In-Space Manufacturing and Resources

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Earth and Planetary Exploration Applications

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Introductory Statement

Tara Ruttley

The National Aeronautics and Space Administration (NASA) has spent decades implementing research programs in Low-Earth Orbit (LEO), starting with Skylab, NASA's first sustained space station. A rudimentary research lab outfitted inside of a repurposed Saturn V propellant stage, Skylab paved the way for experiments ranging from solar and Earth observations to physical and biological sciences and human physiology over its brief 24-week lifetime. Then, in the 1980s, space shuttle flights housed more capable Spacelab research facilities, and the microgravity science yielded breakthroughs in all disciplines with each short-duration flight. I joined NASA in 2001, a few months after the first International Space Station (ISS) crew was launched to the partially built, newest, most capable long-duration laboratory in LEO. Since then, the ISS has evolved into the premier microgravity research facility it is today, enabling over 3000 scientists from over 100 countries to perform over 4000 investigations to date across every imaginable discipline. If there were ever an ideal time to be a researcher designing microgravity experiments, this has been it.

In those twenty years of ISS access, NASA has learned how to better prepare astronauts for long-duration space exploration. We've developed the optimal countermeasures for preventing bone and muscle loss and keeping the heart healthy, and we've learned that long-duration stays can significantly affect astronaut vision. We've refined emergency medicine and ultrasound procedures, evaluated astronaut behavioral health, and improved nutrition. We better learned how to ignite and extinguish flames, and leveraged surface tension and capillary action to better manage fluid flow. We've tested the newest radiation dosimeters and we have harvested plants that have gone from the on-orbit Veggie "farm to table" facility for astronaut taste tests.

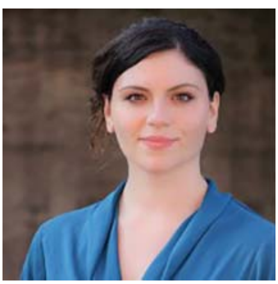
While tackling those challenges for human exploration of space, NASA was given an additional mission: use the ISS to commercialize LEO. This required us to ask of American industry, "what can we do for you?" Companies responded with ideas to use the unique microgravity environment that only ISS can offer for in-space production experiments such as cutting-edge tissue engineering, 3D bioprinting of cells and tissues, retinal implant development, and exotic glass optical fiber manufacturing.

This is only the beginning. With unprecedented access to LEO, businesses are now racing to design, develop, and test in-space manufacturing and production facilities that will one day deliver state-of-the-art materials and technology that will improve the lives of those of us on Earth. They're also making plans for their own commercial space stations independent of the ISS that will create a busy, flourishing new LEO economy in ways that humanity has never before been a part of. With so much to look forward to in the future of human space exploration and development of the LEO economy, what a time to be part of the space revolution!

Dr. Tara Ruttley
Associate Chief Scientist for Exploration and Applied Research
National Aeronautics and Space Administration Headquarters

Introductory Statement

Nicol Caplin



Since 1975, ESA has become established as a key enabler for European access to space. With 22 member states, three associate states, and a growing number of agreements with other countries, ESA is a truly international organization that possesses "strength in numbers" and can therefore carry out activities in space on a scale beyond that of any single European country's capability.

ESA's core values embedded via exclusively peaceful means promote European space research, technology, and applications. Alongside implementing mandatory activities, ESA also conducts a selection of optional programs which is notionally funded by each member state that wishes to contribute. Within this, the Human and Robotic Exploration division has rapidly expanded to provide cutting-edge scientific and technological research applications for the over-arching goal of exploring space for the benefit of humankind.

The present-day focus for the HRE research efforts centers on two themes: Research that is enabled by space and research that enables the achievement of further exploration goals. The Science in the Space Environment (SciSpacE) Team coordinates research in the areas of life (including human research) and physical sciences across multiple platforms and facilities. These include platforms for microgravity research such as sounding rockets, drop towers, parabolic flights, and of course the International Space Station.

In November 2000 the first astronaut crew entered the very early two-module configuration of the ISS, and less than a year later the first European experiment facility[1] was up and running. ESA's single largest contribution to the ISS is the Columbus laboratory. Launched in 2008, it provides European researchers with a permanent laboratory in Low-Earth orbit, for conducting research across a range of disciplines.

1 https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Research/First_European_experiment_facility_up_and_running_on_the_ISS.

Fast forward to today and insights from European research and the international community are gearing up to explore further into space with human and robotic missions. The ISS will continue to serve as an orbiting laboratory, delivering crucial information to researchers that enable deeper exploration while simultaneously improving life on our home planet.

ESA are a key player in the planned Gateway[2] facility; a spacecraft in Lunar orbit that will host scientific and technological projects that will provide a test bed in a much harsher space environment, away from the Earth's protective layer. This environment is more representative of deep space, with far more challenging conditions to ensure spacecraft, experiments, and indeed crews can exist within.

If humanity's goals of once again reaching the Moon and someday landing human crews on Mars are to be achieved, carrying out research in such an intrepid environment will be vital in fully understanding the implications and risks to embarking on such a mission. In addition to this, we should be aiming to explore space in a sustainable manner.

In-space manufacturing is a growing area of research and a welcome one. Our planet is already suffering the effects of being depleted of materials, so it makes not only sense from an environmental perspective but also has huge potential to be an economically effective way of building what humans need to go further. This can take on many forms, from 3D printing of plastic and metals right the way through to biomining processes and chemical extraction of precious resources from regolith.

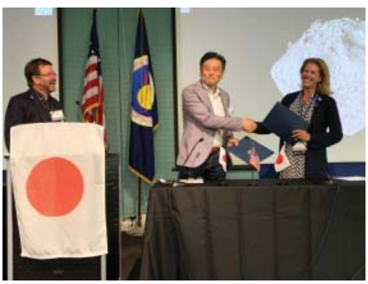
We are making the preparations to go further into space, sustainably, for the benefit of everyone – Who knows what wonders we will discover? The book *In Space Manufacturing and Resources* is a timely addition to international literature in an important niche field that is evolving at a remarkable pace. It effectively compiles the current relevant outputs for space utilization and exploration.

Dr. Nicol Caplin
Deep Space Exploration Scientist
European Space Agency

2 https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Exploration/Gateway.

Introductory Statement

Masaki Fujimoto



Dr. Masaki Fujimoto (Deputy Director General of ISAS, JAXA) greeting Dr. Lori Glaze (Director of Science Mission Directorate's Planetary Science Division, NASA) for JAXA's participation to the Solar System Exploration Research Virtual Institute.

We are in an exciting era of space exploration. International space agencies are working together to advance space science and technologies, leading to new scientific discoveries announced almost every day. Discoveries always inspire further fundamental questions, where new technologies are developed to promote new explorations for answering. Such chain activities gain more and more momentum in various fields, accelerating international collaborations as a natural consequence. I feel very honored to be a part of the current global and international endeavor for space developments.

Japan launched its first satellite, Ohsumi, in 1970. Numerous experimental and scientific challenges followed, including the 1985 Halley's comet observation satellites Sakigake and Suisei and the first Japanese interplanetary mission, Mars Orbiter Nozomi, launched in 1998 and passed Mars in 2003. In that year, Japan Aerospace Exploration Agency (JAXA) was established as an independent administrative institution, integrating the Institute of Space and Astronautical Science (ISAS), the National Space Development Agency of Japan (NASDA), and the National Aerospace Laboratory of Japan (NAL). Since then, JAXA has been the core performance agency to support the Japanese government's aerospace development and utilization.

JAXA has completed many science missions and significantly contributed to advance astronomical and planetary sciences. AKEBONO (aurora observation satellite), HITOME and SUZAKU (X-ray astronomy satellite), AKARI (infrared imaging satellite), HAYABUSA (asteroid explorer), and KAGUYA (lunar explorer) are good examples of previous missions. Hayabusa 2 (asteroid explorer), IKAROS (small solar power sail demonstrator), AKATSUKI (Venus climate orbiter) have successfully performed their primary objectives and are now in their extended phases. Currently ongoing missions include BepiColombo (Mercury exploration with ESA), HISAKI (planetary atmosphere), HINODE (solar physics), REIMEI (technology demonstration), GEOTAIL (magnetospheric observation), and ARASE (energization and radiation in geospace). XRISM (X-ray imaging and spectroscopy mission), MMX (Martian Moons exploration), and SLIM (smart lander for investigating Moon) are under development and scheduled to be launched in a few years.

We will continue exploring scientific questions regarding the origin and the evolution of the solar system, where a broader range of international collaborations and private associations will be required. JAXA provides a wide range of opportunities including to industries to help private companies enter the space business. We have programs to share our intellectual property acquired through aerospace research and experience, allow industries to use our test facilities, offer a system for cooperative research, and provide launch opportunities for small secondary satellites.

We expect so many new research fields to be involved in future explorations, including human space activities and the development of the lunar economy. We are looking forward to new activities related to space manufacturing and space resources as crucial technologies in this decade and the next with significant pioneer splits and international collaborations.

Dr. Masaki Fujimoto
Deputy Director General
Institute of Space and Astronautical Science
Japan Aerospace Exploration Agency

Introductory Statement

Enrico Palermo

The Australian Government established the Australian Space Agency in 2018 to leverage the rapid growth of the global space economy and its shift to a commercial stage. Space is an emerging industry for both government and the private sector that presents a wealth of economic opportunities–and space manufacturing has a key role to play in harnessing those opportunities, as well as supporting our national strategic interests. Space manufacturing is an important element of the Australian Government's goal to triple the size of the national civil space sector to $12 billion by 2030 and continue making progress in the years beyond[1].

Soon after it was established, the Agency began implementing programs to build capacity and capability in the sector. One of our first steps was the Moon to Mars initiative–the result of a partnership between NASA and the Agency to support Australian space manufacturing efforts that align with NASA's exciting future plans for space exploration. This initiative has had great success with manufacturing businesses across the value chain that already work in the space sector and want to increase space heritage, as well as businesses in adjacent industries looking to diversify their manufacturing outputs to include products with space applications. Under the Moon to Mars initiative we have also reached an agreement for an Australian designed, built and operated semi-autonomous rover to be included in a future lunar mission with NASA. In addition, we are delivering a National Space Mission for Earth Observation which will include Australian industry designing, constructing, launching, and operating four new Earth observation satellites. It will take Australian from a consumer to a contributor of critical Earth observation data.

1 https://www.industry.gov.au/data-and-publications/australian-civil-space-strategy-2019–2028.

Space is also one of six manufacturing priority areas the Australian Government is investing heavily in to drive the national economy. This is coupled with a Space Manufacturing Road Map[2] that sets the future vision for manufacturing investment in the space sector and targets key growth opportunities–including products that go into space, space components, and associated products and infrastructure. This ambition is backed by the Agency's own series of technical roadmaps, which identify diverse space manufacturing opportunities corresponding to our seven National Civil Space Priority Areas[1].

Australia's competitive advantages give us great enthusiasm for the future. For example, we have world-leading expertise in remote asset management in the mining and resources sector, and a range of remote and extreme environments ideal for testing space-focused technology. Australian companies are combining robotics technology with satellite communications to remotely service pipelines underwater, and trialling Satellite-Based Augmentation Systems to aid precision control of mining vehicles. Mine sites in the Pilbara region in Western Australia can be operated remotely from 1600 kilometers away - so imagine the opportunities to operate activities in space, which starts just 100 kilometers above us. By leveraging existing capabilities like these, Australia can become a major player in a global space economy tipped to be worth US$1 trillion by 2040[3].

Dr. Enrico Palermo
Head of the Australian Space Agency

2 https://www.industry.gov.au/data-and-publications/space-national-manufacturing-priority-road-map.
3 https://www.morganstanley.com/ideas/investing-in-space/.

Preface

I made my last major move, scientifically and privately, in 2018 from the Netherlands to Australia. At that time, Australia had started to engage with satellite and diverse computing-related space activities. This turned within just three years into a broad development including the "new space economy" (on resources and human space exploitation) and having the Australian Space Agency settled in Adelaide. When I started with space research in early 2019, it was no more than a curiosity for me. I had such moment of change already in 1994, when starting with microreactors and microfluidics. This "curiosity" has turned into commercial business and success after 20 years of research. Being a child of the 1960s, I am fascinated by the moon landings and Apollo program. My curiosity had now led me into a laboratory at the International Space Station. I am so passionate, seeing more far-fetching goals, such as a moon village, and for any resource and sustainability engineer, the journey to Mars must be utmost exciting and challenging. It is a privilege reporting about in the progress that is being made in this book at this pivotal turning point, with some of the most agile global players in space science and space industry; sincere appreciation to all those. This book highlights current developments of which we are unable to imagine the full range of future implications. Einstein once said "Think truly to the future and make those dreams come true."
Volker Hessel, University of Adelaide

When I joined the space industry, just over seven years ago, the idea of a robust commercial space economy in low-Earth orbit (LEO) – that included anything other than launch vehicles and satellites – was just a vision. Today we are witnessing emerging markets for in-space manufacturing take shape at a pace that seems to grow exponentially each year – with no signs of slowing down. Public–private partnerships driving the transition from government-funded space agencies to commercial companies providing launch services offering expanded access to LEO, platforms that maintain a permanent presence in space beyond the International Space Station, and services to sustain future cities in space, are creating an expanded definition of global that includes not just the circumference of Earth but 250 miles overhead. And the expanded exploration opportunities – to the moon, Mars, and perhaps beyond – that this transition provides are a legacy and a gift we are leaving for future generations. The chapters in this book will hopefully not only provide a new

perspective but inspire you to dream as well, perhaps envisioning possibilities that have yet to be imagined. Sincere thanks to all of those who have shared their work and their vision in these pages, and to their courage as trailblazers to lead the way.
Jana Stoudemire, Axiom Space

I worked on Venusian geology in my early career in mid-90's, when the accessibility to spacecraft data was very limited. I had to spend a significant amount of time to obtain the Magellan mission data generously distributed by NASA as CD-ROMs, which made my work more theoretical than observational. However, thanks to the evolution of communication technologies, the situation has been significantly improved. Also, the science community now prefers to disclose more and more data to the public with the strong belief that it is the best to enhance science. Now we can access growing (and already huge) amounts of raw data of numerous space missions of about 100 extraterrestrial bodies. Also, online international meetings regarding space missions have become important routines of my daily schedule; we can work together with world-leading experts in various fields for operating ongoing space missions and preparing future missions. There is no doubt that our scientific interests will be further accelerated through new findings from the current and the near-future missions, which stimulate curiosities in outer space and incubate new businesses including tourism and settlements. As innovative technologies, including AI, have helped democratize many different markets on Earth, the same is happening in space exploration and development. This book is full of such aspects, and I'm very proud to be a part.
Hideaki Miyamoto, University of Tokyo

The rapidly emerging opportunities offered through the new economy of extended space travel have opened up numerous exciting areas of research. My area of interest, the development of healthy nutritious foods that can be produced and processed safely and easily, raises many key questions that can only be addressed by taking a cross-disciplinary view on these grand challenges. How to develop foods that respond to the nutritional needs of astronauts and take account of metabolic challenges of extended space missions; how to ensure a balanced energy expenditure and intake; how to ensure the immune system is not compromised and the gut microbiota continue to thrive in a healthy state; how to select, develop, and grow foods in microgravity; how to engineer plants in readiness for spaceflight application; how to create foods in situ through space farming; how to develop food processing technologies to ensure processability, minimize loss of nutrients, and maximize storability. Finally, it is critically important that the produced foods are well designed in taste, aroma, and flavor, such that they are palatable and would be enjoyed even after repeat consumption. If these challenges can be solved, then we are well placed to ensure future space travelers have the nutrients and foods that they will require to achieve extended space travel. Furthermore, these in-space approaches to manufacturing essential resources for food will have many terrestrial applications and as the space industry develops further, so too will the terrestrial equivalents.
Ian D. Fisk, University of Nottingham