercial). This is a recognised priority in both national and international space strategy's to improve connectivity and collaboration to open up new R&D opportunities, business models for the space economy and drive productivity[19]. As such there are a number of existing and newly established initiatives to support these connections.

For example, the UK for over 12 years has hosted (through the Science & Technology Facilities Council, part of UK Research and Innovation) dedicated funded structures from ESA to facilitate space-related business incubation; ESA BIC UK[20] (N. B. this programme exists in several of the ESA member states). This programme has supported ~100 businesses in the UK, to develop technology, commercialise products and attract private funding. These UK Government funded infrastructures including the Catapult network (in particular the Satellite Application Catapult) and the Innovate UK Knowledge Transfer Network are actively supporting the commercial development opportunity for space, working across

[16] ESA Erasmus Archive https://eea.spaceflight.esa.int/portal/

[17] UK Space Agency Funding Programs (Including student support for ESA Programs
https://www.gov.uk/guidance/apply-for-funding-academic-community-and-educational

[18] ESA Announcements of Opportunity https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Research/Research_Announcements

[19] UK National Space Strategy https://www.gov.uk/government/publications/national-space-strategy

multiple sectorial areas from in-orbit manufacturing and energy to health and life science. For example, the Satellite Applications Catapult has launched the Space Enterprise Community to help organisations better connect both within and to the space sector[21]. Recognising the opportunity to better connect local expertise to national sector developments, in 2020 the UK Space Agency supported the further development of space clusters across the entire UK. To date there are 17 space clusters in the UK, from established clusters such as Harwell and Space Scotland, to emerging clusters such as North West England and Space East (N.B. more details on UK Space Clusters can be found here[22]).

With the European Space Agency deploying new mechanisms to further stimulate the growth of a sustainable low earth orbit and future lunar economy (through mechanisms such as the Phi-Labs Programme and Business in Space Growth Networks)[23] coupled with the UK's drive to grow a diverse and ambitious space economy, there is an opportunity to further augment cross-sector connection and collaboration to create a sustainable pipeline for the space ecosystem.

In the following section we go into more detail into space-based capabilities and examples of materials R&D research.

Laboratories and facilities available on the ISS:

The list of acronyms and abbreviations below provides disjoint glimpses of the rich variety of multiuser laboratories and facilities accommodated in the different ISS science modules for studies in the field of materials and fluids (e.g., the American Fluids and Combustion Facility, FCF; the European Fluid Science Laboratory, FSL; the Japanese Fluid Physics Experimental facility, FPEF, MSG, the Microgravity Science Glovebox), inorganic material science (e.g., the Materials Sciences Laboratory, MSL with the Low Gradient Furnace LGF, the Solidification and Quenching Furnace SQF and the Float Zone Furnace FMF; the High Gradient Directional Solidification Furnace Experiment Module, HGDS; the Directional Solidification and Vapor Transport Experiment Module, DSVT; the Advanced Tubular Furnace With Integrated Thermal Analysis Under Space Conditions, TITUS; the Quench Module Insert, QMI; the Diffusion Module Insert, DMI; the Advanced Thermal Environment Furnace ATEN; the Advanced Furnace for Microgravity Experiment with X-ray radiography, AFEX; the Gradient Heating Furnace, GHF, etc.) organic material science (the Protein Crystallization Diagnostics Facility, PCDF; the Solution Protein Crystal Growth Facility, SPCF; etc.) and biotechnology (the BIOLAB; etc.).

Previous UK materials-science space experiments and related facilities

The "Thermovibrationally-driven Particle self-Assembly and Ordering in Low grAvity" project (related UK Space Agency Acronym: "T-PAOLA", NASA/ESA Opsnom: "PARTICLE VIBRATION", PI M. Lappa, University of Strathclyde) was originally conceived to explore a new contactless manipulation strategy for the control of solid particles dispersed in a fluid in microgravity conditions, based on the application of "vibrations" and "differential heating". It was selected by UKSA/STFC in the framework of the 2018 AO for UK Microgravity Experiments, and is presented here as a relevant exemplar as it has opened vast perspectives for the production of new materials in space with properties that cannot be obtained in normal gravity conditions, relevant examples being metal or plastic alloys where the position of the minority phase (the dispersed particles) can be controlled precisely and even forced to form well-defined internal structures or "frameworks".

[20] ESA Business Incubation Centres UK https://esa-bic.org.uk
[21] Space Enterprise Community https://spaceenterprise.uk
[22] Space Clusters in the UK https://www.investorlaunchpad.uk/cluster-directory/
[23] ESA Business in Space Growth Network https://bsgn.esa.int

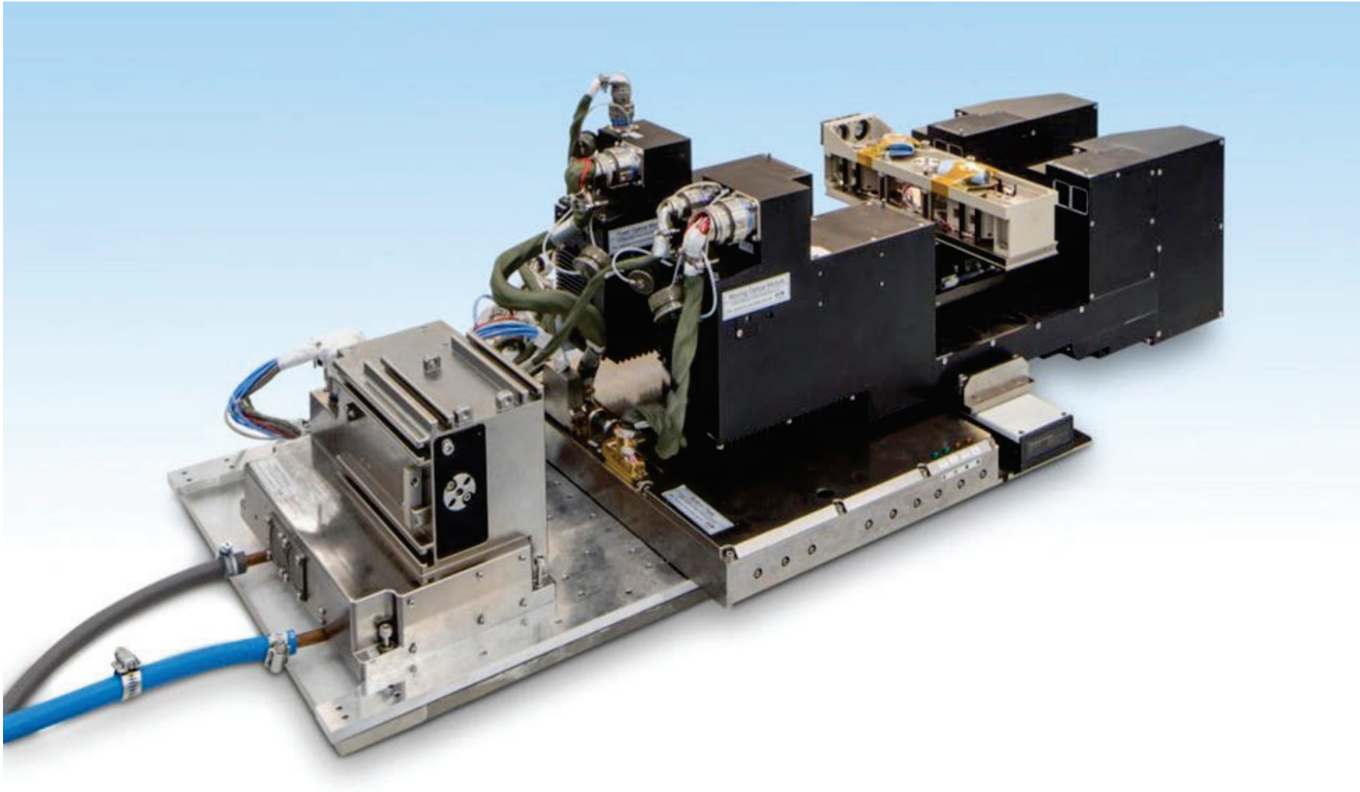

Figure c. The Selectable Optical Diagnostic Instrument (SODI) [Credit: QinetiQ & ESA]

The Selectable Optical Diagnostic Instrument (SODI)

These experiments have been executed in space during 2023 using the Selectable Optical Diagnostic Instrument (SODI). SODI is an instrument for scientific research in the fields of fluid-dynamics, materials science and biology, originally developed by an industrial consortium (led by QinetiQ) in the frame of a dedicated contract with the European Space Agency. Essentially, it is a payload equipped with various optical diagnostics. Moreover, it is based on a modular concept, i.e. it consists of different subsystems, which the astronauts can install in the work volume of the Microgravity Science Glovebox (MSG), a general-purpose NASA Facility.

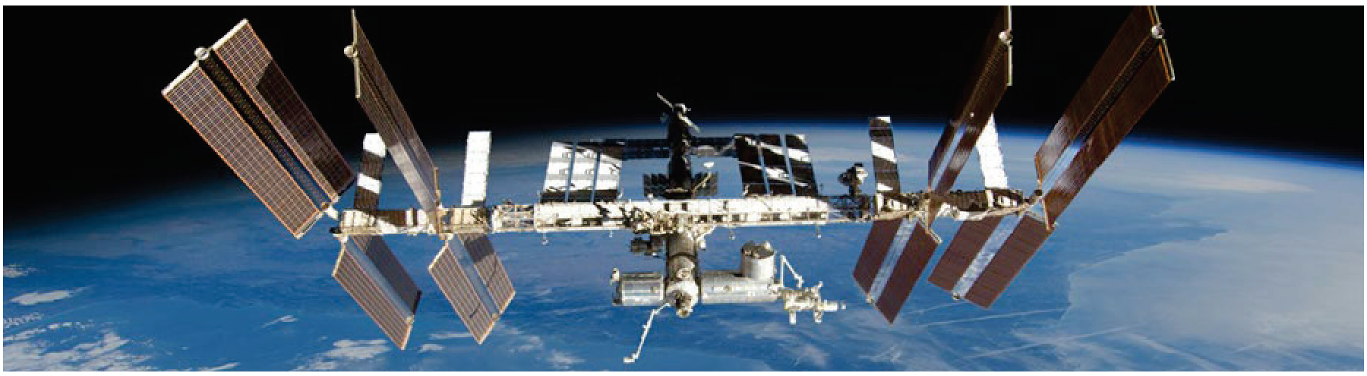

Figure d. International Space Station (Credit: NASA)

Figure e. Frank Rubio installing the PARTICLE VIBRATION hardware in the MSG Work Volume on board the International Space Station (3 Feb 2023) [Credit: ESA & NASA].

The MSG can feed smaller payloads with the required power; it also allows them to exchange data with ground and provides the required level of containment (when potentially hazardous liquids or materials are used for the experiments). The combined exploitation of SODI and MSG for the PARTICLE VIBRATION project has been made possible by a specific PIA (Payload Integration Agreement) existing between NASA and ESA, later extended to the UK Space Agency (UKSA) on purpose to allow this project.

Additional specific hardware has been manufactured directly in the United Kingdom by QinetiQ. It consists of “cell arrays” hosting the containers with the fluid and particles required for the experiments and the Peltier elements needed to establish the required temperature gradients.

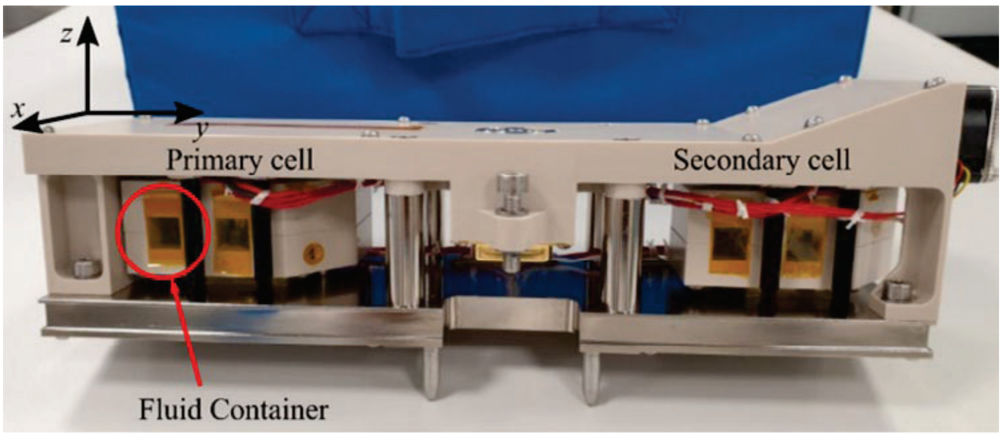

Figure f. PARTICLE VIBRATION cell array, composed of a primary and a secondary cell. Each cell array hosts two fluid containers. Four distinct windows can be seen because each fluid container has two windows (Credit: QinetiQ, UKSA and ESA)

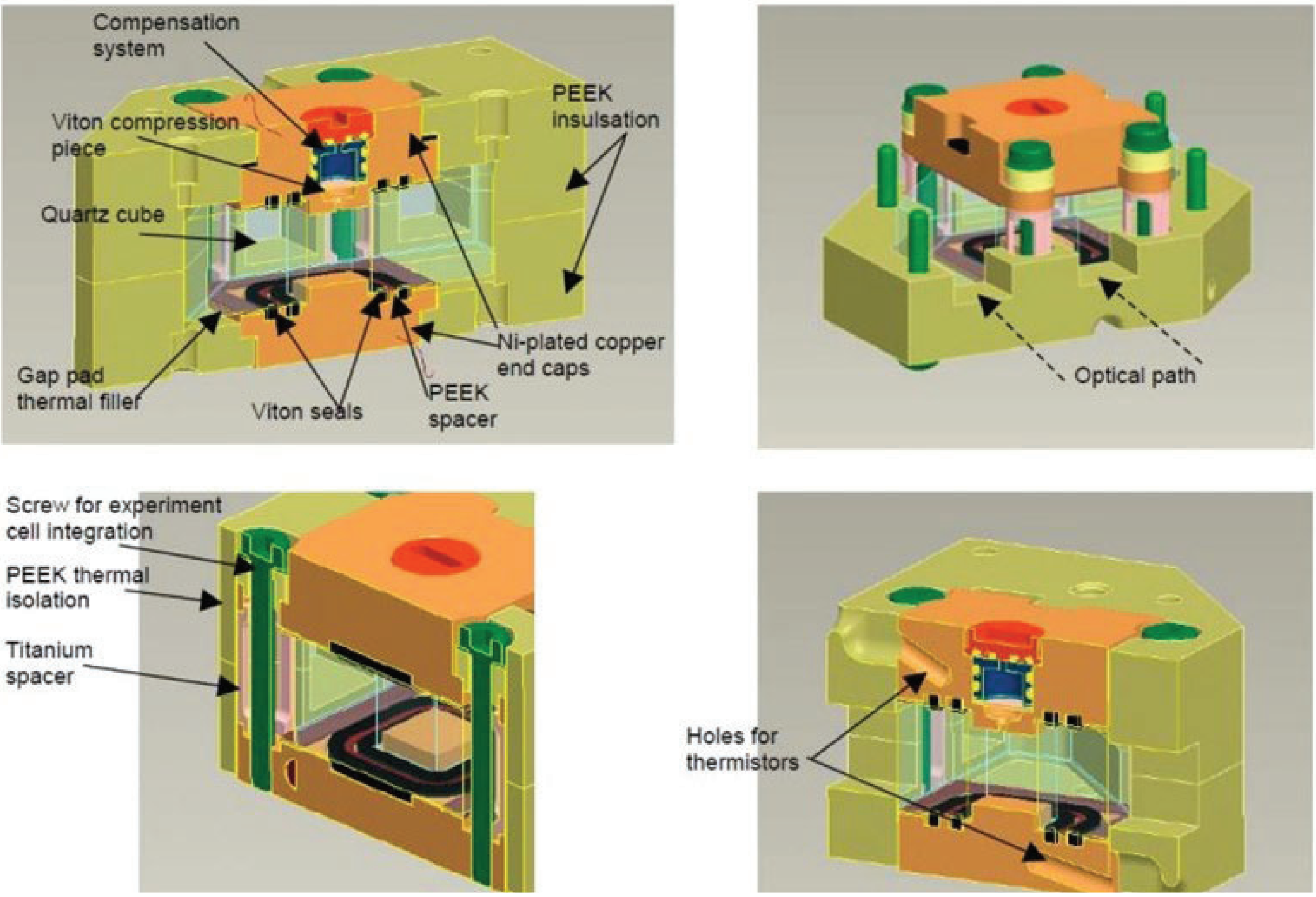

Figure g. PARTICLE VIBRATION Fluid containers (Credit: QinetiQ)

Figure h. SpaceX Falcon 9 launch, Dragon cargo spacecraft approaching the ISS (Credit: SpaceX & NASA)

NASA and SpaceX successfully launched the SpaceX Falcon 70-meter long rocket containing the hardware for the execution of the PARTICLE VIBRATION experiments from Kennedy Space Center Launch Pad 39A on Nov. 26, 2022 (7:20 PM UK Time). The CRS26 SpaceX Dragon cargo spacecraft autonomously docked to the space-facing port of the station's Harmony module at 7:39 a.m. EST, Nov. 27, 2022 (12:20 UK Time). The astronaut Frank Rubio completed without issues the installation of the Particle Vibration hardware in MSG on 3rd Feb 2023. After the hardware installation and the ensuing functional and optical checkouts, more than 160 different experiments were successfully executed over a period of three months (February-April 2023). Throughout the duration of the project, the "data", i.e. the telemetry (temperature) files and 'representative' images generated by the interferometers of the SODI hardware (showing the evolution of the vibrated particles at selected times) were transferred from the ISS to the PI (Prof. M. Lappa, located at the University of Strathclyde) through a complex infrastructure, involving the NASA's Marshall Space Flight Center, located in Huntsville, Alabama, USA (also known as the Huntsville Operations Support Center (HOSC)) and the E-USOC, located in Madrid Spain (one of the ESA User Support and Operations Centres).

Possible applications of this research are special metal alloys characterized by an internal skeleton or backbone able to address stresses or forces acting in specific directions or non-metallic materials able to conduct electricity (e.g. a framework of metal particles in a non-conducting material such as plastic or glass). Other relevant applications concern the pharmaceutical field, where protein crystals are typically obtained as seeds in an external liquid solution.

With regard to this experiment, Science Minister George Freeman said:

> "This experiment paves the way for exciting scientific discoveries that could transform methods of manufacturing, demonstrating just how valuable a resource space can be for growth and industry in the UK and around the world. The organisations behind the experiment, QinetiQ and University of Strathclyde, provide two examples of the diversity of expertise across the UK space sector, which is already worth £16.5 billion to our economy. I look forward to seeing the next steps for this innovative work."

Ground-based facilities

Conducting research in space requires considerable ground based compatibility testing first in order to a) decide the right testing protocol and b) elaborate relevant safety and payload regulations; moreover, c) ground testing can be used as a precursor to a campaign. Below are some examples of ground based facilities. In the UK you can also use the following links to explore space related capabilities including:-

- Satellite Applications Catapult UK Space Capabilities Catalogue
  https://sa.catapult.org.uk/space-capabilities-catalogue/
- UK Space Facilities https://www.ukspacefacilities.stfc.ac.uk/Pages/home.aspx
- ESA Ground facilities https://www.ukspacefacilities.stfc.ac.uk/Pages/home.aspx
- Finally for students, the opportunities with the ESA Academy to utilise microgravity platforms
  https://www.esa.int/Education/ESA_Academy

Drop towers

The so-called drop towers are long shafts used for dropping experiments. Their fundamental component is a special tube, or pit where vacuum is realised and where a capsule containing the "experiment" and related diagnostic tools is dropped. While the experiments drop, free-fall, or microgravity conditions are attained. Typically, scientists rely on video cameras to observe the experiments as they fall[24].

A relevant example accessible by UK researchers is represented by the Bremen drop tower, one of the tallest and best-

[24] M.Lappa, (2004),"Fluids, Materials and Microgravity: Numerical Techniques and Insights into the Physics", 538 pages, Elsevier Science (2004, Oxford, England).

known drop tower facilities in Europe. At the heart of the facility is the 146 m high tower surrounded by support facilities that include control rooms, laboratories and hardware workshops. The tower itself relies on a steel tube from which air can be evacuated. It also includes all the technical sub-systems needed to accelerate, guide and decelerate the capsule containing the experiments.

Figure ix. Bremen drop tower capsule (Credit: ZARM Drop Tower)

Figure x ESA astronaut Alexander Gerst during parabolic flight (Credit: European Space Agency)

[25] M.Lappa, (2004),"Fluids, Materials and Microgravity: Numerical Techniques and Insights into the Physics", 538 pages, Elsevier Science (2004, Oxford, England).

Parabolic flights

Another resource available to UK scientists, researchers and professionals is represented by the parabolic flights organised by ESA. These opportunities can be used for short-duration scientific and technological investigations and should be regarded as the only way to test microgravity with humans without going through lengthy astronaut-training and flights to the International Space Station.

A typical ESA parabolic flight campaign offers 30 periods of weightlessness per flight with three flights conducted over the course of a week. The aircraft is put into a suborbital trajectory that provides free-fall, or weightlessness. Each cycle begins by having the aircraft perform an acrobatic maneuver that starts from level flight and pitches upwards gradually to approximately 50 degrees subjecting the passengers to a 1.8-g pull up lasting about twenty seconds. After that, the pilots cut back on thrust just enough to counter atmospheric drag and the airplane is launched into a ballistic trajectory. During these 22 seconds, in theory, the aircraft is in orbit and as such also in freefall[25]. From a practical point of view, however, because of the atmospheric resistance, only centi-milli- gravity levels (10^{-2}g - 10^{-3}g) can be effectively attained. At the bottom of the parabola, the aircraft slowly pulls out of its dive and levels off for the next arc, restoring weight to the cabin. Given the number of arcs that can be flown on a typical flight, scientists can conduct several experiments or can repeat short runs of a single experiment many times.

Figure xi. Refitted Airbus A310 aircraft for parabolic flights (Credit: Novespace & European Space Agency

In the following section, the method for developing this paper will be outlined coupled with the thematic chapters, which discuss the context of the opportunity of space for materials science and innovation, as articulated from the community engagement with the paper.