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The Space Journal
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#4 (14) Winter 2017/18
#4 (14) 2018
Winter 2017/18
$14.99 CDN $12.99 US
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0 74470 58068 3
Display until 04/10/2018

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Did we fly to the Moon too soon?

Unbelievably it has been almost a half century since Neil Armstrong and Buzz Aldrin bounced across the lunar landscape for the first time.

Certainly, in terms of human exploration, project Apollo was perceived as a stepping stone to greater things rather than marking a pinnacle of human achievement.

But the sudden cancellation of the final three missions - despite the fact that the hardware for each had already been built - ably illustrates the financial and political difficulties of sustaining space exploration. Apollo 20 was shelved in January 1970. Eight months later, Apollo 18 and Apollo 19 were also cancelled, making Apollo 17, all the way back in December 1972, the final and most recent human mission to the Moon.

Five decades on and the United States, Europe, Russia, China, Japan and India, along with a handful of private entrepreneurs and firms, all harbour new lunar exploration ambitions.

In October 2017, US Vice-President Mike Pence announced a significant re-direction for NASA - a new road map to create a sustained human presence on the Moon's surface. It's a big change for the agency which, for the past decade, has been heading, somewhat tentatively, for a future of deep space exploration and taking humans to Mars.

But words are not enough and to become reality ambitious programmes require ambitious sums of money, along with sustained long-term political commitment.

Fortunately, NASA's rapidly maturing new hardware for deep space missions can also be easily re-purposed to take us back to the Moon. Its giant rocket - known prosaically as the 'Space Launch System' (SLS) - and a crew capsule called Orion designed to carry people into deep space, can easily become the mainstay of future lunar missions.

A so-called cislunar architecture and an associated economy that supports or is part of a return to the Moon offers many opportunities.

Fresh political direction and some of the essential hardware may almost be in place but establishing a sustained presence on the Moon is also going to require the creation of a lunar lander, habitats, life support systems and more.

Long-term funding (at one point, NASA estimated a return to the Moon would cost upwards of US $100 billion) and time (particularly in a political context) are rare commodities in our modern world.

To succeed, space exploration projects still need to be challenging and inspirational, perhaps with a nod towards commercialism. They must also cover the bases of meaningful international partnerships and private sector participation, and include the less glamorous aspects of building components, delivering cargo and providing 'multi-layered' services.

Today, the nature of leadership in space is very different to the politically driven aspirations of the 1960s and 1970s. Back then it was more about doing things that no other country could do - and being there first.

Ten years after Apollo 11, the science writer and science fiction author Arthur C Clarke suggested that space travel might be "a technological mutation that should not really have arrived until the 21st century".

If mankind was not really ready to go to the Moon in the late 1960s and the early 1970s then perhaps now is exactly the right time.

Clive Simpson
Managing Editor, *ROOM - The Space Journal*

Space exploration projects still need to be challenging and inspirational, perhaps with a nod towards commercialism


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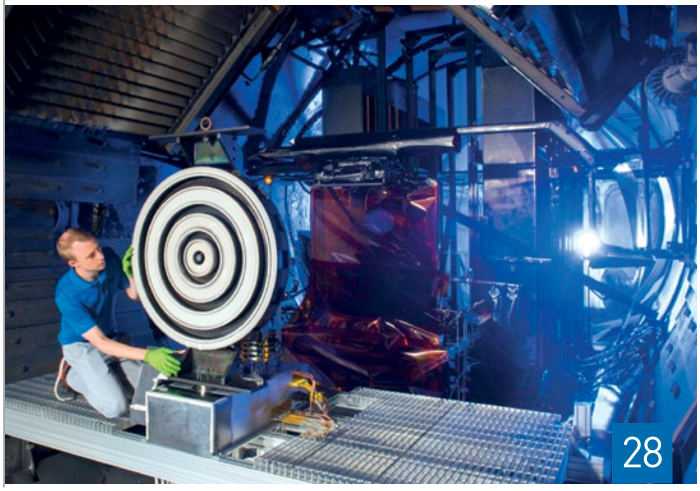
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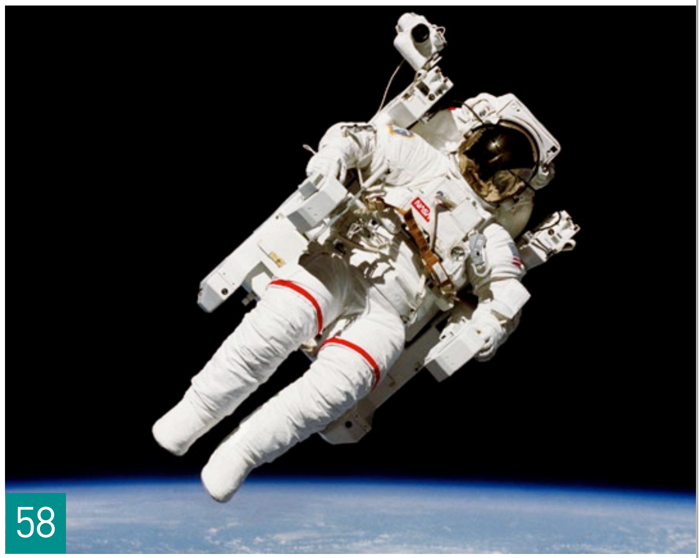

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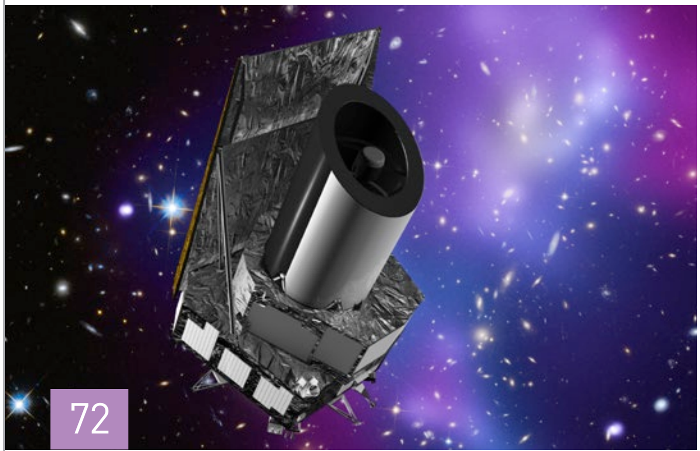
SPACE ENVIRONMENT



SPACE SCIENCE

OPINION

SPACE LOUNGE

REVIEWS

SLS ushers transformation of deep space exploration

▶ SLS Block 1, the initial configuration of NASA's new super heavy lift launch vehicle, will be able to lift at least 70 metric tons to low Earth orbit and is the cornerstone of a new deep space exploration system that includes the Orion crew vehicle and upgraded ground systems and launch facilities at Kennedy Space Center.

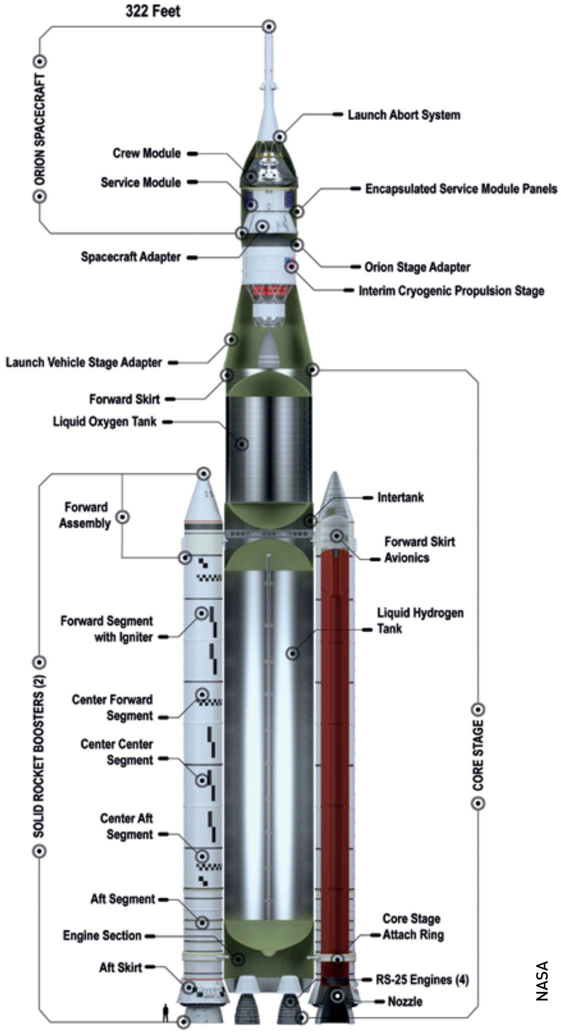
Kimberly F. Robinson
NASA Marshall Space Flight Center, Huntsville, Alabama, USA

The Space Launch System (SLS) is NASA's new super heavy-lift launch vehicle. Designed to return America's human spaceflight programme to deep space, it will provide unparalleled mass, volume and departure energy to help propel nearly any payload to nearly any destination. As part of a new deep space exploration system that includes revamped launch facilities at Kennedy Space Center (KSC) and the Orion spacecraft that will take astronauts farther into space than any humans have ever ventured, SLS is designed to be flexible and evolvable. The massive 'Saturn V-sized' rocket is currently under construction all over the United States, with structural fabrication of major components complete and the focus now on final outfitting for first flight.

SLS represents a game-changing spaceflight capability, enabling mission profiles that are currently impossible to become possible. Conceived and designed for exploration of deep space, the primary purpose of SLS is to enable NASA's journey to Mars and propel humans beyond low Earth orbit for the first time in almost half a century.

The initial configuration of SLS - Block 1 - will be capable of delivering more than 70 metric tons of payload to low Earth orbit (LEO) and will send NASA's new Orion crew vehicle into lunar orbit on the deep space exploration system's first mission, Exploration Mission-1 (EM-1), scheduled for 2019.

Largely a test flight, EM-1 will verify and validate new systems and operations and provide valuable



◀ The architecture of the SLS Block 1 internal configuration uses a Space Shuttle-heritage, flight-proven propulsion system that's been upgraded and modernised, including four RS-25 engines and twin five-segment solid rocket boosters. The core stage, which is 64 m tall, is an all-new development.

data before astronauts fly on the second mission, Exploration Mission-2 (EM-2) in the early 2020s. EM-1 will also provide an opportunity for 13 CubeSat secondary payloads to be deployed in deep space, where they will perform a variety of scientific experiments.

During the next decade and beyond, SLS will evolve into a more capable Block 1B configuration and serve as the workhorse for missions in the 'proving ground', the area of space primarily around the Moon where NASA will test and verify technologies and processes needed before executing missions to Mars. Using a more powerful Exploration Upper Stage, Block 1B will have the capability to loft 105 metric tons to LEO and co-manifest additional payloads with Orion. As part of its proving ground missions in the 2020s, NASA plans to use the Block 1B vehicle to loft elements of its deep space gateway and transport system to cislunar space. In its ultimate Block 2 configuration, SLS will be capable of delivering more than 130 metric tons to LEO.

SLS offers game-changing opportunities for spacecraft designers and mission planners

Heritage development

The SLS architecture takes advantage of resources established for the Space Shuttle programme, including workforce, tooling, manufacturing processes, supply chains, transportation logistics, launch infrastructure, and high-efficiency liquid oxygen and hydrogen propellant technology. The Block 1 initial configuration of the vehicle will be delivered with only one clean-sheet new development, the core stage.

The SLS core stage, which supplies the liquid oxygen and liquid hydrogen propellant for four main engines, represents almost two-thirds of the vehicle's 98 m height, standing 64 m tall with a diameter of 8.4 m. At Michoud Assembly Facility, outside New Orleans, Louisiana, core stage prime contractor Boeing used the world's largest space vehicle welding tool, the 52 m-tall Vertical Assembly Center to weld barrel sections, rings and domes together to form the test and flight articles.

Technicians have welded both the liquid oxygen and liquid hydrogen propellant tanks for the first flight. The tanks are undergoing proof testing and will soon be ready for final outfitting. The test articles, manufactured prior to the flight tanks, will be shipped to Marshall Space Flight Center in Huntsville, Alabama, where they will be subjected to rigorous structural testing to verify computer models of hardware performance.

The core stage will be powered by four RS-25 engines, which previously served as the Space Shuttle Main Engine (SSME), built by Aerojet Rocketdyne. These human-rated engines support the SLS pursuit of safety, with a record of 100 percent mission success over 135 Space Shuttle flights. At the end of the Space Shuttle programme, 16 RS-25 flight engines and two development engines were transferred to the SLS programme and placed in inventory at NASA's Stennis Space Center in Mississippi, providing enough engines for the first four SLS flights.

The SLS architecture takes advantage of resources established for the Space Shuttle programme

BIG SCIENCE IN SMALL PACKAGES

SLS offers unique opportunities to deploy smallsats into deep space and on its first mission will release 13 CubeSat secondary payloads, including both NASA research experiments and spacecraft developed by industry, international and academia partners.

Near Earth Asteroid (NEA) Scout is designed to rendezvous with and characterise a candidate near-Earth asteroid, using solar sail propulsion.

Lunar Flashlight will use a green propellant system and will search for potential ice deposits in the Moon's permanently shadowed craters.

BioSentinel is a yeast radiation biosensor, planned to measure the effects of space radiation on DNA.

Lunar IceCube, a collaboration with Morehead State University in Kentucky, will prospect for water in solid, liquid, and vapour forms as well as other lunar volatiles from a low-perigee, highly inclined lunar orbit using a compact infrared spectrometer.

LunIR, a partnership with Lockheed Martin, is a technology demonstration mission that will perform a lunar flyby, collecting spectroscopy and thermography data to address questions related to surface characterisation, remote sensing, and site selection.

The CubeSat mission to study Solar Particles (CuSP) will study the sources and acceleration mechanisms of solar and interplanetary particles in near-Earth orbit, supporting space weather research by determining proton radiation levels during Solar Energetic Particle (SEP) events and identifying suprathermal properties that could help predict geomagnetic storms.

The LunaH-Map payload will help scientists understand the quantity of hydrogen-bearing materials in lunar cold traps (~10 km), determine the concentration of hydrogen-bearing materials with 1 m depth, and constrain the vertical distribution of hydrogen-bearing materials.

ArgoMoon, sponsored by the European Space Agency (ESA) and the Agenzia Spaziale Italiana (ASI), will fly along with the Interim Cryogenic Propulsion Stage (ICPS) on its disposal trajectory to perform proximity operations with the ICPS post-disposal, take external imagery of engineering and historical significance, and perform an optical communications demonstration.

The EQUilibriUm Lunar-Earth point 6U Spacecraft (EQUULEUS) spacecraft sponsored by the Japanese Aerospace Exploration Agency (JAXA) will fly to a libration orbit around the Earth-Moon L2 point and demonstrate trajectory control techniques within this region for the first time by a smallsat.

The Outstanding MOon exploration TEchnologies demonstrated by NAno Semi-Hard Impactor (OMOTENASHI) mission, also sponsored by JAXA, will land the smallest lander to date on the lunar surface to demonstrate the feasibility of the hardware for distributed cooperative exploration systems.

▲ NASA and core stage prime contractor Boeing have completed welding on four major structures that comprise the all-new core stage: the forward skirt, the liquid oxygen and liquid hydrogen propellant tanks, and the engine section. The fifth component, the intertank, is bolted rather than welded and major structural assembly is also complete.

Modifications to Stennis Test Stand A-1 to support RS-25 testing were completed in 2014, and testing has been underway since the beginning of 2015 to certify that the engines will handle increased propellant pressure and temperature inlet conditions, as well as other SLS-specific performance requirements. Hotfire testing has also supported development and certification of the new state-of-the-art engine controllers and software. The engine controllers for the RS-25 engines for first integrated flight have been tested and installed and those engines are ready for integration into the core stage.

The B-2 test stand at Stennis Space Center is currently being refitted for the SLS 'green run' - the test firing of the EM-1 integrated core stage. The test will be the largest liquid-engine test since the stage tests of the Saturn V in the 1960s. From there, the core stage with the four engines integrated will be shipped to KSC, where it will be mated to the solid rocket boosters and the components that comprise the upper part of the rocket.

The majority of the thrust for the first two minutes of flight will come from a pair of solid rocket boosters, also of Space Shuttle heritage. Prime contractor Orbital ATK has upgraded the boosters from the four-segment motor flown on the Shuttle to a five-segment motor with roughly 20 percent more power. The most powerful flight boosters in the world, each measures 54 m long and 3.7 m in diameter and is capable of generating up to 3.6 million pounds of thrust.

Other improvements to the boosters since the Space Shuttle Programme include a larger nozzle throat and asbestos-free insulation and new avionics. Two qualification motors were successfully test-fired in 2015 and 2016, and the EM-1 booster forward and aft assemblies are currently being refurbished and outfitted for flight at Kennedy Space Center. At Orbital ATK's specialised facilities in Utah, motor segments are being cast with propellant, evaluated using nondestructive methods such as x-rays, then painted and finished for flight at a steady pace.

In-space propulsion for the Block 1 vehicle will be provided by an Interim Cryogenic Propulsion Stage (ICPS), which uses a single Aerojet Rocketdyne RL10 engine for propulsion. In order to expedite launch, programme managers decided early in the vehicle's development to leverage the proven United Launch Alliance Delta Cryogenic Second Stage (DCSS), flown on the Delta IV Heavy launch vehicle, for in-space propulsion for the first flight.

The EM-1 ICPS was recently completed - the first major element of the EM-1 vehicle to be delivered to Kennedy Space Center. The ICPS is at Kennedy's Space Station Processing Facility (SSPF) until it is needed for stacking on the core stage. As mentioned earlier, the Block 1B configuration will replace the ICPS with a more powerful Exploration Upper Stage, which uses four RL10 engines, to increase performance.

For the first flight, the Launch Vehicle Stage Adapter, which connects the core stage to the ICPS, has completed major structural assembly and is being outfitted for flight at Marshall Space Flight Center. The Orion Stage Adapter, which connects the Orion spacecraft with the ICPS, is also being fabricated and outfitted at NASA's Marshall Center. Technicians there are installing brackets and other hardware that will secure the 13 small payload dispensers and an avionics box in the adapter that will deploy the payloads for their journey into deep space.

▲ The SLS programme and prime contractor Aerojet Rocketdyne have been testing new engine controller units for the RS-25 main engines at NASA's Stennis Space Center in Bay St Louis, Mississippi. The engines are also being certified to ensure they can withstand the increased propellant pressure and temperature inlet conditions they will experience during the first flight of SLS and Orion.

▲ The solid rocket motors that SLS uses have five propellant segments compared to the four-segment motors for the Space Shuttle. NASA and prime contractor Orbital ATK have conducted several static tests of development and qualification motors as part of the flight certification process.

Mission possibilities

SLS offers game-changing opportunities for spacecraft designers and mission planners. For missions to, or staging in, the Earth-Moon vicinity, SLS offers unrivaled lift capability. The Block 1B configuration of the vehicle, which will be the version available for payloads during most of the 2020s, will be able to lift 105 metric tons

▲ The Interim Cryogenic Propulsion Stage (ICPS), built by Boeing and United Launch Alliance, has been completed and is currently in storage at Kennedy Space Center in Florida until needed for stacking on top of the core stage. A modified Delta Cryogenic Second Stage (DCSS), the ICPS will provide the final in-space push to send Orion beyond the Moon.

to low Earth orbit and will be able to deliver 40 metric tons to translunar injection (TLI). The crew configuration of the Block 1B vehicle will carry up to an additional 10 tons of payload along with the Orion spacecraft. The Block 2 configuration will increase that performance to more than 130 metric tons to LEO, and at least 45 metric tons to TLI.

For missions beyond Earth and the Moon, SLS offers substantially greater characteristic energy (C3) than contemporary evolved expendable launch vehicles (EELV). For the missions to the outer planets, for example, this can enable a larger science payload, reduced transit times, or both.

SLS also offers greater volume than any other launch vehicle. Beginning with Block 1B and the EM-2 mission, a Universal Stage Adapter will allow a payload to fly with Orion with as much accommodation volume as the current industry-standard 5 m diameter fairing. The Block 1B configuration will also enable the use of an 8.4 m fairing for primary payloads.

Greater payload volume can decrease the need for payload elements such as antennas to be folded for launch and then deployed in space, thus decreasing spacecraft complexity and risk. Reducing transit time by enabling a direct trajectory without gravitational assists reduces mission risk and operational cost, and can eliminate the need to design for inner-solar system conditions.

For robotic science probes to the outer solar system, SLS can cut transit times to less than half that of currently available vehicles, producing earlier data return, enhancing iterative exploration, and reducing mission cost and risk. In the field of astrophysics, SLS's greater payload volume creates the opportunity to launch large-aperture telescopes that will provide an unprecedented look at our universe.

NASA is developing SLS in parallel with two other exploration systems development efforts - the Orion crew vehicle programme, managed at NASA's Johnson Space Center in Houston, Texas, and the Ground Systems Development and Operations programme, which is converting the facilities at Kennedy Space Center into a next-generation spaceport capable of supporting launches of multiple types of vehicles.

These capabilities are part of a larger NASA strategy of working with commercial partners that will support crew and cargo launches to the International Space Station (ISS), while the agency focuses its development efforts on an incremental approach to developing the systems necessary for human exploration beyond Earth orbit and eventually to Mars. SLS is a foundational asset for NASA's journey to Mars that will provide unrivalled mass, volume and departure energy for payloads, offering numerous benefits for a variety of missions.

The primary purpose of SLS is to enable a new era of human space exploration unlike any before it. As NASA continues to mature plans for deep space exploration, SLS and Orion are crucial assets in that journey. The first human beings to launch on SLS will go where no humans have ventured before, making new discoveries, returning new knowledge and inspiring new generations to continue exploration of deep space. ■

CUBE QUEST CHALLENGE

Three EM-1 CubeSat payloads have completed the final ground tournament of NASA's Cube Quest Challenge and are now manifested on EM-1 where they will compete for further prizes.

Cislunar Explorers, from Cornell University in Ithaca, New York, has designed one 6U CubeSat that will split into two spacecraft that will orbit the Moon using a novel propulsion system of inert water to carry out gravity assists with the Moon, and then be captured into lunar orbit.

The University of Colorado-Earth Escape Explorer (CU3), is a CubeSat from the University of Colorado in Boulder that will be using solar radiation pressure rather than an onboard propulsion system.

Team Miles, of Fluid & Reason, LLC, Tampa, Florida, a group of citizen scientists, has a mission that will fly autonomously using an onboard computer system and be propelled by next generation plasma thrusters.

About the author

Dr Kimberly Robinson serves as the payload mission manager for the first flight of NASA's Space Launch System (SLS), which will transport high-priority science missions beyond Earth's orbit for a new age of exploration. She earned a bachelor's degree in Mechanical Engineering from Vanderbilt University, and her master's and doctorate degrees in Industrial and Systems Engineering from the University of Alabama in Huntsville.

SAVE THE DATES

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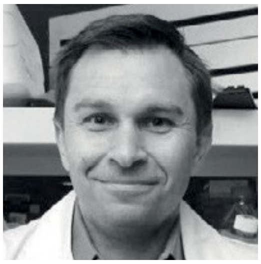

David A Sinclair
Chief Scientific Advisor, Liberty Biosecurity and Professor of Genetics, Harvard Medical School, Massachusetts, USA

Kyle Landry
Chief Scientist, Expeditionary Science and Special Programs, Liberty Biosecurity, Massachusetts, USA

David J Livingston
Chief Scientific Officer, Metro International Biotech, Massachusetts, USA

Shielding the human genome

Mitigating the threat of space radiation

Ponder for a moment what we know space is capable of inflicting on the human body. Cancer, impaired vision or blindness, loss of cardiac function, muscle atrophy and decreased bone resiliency, diminished cognitive function and behavioural changes... The driver of these diseases and the genetic mutations that give rise to them? Space radiation. Especially galactic space radiation, given its energy and unique ability to cut through human DNA. It is this type of radiation that will be bombarding astronauts continuously from deep space as they make their way to Mars. Unfortunately for our astronauts, there is no engineering or technology solution available today that can sufficiently mitigate this threat.

For decades, NASA and others have studied the radiation problem and searched for solutions. Left unchecked, sustained exposure to space radiation will make long-duration manned missions beyond Earth's ionosphere dangerous and, in some worst-case scenarios, lead to disease and death. It was this challenge that led NASA in 2016 to describe exposure to space radiation as the most dangerous aspect of travel to Mars.

Without radical advances in science, astronauts sitting atop NASA's Space Launch System (SLS) might ask themselves if the greatest risk to their endeavour might be within them, the cells making up their own

bodies as the weakest link in their mission. The irony would not be lost upon them, especially as they sat in the capsule above the thousands of components that would comprise the most powerful rocket ever built. Could it be that the more than six million years of human evolution that optimised us for life on Earth will stand in the way of our ability to successfully explore the solar system?

This was the basic question a group of world-class scientists and former national security officials from both the United States and Australia - organised by Liberty Biosecurity and its sister pharmaceutical division, Metro International Biotech (Metrobiotech) - had gathered to consider in early 2016.

They knew that left unanswered, the threat posed by space radiation could dash the hopes of humans ever colonising the solar system. Emboldened by hundreds of scientific and medical innovations, and with billions of dollars worth of previous biotechnology successes under their

It was this challenge that led NASA in 2016 to describe exposure to space radiation as the most dangerous aspect of travel to Mars

collective belts, the team embraced this challenge and set about developing a suite of bioscience applications that would help propel humans into deep space travel. The group committed itself to the goal of developing an alternative pathway, one that would leverage biology itself to solve the most challenging biological problems facing humanity as it embarked on exploring the heavens.

DNA replication

Cocooned in the protective embrace of our planet's ionosphere for millennia, humans have developed DNA replication and repair capabilities optimised for life on Earth. Epigenetic changes - that is changes in a person's genetic code resulting, over time, from environmental exposure - have for most of our history largely been the result of exposures encountered by our ancestors over roughly 250,000 generations.

The more well-known drivers of epigenetic changes to our DNA have been infectious disease, diet and the process of ageing. Given the naturally protective shielding afforded by Earth's ionosphere, the human body has never been forced to develop the ability to mitigate damage caused by radiation exposure, particularly the cosmic radiation humans will encounter in long range space travel. It is this absence of agile mechanisms to repair cosmic radiation-induced

For the better part of the last century, the only useful treatment for certain types of radiation exposure was to consume potassium iodide, a blocker of thyroid radioiodine uptake. Potassium iodide is effective in reducing the risk of thyroid cancer in a person given inhalation or ingestion of radioiodine - great if you are trying to protect the thyroid gland but of little value in protecting a person from cancer or other maladies induced by whole body radiation exposure - exactly the problem facing astronauts beyond low Earth orbit. Potassium iodide is not a general radio-protective agent. Launching iodine to Mars as part of an astronaut's kit is not necessarily 21st century cutting edge pharmaceutical science. Something better is needed.

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Metro International Biotech, Visiting Researcher at the Sinclair Laboratory, Harvard Medical School, Massachusetts, USA

Lindsay Wu
Director for Liberty Biosecurity (Australia), Senior Research Fellow at the University of New South Wales, Australia

Roxanne Bavarian
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▲ A Liberty senior board meeting in Virginia in 2016 where members combined their world-class science, national security and entrepreneurial backgrounds to address several key national challenges, including those facing manned space missions beyond Earth.

damage to our DNA code that leads to the onset of cancer or other radiation-induced diseases and results in NASA designating it public enemy number one for humans on their way to Mars.

Could cosmic radiation's check on the human dream to explore the solar system and beyond be overturned? Could a biological solution be found to this most basic of biological threats?

To the members of the Liberty-Metrobiotech gathering in Virginia it became clear that breakthroughs being made by two of their scientific teams focused on vastly different technologies - one supporting the development of new pharmaceuticals, the other tasked with leveraging novel biology to defeat pathogens and destroy biofilms for national security and clinical applications - were beginning to converge on solutions to a common problem: the challenge of getting humans to Mars.

Our understanding of the body's ability to 'upregulate' and stimulate the repair of damaged DNA is relatively new and has only been studied closely over the last 20 years when the biological processes regarding DNA repair in the body were mapped and more fully understood.

Dr David Sinclair, the Chief Scientific Advisor to Liberty and one the world's leaders in the field of ageing and DNA repair, saw how his company's work and that of his two academic laboratories at Harvard University and the University of New South Wales in Australia (UNSW), could together answer this question and recalls the conversation in Virginia: "It was like a light bulb went on in the room. We said that we were going about the problem the wrong way. We need to not shield the spacecraft but instead shield the human genome. We find a way to do that and we go to Mars. We fail and we stay Earthbound as a species."

The group in Virginia realised it was very unlikely there would be a way to structurally engineer a solution to the problem of radiation exposure; the shielding and launch weight restrictions for vehicles and habitats are simply too great to launch from Earth. Besides, vehicle and habitat shielding materials available today are ineffective at stopping some forms of space radiation, especially radiation emanating from deep space sources like supernovas (these being some of the greatest threats to the health of our astronauts.)

Radiation equation

Absent radical reductions in travel times to and from Mars, the time in which astronauts would be exposed to this most dangerous type of space radiation would remain constant at about 600 days back and forth at best. These levels of exposure also do not account for the time astronauts will spend on the surface of Mars, which is itself a hostile environment for humans, as it is saturated with 100 times the amount of radiation a person would encounter on Earth. This is the equation NASA grapples with as it plans for a Mars mission - and it is one that has never balanced in NASA's favour.

The pharmaceutical team, comprising organic chemists, biologists and geneticists, and driven by research from Sinclair's academic team at Harvard

Unfortunately for our astronauts, there is no engineering or technology solution available today that can sufficiently mitigate this threat

was reporting that the company's lead proprietary development compound was demonstrating an ability for animals to repair their DNA after being exposed to ionizing radiation sources.

The team in Virginia saw that these initial studies had the potential to profoundly impact a variety of clinical indications that remain plagued by the threat of radiation exposure: high-dose radiation medical treatments, civilian nuclear accidents such as those at Fukishima and Chernobyl, military and homeland security applications and, of course, space travel.

The team commissioned further studies to baseline and then gauge their compound's ability to mitigate radiation induced DNA damage and determine what radiation-induced indications it could treat.

In 2017, Dr Sinclair's academic team published their results in the journal *Science*, providing definitive proof that stimulation of certain biological processes could not only mitigate DNA damage, but also repair it. In late 2017, Liberty and Metrobiotech commissioned a large animal-based study to examine their compound's ability to mitigate whole body radiation damage across a range of exposures comparable to those that would be experienced during spaceflight, and is measuring radiation-induced molecular changes to the genomes of the animals.

What was ground-breaking in the 2017 experiments published in *Science* was that Dr Sinclair's team demonstrated that it was now possible, for the first time, to upregulate DNA repair functions through a boosting of oxidized nicotinamide adenine dinucleotide (NAD+), a coenzyme necessary for all animal life on Earth. At the heart of the company's development compound programme is the optimisation of a drug that would be able to stimulate NAD+ levels in the body, and the team in Virginia was ready to deploy it against the challenges posed by space radiation.

The Liberty-Metrobiotech development compound was showing Dr Sinclair that the increased levels of NAD+ were upregulating SIRT1 activity in irradiated test animals by 'popping apart' the molecular stranglehold or block imposed on DNA repair by the naturally occurring DBC1 protein in the body. Dr Sinclair and the Chief Scientific Officer at Metrobiotech, Dr David Livingston, believe that pharmaceutically managing NAD+ levels through dosing with their compound should allow astronauts assaulted by galactic space radiation particles to enhance repair of their DNA and mitigate the threat of cellular death and disease.

It was the compound's function in animal model radioprotection that led NASA's iTech judges in 2016 to recognise the work of the Liberty team with one of only three national awards for innovation presented in the inaugural year of the competition.

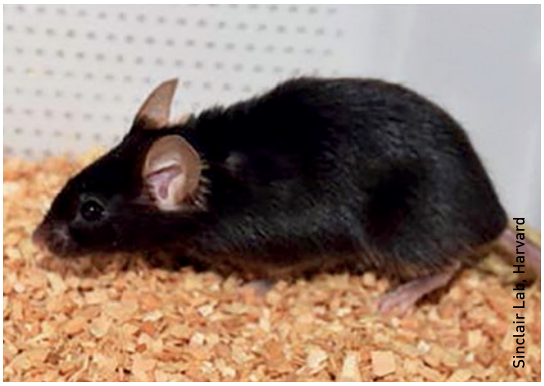
NAD+'s evolutionary role is about as basic as it gets - without it, your body's metabolic function would cease and you would die in less than 30 seconds. All animal species on our planet are dependent on NAD for life.

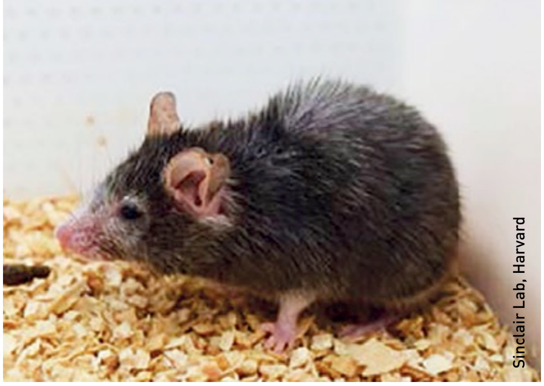
The level of NAD+ in the human body naturally decreases with age, on average plateauing in our early to mid-30s. Liberty-Metrobiotech's development compound has demonstrated an ability to boost NAD+ levels in the body, thereby improving stress and disease resistance while enhancing the body's ability to repair damaged DNA. This DNA repair capability of NAD+ is achieved by breaking the molecular bonds of the SIRT1 and DBC1 proteins.

While SIRT1 is involved in DNA repair, DBC1 hinders it, leading to an accumulation of unrepaired DNA breaks, cellular damage and eventually disease and death. To repair DNA, you need to keep DBC1 from getting in the way of SIRT1 doing its job.

▲ The pharmaceutical discovery and development team at Metro International Biotech led by Dr David Livingston (second from right). Combined, this team of researchers has made key discoveries that have driven several billion dollars of pharmaceutical sales over four decades.

▶ Laboratory animal testing indicates that rats supplemented with Liberty-Metrobiotech's Development Compound and subsequently exposed to radiation showed virtually no signs of DNA damage (left), whereas rats that had not been supplemented prior to identical radiation exposures showed significant signs of DNA damage akin to symptoms of advanced ageing (right).





In their search to identify new and transformative technologies from across the United States, NASA's iTech panel of industry and government representatives, highlighted the value and applicability of the work by Dr Sinclair's teams, and the investments by Liberty in a complex, multi-stage animal testing programme to identify optimised dose and exposure ranges for mitigating radiation damage and repair of effected DNA in astronauts.

This continuing programme of research is also being pursued by the Sinclair Lab at Harvard University under Dr Michael Bonkowski and Dr Roxanne Bavarian, both of whom seek to identify the potential impact the compound may have on a range of therapeutic applications back on Earth.

Specifically, Dr Bavarian will also study using the development compound to see if this drug and other sirtuin-activating compounds show promise in blocking the mechanism driving radiation-induced oral and gastrointestinal mucositis. These two indications and others like them are persistent health risks for people facing radiation-associated toxicities resulting from cancer treatment.

An ongoing human clinical trial programme being sponsored and coordinated by Metrobiotech is assessing safety and oral bioavailability of the compound, and will be followed by testing for efficacy in human diseases. Results will be shared with NASA and appropriate follow-on human trials are planned for radiation mitigation. It is this type of broad translational research and pharmaceutical development that will protect not only astronauts sitting atop the SLS, but their family members back home challenged with cancer and other more 'Earthly' diseases.

"The fact that pharmacology, chemistry and biology will be as important as telemetry and rocket design is exciting for our scientists."

The end of 2017 was marked with a potential genomic shield for astronauts on the SLS that Dr Sinclair called for being found. With a potential solution for the challenge of space radiation identified, Liberty's team turned their attention to a second key biological problem that needed to be managed for humanity to be successful in its missions to Mars and beyond: how to mitigate the threat from microbial species that demonstrate increased pathogenicity and other opportunistic characteristics when exposed to space vehicle environments.

Environmental factors

It is common knowledge that the ISS is a very 'dirty' place, replete with microorganisms that develop unique and possibly more antibiotic-resistant capabilities resulting from exposure to zero gravity and other environmental factors. The challenge facing NASA? Neutralise these species without chemicals, antibiotics, acids and solvents. And just in case that problem was not hard enough, destroy the biofilms that envelop and protect these microbial species in a way that does not impact sensitive equipment or surfaces akin to those in and on a space vehicle. A final requirement, if possible, is to ensure that this capability is organically based and is safe enough for astronauts to have on their skin and on their food. After all, the humans we send to Mars are going to have to live in this hermetically sealed environment for several years.

While the pharmaceutical team was presenting its findings to NASA in Washington, Liberty's Expeditionary and Special Programs Division - a multi-disciplinary team that identifies and develops capabilities of interest for US and allied national security communities - was reporting that a novel species it controlled, known internally as the Advanced Decontamination and Bio-neutralisation Material (ADBM), was showing unique properties that allowed it to quickly destroy complex multi-species biofilms.

These biofilms are almost indestructible biological 'concrete' that form on virtually all surfaces on Earth and in the vacuum of space. It is this biofilm that provides safe harbour for viruses, pathogenic bacteria and spores that, when in space, mutate in unexpected ways and can present a host of both novel and serious health threats to astronauts.

The species was characterised by Liberty's Expeditionary and Special Projects team, led by Liberty's Dr Kyle Landry, which quickly identified that ADBM, like many of its group, demonstrates both the qualities of antibiotics (Penicillium is a cousin) and characteristics seen in other members of the group, some of which are agents of diseases in plants and humans.

Equipped with an analysis of ADBM's genome, it became clear to the team that the species had adopted characteristics over its evolutionary cycle allowing it to become extremely efficient at destroying biological signatures akin to those that contaminate long-duration human occupied spacecraft - such as the ISS containing many complex biofilms, some of which have given home to opportunistic bacteria and other pathogens.

The organic nature of ADBM's biofilm removal application, combined with thermophilic and other unique biological characteristics of the species, to include pathogen destruction, soon caught the eye of NASA's Jet Propulsion Laboratory (JPL) in Pasadena.

JPL's Biotechnology and Planetary Protection Group (BPPG) and Liberty soon began to work on optimising analytical and bioinformatics sensing

ADBM is an optimised secretion from a thermophilic ascomycete, previously unknown to science. Active components of ADBM include novel thermostable enzymes, peptides and small molecules that can destroy DNA and RNA biological signatures and remove biofilm on a variety of sensitive surface materials akin to those found on space vehicles and planned physical habitats for astronauts on Mars.

ADBM's functional properties come from biologically-based compounds, not acidic, caustic, or oxidative chemicals such as sodium hypochlorite, hydrogen peroxides, and ethanol, which are standard compounds used for sanitisation and decontamination of equipment and surfaces.

mechanisms required to identify trace amounts of DNA on spacecraft and in JPL clean rooms, a perennial challenge for JPL as it attempts to prevent the unintended movement of biological signatures from Earth to space and landing locations across the solar system.

It was while conducting this initial work that JPL and Liberty decided to identify and enhance the genomic characteristics of novel species that JPL had collected over decades from sites across the planet and isolated on spaced-based platforms like the ISS.

The ability to transfer and regulate these unique genomic characteristics into a species that produces ADBM could have a profound impact on human health on Earth, while at the same time equipping astronauts going to Mars with an all-organic means to control potentially harmful unwanted biological mutations and growths on their vehicles and habitants. By late 2017, the Liberty and JPL teams had optimised a biological engineering plan that could be implemented at the ISS and on Earth-based testbeds during 2018.

The last two years have stressed the boundaries of what we know about biology, allowing us to identify areas where Mother Nature herself might just be the best solution to many of the challenges that will face our astronauts as they explore the solar system. Liberty's Dr Sinclair is optimistic about the future and how innovative management of biology will allow our species to explore the solar system.

"We are in a new age of discovery driven by genomics and the leveraging of novel biology,

We are in a new age of discovery driven by genomics and the leveraging of novel biology

◀ ADBM in its native state, exhibiting its anti-microbial capabilities with a clear zone of inhibition around its perimeter.

Mother nature has optimised, for reasons largely unknown to science, some bacterium to demonstrate significant capabilities to resist radiation and a whole host of environmental insults that include exposures to vacuums and extreme cold - the very conditions encountered in space. The most famous of these is Deinococcus radiodurans, an extremophile bacterium first discovered in the 1950s.

▲ The Liberty-Metrobiotech Team receiving one of three inaugural NASA iTech awards for its innovative solution to defeat the challenges of radiation exposure to astronauts, and (right) Dr Sinclair presents the groups findings at the 33rd annual Space Symposium in Colorado Springs.

▼ Space radiation could be one of the biggest issues affecting astronauts launching on NASA's SLS on future voyages to the Moon and Mars.

not unlike the 1940s when penicillin was being optimised as a drug and millions of humans would soon no longer fear death because of a simple infection. The fact that pharmacology, chemistry and biology will be as important as telemetry and rocket design is exciting for our scientists and is leading them to push the boundaries of the possible. I can imagine those astronauts sitting atop the SLS will be glad they were willing to look at these formerly insurmountable challenges and say, 'yeah, we can do this'." ■

www.libertybiosecurity.org

About the authors

Dr David A Sinclair, co-founder and Chief Scientific Advisor, Liberty Biosecurity, and Professor of Genetics, Harvard Medical School, is best known for his work on understanding why we age and how to slow its effects. He was recruited by Harvard Medical School in 1999, where his laboratory's research has focused primarily on understanding the role of sirtuins in disease and aging, with associated interests in energy metabolism, neurodegeneration, and cancer. One of Australia's most prominent scientists, Dr Sinclair was the recipient of Australia's Research Medal 2014, and was named that same year by Time magazine as one of their 100 Most Influential People in the World.

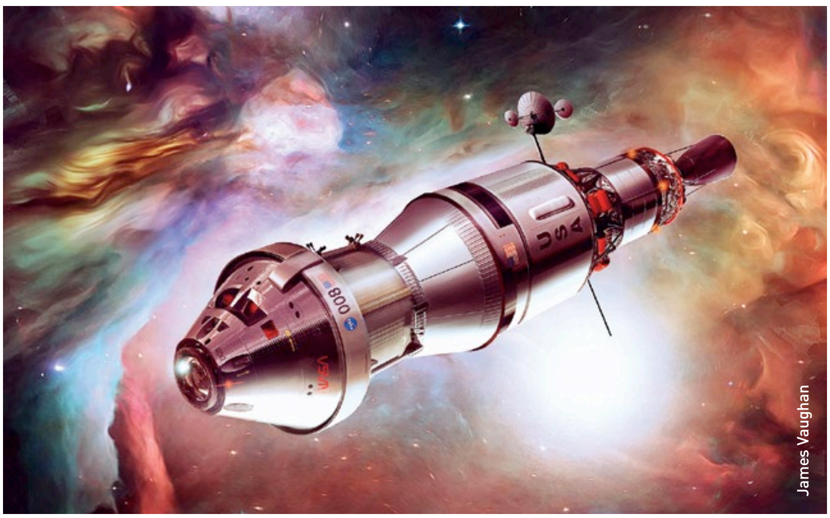
Dr Kyle Landry, Chief Scientist, Expeditionary Science and Special Programs, Liberty Biosecurity, is an expert in microbiology and the isolation of novel enzymes. In addition to directing research efforts at Liberty's Expeditionary Programs Laboratory, Dr Landry is a Scientific Research Fellow at Harvard University and lectures at Boston University.

Dr David J Livingston, Chief Scientific Officer, Metro International Biotech, is a veteran drug developer, having worked in pharmaceutical development since the 1980s. He established a protein engineering programme leading to successful drug development at Integrated Genomics (now Genzyme/Sanofi); was a founding scientist, Vice President and programme executive at Vertex Pharmaceuticals, leading to the development of an approved HIV anti-viral therapy and the first clinically evaluated caspase inhibitor. Dr Livingston also served as the CEO of Praelux, and led its acquisition by GE Healthcare/Amersham, and was then recruited to become the Executive Director of the Slater Centre for Biomedical Technology in Providence, Rhode Island.

Dr Michael S. Bonkowski PhD, MS, Metrobiotech Postdoc, Research Instructor, Sinclair Laboratory, Harvard Medical School Department of Genetics, is a pharmacologist, physiologist and animal scientist. His goal is to understand the links between metabolism, DNA damage and age-related diseases. His focus is to develop direct and indirect ways to drive the activity of nutrient sensors using dietary manipulations and small molecules to prevent and potentially reverse patho physiology.

Dr Lindsay Wu, Science Director for Liberty Biosecurity (Australia) and Senior Research Fellow at the University of New South Wales, holds an academic position leading the Laboratory for Ageing Research at UNSW Australia. He is prominent in the fields of metabolic biochemistry and the molecular biology of ageing, and is an expert in eukaryotic protein secretion, having pioneered new methods for enriching, detecting, and characterising secreted proteins from eukaryotic cells. Dr Wu is a prominent author with publications in Cell Metabolism, Diabetes, and Molecular Metabolism.

Dr Roxanne Bavarian, DMD, Researcher, Sinclair Laboratory, Harvard Medical School, is a is a dentist pursuing a combined residency and doctoral programme in the field of oral medicine based at Brigham and Women's Hospital/Dana Farber Cancer Institute, and the Harvard School of Dental Medicine. Her clinical work with unique patient populations has afforded an her an opportunity to study the mechanisms of oral diseases associated with cancer treatment, with the goal of identifying novel therapeutics to prevent and treat them.

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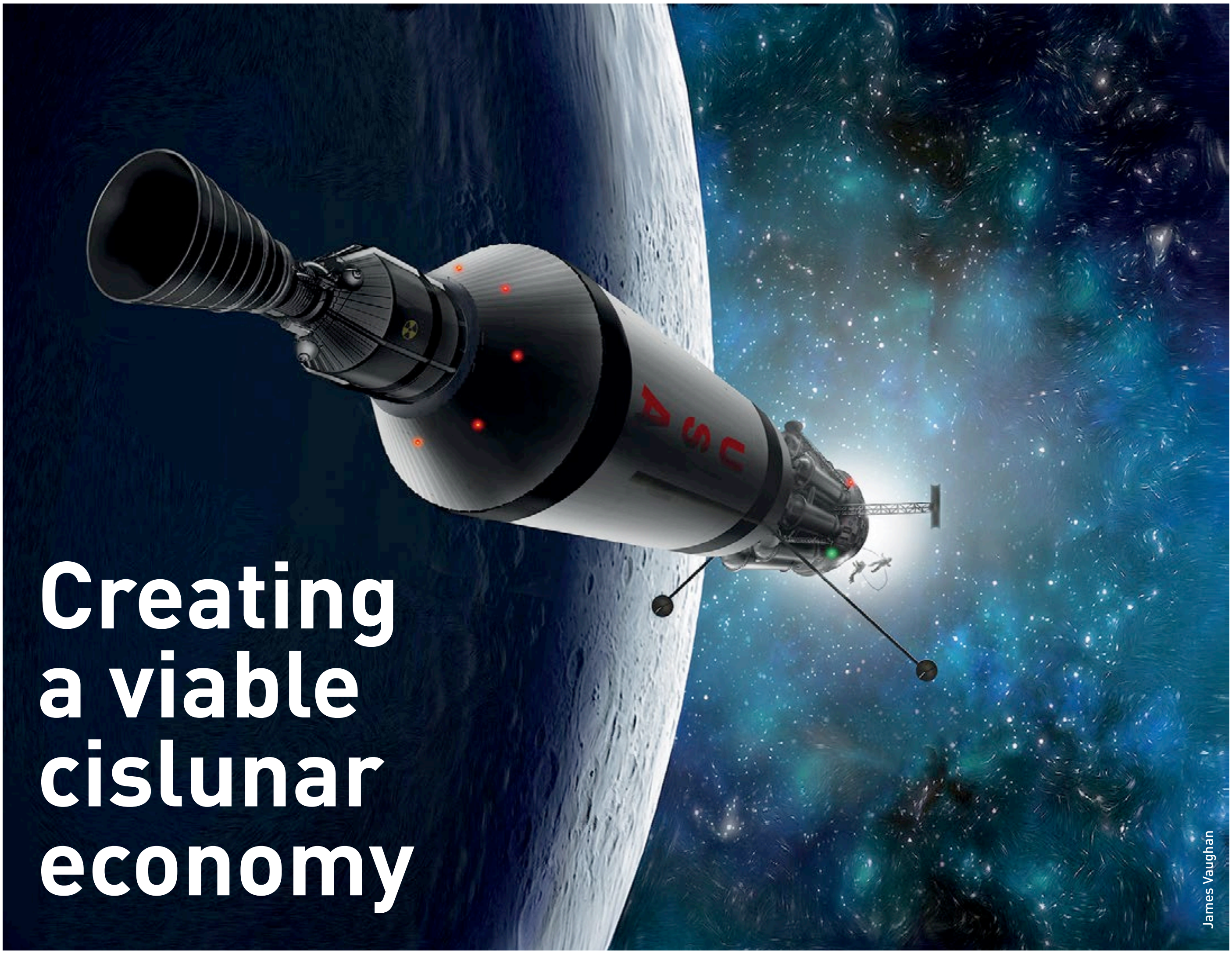


James Vaughan

Creating a viable cislunar economy

George Sowers
Colorado School of Mines/Sowers Space Solutions, Denver, Colorado, USA

Humankind is on the edge of a third great economic revolution that will see the exploitation of the almost infinite resources of space and here George Sowers suggests that the transportation system will be the first economically viable sector to be established and a key to unlocking the huge potential of a cislunar economy.

In the history of humankind there have been two major economic revolutions. First, the agricultural revolution of roughly 10,000 years ago transformed humans from hunter-gatherers to farmers. A new kind of farming lifestyle greatly increased the ability of human communities to capture energy and enabled a hundredfold increase in human population.

Then, some 300 years ago, came the industrial revolution which enabled the economic utilisation of energy locked in Earth for 300 million years in the form of fossil fuels, and with it a tenfold increase in human wealth and population.

But the use of fossil fuels and the burgeoning human population has put tremendous stress on our planet and its climate. Furthermore, fossil fuels are limited and will eventually be depleted. Some view this circumstance with gloom and foresee an eventual collapse of society. Others are hard at work on the third great economic revolution - space and space resources.

Compared to the finite and increasingly depleted Earth, the resources available in space are essentially infinite. Development and exploitation of these resources will enable humankind to continue its trajectory of ever-increasing prosperity and

Economic revolutions through human history.

REVOLUTION	TIMEFRAME	LOCATION	ENERGY CAPTURE	IMPACT
Evolution of modern humans	~100,000 years ago	East Africa	4,000-5,000 kcal/cap/day	Global
Agricultural	~10,000 years ago	Levant (hilly flanks)	10,000-30,000 kcal/cap/day	Increased population, empires, crowding, disease
Industrial	~300 years ago	England	50,000-230,000 kcal/cap/day	Manufacturing, mining, transportation, prosperity, pollution, climate change
Space Resources	10-50 years from now	Cislunar space	Hydrogen/oxygen propellants, solar power >>250,000 kcal/cap/day	Universal prosperity, green earth, reduce/eliminate scarcity

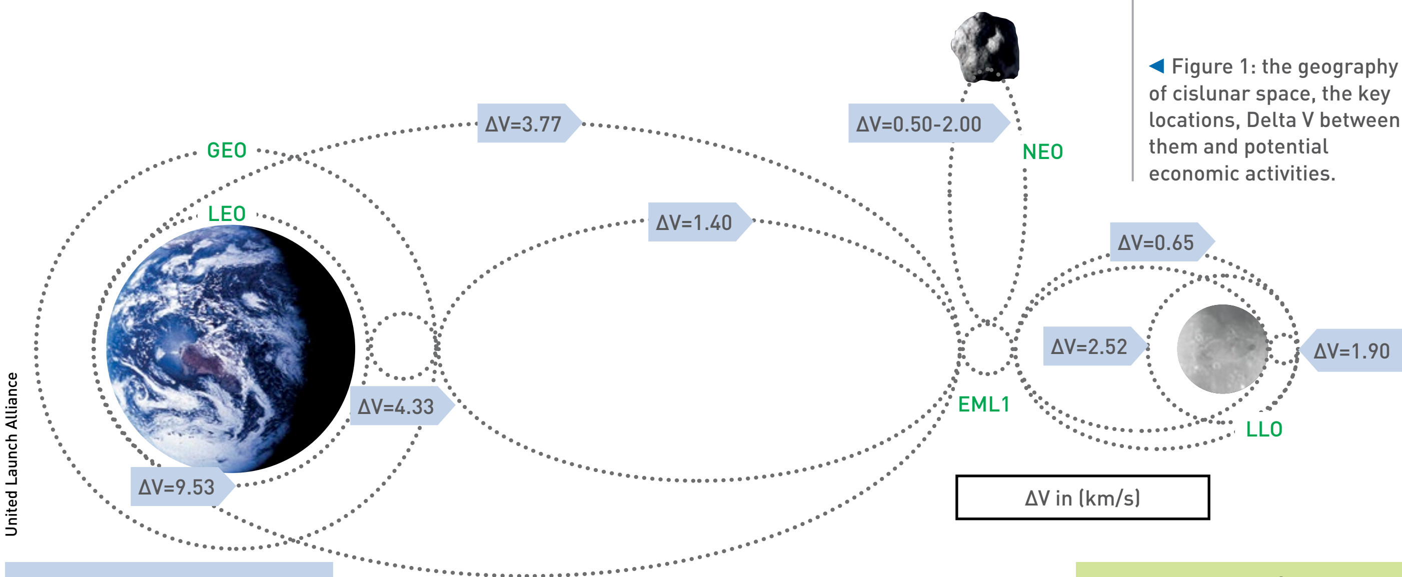
The use of fossil fuels and the burgeoning human population has put tremendous stress on our planet and its climate

well-being while preserving, or even enhancing, our unique home in the universe, Earth.

There are more than enough resources available just in the inner solar system to fuel the next economic revolution. For example, the energy output of the Sun is some 13 orders of magnitude greater than the current energy consumption of all humanity.

Water exists in great quantities on the Moon, in asteroids and on Mars. It has many uses including rocket propellant (when broken into hydrogen and oxygen). In other words, water is the oil of space but far more abundant than oil ever was on Earth. Similarly, just a few average sized metallic asteroids contain more metals than have ever been mined on Earth.

The potential of space resources is apparent. The challenge is how to get at them and what's required is the infrastructure of a robust space



◀ Figure 1: the geography of cislunar space, the key locations, Delta V between them and potential economic activities.

LEO
ISS
Remote sensing
Commercial Station
Communication
Space control
Debris mitigaton
Science
R&D
Tourism
Manufacturing
Propellant transfer
Data servers

GEO
Observation
Communication
Space control
Debris mitigation
Space solar power
Repair station
Satellite life extension
Harvesting

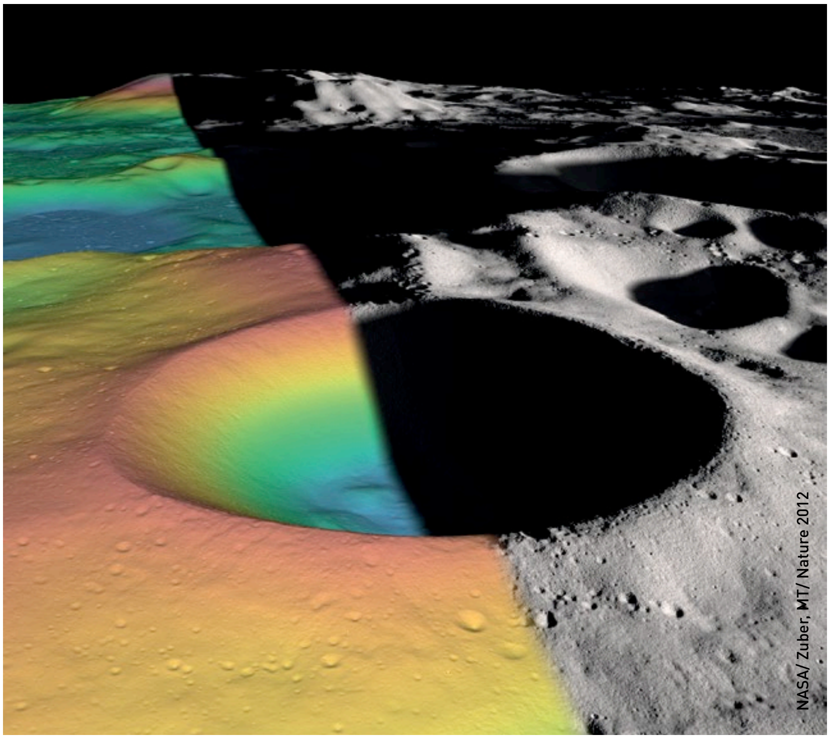
High Earth Orbit
Science/astronomy
Communication link
Way station
Propellant depots
Repair station
Lunar solar power Satellite
Manufacturing
Planetary defence

Lunar surface/asteroid
Science/astronomy
- Lunar observatory

Human outpost
Tourism
Mining
- Oxygen/water
- Regolith
- Rare Earth elements
- HE3

Manufacturing
Propellant depots
Solar power to Earth

Existing market / Emerging market / Future market



▲ Shackleton crater near the south pole of the moon. True illumination on the right. Color elevation contours on the left.

economy. The first place to begin is cislunar space, the Earth, Moon and the immediate neighbourhood, including the region that contains near Earth objects (NEOs) or asteroids.

Free market power

Creating a robust economy in space means harnessing the power of the free market. Competition in the free market spurs innovation leading to efficiency and growth. But the foundation of the free market is the consumer - and for the time being all consumers live on Earth.

The future space-driven economy needs to deliver value to consumers on Earth. Hence, the close environs of Earth, cislunar space, is where we must begin. The commercialisation of cislunar space leads to what had been dubbed the cislunar 'econosphere', an economic environment through

There are more than enough resources available just in the inner solar system to fuel the next economic revolution

which space resources can be developed and Earth freed from its resource constraints.

The geography of cislunar space determines the types of economic activities that might take place in various locations. The key locations are low Earth orbit (LEO), geosynchronous orbit (GEO), Earth-moon Lagrange point number one (EML1), low lunar orbit (LLO), the lunar surface or a near Earth object (NEO) or asteroid.

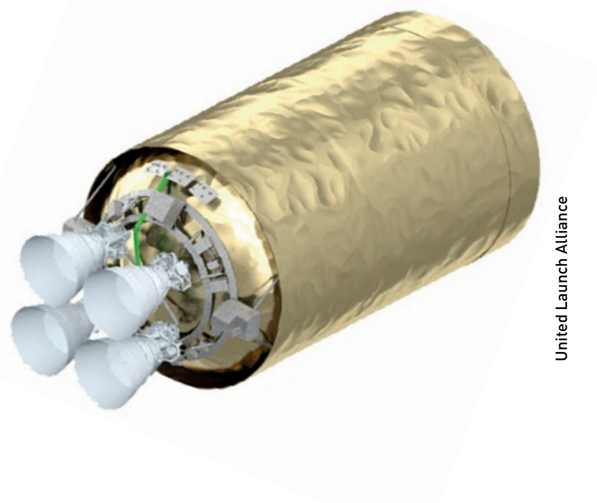
Of critical importance is the energy required to move from one location to another. A useful proxy for this energy is Delta V, the increment of velocity that must be added to a spacecraft to travel from one location to another. Figure 1 shows the relative locations in cislunar space, the delta V between the locations as well as some of the economic activities that might take place at key locations.

One of the first economically viable uses of resources in cislunar space will be propellant manufactured from water. There are several reasons for this. First, one of the most significant findings of space science of the last decades has been the abundance of water in the inner solar system. The permanently shadowed regions near the poles of the Moon harbour significant quantities of water in the form of ice.

Shackleton Crater is near the lunar south pole and not far from the Cabeus crater where a spent Centaur upper stage was crashed to examine the spectral content of the ejecta plume. Water content was measured in the 5-10 percent range. In addition, many asteroids, including NEOs, are thought to contain large quantities of water. And we believe there is water on Mars. Second, water has many uses in the space economy, but the most significant near-term use is as propellant.

Benefits of space-sourced propellants.

CISLUNAR ACTIVITY	SPACE-SOURCED PROPELLANT BENEFIT
Transportation from Earth to GEO	10-20% lower cost
Transportation from Earth to lunar surface	70% lower cost
Cost of a human mission to Mars	2-3 times reduction
In-space transportation	Essentially the cost of space sourced propellant



▶ The advanced cryogenic evolved stage (ACES) will form part of a fully reusable in-space transport system.

Water's constituents, oxygen and hydrogen, when separated and liquified, are the most efficient chemical rocket propellants known. Finally, space sourced propellants can dramatically reduce the cost of every other activity in cislunar space.

To take full advantage of space-sourced propellant requires refuelable in-space vehicles. Nothing like this exists today but United Launch Alliance (ULA) is currently developing a new upper stage which will embody all the necessary features.

Called the Advanced Cryogenic Evolved Stage (ACES), it includes advanced technology eliminating the need for any fluid commodities other than liquid hydrogen and liquid oxygen propellants. In addition, ULA has perfected the technology and processes to transfer cryogenic fluids from one tank to another under space conditions.

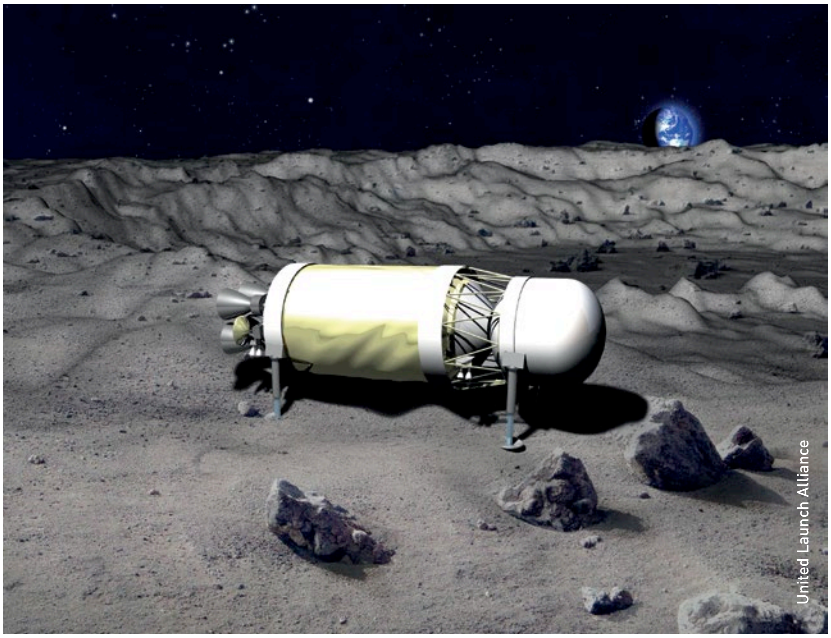
ACES will debut as an upper stage in the early 2020s. When equipped with a landing kit, ACES can also function as a lander, enabling surface access to the lunar surface. The landing version of ACES is called XEUS.

Together, ACES and XEUS form the elements of a fully reusable in-space transportation system that can be fuelled by propellants mined from water found on the lunar surface or asteroids. With such a transportation system in place, we can imagine trade routes within cislunar space transporting raw materials from the Moon and asteroids to central distribution and manufacturing nodes like EML1, and then down into Earth's orbit or surface.

Due to the enormous energy required to climb out of Earth's gravity well, once manufacturing capability is established in space, only very high value, low mass items will be transported directly from Earth. Examples include people and microchips.

On the other hand, mass-less entities like photons have no problem with gravity. Hence, information will be a major export from Earth to cislunar space. This information will take the form of instructions and product designs for in-space manufacturing facilities as well as information to keep the cislunar economy humming along. Similarly, photons in a form readily converted into terrestrial electricity will be a major import from to Earth from cislunar space. This important aspect of the cislunar econosphere is highlighted below.

The transportation architecture will be enabling for all other activities in cislunar space. However, the costs to emplace such an infrastructure are daunting. The easy answer is to assume that governments (taxpayers) can be persuaded to bear the expense. But it would be far better if one could devise a commercial business model that would build the infrastructure incrementally while returning profit along the way.



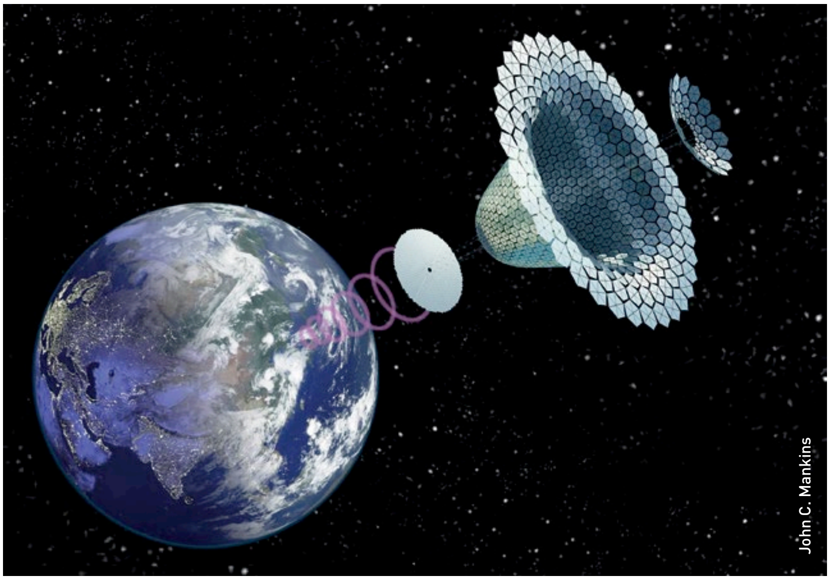
▲ XEUS, the ACES stage equipped with a landing kit.

An example of such a business model was developed by ULA based on using space-sourced propellant to ferry satellites from low Earth orbit to geosynchronous orbit. Based on this model, ULA set a price for propellant at the EML1 node of US$1 million/ton. This price can now be used by the emerging space mining companies to refine their own business models. In addition, ULA's analysis was used to derive requirements for a potential lunar mining facility in terms of mass, cost and efficiency.

Once a transportation infrastructure is in place, all other activities in cislunar space become much more economical. One of the most important activities for the cislunar econosphere will be providing energy to Earth. Worldwide energy consumption is currently on the order of 12.5 terra-watts valued at about US$7 trillion per year. Over 85 percent of this energy is supplied by fossil fuels in the form of oil, natural gas and coal. These resources are necessarily finite and will grow increasingly more expensive as reserves are depleted. Furthermore, use of these resources has harmful consequences for Earth's environment and climate.

Use of solar power from space can alleviate issues of scarcity and environmental damage of fossil fuels. And unlike terrestrial solar and wind power,

It would be far better if one could devise a commercial business model that would build the infrastructure incrementally



▲ The Solar Power Satellite-Alpha concept. Solar energy is collected, converted to microwaves and beamed to Earth.

space solar power (SSP) is well suited for base load and requires a much less intrusive terrestrial footprint. At geosynchronous orbit, a solar power satellite will receive a daily solar power incidence of 32.8 kW-hr/m^2. This compares to 7.5 kW-hr/m^2 in June at my home in Colorado in the USA and just 2.5 kW-hr/m^2 in December.

Space Solar Power satellite business case.

ASSUMPTIONS	
Mass if manufactured in space (EML1)	6,000 tons
Manufacturing cost	US$1,000/kg
Transportation cost	US$2 million / ACES-XEUS round trip
Propellant cost	US$1 million/ton (EML1), US$0.5 million/ton (lunar surface)
Amortisation period	10 years
Operating cost	US$200 million/yr
Ground infrastructure cost	US$100 million
ACES capability	160 tons from EML1 to GEO & return
XEUS capability	70 tons from lunar surface to EML1 & return
Electricity price to grid	US$0.1/kW-hr
RESULTS	
Total transportation cost	US$6.3 billion
Total non-recurring cost	US$12.4 billion
Annual revenue	US$1.75 billion
Annual profit	US$317 million
Return on sales	18 percent

The assumptions are challenging and require the development and establishment of large scale space mining and manufacturing infrastructure

One concept for a two giga-watt SSP satellite - called Solar Power Satellite (SPS) Alpha - was developed by John Mankins under contract to NASA. It is a very large object, measuring 3 x 5 km and with a mass, if launched from Earth, of 12,000 tons. At today's prices, just the launch costs would total U $320 billion - clearly unaffordable. However, if one can source most of the raw materials on the Moon, manufacture the components at EML1, and assemble it in place at GEO, the economics move into the realm of feasibility. All transportation is assumed to be provided by ACES and XEUS.

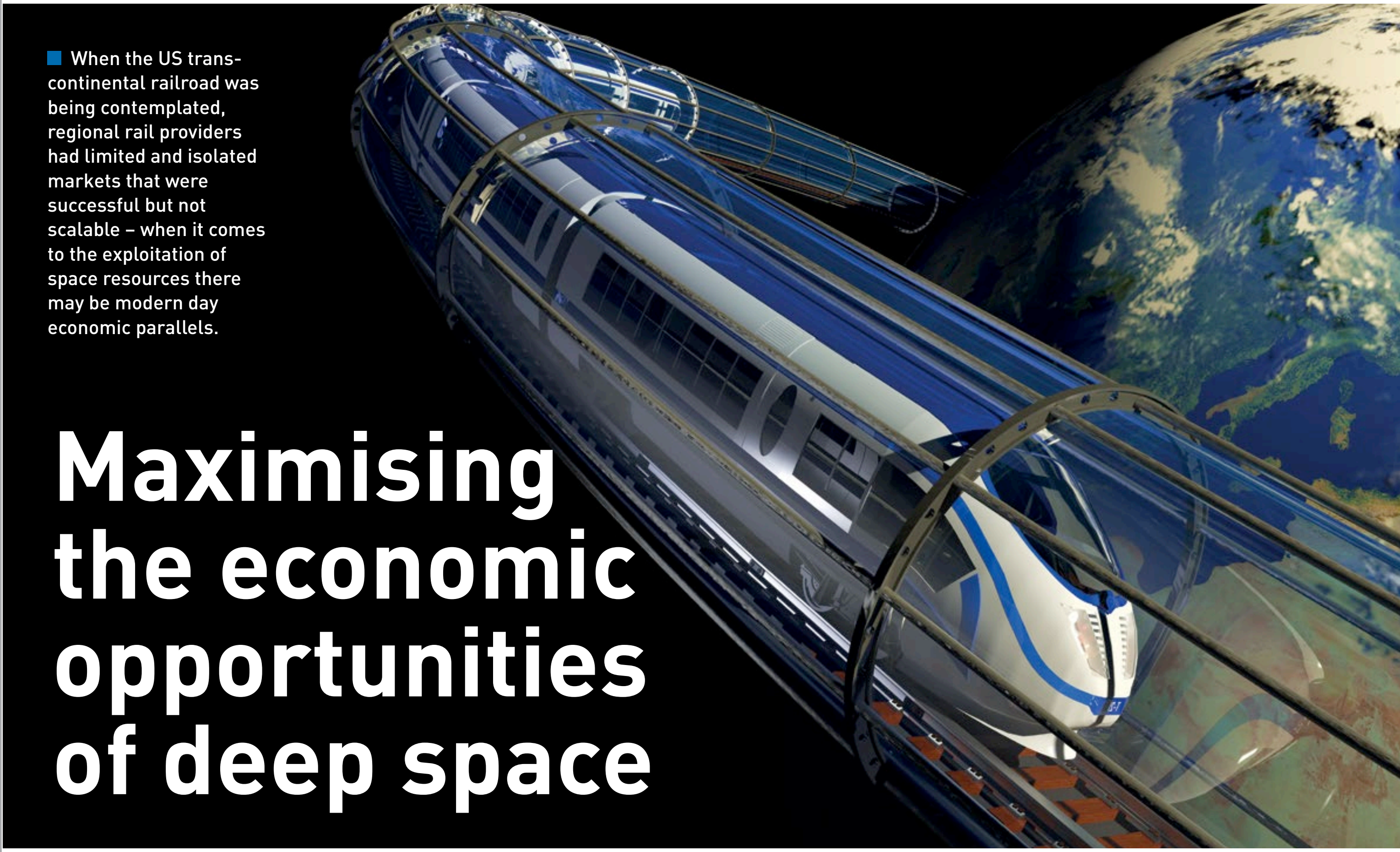
Given these assumptions, the business case is feasible and offers reasonable returns. The total non-recurring cost, as well as the development cost per kilowatt of capability, is comparable to a large scale nuclear powerplant and well within the resources of large commercial power companies.

The assumptions are challenging and require the development and establishment of large scale space mining and manufacturing infrastructure. But once established, this infrastructure can enable the construction of hundreds of solar power satellites, reducing and eventually eliminating our reliance on fossil fuels while enabling increased prosperity through inexhaustible, carbon-free, low cost energy.

Interest in developing the cislunar economy is expanding around the globe as companies and governmental agencies begin to realise the incredible potential of the next great economic revolution for humanity. The transportation system will be the first economically viable sector of the econosphere to be established, enabling everything that follows. The capstone will be space solar power, tapping into the enormous worldwide energy market and providing benefits to billions of people on Earth. ■

About the author

Dr George Sowers has 30 years of experience in the space transportation field working for Martin Marietta, Lockheed Martin and the United Launch Alliance (ULA). He recently retired from his position as Vice President and Chief Scientist at ULA where his team developed an architecture for fully reusable in-space stages fuelled by propellant mined, refined and distributed in space. Dr Sowers has now joined the faculty of the Colorado School of Mines as part of a newly created graduate programme in space resources. He holds a BS in Physics from Georgia Tech and a PhD in Physics from the University of Colorado. Dr Sowers is a fellow of the American Institute of Aeronautics and Astronautics (AIAA).



When the US trans-continental railroad was being contemplated, regional rail providers had limited and isolated markets that were successful but not scalable – when it comes to the exploitation of space resources there may be modern day economic parallels.

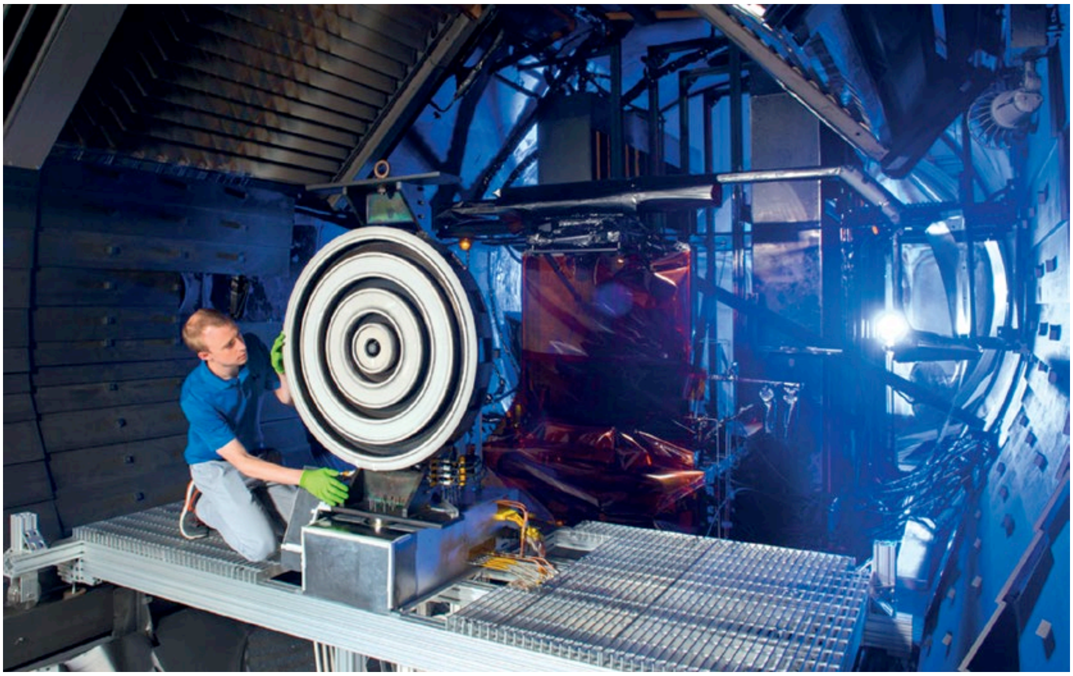
Maximising the economic opportunities of deep space

Dylan Taylor
Founding Partner, Space Angels, and Founder, Space for Humanity, USA

The space economy has reached a fever pitch not seen in the post-Apollo era. Many new capital sources came into the industry in 2017 via high profile venture capitalists such as Sequoia, Shasta Ventures, Andreessen Horowitz and Lightspeed Venture Partners - and that trend seems to be increasing. Strategic mainstays in the space industry have also ramped up their innovation programmes and acquisition pipelines. The angel community is flourishing with dozens of new angels making their first investments in the sector in 2017. However, notably nearly all of this capital has flowed into space opportunities that are LEO and GEO based, with some limited opportunities focused on the Moon. But what are the potential opportunities for the deep space economy and when are those opportunities likely to materialise? Is there a necessary sequencing to how the deep space economy will evolve and what are the key enablers and inhibitors at each phase? What are the key subsectors of the deep space economy and what roles do both the government sector and commercial space have to play in their evolution?

For a successful economic ecosystem to thrive, two things must be present - supply and demand. Supply in a deep space economy is a complicated input due to the extreme costs of bringing economic inputs into space and the lack of existing in-space infrastructure. Therefore, in order to build a successful deep space economy, the key first step will be to address these two areas.

Not surprisingly, the most notable deep space companies to date have been the so-called asteroid mining companies: Planetary



▶ Scott Hall makes adjustments to the X3 ion thruster at the University of Michigan before a test.

Resources (PRI) and Deep Space Industries (DSI) being the most prominent. Previously, Kepler Energy and Space Engineering (KESE) announced plans for asteroid mining as well, but they appear to have stalled due to a lack of available funding. Both PRI and DSI seem to have pivoted from pure play asteroid mining to position themselves as space resource companies, focusing in the near term on identifying sources of water that could be made into fuel in-space. This pivot could be why they have been more successful in attracting capital.

The Duchy of Luxembourg has famously put capital behind this category and seems committed to ensuring that the industry develops. Earlier in 2017 it invested US$29 million in Planetary Resources and also agreed to fund a spacecraft for Deep Space Industries under certain unspecified conditions. The motivation appears to have been two-fold: to create jobs in Luxembourg and to continue to accentuate its brand as a pioneering, forward-looking sovereignty that helped launch the global satellite industry. But short of a sovereign nation, time frames for financial returns far exceed more typical investors such as Angels and Venture Capitalists (VCs), limiting the capital available for such opportunities.

Space resources and space manufacturing are promising areas for deep space investment

Since in theory all of humanity would benefit from an in-space resource mining capability, a look to history could perhaps better inform us of successful models in the past. For example, when the trans-continental railroad was being contemplated in the United States, a classic chicken and egg scenario emerged.

Regional rail providers had limited and isolated markets that were successful but not scalable. Their costs of operation were plagued with inefficiency due to a lack of standards and scale. To solve these issues, the regional providers required national standards and national connectivity which everyone agreed would be a boon for all involved.

However, how could each regional provider possibly pay to connect large swaths of land with essentially zero population and no hope of recouping their individual investments unless all the other players opted in as well? No one provider could justify it, even though each provider would benefit dramatically.

In 1863, the US government realised that it could dramatically accelerate its emerging economy and structured a unique financing programme. Under the proposal, the US Government did not fully donate money for the transcontinental railroad but provided money for completion of each mile, while simultaneously underwriting bonds that were sold in the private market for the construction of each mile. The underwriting was in the form of mortgage bonds, issued by the railroad

▲ Artist's rendering of a proposed Analytical Space orbital relay cubesat.

but guaranteed by the US government. The programme was a combination then of strategic investment at a scale no one investor could possibly put together, and the creation of a railroad bond market underwritten by credit superior to any private institution.

Once the financing was in place, the railroad rapidly took off and remarkably, was completed less than six years later. While the 1870s were characterised by stagnant economic growth as the ravages of the civil war were repaired, the 1880s and 1890s represented the largest economic expansion in percentage terms in the history of the US.

Much of this economic growth has been attributed to the completion of the railroad and the foundation it laid for truly national commerce. This example is useful in that it demonstrates that capital alone doesn't necessarily need to be gifted by sovereigns in order for infrastructure to be built. Rather, with sovereign credit, underwriting the riskiest time frame of investments, and/or underwriting at a massive scale, they can create the impetus for large projects to become viable.

Given the need for large scale infrastructure in space, leveraging in space mining, as well as other capabilities necessary to a deep space economy, I would like to suggest a new term, 'Deep Space Posts' (or DSPs). Similar to any frontier that has been settled by humanity in the past, DSPs are the modern day trading posts. They are one part 'pick and shovel', meaning in-situ resources to enable exploration, and one part gathering points in the frontier for refuelling and commerce.

The commercialisation of non-chemical propulsion could happen sooner than expected

Given the vastness of deep space and the enormous benefits to scale, DSPs are practically the only way that a deep space economy can emerge. They are the necessary enablers. I would suggest that DSPs are the types of large scale projects that sovereign nations should consider supporting and/or underwriting. Their benefits downstream to a vibrant deep space economy can't be underestimated.

Next, let us discuss a few of the key enablers for DSPs to both emerge and to be successful.

Space manufacturing

In addition to space resources, space manufacturing appears to be another promising area for deep space investment. Space manufacturing has been pioneered by the additive manufacturing demonstrated in microgravity on the International Space Station (ISS) by NASA partner, Made in Space.

What remains to be demonstrated is to refine the material used and scale up this technology, such that building blocks for habitats as well as functional machines can be manufactured. This will require refinements to 3D printing technology to enable additional materials, such as metals and ceramics, to be used but just as importantly it will require a resource mining capability to augment supplies brought to space from Earth.

Forms of self-replicating machines, as envisioned by Eric Drexler and Richard Feynman, would vastly accelerate the deep space capability. These wouldn't be autonomous, of course, but rather 3D printers capable of creating component parts for additional 3D printers and only being modestly supplemented by highly specialised parts from Earth.

Given the rapid progress 3D printing has already shown in a very short period of time, there is optimism this could be a larger sector than even in-space resource mining in the medium term. For example, it has been widely reported that optical cable can be manufactured in micro-gravity and yield superior transmission capabilities. Since optical cable is a multi-billion euro market it could lead to a very large funding mechanism to dramatically enhance in-space manufacturing capabilities.

Deep space propulsion

With respect to deep space propulsion, SpaceX seems to be keenly focused on pioneering a Mars-based propulsion system and, to do so, it will likely need to raise even more third party capital on the order of several billion dollars. It remains to be seen if this investment can be recouped with the fees paid by future Mars settlers. There is likely to be a crossover point for deep space propulsion whereby chemical rockets give way to ion and/or nuclear based propulsion.

The impracticality of chemical rockets for travel anywhere more than 100 astronomical units (AU) from Earth is well understood. However, for the foreseeable future, the economics of space resource mining will allow for relatively easy and inexpensive refuelling. This, coupled with gravity assists, could allow for chemical based deep space propulsion to be practical for the next 20-30 years. However, with the recent advances in ion based propulsion, the commercialisation of non-chemical propulsion could happen sooner than expected.

Recently, a 'nested' Hall Effect design has been demonstrated at scale by the NASA Glenn Research Center, breaking previous thruster force records. While the impulse generated by the so-called 'X3' is still appreciably small, the nested design allows for multiple thrusters and is potentially scalability to large spacecraft designs.

Given the high specific impulse and the persistence of the acceleration, ion based deep space propulsion seems to be a leading candidate for commercialisation. Recent start-ups focusing on ion based propulsion in LEO include Accion Systems, a spin-off from MIT that has received US$7.5 million in venture funding from well-known VCs such as Shasta Venture, RRE, Slow Ventures and Founder Collective. Accion had previously secured several million dollars in financing from partnerships with the US Department of Defense. More exotic forms of propulsion such as nuclear and matter/anti-matter appear to be in the distant future from a commercial space perspective.

In-space communication networks

As deep space becomes more prevalent and additional infrastructure is created, in-space communication will be even more critical. Currently, deep space communication is constrained by ground station bottlenecks and frustratingly narrow bandwidth.

New protocols are emerging, the most promising of which are laser-based systems. A spin-off from Harvard called Analytical Space is focused on demonstrating this capability from LEO. The technology, however, could be used to build a laser-based deep space communications network that could be used for everything

> **The Moon allows for the consolidation of space infrastructure at a fixed point in space**

from data transmission, to positioning and navigation. This could even be leveraged by the scientific community on an outsourced basis for planetary science.

As we have seen with the terrestrial economy, all commerce is being converted to ones and zeros, including even manufactured items. It is clear that in-space bandwidth will have to be dramatically improved and that the economic viability for such a network, given the demand for its capability, is not too far distant.

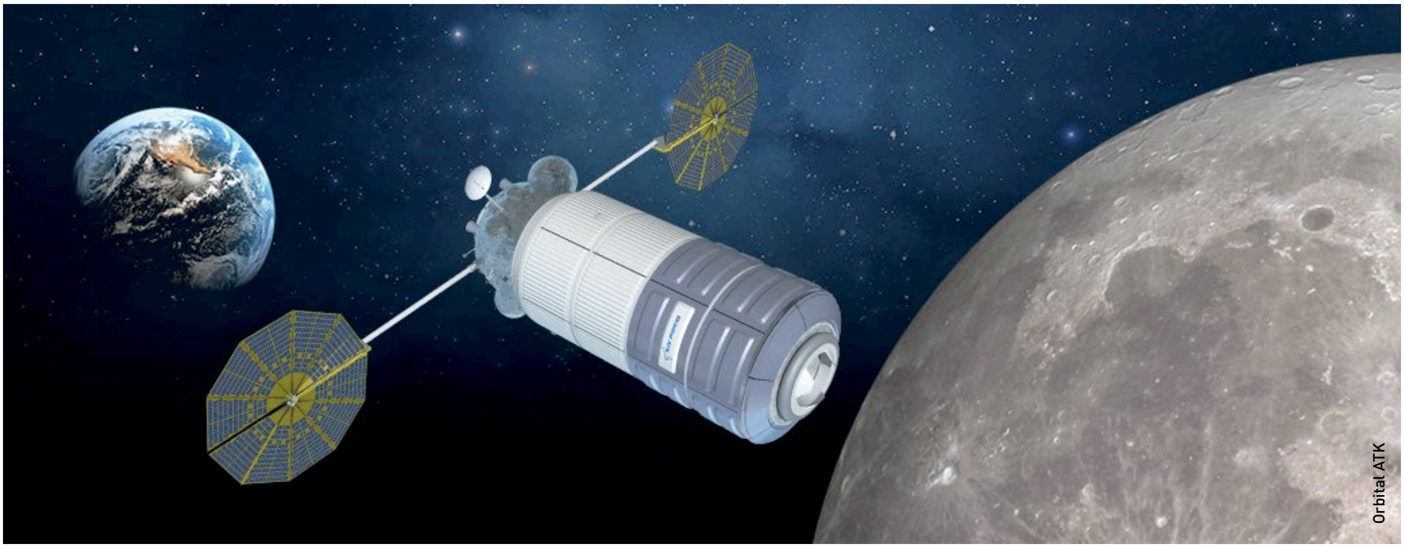
The Moon

With the US recommitting to the Moon in the re-launch of the US National Space Council, and the emergence of private companies, such as Moon Express and Astrobotic, coupled with plans announced by China, Japan and Russia, it is likely the Moon will be a large focus in the near term.

Many have argued that the Moon is critical to success in deep space. While I agree with that premise, I do so based upon the same arguments made for the emergence of DSPs. The Moon allows for the consolidation of space infrastructure at a fixed point in space. Given its proximity to Earth, and its own resources, it is likely the Moon will emerge as both the first DSP as well as the largest DSP as deep space becomes more prevalent.

▼ Natalya Bailey, CEO of Accion Systems, holds one of the company's propulsion systems for small orbiting satellites. With her is co-founder Louis Perna (left) and engineer David Tovani.


Accion Systems



▲ Concept image of Orbital ATK's cislunar habitat, based on its Cygnus spacecraft. Orbital is one of six US companies developing full-sized ground prototypes and concepts for deep space habitats under NASA's NextSTEP-2 partnerships programme.

I don't see settlement being focused on the Moon however. The impetus for space settlement seems to be strongly focused on both exploration and diversification of humanity from a risk perspective. Other than for more tourist based ambitions, the Moon doesn't really qualify on either dimension. I would expect Moon settlements to be organised around the DSP model and tourism, but not long term settlement.

With the Moon emerging as a DSP, a cislunar return capability will be critical. SpaceX announced last year its intention to fly private passengers on a cislunar return at an unspecified future date. Bigelow aerospace also recently announced its intention for a lunar orbiting hotel for tourists.

Given the need for both tourism and shuttling of people and resources to the Moon, I would expect an economically viable cislunar capability to emerge by the early 2020s. The most likely leader in this space should be SpaceX but certainly SLS and other deep space rockets could service this demand as well.

In conclusion, there is little doubt that deep space will be the ultimate destination of humanity's compulsion to explore space. In order to create a deep space economy, the first key step will be to enable in-space resources and in-space manufacturing.

Space resource companies are likely to focus on prospecting and mining of water, and in-space manufacturing should allow for rudimentary parts manufacturing. These two capabilities should in turn lead to the establishment of DSPs and the coagulation of basic infrastructure in-space. From there, refinements to deep space propulsion, deep space communication and in-space mission capability can be better established. This should enable even bolder visions for both space resource mining and space manufacturing capability, which should in turn make space settlement both desirable and practical.

As the demand for deep space services increases, a virtuous cycle that funds additional supply should emerge. I would expect this to play out in the 2020s and early 2030s. This, coupled with a Moon-based economy, should lead to a multi-trillion euro off-world economy by the end of the next decade and an economy on par with the European Union or the North American Free Trade Agreement (NAFTA) region by the end of the following decade.

In order for this vision to become a reality, however, sovereign nations will have to continue to play a role in underwriting some of the very long time frames involved in order for a return on invested capital to be realised. This could come in the form of direct investment or guaranteed underwriting of financing. ■

As the demand for deep space services increase, a virtuous cycle that funds additional supply should emerge

About the author

Dylan Taylor is an investor and thought leader in the space industry. A founding partner of the Space Angels Network, Dylan speaks regularly on matters regarding the future of the space industry and the space economy. He is a Crown Fellow of the Aspen Institute, Delphi Fellow of Big Think and a Young Global Leader of the World Economic Forum. He holds an MBA from the University of Chicago.

Growth drivers, requirements and threats in the smallsat industry

The small satellite market is changing and in its 'Small Satellite Assessment' study Orbital Access predicts a more than tenfold worldwide increase in payloads launched into low Earth orbit (LEO) on satellites that benefit from both a revolution in size reduction and new lower cost launch opportunities. With mega-constellations becoming the largest drivers of this future growth, Stuart McIntyre asks what else can those in the industry look forward to and where do the pitfalls lie?

Stuart McIntyre
CEO, Orbital Access,
Prestwick Scotland

There is no doubt we are witnessing an unprecedented growth and development period within the global small satellite market. The space industry, which for many decades has been dominated by large enterprises and government organisations like NASA, ESA and Roscosmos because of the enormous costs involved, is going through a commercial revolution. It now includes a rapidly growing number of emerging start-ups and everyday individuals.

Advancements in technologies, materials and components have led to miniaturisation and a massive reduction in cost while the need is increasing for applications such as communications, remote sensing (Earth observation and meteorology), navigation and the next generation of entertainment technologies like virtual reality (VR).

Industries such as agriculture, oil and gas and shipping are increasingly using satellite imagery to monitor their operations. It is estimated that 80 percent of global space revenue is coming from downstream services.

Due to these advances and the game-changing cost reductions, cubesats are now available for under US$35,000, which even opens the door for the creation of 'personalised' satellites. Equally, the price tag for launches has decreased significantly which has allowed for more satellites to be launched than ever before. And we are only at the beginning of this shift from 'old' to 'new' space.

The Orbital Access study predicts that, over the next 20 years, the smallsat market will show a more than tenfold worldwide increase of payloads launching into LEO. The forecasts foresees demand ranging between 4,040 payloads per annum in 2036 (potential model) and 1,812 (pessimistic model).

Even at the baseline level (2675 payloads) the study shows that we can expect to see strong growth for satellite production, launch and applications markets. By comparison, 2016 saw 269 small satellites launched, which although more than any previous year in history, is only a sign of what's in store over the coming decades.

Growth drivers

The largest drivers of this future growth in the satellite industry are the mega-constellations such as those planned by OneWeb, SpaceX and Planet, where small, cheap and easily replaceable units are taking over from the large, expensive and durable satellites of the past. OneWeb alone is planning to create a satellite fleet of up to 2,000 satellites (648 initially) and SpaceX another 4,000. This will also lead to the first large-scale mass production of satellites.

Beside the huge initial demand for LEO satellites and launches, there is a consistent need for replenishment, due to their relatively short five to eight year design life. Developments in electrical propulsion expected towards the late 2020's may extend that lifespan but at the end of their useful life they will need to be deorbited and replaced by new satellites. Shorter, on-orbit design life and increasingly rapid on-orbit obsolescence will drive replenishment and replacement demand in addition to new service deployments.

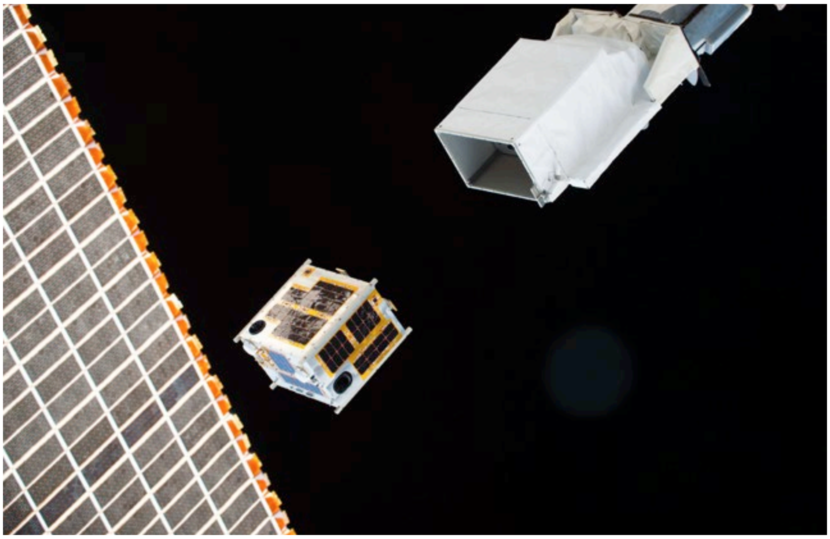
▲ An MD11 aircraft carrying the Future Small Payload Launcher (FSPL) being developed by Orbital Access and using the Reaction Engines' Sabre engine.

Mega-constellations will also influence the share of payload masses. Overall the smaller mass categories - with the exception of picosatellites (0.1-1 kg) - will experience strong growth while the larger mass categories are expected to stagnate or even decline. Nanosatellites (up to 10 kg) will continue to take the greatest share. Microsatellites (10-200 kg), however, are becoming the standard mass classification for mega-constellations.

The second largest driver of market growth is technology, lowering the overall cost of entry to the market. The increase of commercial off-the-shelf units and parts significantly reduces the cost of satellites. Miniaturisation - due to improved technologies for photovoltaic cell performance, thermal control, propulsion and power supply - has led to reduced battery mass and smaller solar panels among other components. It allows smaller spacecraft to operate with the same capabilities as their larger counterparts.

The introduction of a standardised construction method for form and mass had led to cubesats with the initial standard of 1U (unit). By stacking them, configurations of 1.5U, 2U and 3U grew popular in 2013, particularly with commercial

The increase of commercial off-the-shelf units and parts significantly reduces the cost of satellites



▲ The DIWATA-1 satellite is deployed from outside of the Japanese Kibo module on the ISS. Intended to observe Earth and monitor climate changes, this was the first microsatellite owned by the Philippine government that involved Filipino engineers in the development. It is estimated that 80 percent of global space revenue is now coming from downstream services, such as Earth observation applications.

companies, universities and research agencies, as well as governments.

The study also predicts that commercial satellites will most likely aim for the 400 km to 650 km altitude band as this provides the best trade-off between satellite lifetime and initial deployment costs.

The preference for this bracket is supported by historical data that shows 62 percent of all payloads between 2012 and 2016 were delivered to an altitude less than 600 km. The shift from using lower than 450 km orbits to higher altitudes will become visible half way through the prediction period. Alongside the change in orbit altitude, we will also see a similar shift to higher inclinations for small satellites. Interestingly, the International Space Station (ISS) is one of the reasons for this skewed picture as its 400 km orbit determines the orbit of satellites released from the station. Ten out of 42 launches to LEO between 2012 and 2016 were from the ISS.

While payload rideshares from launches to the ISS have created a supply-led picture, true demand for altitude preferences and inclinations will become evident when cost-effective small payload launch systems become operational. If ISS funding continues beyond 2024, a continued focus of driving payloads to the station's orbit and inclination can be expected.

With the rise of a new generation of dedicated two-stage-to-orbit launchers comes a new network of launch sites or spaceports for horizontal take-offs and landings

Other important demand drivers for launching small satellites are congestion and debris mitigation. Congestion will become a factor towards the end of the prediction period when the large number of satellites launched to mid altitudes will push satellite operators to higher orbits.

Likewise, the exponential growth of space debris is a very serious issue and with the rapid increase of the number of satellites in space, the danger of the feared Kessler Syndrome - an unstoppable cascade of collisions in LEO - is mounting. Unsurprisingly, there are a number of systems under development to reduce space debris.

Launch systems

Launching a plethora of new satellites into orbit is still the costliest part of a project. Limited opportunities and access to orbit remain a problem for many companies, both new and established. What they all need to be more successful and satisfy the growing thirst for more data from space is a cheaper way to get their satellites up into space and a greater number of launches with increased certainty and flexibility.

The same process of advancements that has led to lowering the cost for satellites themselves also applies to the launcher market, further reducing cost and allowing more frequent launches as well as utilising special inclinations and altitudes.

While smallsat business continues to outpace the launch vehicle market, a new generation of dedicated launch systems will have a significant impact on the industry by providing more primary payloads, with the opportunity to reach orbits that would normally be too expensive and with far greater launch availability.

The successful development of fully reusable vehicles will also have a measurable impact on lowering cost. Of course, the technological challenge to build more and more efficient launchers is only one aspect. Launch suppliers also need to build up trust in their operations, demonstrating to customers that they can balance demand and delivery.

With the rise of a new generation of dedicated two-stage-to-orbit launchers comes a new network of launch sites or spaceports for horizontal take-offs and landings. Right now the only launch stations in use are for vertical launches - 16 across the world and a quarter of them in China. And while there are 10 licensed spaceports in the USA, none of them is yet in operation, which provides a great opportunity to other countries, bearing in mind

Other important demand drivers for launching small satellites are congestion and debris mitigation

that the highest growth in the industry is predicted to be in the 'rest-of-the-world' region.

Spaceport development across the globe becomes an essential element to further reduce cost by avoiding costly transport of satellites to launch pads in the USA, French Guiana, Russia or Japan, and increase launch frequency.

In addition, becoming a spaceport is a very promising opportunity for smaller coastal airports especially when considering that each launch site will need services around it and will probably create a cluster of space companies. Scattered around the world there are a number of airports owned by private companies or local governments, all keen to turn their assets into high value propositions. The prospect of playing host to a local cluster of the internationally flourishing space industry is a very real one.

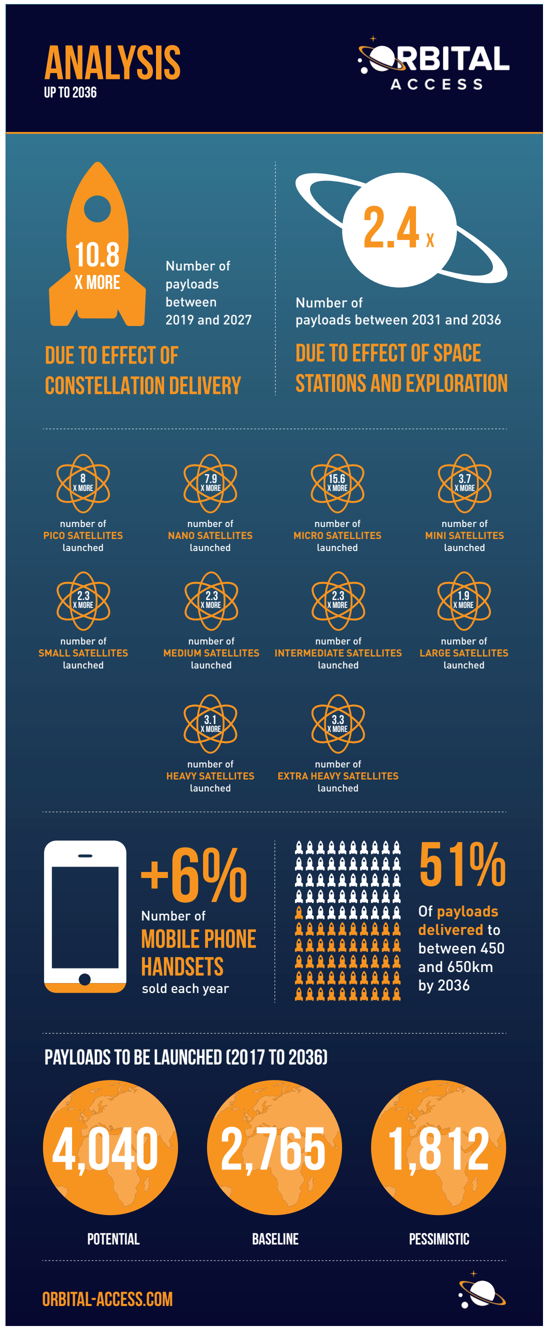
One example is Prestwick Airport in Scotland. Around the airport is a cluster of large aerospace companies, including Spirit Aerosystems, which manufactures wing components for Airbus and Boeing aircraft, and UTC Aerospace Systems, a major supplier to international space programmes. There is also GE Caledonian, which provides aero engine overhaul facilities, and BAE Systems Regional Aircraft, which is currently working with Orbital Access on a future launch concept. And just 30 minutes drive away in Glasgow sits the largest workforce of space industry employees in the UK outside of London and the south east.

In south west UK, Newquay in Cornwall (a former RAF base) has been developing rapidly since its transfer to civil ownership in 2008. It is now one of the most technologically advanced airports in the UK with new navigational aids, radar system, control tower and runway upgrades.

Newquay also has an enterprise zone which so far is the only such zone focused on aerospace to be part of a UK commercial airport. This unique status has attracted many hi-tech companies, including Leonardo, Bloodhound SSC and Bristow Helicopters. The Enterprise Zone also extends to the Goonhilly Earth Station in Helston which is one of the UK's best space industry assets.

Risks and threats

Of course, there are still risks and threats that can slow down growth of the smallsat industry. One is liability. Being able to buy insurance is paramount because without it you cannot launch.



▶ Orbital Access forecast and analysis up to 2036.

Traditionally, the insurance price tag that came with the large satellites and expensive launches has been hefty. Smallsat operators launching primary payloads would need some form of liability cap to be in a position to afford the launch.

Consequently, some countries - including the UK - introduced such a cap alongside its amendment of the UK Outer Space Act in 2015, which imposed a €60 million limit on the amount

▲ An aerial view of Cornwall Airport in Newquay, UK, along with an artist's impression of potential spaceport facilities.

that spaceflight companies are required to indemnify the government.

In contrast, the UK's Draft Spaceflight Bill only reserves the option to cap liability on a case-by-case basis when granting operator licences, instead of a fixed limit. The intention is to allow for more flexibility with new technologies and developments - but the question is, will that uncertainty provide the confidence for both insurers and smallsat operators?

Without indemnification, licensed operators would have unlimited liability and bear all the risks. Not to mention the high insurance premium. Both are damaging when it comes to raising investment and would place UK space companies at a competitive disadvantage.

The second threat comes from the lack of availability of primary payloads, even though there has been an increase in small satellites being launched together. At present, most companies wanting to launch payloads of up to 500 kg have to wait to hitch a ride on other governmental or commercial launches and this means their needs are treated as an 'add-on' to the primary payload and its schedule, leaving some customers with a wait of 18 months or more for a suitable launch.

Cancelling contracts and changing providers is a costly alternative not many can afford so the wait for a shared ride is a substantial roadblock that is creating a massive backlog in the market. Currently Arianespace has a backlog of almost 60 payloads and SpaceX around 40. There is real pressure on the global launch industry to provide more frequent and reliable launches than currently available - otherwise the bottleneck will continue to trap some of these smallsat assets on the ground. ■

The wait for shared ride is substantial roadblock and is creating a massive backlog in the market

About the author

Aviation runs in the family of **Stuart McIntyre**, whose grandfather, together with the Duke of Hamilton, became the first aviators to fly over the summit of Mount Everest. He studied aeronautical engineering with management and has worked in the aerospace industry for a number of years for companies such as BAE Systems, Caledonian Airmotive, and Jetstream Aircraft Prestwick. He also gained experience outside the aerospace industry as CEO at medical device manufacturer Microsulis Medical.

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Cubesats - changing the landscape for app developers

Today's development of software for spacecraft is very conservative and limited to a small set of experts in the space business, largely due to the existing constraints imposed by space hardware and to the typical criticality of space missions. But cubesats are changing the landscape as they grow in popularity and the possibilities offered by ever smaller and cheaper components are making space accessible to a wider number of people.

Onboard processors with great amounts of processing capability are allowing the space community to move towards spacecraft capable of executing actual operating systems. This ongoing transformation is similar to what happened for smartphones a decade ago.

The European Space Agency (ESA) is already tackling the needs for mission operations of such systems by developing a software framework for nanosatellites inspired by the latest technologies that already exist here on Earth.

There is a difference in orders of magnitude when comparing the processor speed and memory of flight hardware of a typical satellite system with mainstream desktop computing platforms on Earth. A 10-year lag is observed between the radiation-hardened processors and the commercial devices available in retail stores. [1]

▲ Illustration of new Vector-R (Rapide) second stage deploying seven cubesats. Vector describes itself as 'a disruptive company' that connects space startups and innovators with affordable and reliable launch services. Its first customer-funded launch took place from Spaceport Camden in Georgia, USA, in August 2017.

Software and hardware often go hand in hand. The limitation of the hardware resources together with requirements driven by the criticality and timeliness aspects of onboard control logic have led to very different software development processes for onboard software. Unfortunately, it has not benefited much from many recent advancements in the IT and general software development domain.

Contrary to popular belief, spacecraft computers do lag behind mainstream desktop computers by several technological generations.

Today's onboard software

The classical onboard software is currently seen as an almost immutable piece of software which is developed for a particular use where future updates would imply patching specific memory areas, though in the majority of cases it is developed for embedded devices that will never be updated again.

When thinking of today's flight software, one analogy to make is to compare it to the software in the Nokia 3310 mobile phone first released in 2000. Software development processes and techniques for flight software have not changed as significantly as they have here on Earth.

The emergence of smartphones rebranded the old concept of software applications into 'apps' which are units of software that can be easily developed, downloaded and launched on a smart phone platform. This concept revolutionised the way we think of software and today there are literally millions of apps available for smart phones that can be downloaded by anyone around the globe. [2]

USB for space

Who remembers the myriad of computer connectors that existed two decades ago? Before the USB, there were serial ports, parallel ports, DIN connectors, PS/2, game ports, and many others.

USB is now a small, simple, and robust industry standard for the connection of computer peripherals. Hot swapping is taken for granted today but back in the day some connectors would only work after restarting the computer. This has massively simplified plugging devices together and today they are even used as power chargers.

In software, we have experienced the establishment of successive abstractions that simplify the process of developing, distributing and deploying software.

One example is the success of smartphone platforms that take advantage of well-defined software architectures. Regardless of the hardware of a smartphone, the Android framework defined interfaces to the app software developers, allowing the same software app to be deployed and run on various hardware platforms without the need for heavy adaptation or customisation.

A similar approach has been taken by Apple with iOS, albeit on its proprietary hardware and both approaches have facilitated the rapid development of a multitude of apps for the respective platforms.

The Consultative Committee for Space Data Systems (CCSDS) is a standardisation board that brings together the 11 largest space agencies in the world. It has defined a service-oriented architecture for mission operations of space assets known as Mission Operations (MO) services.

This architecture allows the development of more complex systems in niches such as satellites, robotic operations and human spaceflight. The objective is the standardisation of services to facilitate the development of interoperable applications. The potential is enormous as such an effort might turn into the new 'USB of space'. [3]

Cubesat boom

The recent advances in the miniaturisation of space components and electronics has allowed the design of successively smaller satellites which are considerably cheaper to build and launch than conventional satellites. Creating a new and still expanding market for small satellites.

Contrary to popular belief, spacecraft computers lag behind mainstream desktop computers by several technological generations

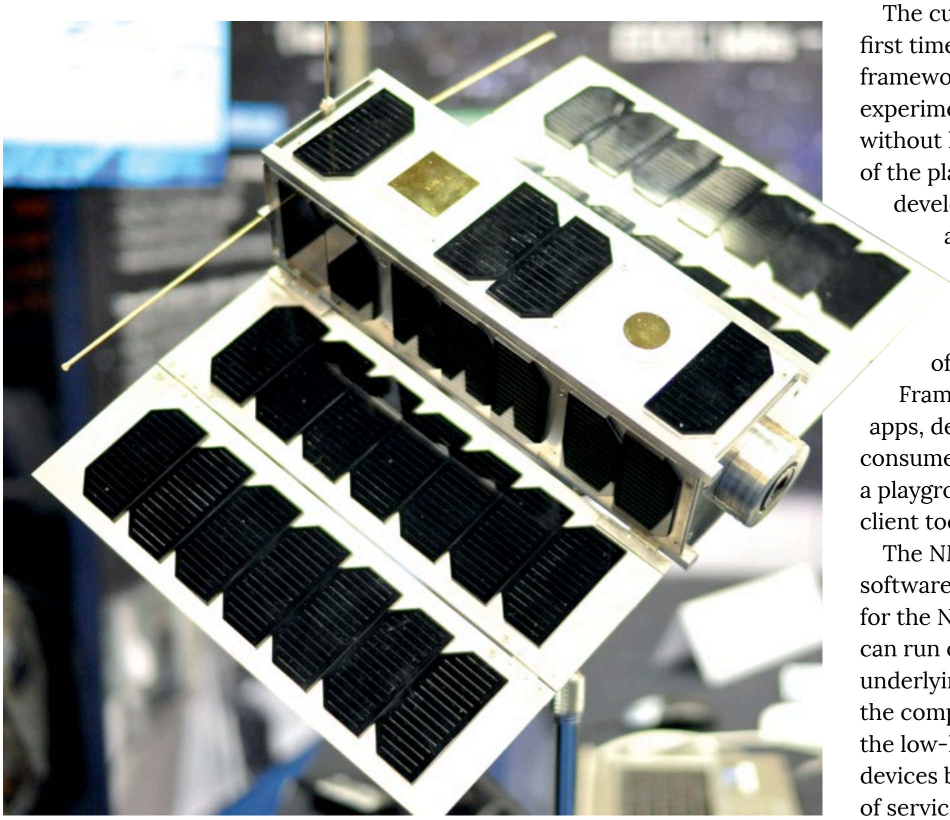
This on-going transformation is similar to what happened for smartphones a decade ago

ESA is involved in multiple projects related to cubesats. One of these is OPS-SAT, a cubesat mission with the objective of trying new operational concepts in space.

It has an experimental platform composed of a system-on-chip device with 1 GB of RAM, an ARM 925 MHz processor and a lightweight version of Linux. This allows many software experiments to be tested in space that could never be flown otherwise. Its limited cost and the use of high performance hardware offer the opportunity for transferring some of the terrestrial software advancements into the realm of flight software. [4]

The mission will be open to experimenters worldwide that can try their new operational ideas, in most of the cases in the form of software apps, in this 'space laboratory'.

▼ ESA's OPS-SAT mini-satellite is made up of three standardised 10 x 10 x 10 cm CubeSat units with deployable solar panels on each side.



Tomorrow's space software

Similarly, it would be great if a reusable space software framework could be established and used both onboard and on-ground in a similar way to what has been done in the smartphone arena with Android and iOS. ESA recently developed a framework dedicated to CubeSats, the NanoSat MO Framework (NMF), which allows onboard software to be developed as apps. The framework's main objective is to facilitate the development of software for nanosatellites to simplify its orchestration; for instance, starting and stopping onboard apps. [5]

The core functionalities of the framework are monitoring and control of onboard status and activities; monitoring and control of the platform peripherals, and onboard software management.

The NMF is built upon the CCSDS Mission Operations services architecture and thus inherits many of its benefits. For example, it was possible to define a multi-segment software framework dedicated to nanosatellites that is neither limited to the space segment nor the ground segment, and instead covers both segments simultaneously. A set of pre-built components is available that allows quick development of new software solutions, interoperable in end-to-end scenarios.

The overall design of the framework is inspired by current smartphone technologies. Not only does it use the concept of apps but also encompasses a Software Development Kit (SDK), a packaging mechanism for the digital distribution of apps, and abstract services that allow any app to retrieve information from the spacecraft platform.

The cutting-edge framework will fly for the first time in ESA's OPS-SAT mission and the framework's SDK will be used by OPS-SAT experimenters to develop their software quckly without having to understand the low-level details of the platform. This will reduce the software development effort and also increase reuse across future missions.

The NMF SDK is a set of development tools and software source code that facilitates the creation of applications with the NanoSat MO Framework. It is composed of demos of NMF apps, demos of NMF ground applications, a consumer test tool, an NMF package assembler, a playground environment, a software simulator client tool, and finally documentation. [6]

The NMF SDK is the starting point for a software developer willing to develop applications for the NMF. It allows them to develop apps that can run on any nanosatellite regardless of the underlying hardware. It is also possible to hide the complexity of the spacecraft, for instance, via the low-level interfaces to the various on-board devices by providing high-level interfaces in form of services.

The SDK also allows the development of software for use on the ground. For example, the European Space Operations Centre (ESOC) in Darmstadt, Germany, is developing a project using the NMF SDK that aims at making a web-based generic Mission Control System that is able to connect to multiple apps.

This is only possible because of the standardised CCSDS Mission Operations services architecture. In the future, this tool will be used by the OPS-SAT experimenters to operate their app in space from a simple web browser at home or in the office.

Standardised, reusable and simple software is a very different vision from what exists today.

Apps in space

By shifting the software development approach to a low-risk activity focused on specific functionality rather than the traditional development of a complete system, smaller companies will be able to specialise in particular spacecraft functionalities and easily enter the space software arena by providing a reusable software product that could be used in many different spacecraft.

Nowadays, there is a high demand for app software developers to cope with the new generations of smartphones with more and more advanced processing capabilities and constant internet connectivity.

These developers do not know the implementation details of every single smartphone. Instead, they develop their apps against well-defined standard interfaces that are the same across most smartphones.

Smartphone apps always cover very specific functionalities, such as managing the camera or the contacts list. They are never intended to cover a large set of tasks. Extending this idea to the space domain would create a new set of space software developers focused on particular satellite's operations and functionalities - just as the Uber and Snapchat apps have very different purposes. A paradigm shift in space software. ■

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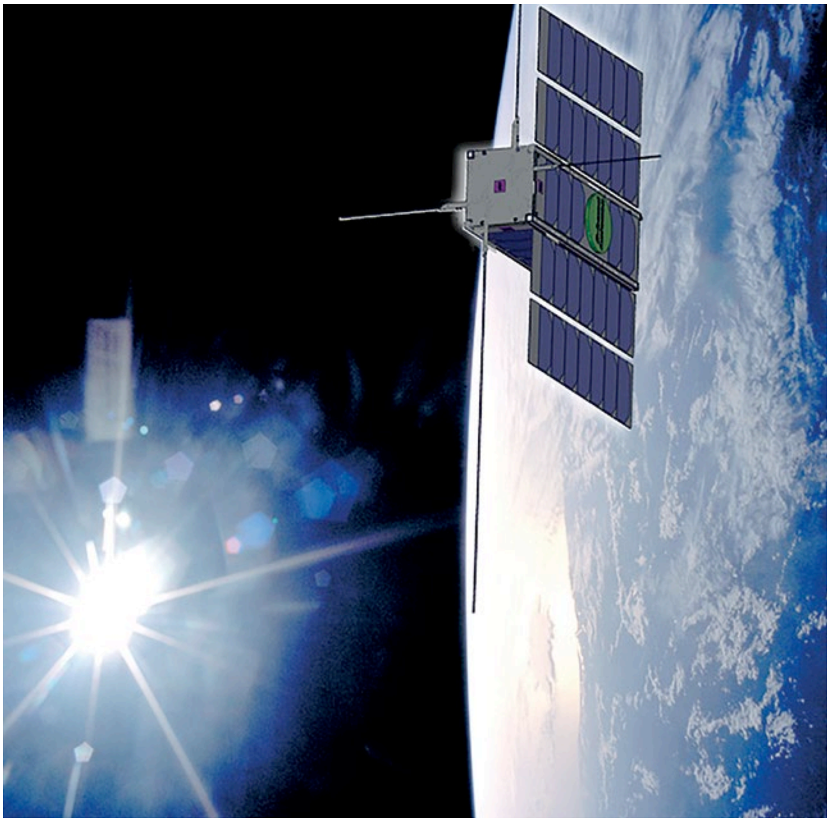

▲ ESA's OPS-SAT will test and validate new techniques in mission control and on-board systems. It will be operated by ESA's European Space Operations Centre as a test and validation resource for over 100 European industrial partners from 17 countries.

About the authors

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Smaller companies will be able to specialise on particular spacecraft functionalities and easily enter the space software arena

Jean-Yves Le Gall
President, CNES,
Paris, France

Our space future lies in innovation

A passionate advocate of space and astronautics, Jean-Yves Le Gall travels the globe tirelessly to promote the cause of astronautics in his roles as President of the French national space agency (CNES), Chair of the Council of the European Space Agency (ESA) and President of the International Astronautical Federation (IAF). Earlier in his career, whilst at the helm of Arianespace, he was the artisan of the technical procedures that delivered Ariane 5, Europe's most successful launcher to date. Here, in conversation with ROOM's Managing Editor, Clive Simpson, Mr Le Gall offers his unique personal perspective on the status and future direction of the global space industry.

What are the priorities of CNES?

CNES [Centre National d'Etudes Spatiales] is the historical lead player in Europe and plays a prominent role in ESA. Our priorities for the coming years were confirmed in December 2015 and are now applied across our five fields of activity - launchers, science, observation, communications and defence. Our forward-looking strategy is based around this.

We have a budget [2017] of €2.3 billion and out of this we pay about €900 million to ESA. In terms of what is driving the priorities for CNES and its future I think that we have three key points which, incidentally, probably also drive space activities worldwide.

It seems that wherever I am in the world space strategy tends to fall always into three parts. The first one is common to all parties and is related

Now we have an approach which is bottom up - we go to potential users, ask them what they need and we try to develop exactly that

International cooperation beyond 2030 will evolve around the journey to Mars

to innovation. A few years ago we used to say technology was the key driver but now it is much more than technology, it is innovation.

The second point - and we have a very cruel reminder about this with what happened in the Caribbean and United States in the autumn of 2017 - is our climate.

Climate change is a reality and the real reason for what happened is down to a strong increase in temperature. Usually the southern Atlantic at that time of the year is around 27 Celsius, but this autumn it was 31 and because of this a simple tropical storm becomes a hurricane.

So, the second major issue is climate and in that of course, France is leading the way with key programmes to limit the emissions of greenhouse gas, reduce carbon dioxide and monitor methane levels.

Our third priority is exploration - because exploration is the essence of space activity. When the first satellites were launched 60 years ago they allowed us to look at the universe and explore in new ways.

Today, these are the three foundation points - innovation, climate and exploration - and they form the backbone of our activities.

How do you see your role as head of the ESA Council?

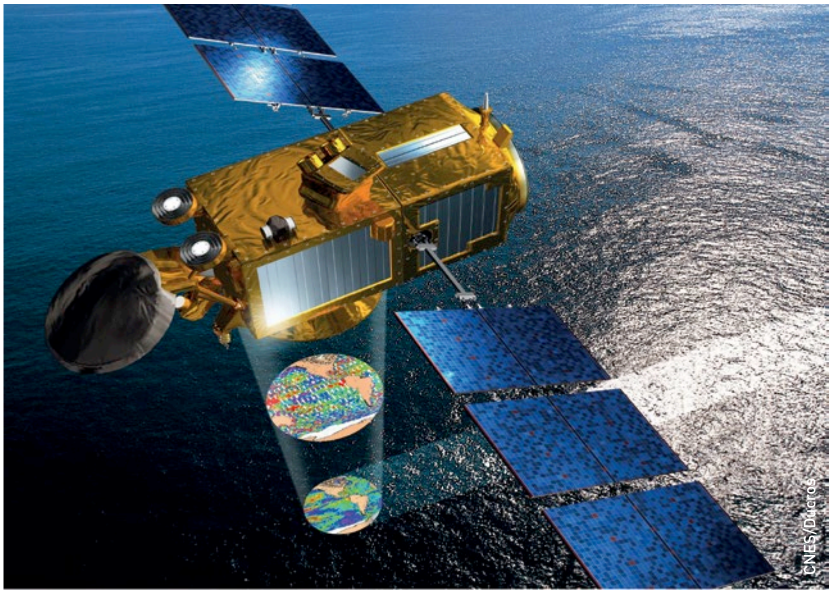
This role is very interesting at a time which is challenging for ESA because we have a number of key and exciting decisions ahead. It is also a challenging time because of what is happening worldwide and because we have many newcomers across the space segment - today we have 60 space agencies in the world, whereas a few years ago we had just six. As well as emerging countries, we are also witnessing the NewSpace revolution which is bringing with it new approaches, new methods and new players.

In respect of expanding global competition and commercialisation, do space agencies have to change?

Yes, and at CNES we have already changed. Our role is now to focus on innovation and to develop the space systems of the future alongside the global NewSpace trend fuelled by innovation and application miniaturisation. In 2017 our motto became 'Inventing the Future of Space' and this is exactly what we are doing. Today, industry does not have so much money to invest and so we are developing new systems and we are very proud of that. We have led a very strong transformation of CNES during this last year and we are going to continue.

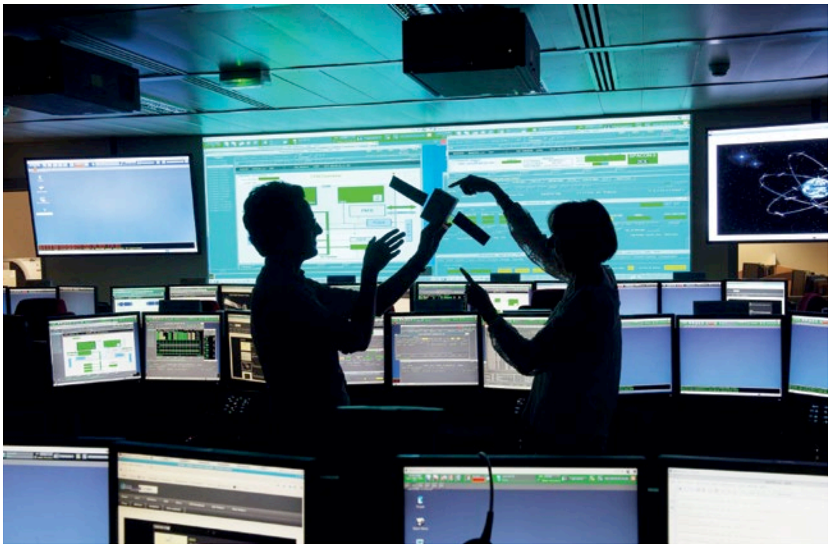
How is the approach to developing space systems evolving?

Today things are much more focused on applications. In fact, in the past, technology policy was driven by management policy and was very much top down, so it meant that we were first developing engineering and then inventing a space system. Only once the space systems were invented were we saying, "Hey guys, we invented the best space systems in the world, can you use it?'"



▲ Through CNES, France plays a key role on the international Jason -3 satellite launched in January 2016 to measure ocean surface topography. CNES headquarters in Paris are pictured below.

▲ Merlin satellite.



▲ Galileo mission control centre.

Now we have an approach which is bottom up - we go to potential users, ask them what do you need and we try to develop exactly what they need. This probably is the main difference between the top down and bottom up, and this is structuring the shape of CNES for the future.

This new policy encapsulates probably the two most important issues of space activity today - to connect and to observe. With the internet and the global goal of connecting some six billion people to high speed internet, it is clear that satellites are very useful for connectivity.

Space also plays a very significant role in Earth observation as well. When you speak about the Internet of Things, you need to have up to date and detailed maps of Earth and so on - and only satellites can do that.

Will 'Brexit' have an impact on European space?

The result of the United Kingdom referendum obviously raises a number of issues and no one can be sure how things will turn out. I firmly believe the UK will remain part of the European space effort through ESA but, of course, the UK will probably have to leave EU space programmes. I think there will eventually be new European space policies without the UK - maybe that is a pity but it will be a fact.

How do you react to entrepreneurs like Elon Musk of SpaceX and Jeff Bezos of Blue Origin?

It is clear that they have brought a revolution for space activities but with different approaches. Elon Musk is probably much more, let us say, 'business' oriented. Jeff Bezos invests a lot of money and doesn't speak publicly so much, though it is clear he also has a very, very exciting project. For Musk, I do not agree with all of what he says when he proposes to send a thousand people to Mars. But I observe that both he and Bezos have enjoyed significant successes so far. For Musk, in 2016 it was Mars, in 2017 it is the Moon - maybe in 2018 it will be the Earth.

Obviously they receive a lot of support from NASA, a lot of public money, but you cannot deny they have made impressive developments.

Does international cooperation have a future?

I think that the International Space Station [ISS] remains today the finest ever project of international cooperation in the technology arena. For the future I think international cooperation beyond 2030 will evolve around the journey to Mars.

It has been promoted and defined by NASA, and I think it is realistic because they speak about sending four to six people to Mars and then return them. They don't speak about sending 1,000 people on a one-way colonisation trip.

At CNES we've had good cooperation with the Russians, particularly on Soyuz which I am proud to have played a key role in during my tenure as head of Arianespace. There may, however, be less opportunities in the future because Russia now has some more issues on its domestic agenda.

China is very active in terms of space and of course I am sure that it is interested in joining the club of countries on the International Space Station. They have developed a space station, but it is very small. Of course, much will rest on politics but I am sure that in the next 10 years China will become more active in the international arena and I think that China will probably join us on the ISS.

I believe that in spite of some difficulties on security between the US and Russia we will continue to have cooperation on the ISS. With China, when things become easier, I think they will join the club of international space programmes.

What are the biggest challenges now facing the global space industry?

I see the global space industry as in a state of positive evolution not only because there are new applications, but also because there are projects and historical ESA programmes which are challenged by these new obligations.

Some people believe that geostationary satellites are perhaps becoming obsolete because of future large constellations. But the future of constellations it is not yet proven and geostationary satellites are doing pretty well.

So, it means that we have to be cautious because a lot of things are based on the developments of the past 60 years. Of course, they are not perfect but they exist and those who say that everything should change should be careful not to destroy everything because that might be a big mistake.

At CNES we have a technology support programme in place for industry because European manufacturers based in France are playing a key role supplying satellites for large constellations.

But there's a big debate about the role of constellations and geostationary satellites in delivering services such as broadband to the widest number of people. We're certainly helping to shape that debate and I don't want to take sides.

▲ French President Emmanuel Macron was welcomed to the Guiana Space Centre (CSG) in French Guiana at the end of October 2017 by Jean-Yves Le Gall, the CSG's Director Didier Faivre and other European space officials. Mr Macron was accompanied by Jean-Claude Juncker, President of the European Commission.

Looking further ahead, what do you see?

Just as our world is changing, the space world is changing too - often very, very quickly. When I started my term at CNES about five years ago many people thought national space agencies might disappear because of all these changes worldwide. But five years later we haven't disappeared. Quite the contrary, I would say that we are alive and kicking.

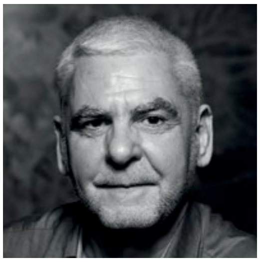
There is definitely a role for space agencies in the future of global space. Obviously we've gone from very few space agencies to something like 60, and a lot of them are very young. If I had advice for them, I would say the key is to work with experienced people and develop your skills because space is definitely the place to be. ■

◀ The CNES Taranis satellite, scheduled to be launched in 2019, will provide valuable data on transient luminous events (TLEs) in the upper atmosphere, variously called 'elves', 'sprites' and 'blue jets' which currently remain shrouded in mystery.

European centre shifts emphasis towards deep space missions

▲ The European Astronaut Centre in Cologne, Germany.

Future space exploration presents challenges for technology and human performance and ESA's European Astronaut Centre is evolving to meet future operational exploration scenarios. It is actively developing its research capabilities and, through a series of exciting initiatives, is working towards making the facility a test-bed for technologies that are important for future human space exploration missions.



Victor Demaria-Pesce
Senior Scientific Adviser, ESA/EAC, Cologne, Germany

The European Astronaut Centre (EAC), located in Cologne, Germany, was established in 1990 by the European Space Agency (ESA) and its Member States for the selection, training, medical support and flight assignments of the European astronaut corp. It has become the 'home' of European astronauts.

Human spaceflight is one of the key activities undertaken by ESA on behalf of its Member States and optimal health, as well as physical and technical training of astronauts, is crucial to the success of the human spaceflight programme.

The EAC 'Integrated Team' is a model for cooperation between ESA, Member States (those with specific competencies in human spaceflight) and industry teams; despite the different affiliations of the team members, they show extraordinary dedication to the common tasks.

EAC has unique training, medical operations and astronaut operations/support expertise in Europe. While currently focused on the International Space Station (ISS) programme, a large part of EAC's competencies is relevant for any future human spaceflight programme and its operational experience is a particular asset, having a heritage in spaceflight from earlier decades.

EAC is now also focused on future exploration beyond the ISS and low Earth orbit (LEO) operations, and is actively developing collaborative programmes related to deep space exploration missions.

Fit for spaceflight

EAC's Space Medicine Office aims to minimise risks to the health of astronauts throughout their professional careers.

The office is tasked with ensuring astronauts are physically fit for spaceflight and keeping them healthy before, during and after space missions. It also develops programmes for preventive health as well as human behaviour and performance, and provides medical training and support to astronauts,

Its activities can include medical certification during the pre-flight mission, or protecting work/rest schedules and monitoring sleep and exercise programmes through inflight activities, as well as taking care of primary care on landing, the co-ordination of rehabilitation team and clinical treatments/assessments.

Although the medical practice of the office has traditionally been ISS-oriented, it is now focusing on exploration with a strong foresight activity on technology and processes that will be needed for exploration missions.

Astronaut training

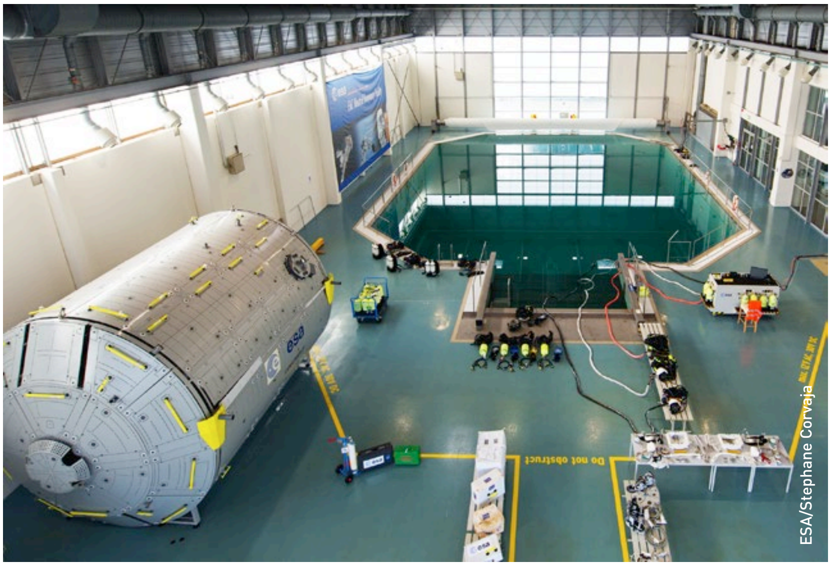
The Astronaut Training division has the responsibility for providing training to all ISS astronauts and cosmonauts in relation to ESA contributions to the ISS programme. This includes the analysis of astronaut tasks and definition of training objectives, considering the planning and scheduling of their tasks and flight assignments.

The division is also in charge of the preparation and implementation of training programmes for space missions to the ISS, developing the curricula, courses and lessons, and defining the criteria for selection, training and certification of instructors.

This involves the definition of the requirements for training facilities: the training hall, the Columbus training facilities and the Neutral Buoyancy Facilities, as well as their maintenance.

In order to maintain its established expertise and to prepare for the future, EAC also:

- continuously ensures the high quality of its services and improves its underlying skills and tools by considering technological and medical progress (e.g. virtual reality training technologies, new rehabilitation techniques) as well as lessons learned from the astronauts
- acquires new competencies related to astronaut operations, training and space medicine in order to achieve a more independent and stronger European position in these areas
- performs the 'Direct Return' of European astronauts (i.e. return of ESA astronauts to EAC/Cologne immediately after landing in Kazakhstan), which also enhances the visibility of ESA's human spaceflight programme to the general public
- establishes EAC as 'Crew Operations Support' (ECOS): a cross-divisional team of operations experts integrating and testing ISS operations hardware in domains of crew operations or astronaut health, including both in-house and external developments
- concentrates on ESA activities that are closely related to the performance and operational tasks of astronauts that benefit from synergies with EAC expertise and increasing overall ESA efficiency. A team of EAC operators/instructors and astronauts support systematic design reviews and operations readiness reviews of hardware that will later be operated by ESA astronauts
- pursues and further develops complementary training tools which offers additional training opportunities and provides a platform for cooperative astronaut training activities with international partners.



▲ EAC's Neutral Buoyancy Facility hall includes a water tank, mock-ups, and scuba diving equipment.

Future space exploration

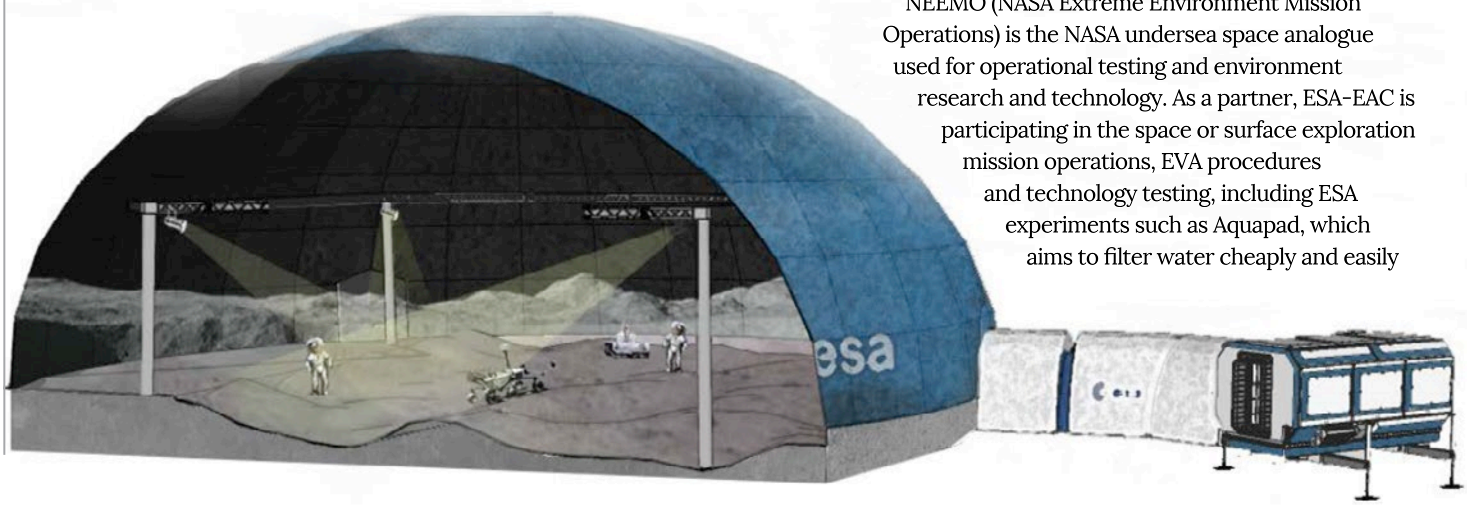
Congruent with international exploration roadmaps, EAC is evolving for the transition from

Optimal health, as well as physical and technical training of astronauts, is crucial to the success of human spaceflight

▲ Italian astronaut Luca Parmitano, during EVA pre-familiarisation training in ESA's Neutral Buoyancy Facility.

▲ Astronaut Tim Peake, from the UK, preparing for EVA training.

▼ Artist's impression of the LUNA European Exploration Laboratory showing the fully enclosed dome structure and the self-deployable habitat for extreme environments (SHEE).



ISS exploitation towards future deep space human exploration programmes and operational scenarios.

For example, it is expanding its training and medical skills and tools with respect to the requirements of future human exploration missions, such as developing skills and tools that are relevant for more autonomous astronaut operations and inflight training; surface EVA (extravehicular activity) operational concepts; and exploration-related medical aspects such as space radiation, psychological aspects, medical autonomy, telemedicine. These are domains that will occur in exploration scenarios beyond LEO.

A number of initiatives have been undertaken towards this objective, aimed at demonstrating important technologies at EAC, bridging the gap between science and operations, and looking for simultaneous Earth/Space applications.

Analogues have been developed to provide similar physical conditions to those that would be experienced in extreme space. These offer a wide spectrum of possibilities for utilisation for multiple operations and technology testing, training and biomedical research.

Underwater space

During an EVA, astronauts work in a stressful environment performing complex tasks, so a high level of training is one of the keys for success. The best environment for EVA training on Earth is underwater, because it provides a neutral buoyancy, simulating microgravity, and so EAC built the Neutral Buoyancy Facility (NBF) which includes a water tank, mock-ups and scuba diving equipment.

EAC is currently studying an infrastructure evolution of the NBF in order to develop EVA simulation capabilities in a Moon 1/6 G simulated gravity. In the near future, it will be possible to define exploration objectives and identify typical exploration tasks on the Moon.

NEEMO (NASA Extreme Environment Mission Operations) is the NASA undersea space analogue used for operational testing and environment research and technology. As a partner, ESA-EAC is participating in the space or surface exploration mission operations, EVA procedures and technology testing, including ESA experiments such as Aquapad, which aims to filter water cheaply and easily using a new type of biomimetic membrane that copies nature, and Nutritional Assessment, examining nutrition for astronauts in extreme environments.

CAVES (Cooperative Adventure for Valuing and Exercising human behaviour and performance Skills) is a scientific exploration mission deep underground in the Sa Grutta caves of Sardinia, Italy. It is aimed at training astronauts in an ISS-representative environment, bringing a multi-cultural crew of astronauts face-to-face with situations and stresses very similar to spaceflight. Even beyond ISS, the concept of this analogue allows the improvement of operations effectiveness and safety.

Complementing CAVES, Pangaea is a field geology and geo-microbiology training course focusing on developing knowledge and skills for planetary geology and astrobiology so that astronauts can be effective partners to scientists and engineers for the definition of geological robotic/human exploration scenarios and operations.

Artificial lunar analogue

The LUNA European Exploration Laboratory is a lunar analogue test facility for the development and validation of lunar surface operations and part of ongoing developments to address future exploration challenges. It is being built in collaboration with the German Aerospace Centre (DLR) in Cologne with a half-spherical fully-enclosed dome structure housing the testbed and a habitation element.

The structure will have a diameter of 34 m and the effective surface operations area is projected to be approximately 900 m^2, including experiment preparation areas. The testbed will comprise a lunar regolith simulant sourced from the local Eifel region volcanic and basalt sources, which provides a satisfactory mechanical and compositional simulant.

The simulant testbed area is planned to be 50 cm in depth, although the surface terrain and source simulant is expected to be reconfigurable, depending on specific experimental requirements. Modular scaffolding will be placed within the facility to allow for dynamic lighting conditions.

LUNA will have a configurable communication structure (e.g. implementation of a delay tolerant network, wired and wireless protocols) and will integrate with the existing EAC control centres. Access to the facility will be provided via two large opening doors to facilitate the entry of large payloads.

This surface analogue will primarily support ESA activities in the domain of rover simulations such as within the framework of METERON (Multi-Purpose End-To-End Robotic Operations Network), human-machine interface testing and Spaceship EAC activities (see below) e.g. demonstration/validation of In Situ Resource Utilization (ISRU) tools.

LUNA is also being developed to address the need within the EU to provide a lunar analogue facility that can be readily made available to research groups and exploration-focused stakeholders, while benefiting from the operational expertise present within EAC and the larger DLR campus. The facility is expected to be operational by May 2018.

Spaceship EAC

This project is aimed at investigating innovative technological and operational concepts in support of ESA's exploration strategy which, in accordance with the Global Exploration Roadmap, foresees a sequence of increasingly complex missions to cislunar space and the lunar surface.

Initial robotic exploration missions will be followed by robotic/human cooperation (robots on the surface controlled by astronauts in orbit) and eventually by human surface missions. Spaceship EAC utilises the operational experience of EAC with the goal of developing operational concepts and low technology readiness level (TRL) technologies in support of lunar human exploration and habitation scenarios.

Moreover, Spaceship EAC has facilitated the creation of an expanding European network of universities and research facilities cooperating on relevant topics. EAC is now a participant in ESA's Networking/Partnering Initiative (NPI) and welcomes proposals from universities and research organizations in ESA Member States for doctoral and post-doctoral research in technical domains relevant to the Spaceship EAC project such as in-situ resource utilisation ('living off the land'), energy production and storage, materials and additive manufacturing, water processing and waste management, simulation and virtual reality, robotics and human-robotic interaction, and life support and habitability.

Taken together these initiatives improve the skills and facilities already present at EAC, building upon the unique assets and expertise to make EAC the centre within ESA for human exploration operations and vital space medicine activities. ■

About the author

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The author thanks his colleagues Frank De Winne, A. Diekmann, G. Weerts and A. Cowley for their invaluable contribution to this article.

EAC initiatives are aimed at bridging the gap between science and operations, and looking for simultaneous Earth/Space applications

The best environment for extravehicular activity (EVA) training is underwater because it provides a neutral buoyancy, simulating microgravity

NASA/Made In Space

▶ Testing of the Made In Space 3D printer involved 400-plus parabolas of microgravity test flights.

Enabling private sector success - a space generation perspective

As we move towards better technology and bigger budgets for space activities, the commercial space industry has an opportunity to grow and develop into something more than just a contractor to governments. The private sector is booming at state and regional levels as a result of public-private partnerships and the beginnings of privately financed activity - but on the international stage it struggles to find a voice because, in no small part, nation-states still dominate international relations and law. If the private space sector is to succeed, it will need to foster dialogue with governments which, in turn, will need to find the balance between supporting industry with good policy and avoiding excessive regulation.

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The United States' private space sector is robust and flourishing, not only in its most visible components, with launch service providers like SpaceX and Orbital ATK, but in all facets of space exploration and utilisation.

This is largely due to the approach taken by the US government to support and regulate private investment in space under the Commercial Space Launch Competitiveness Act, wherein launch standards are based on 'voluntary industry consensus standards'. Progress reports are being submitted to Congress every 30 months until December 2021 when findings will be revisited and fed into future US space policy.

Many private companies in the US rely on government support in the form of grants or

Commercial space has the opportunity to grow and develop into something more than just a contractor to governments

contracts and the Act demonstrates a willingness by the US government to allow innovation in the private sector. In particular, NASA is dedicated to entrepreneurship in the private sector through a competitive grants system.

It'ws Small Business Innovation Research and Small Business Technology Transfer (SBIR/STTR) programmes recently picked 19 proposals from small business and research institutes that total US$14.3 million in awards.

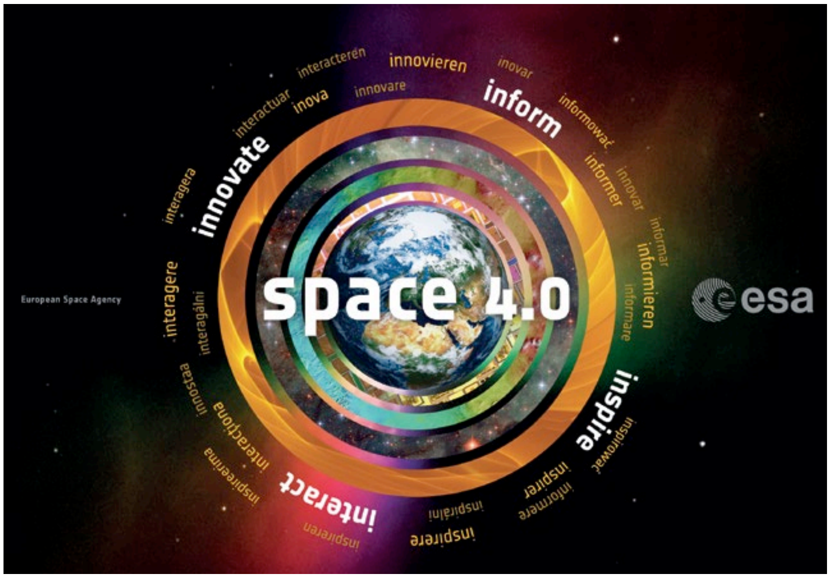
These awards are incentives for growth in entrepreneurship in the research and development of space technologies. NASA is incentivising the private sector in ways that will create more innovation that will eventually be self-sustaining. The 2016 Economic Impact Report for the SBIR and STTR programmes showed a total of $180.57 million in funds that supported the creation of approximately 2,175 American jobs, and $474.46 million in GDP. Contracts for launch and cargo services, as well as vehicle development, are also a significant investment in the private sector.

The US Government itself is still a big obstacle when it comes to industry stability, because policy changes that occur between different presidential administrations can make significant financial investment into long-term projects risky.

Challenges range from shifting focus of policy goals to changes in funding structures or availability of funds for the private sector. A well-known example is the shift of interest between the Moon, asteroid exploration and Mars, and the effect of this on NASA's Space Launch System (SLS).

Former President George W Bush introduced a plan to create a new booster to return the US to the Moon and then to Mars. Barack Obama then scrapped this programme before reinstating it with a new focus on Mars and no plans for a return to the surface of the Moon. Constantly changing goals significantly impede generational projects, limiting the chance for the private sector to evolve and grow with a project that may be cut or rearranged with every change of administration.

As the private sector is becoming increasingly entangled in the civil and defence sectors however, there is growing interest from the US executive and legislative branches in the issues. The new Trump administration has revived the



National Space Council to address rising questions in space policy, such as the continued and future role of the private sector in civil and defence space and the next destination for US space exploration.

A plan for Europe

A European Space Agency (ESA) Council meeting in December 2016 focused on 'Space 4.0 for a united space in Europe', ESA's main objective for the 21st century.

The Joint Statement on Shared Vision and Goals for the Future of European Space, made by ESA and the European Union (EU) on 26 October 2016, specified the following three goals:

- maximise the integration of space into European society and economy, by extending the use of space technologies and applications to support public policies, providing effective solutions to the big societal challenges faced by Europe and the world;
- foster a globally competitive European space sector by supporting research, innovation, entrepreneurship for growth and jobs, seizing larger shares of global markets;
- and ensure European autonomy in accessing and using space in a safe and secure environment by consolidating and protecting its infrastructures; by which the EU and ESA emphasise their intention to reinforce their cooperation in the future, as foreseen in the ESA-EU Framework Agreement of 2004 and taking into account the ESA Convention, in particular Articles II and V, and the Lisbon Treaty, in particular Articles 4.3 and 189.

Karina Perez
Space Law & Policy Project Group Member, SGAC; Public Policy & Management Student, California State University, Northridge, USA

Anne-Sophie Martin
Space Law & Policy Project Group Member, SGAC; PhD Candidate, Sapienza - University of Rome

▲ ESA business incubation centres across Europe.

It is of significant importance to strengthen cooperation between ESA and the EU and its Member States' agencies in order to achieve common goals and programmes for the benefit of European citizens. It is important to note that ESA is not an EU agency but that they do work in partnership, notably in the space sector.

Uninterrupted development

Furthermore, the aim is to ensure a seamless chain of innovation, enabling more cooperation between academic institutions and research establishments together with industry and end users, to allow for uninterrupted and rapid development from idea to product or service, and sustain competitiveness in an efficient manner; opening up to new partnerships including with actors in sectors other than space, attracting investments from the private sectors, and in particular the digital sector; implementing complementary new funding schemes while also relying on commercial initiatives for dedicated activities.

Education and technology transfer are important to this process and a programme initiated by ESA's Technology Transfer Programme Office supports business incubation by providing technical expertise and business development support to more than 130 companies every year in Europe, and more than 400 start-up companies have received support to date, and spin-in from developments in areas outside space, which contribute to growth and competitiveness, create new jobs and promote innovation.

We know that space serves societal needs, responds to European and global challenges and offers opportunities, notably those related to the attainment of sustainable development goals and socioeconomic growth, mitigation of geopolitical risks, security, science, knowledge, climate change and a digital Europe. The ESA Digital Agenda for Space [ESA/C(2016)108] responds to the challenges of a digital Europe, notably by providing improved access to space data and ESA's technical knowledge.

Constantly changing goals significantly impede generational projects, limiting the chance for the private sector to evolve and grow

Long-term policy

ESA is elaborating and implementing a long-term European space policy in order to develop new concepts for international exploration activities, encompassing novel cooperation opportunities open to all nations and industrial actors by reinforcing its capabilities to foster innovative and disruptive ideas, reorienting dedicated activities within ESA's Basic Activities towards these objectives, in accordance with Article II of its Convention.

Additionally, to optimise ESA's industrial policy and balance the geographical distribution of industrial work, it is necessary to foster competition, innovation and the development of the European industrial sector among all Member States. It is also necessary to facilitate the entry of new economic actors, promote public-private partnership schemes that include the sharing of risks, and integrate its latest Member States. To do so, the market has to support private investment and entrepreneurship, in particular through start-ups and small and medium-sized enterprises (SMEs), and carry out the SME-friendly policy adopted by the Industrial Policy Committee (IPC) so as to favour their contribution to the success of ESA programmes, using in particular the Observatory of Critical Countries (OCC) established by the IPC and the internal mandatory activities steering committee.

The revision of the 2007 Launchers Exploitation Declaration for the exploitation phase of Ariane 6, Vega C and their evolutions will be applicable for a period running until the end of 2035; additionally, the Guiana Space Centre agreement, adopted by France and ESA, has been extended until the end of 2021.

The future demands a robust space economy that can flourish and grow as the technology advances

Public-private space sector

Based on the positive ways in which Europe and the US are working with the private sector in space, progress is being made that facilitates partnerships for the benefit of all stakeholders that can be used as a model in other states or regions in the future. That being said, there are aspects that could be further developed as the private sector continues to grow and more commercial space actors enter the field.

Economic stability is a key factor for the success of private stakeholders in space activities. Overall, the future demands a robust space economy that can flourish and grow as technology advances and the field continues to include more stakeholders.

From a next generation perspective, a few specific elements could encourage growth and prosperity in the space industry. States could consider a single point of contact, if not already in place, (such as the revitalised National Space Council in the US), to handle regulatory issues that arise within the public-private space sector. A continued healthy relationship between the space and aviation sectors, including at the international level through the International Civil Aviation Organization (ICAO) and the United Nations Office of Outer Space Affairs (UNOOSA) is also advisable. Through this relationship, there are already key issues that are being addressed and considered.

Finally, at the 2017 ICAO/UNOOSA Aerospace Symposium, the general points of interest for the commercial space sector - and within the space industry overall - were safety, transparency, harmonisation, and cooperation. These components are not just necessary between aviation and space, but also between the governmental and private actors in space, as they will encourage supportive regulations that allow the commercial industry to flourish while keeping the interests of States in mind. ■

About the authors

Lauren Napier has a BS in Communications and a MA in International Relations. Originally from the US, she has spent the past seven years living in Europe. She has been a member of SGAC since 2013 and has served as a co-lead for the Space Law and Policy Project Group since 2015. Outside of SGAC Lauren has held various positions of leadership in communications, capacity building, and event management.

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Anne-Sophie Martin is pursuing a PhD in Space Law at the University of Rome. She graduated in 2010 from the University of Paris-Sud in the Master Droit des activités spatiales et des télécommunications. Previously, she worked at the Centre National d'Etudes Spatiales (CNES) in Toulouse, France, at the European Commission in Brussels and in Thales Alenia Space in France and in Italy.

Space Generation Advisory Council

ROOM offers members of the Space Generation Advisory Council (SGAC) a forum in which to provide their insight and inputs on various space topics, from technical projects to regional perspectives.

SGAC is an international non-profit, non-governmental organisation, formed out of the Vienna Declaration, adopted by the Third United Nations Conference on the Exploration and Peaceful Uses of Outer Space (UNI-SPACE III) in 1990, and recognising the need to engage with the next generation of space leaders and reflect the voice of students and young professionals in space policy.

Since then, SGAC has grown to support students and young professionals, not only organising global, regional and national events and providing a medium for them to share their insights on space policy, but also enabling their professional development through volunteer opportunities, scholarships and competitions to attend conferences and events.

▼ Shifting policy interests between the Moon, asteroid exploration and Mars, has had its effect on NASA's Space Launch System (SLS).

James Vaughan

Asgardia-1 opens door to humanity's space future

▲ Liftoff off the OA-8 Antares-Cygnus cargo carrier with the Asgardia-1 satellite.

The Asgardia space nation has embarked on its maiden flight, creating the first independent outer space territory in world history. The historic beginning of a new era in human settlement of the universe was marked by the Asgardia-1 satellite with the signal 'Hello Igor' on its activation in Earth orbit. The satellite carries 0.5 TB of data storage comprising the nation's Constitution, national symbols and data uploaded by citizens.

Lena De Winne
NGO Asgardia, Vienna, Austria

Asgardia-1 was launched on 12 November 2017 from NASA's Wallops Flight Facility in Virginia as a part of the OA-8 Antares-Cygnus mission to the International Space Station (ISS) and deployed after Cygnus completed its mission at the ISS and was placed into a higher orbit.

Speaking from the launch site, Igor Ashurbeyli, Asgardia's Head of Nation, said: "Asgardia-1 is the only one in the whole world which represents a new territory. As promised, and exactly 13 months after its founding, Asgardia is now in space. I believe that Asgardia-1 is the first step towards unifying humanity."

Asgardia currently has more than 150,000 citizens in 215 Earthly countries, including 175 member states of the United Nations. Asgardians have confirmed the new calendar and voted on the flag, anthem and coat of arms, and adopted the Constitution. In addition, Asgardia's cryptocurrency Solar,SOL has been registered with the European Union's (EU) Intellectual Property Office.

Dr Ashurbeyli used the opportunity of attending the launch to meet with policy experts in Washington DC, discussing the next steps for Asgardia on its journey towards a full member of the United Nations (UN).

Asgardia's first parliamentary elections are being held in the first quarter of 2018 and, for the first time in history, elections to a parliament are based on language rather than borders. There will be a total of 150 MPs and the parliament will select and approve the government, supreme court and supreme space council, resulting in the inauguration of the first Head of Nation around the middle of 2018.

According to Dr Ram Jakhu, Associate Professor at McGill University in Montreal, the elections offer citizens a chance to play their role in shaping the new nation.

"The most exciting aspect of the great Asgardian development is its commitment to trans-national democracy," he said. "My hope is that the parliament will be made up of people from all different backgrounds across the world. Together, they will be the engine that drives Asgardia forward into the next space age."

Russian and Soviet rocket scientist and pioneer of astronautic theory Konstantin Tsiolkovsky is well remembered for his statement, "Earth is the cradle of humanity, but one cannot remain in the cradle forever", a sentiment that is today shared by many eminent scientists.

It is also one of the reasons why wealthy individuals - some with the support of public funding - and space agencies are developing powerful new rockets to send explorers and would-be off-world settlers to the Moon and Mars. In contrast Asgardia is completely independent and equally available to all.

At the same time, it stands to reason that in order to move forward as a species we must do so together as a unified humanity not limited or restricted by borders, religion, wealth or language - a notion that is exemplified by the philosophy of Asgardia.

Asgardia-1 is the only satellite in the world which represents a new territory, even though it may resemble other satellites orbiting Earth. It is unique because it is laying a foundation for the permanent residence of humanity in space.

Asgardia is developing its space territory and future settlements fully within the scope of the boundaries of exisiting legislation, such as the Outer Space Treaty which was ratified in 1967.

Freedom of exploration and the use of outer space is not only allowed by the Treaty (and the 1963 Declaration of Legal Principles Governing the Activities of States in the Exploration and Uses of Outer Space) but has become a fundamental principle of international law applicable to all states.

Asgardia's first satellite launch means the nation is exercising its freedom in outer space whilst citizens and legal experts continue to manage its growth and development.

As part of this, Asgardia is in the process of running parliamentary elections for its more than 150,000 and steadily growing number of citizens as they undertake the task of consolidating the leadership structure.

During the first half of 2018, 150 MPs will be selected (on the basis of the language selected by each voter during their registration in Asgardia), to take on the responsibility of leading the nation and setting its future course by adopting laws, calling referenda and appointing ministers and justices.

▲ Dr Igor Ashurbeyli at the launch of Asgardia-1.

To paraphrase world famous astronaut Neil Armstrong, the first person to walk on the Moon, the launch of Asgardia-1 can be seen as a first small step leading to another giant leap forward for humankind.

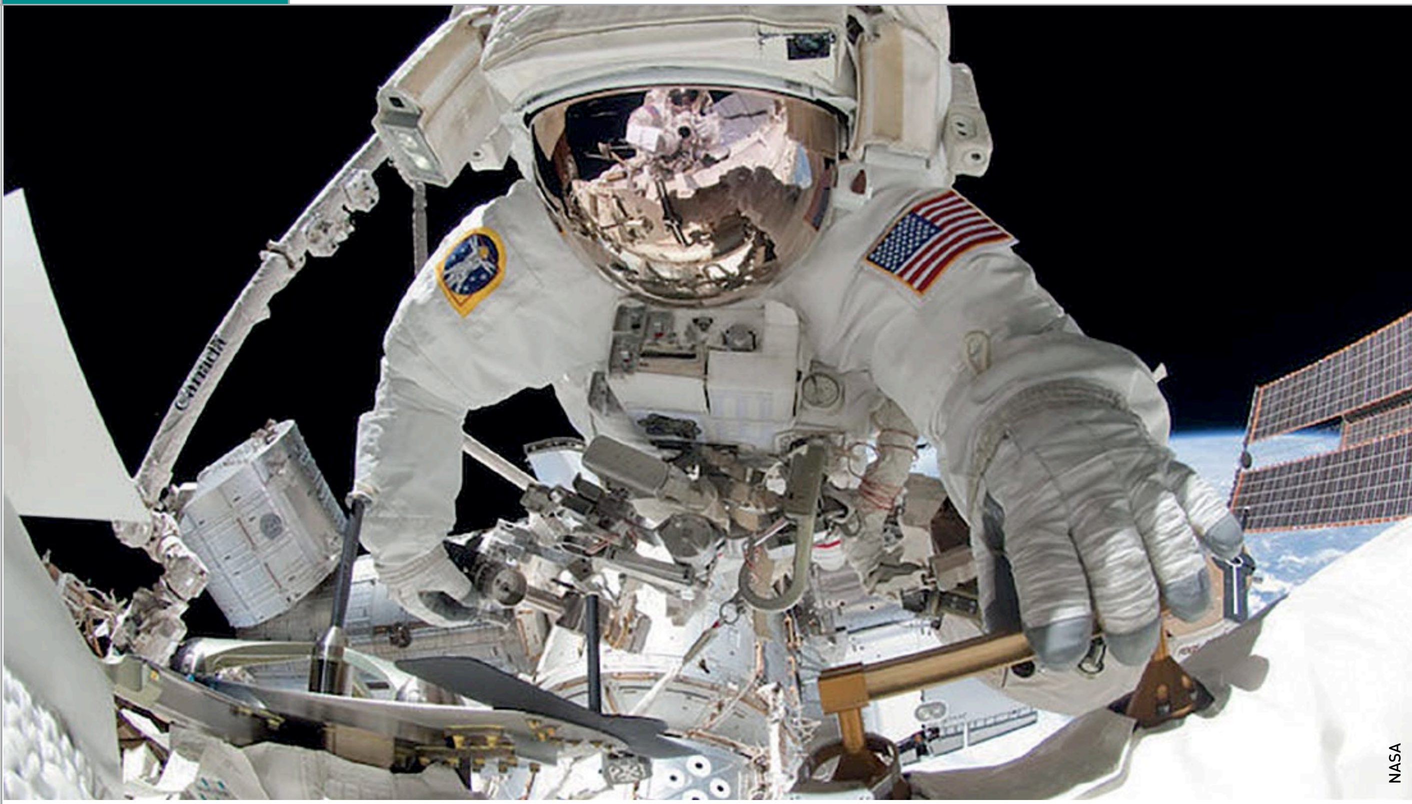
Much has changed since Armstrong first stepped on the Moon in 1969 when the magnitude of his achievement resonated throughout the world - history may one day recognise the launch of Asgardia-1 in similar terms, marking the creation of the first nano territory in space and leading to a new era for humanity.

Following in those famous footsteps, Asgardia plans to create a network of satellites to help protect Earth against asteroids, solar flares, man-made space debris and other space hazards. These will be the precursor to Dr Ashurbeyli's ultimate goal of creating permanent Asgardia settlements both in orbit and on the Moon.

Asgardia's approach is completely different because, instead of representing the inhabitants of one particular country or a slim cross-section of wealthy nations, its population already comprises a unique mix of people from around the globe who share a common vision that humanity is destined for greater things. ■

▼ The Asgardia-1 satellite prior to its launch.

Acknowledgement
Special thanks to Dr Ram Jakhu at McGill University for his assistance with this article.



NASA

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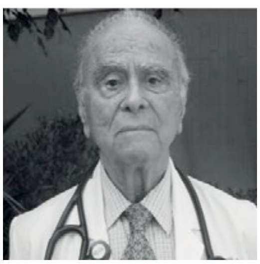

Jorge Kuri
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Zero gravity and the human heart

Space cardiology is of the utmost importance in space medical studies and in this article Mexico's father of space medicine Ramiro Iglesias and cardiologist Jorge Kuri provide an overview of the human cardiovascular system and look at how 'normal' cardiology on Earth differs substantially from what becomes 'normal' in space.

During extended flights in Earth orbit, on an interplanetary trajectory or in orbits around other planets where normal gravitational forces disappear, the body enters a state of weightlessness or zero-g, allowing astronauts and objects to float freely within the confines of their spacecraft.

Modifications and changes that occur to the cardiovascular system under these conditions are an important part of an astronaut's physical adaptation process to living in an environment so different to that of Earth.

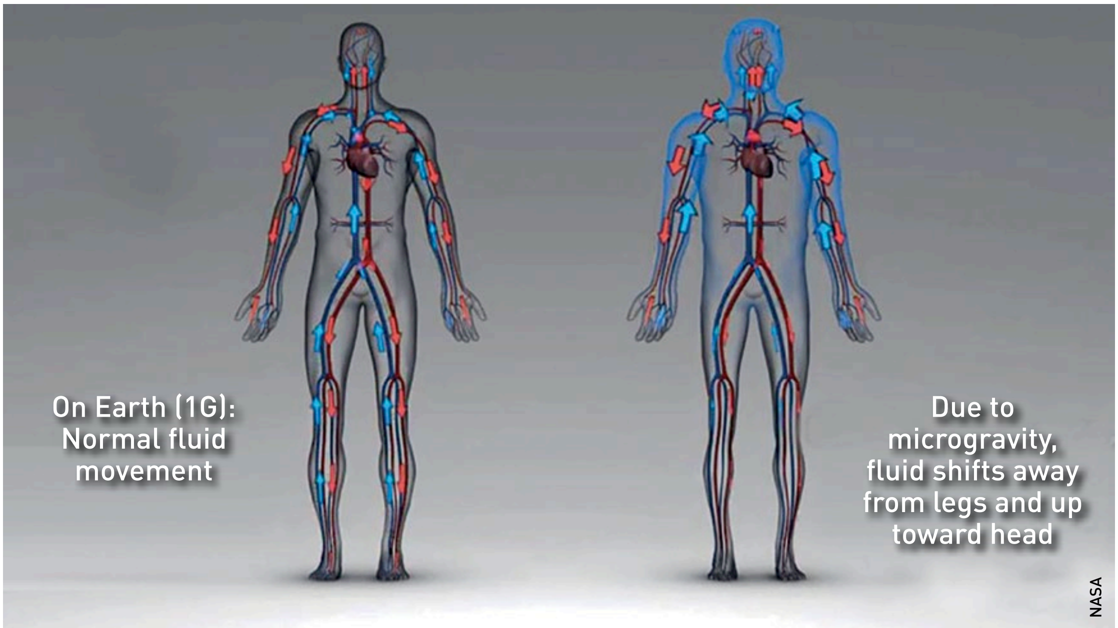
As the body adapts to the physiological challenges associated with living under the extreme environmental conditions in a zero-g environment the cardiovascular system adjusts itself accordingly.

The significant functional, anatomical and pathological changes experienced by an astronaut's cardiovascular system in microgravity provide vast amounts of valuable data about the physiological conditions of an astronaut at any given time.

During spaceflight the major changes that occur in the physiology of the cardiovascular system include:

Migration of fluids - on the first three days of any space mission there is a significant migration of fluids (blood, lymph, interstitial fluid) from the lower extremities to the upper regions of the body and these fluids accumulate in the chest, neck and head.

In this first stage the heart receives a greater amount of blood, heart cavities dilate and the



◀ In microgravity fluid shifts to the upper parts of the body.

heart increases its size, pumping more blood and increasing cardiac output and heartbeat volume.

A second stage begins typically on the fourth day of a mission and is characterised by progressive and imperceptible changes for up to six weeks. Then, from that point onwards, there is a complete adaptation of the cardiovascular system to microgravity.

Fluid accumulation in the upper parts of the body - as a result of the displacement of liquids to the cephalic regions, there is now more liquid per tissue unit in those areas of the body, which is evidenced by facial swelling, dilated veins on the forehead, neck and upper limbs, thinning of the lower limbs and decreased arterial pulse in the lower extremities.

Blood decrease - during the early weeks of a space mission the total amount of blood in the body decreases by about one litre. This is because the volume sensors in the chest and neck interpret the accumulation of fluids in those regions as an 'excess' of the intravascular volume and activate compensatory mechanisms which result in a reduction of the total amount of blood.

Circulation congestion - studies performed on astronauts working onboard the Skylab space station in the 1970s showed that the amount of blood inside the chest rises by about 800 ml. Ventilation, blood perfusion and pulmonary arterial pressure have no regional differences and the value of each of these parameters is the same throughout the lungs; the alveolar area expands and gas exchange improves in the absence of gravity.

Blood pressure - in space, when gravitational attraction is suppressed, regional differences in blood pressure and venous pressure as is normal on Earth disappear, meaning the same figures are recorded anywhere in the body.

On Earth, and in orthostatism (an erect standing position of the body), the mean arterial pressure is 70 mm Hg in the brain, 100 at heart level and 200 mm Hg at foot level whereas in orbit the value is the same throughout the body. Venous pressure on Earth is -10 mm Hg in the brain, zero at heart level and 190 mm Hg at foot level. In microgravity it is uniformly stabilised between 3-5 mm Hg.

Thorax 'remodelling' - another significant change on the human body caused by the zero-g environment is the remodelling of the thorax

During the first three days of the mission there is a significant migration of fluids (blood, lymph, interstitial fluid) from the lower extremities to the upper regions of the body

▼ Members of the Expedition 27 ISS crew mark the 50th anniversary of manned spaceflight on 12 April 2011 (Yuri's Night). Most of the crew display some degree of facial oedema or 'puffy face syndrome'.

▶ Canadian astronaut Chris Hadfield showing signs of venous dilation in the face, neck and forearms.

▶ Right: Chris Hadfield in an astronaut G-Suit, which squeezes blood out of the legs and abdomen into the head and upper body. Microgravity causes decreased arterial pulse in the lower limbs.

▶ Far right: Astronauts experience a decrease of total blood volume (± 1litre).

where the diaphragm is elevated by 5 to 6 cm. The ribcage becomes shorter and wider by lifting the diaphragm and increasing the anteroposterior diameter meaning the intercostal spaces become wider and the alveolar surface expands.

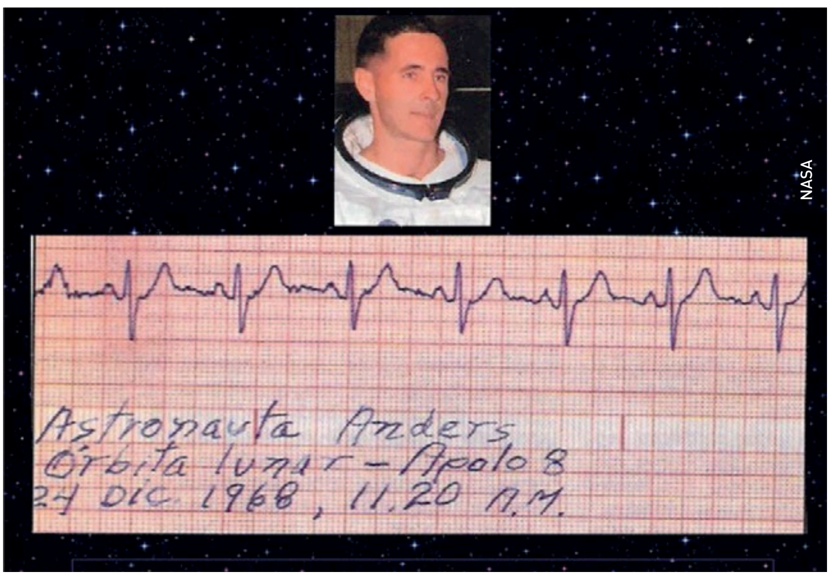
Space data

Clinical examination of astronauts' 'in space' cardiovascular system data has lead to a number of key observations, including facial and eyelid oedema; conjunctival hyperaemia; redness of the face; congestion of the retinal circulation; dilation of the veins in the forehead, neck and upper limbs; difficulty in palpating the apex of the heart which deviates to the upper left side.

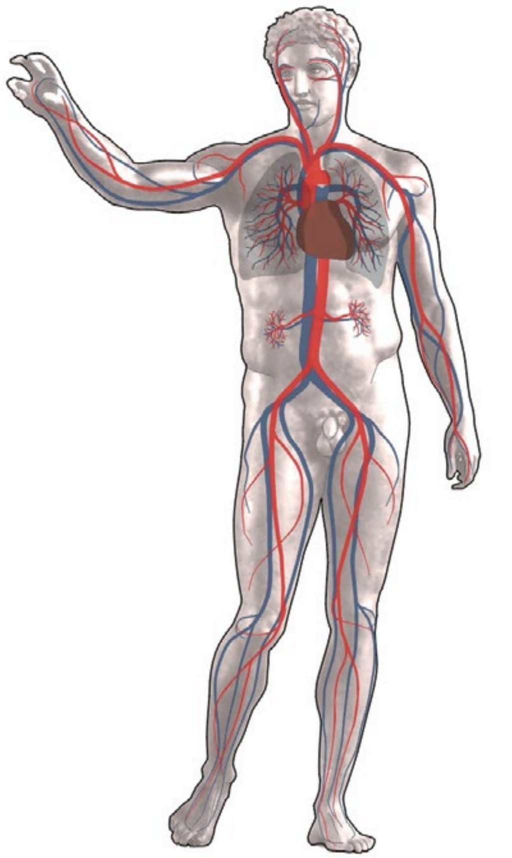
In addition, heart rate tends to be low during sleep (40 beats per minute in sinus rhythm has been recorded); blood pressure is equal in the upper and lower limbs; the diaphragm is upwardly displaced 5 to 6 cm; the thorax becomes cylindrical or 'barrel-like'; the liver area is moved upward; and arterial pulse decreases in amplitude on the pelvic limbs.

Laboratory studies have also provided us with the following information:

- When the cardiovascular system is adapted to weightlessness the total blood volume, cardiac output, heartbeat volume and heart size decrease between 15 - 20 percent.
- The thorax becomes shorter and wider, intercostal spaces become broader and the anteroposterior diameter increases.
- Central venous pressure, contrary to what has been hypothetically assumed, is not high, it is between 3 and 5 mm Hg (figures obtained by right heart catheterisation).
- Haematocrit (ratio of volume of red blood cells to total volume of blood) increases slightly.
- Electrocardiogram suggests vagotonia (overexcitement of vagus nerve causing slowing of the heart rate, fainting, etc).
- Doppler study shows decreased arterial flow in the lower limbs (up to 30 percent).
- Intrathoracic blood volume is increased (800 ml on average).



▼ If he had been on Earth, the slow heart rate on the ECG of Apollo 8 astronaut, Bill Anders, would have suggested vagotonia.



- Perfusion, ventilation and pulmonary blood pressure have uniform values throughout the lungs.
- Pulmonary vasculature is increased and evenly distributed.

Interpreting data

The data obtained in a comprehensive examination of the cardiovascular system in zero-g are different from those obtained on Earth. Assessed on an 'Earth cardiology' basis, the data would indicate multiple pathologies but astronauts experience no such problems; the data are normal in an outer space environment and are in accordance with a process of adaptation to zero-g.

Due to the adaptation process of the cardiovascular system during spaceflight, comprehensive examination of the heart-lung system in space offers very different data to that obtained from examination on Earth. Each of these data are normal under zero-g conditions but when assessed on a 'terrestrial cardiology' basis would be indicative of diverse cardiovascular and pulmonary diseases.

The adaptive changes that happen in the cardiovascular system in space are not permanent, at least as far as current knowledge allows us to state.

How the normal cardiovascular clinical variables in zero-g conditions would present to a doctor unfamiliar with space physiology.

PRESENTATION	INTERPRETATION
Facial and eyelid oedema	Nephrotic syndrome (kidneys leak large amounts of protein into the urine), hypoproteinaemia (abnormally low level of protein in the blood), angioneurotic oedema (of skin and mucosal surfaces), myxoedema (thickening of the skin), Cushing's syndrome (very high levels of cortisol) and compression or obstruction of superior vena cava
Dilated face and neck veins	Right heart failure, constrictive pericarditis, pericardial effusion, tricuspid valve failure or stenosis (narrowing), severe hypertrophy of the right ventricle, significant pulmonary hypertension, tricuspid atresia (missing or abnormally developed valve), right atrium myxoma (non-cancerous tumour), right ventricular infarction (obstruction of the blood supply), obstruction of the superior vena cava and fluid overload of the right chambers (in some congenital heart disease)
Conjunctival hyperaemia (red eye)	Bacterial or viral infections, irritation by chemical or physical agents and allergic reaction
Redness of the face	Sunburn, fevers, high temperature, and chemical or allergic irritation, and blushing
Upward displacement of the apex	Phrenic nerve paralysis, tense ascites (accumulation of fluid), pregnancy in the third trimester, extreme obesity, pneumoperitoneum (abnormal presence of air or other gas in peritoneal cavity) and abdominal distension caused by various digestive problems
Sinus bradycardia (slow heart rate)	Sinus or node disease, full atrioventricular block (AVB) or sinus bradycardia caused by vagotonia
Same blood pressure throughout the body	Partial obstruction of the iliac or femoral arteries
Cylindrical thorax	Pulmonary emphysema
Ascent of the diaphragm	Same conditions as upward displacement of the apex
Decreased breath sounds at bases	Hypoventilation
Liver area upwardly displaced	Right diaphragmatic paresis (muscular weakness), the presence of pneumoperitoneum, liver abscess or another pathology
Decrease in amplitude of the arterial pulse in the lower limbs	Partial obstruction of iliac or femoral arteries

Comprehensive examination of the heart-lung system in space offers very different data to that obtained from examination on Earth

▲ Karen Nyberg conducts an ocular health exam on herself in the Destiny laboratory of the ISS. Astronauts in zero-g experience increased retinal circulation.

▲ Above right: ESA astronaut Andre Kuipers exercises aboard the ISS. In zero-g the diaphragm is elevated by 5-6 cm compared to on Earth.

Upon returning to Earth there is a reverse process whereby the system re-adapts to Earth's gravitational forces; a process which takes some time and depends on the length of the preceding space mission.

Knowledge of these facts is not only of academic interest but it also represents real clinical value, especially looking ahead to when the use of space remote medical care involving tele-cardiology diagnosis might become common practice. ■

About the authors

Cardiologist **Ramiro Iglesias** is a pioneer of space medicine, serving as vice president of the US Aerospace Medicine Association, president of the Mexican Society of Aerospace Medicine and was founding president of the Mexican Association of Aerospace Medicine and the Mexican Society of Life Sciences in Space, currently the Mexican Society of Astrobiology (Soma). He has published numerous scientific papers and authored two books, *Aerospace Cardiology* and *The Path to Cosmic Man.*

In a career spanning more than 50 years, cardiologist **Jorge Kuri** has published 77 scientific articles in national and international journals, presented 91 papers in different Congress of Cardiology and collaborated on six books. He has held several positions at the National Institute of Cardiology, Mexico City, including that of Vice Principal.

Special thanks to **Angela Karina Carbajal** for her dedication and help in writing this article.

Upon returning to Earth there is a reverse process whereby the CVS re-adapts to Earth's gravitational forces

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At the first TEDxESA he shared how Ptolemy is now being used “Down to Earth” to sniff out bacteria causing stomach ulcers and find blood sucking creatures (better known as bed bugs).

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▶ Opposite: Commercial EO and value-added services market 2015 (source: Euroconsult, Satellite-based Earth Observation Market Prospects, 2016 Edition).

Fiji islands from SPOT 7.

Shifting lines and new horizons in Earth observation markets

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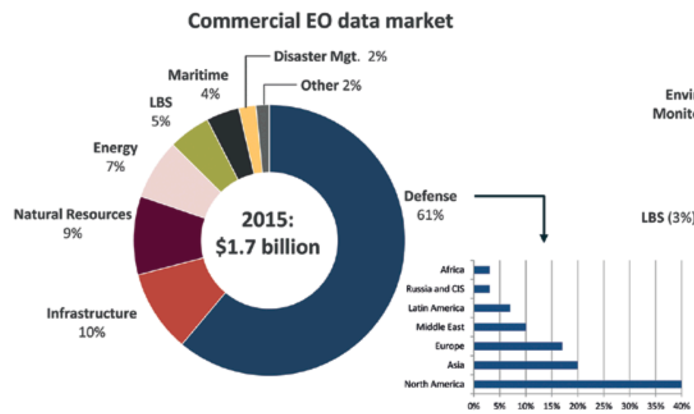
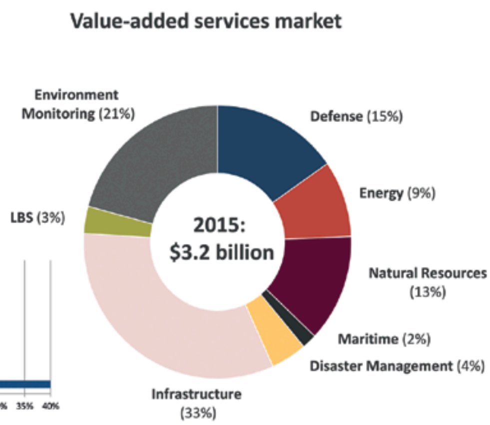
The growth in demand for Earth observation (EO) data has triggered significant interest by established operators and NewSpace companies whose strategies are a mixture of higher resolution and higher revisit. There are two main options: the high end approach, with increased imagery resolution for customers acknowledging the value of these products and the service approach, which assumes that value comes from the information and services derived from EO data. Expanding on their first article on disruptive trends in EO (*ROOM*, Summer 2017), the authors now add a prospective dimension, reviewing possible scenarios and their consequences, addressing the convergence between commercial capacities and defence needs and identifying threats and growth opportunities for European actors.

High resolution imagery is the main commercial market in EO, with a healthy growth: according to Euroconsult's latest research reports on Earth observation [1], the commercial data market reached US$1.7 billion in 2015 (six percent growth on 2014), largely driven by defence and image intelligence (IMINT), which comprised US$1.1 billion, demonstrating the convergence between commercial capacities and defence needs. Other market shares were below 10 percent. Optical data represented 84 percent of the market. The value-added services market reached US$3.2 billion in 2015.

The development of EO is linked to the worldwide digitalisation of society, with our endless appetite for information, increasing number of data sources, interconnected ecosystems, security issues and national prestige and soft power.





More and more commercial EO satellites will be launched over the next decade, fostered by growing demand and new entrepreneurs: over 400 satellites (> 50kg) and 1200 small satellites (< 50kg) could be launched.

Environmental monitoring, food security and climate change are top priorities in political agendas. Border monitoring and global security are also major trends. Natural resources management, engineering and infrastructure, location-based services (LBS) and defence enable the growth of the very high resolution (VHR) market.

In 2025, the market for commercial EO data is expected to reach US$3 billion (six percent compound annual growth rate (CAGR) over 2015-2025). Market forecast for value-added services is US$5.3 billion for 2025 (five percent CAGR). North America will remain the first market (forecast > US$1 billion in 2024). Asia, Latin America and Africa markets are also expected to have strong growth profiles.

New regulations, e.g. evolution of International Traffic in Arms Regulation (ITAR) rules, will boost VHR markets. The free and open data policy applied in the Copernicus programme provides a wealth of environmental data likely to catalyse added-value services.

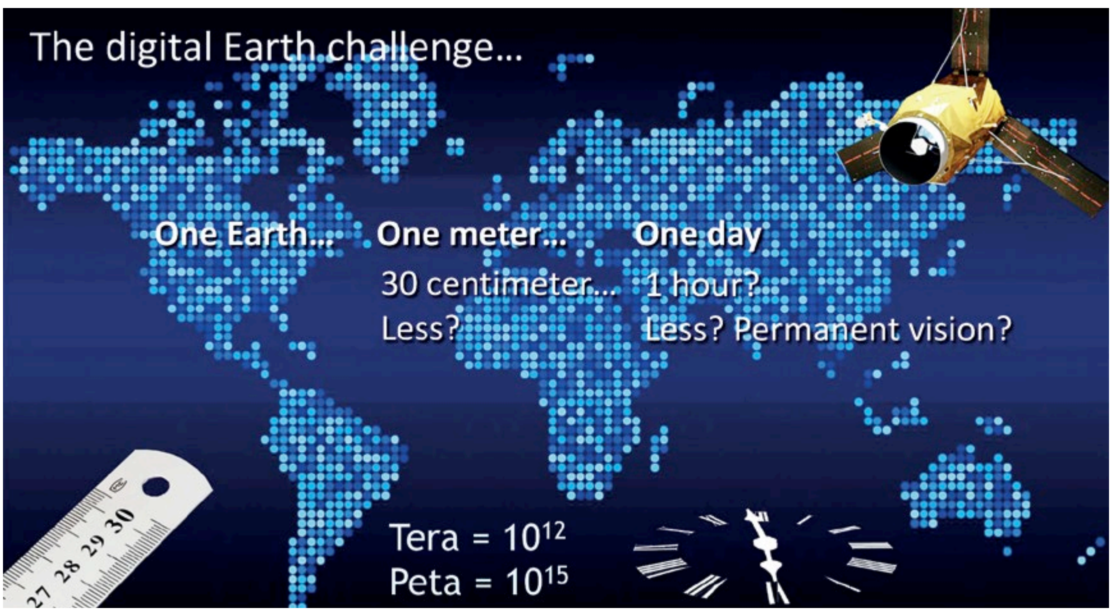
From scarcity to abundance

Three trends shape the global EO landscape:

- the evolution of prices, influenced by increased availability of VHR/HR, impact of 'free' imagery and the redistribution of value between the data and the services
- the evolution of international demand: small and large countries invest in their own EO capacities
- the increasing number of suppliers.

Until now, data prices were mainly driven by criteria related to 'image quality'; resolution (Ground Sampling Distance/GSD), geolocation

> "Predictions can be very difficult - especially about the future."
> Niels Bohr



▶ The digital Earth challenge: Higher resolution or higher revisit – can we have both?

▲ Aircraft graveyard in Tucson, Arizona, taken by the Pleiades satellite.

accuracy, image freshness, spectral richness and radiometric accuracy are also part of the criteria. With the emergence of new actors, standard imagery prices could drop drastically. A typical example is the evolution of EO sales in China. Until recently, China was buying imagery from foreign suppliers, but since 2011 the volume of medium-resolution data acquired by Chinese satellites has exceeded the imported share and China now meets its needs independently [2].

The pricing model could evolve and be driven by service value. With the service approach, the challenge is to propose as far as possible standardised products. Even if the feasibility and the benefits of an evolution towards more 'horizontal markets' are not yet demonstrated, the customer could become a consumer.

EO development is linked to the worldwide digitalisation of society

What is the appropriate number of segments for the analysis of EO data markets? Apart from core military needs, three segments are usually defined by commercial operators: medium, high and very high resolution. This offer-based segmentation does not necessarily fit current demand. Market evolutions could justify a finer-grained analysis. In particular, a 'narrower' definition of VHR (for instance <30-40 cm) could open a new avenue for 'less high VHR' (e.g. between 50 cm and 1 m), if its price is attractive. It could mean that a 'high-end' option could find its own niche, even is this market segment is mainly addressed by 'low-cost' products. Table 1 summarises the shifting factors and growth drivers.

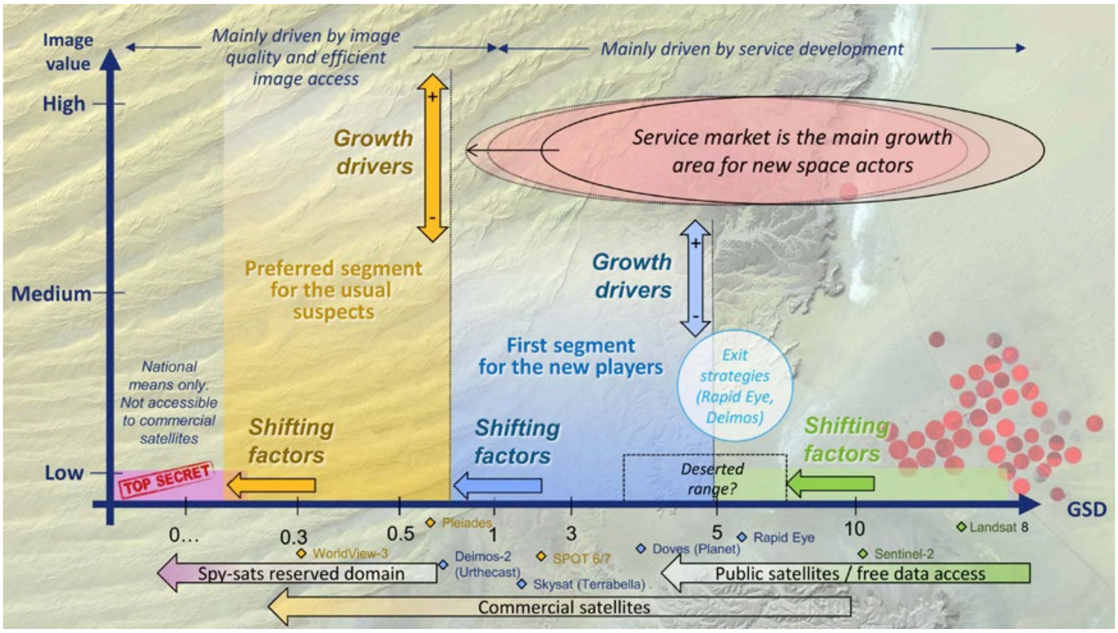
The service market is the main growth opportunity for new operators. From satellite manufacturing to service delivery to the end user, the EO value chain is usually structured in tiers with the upstream, midstream and downstream layers.

Depending on the weight of image data compared to other data (data-agnostic services), there may be opportunities for EO data owners or satellite operators, EO data brokers or for pure service players.

Another important factor is the level of automatic processing and the need for human expertise in the information production process. The need to integrate customer data in service production can raise security and confidentiality issues and may justify a local implementation of the service.

For activities which are usually implemented directly by the end user such as geospatial intelligence (GEOINT), insurance, etc., the

TABLE 1	VERY HIGH RESOLUTION	HIGH RESOLUTION	MEDIUM RESOLUTION
SHIFTING FACTORS	+ Increasing use of commercial data in IMINT + More monitoring needs + Budgetary constraints and impact on national means - Regulations and export rules	+ High competition + Success of services offers and market growth - Regulation and dissemination control	+ Success of the commercial and institutional services using this range of data + Evolution towards higher end + Evolution of public missions (e.g. Copernicus Security)
GROWTH OR CONTRACTION DRIVERS	+ Wider use of commercial satellites + Increasing capacity - Increased competition and newcomers - New national missions - Competition from aerial market and other sources - One-size-fits-all impact on customer base (pricing)	+ Quantitive development of services with lower costs - New national mission - Market saturation - Competition with open data	+ Development of agriculture and land use services - Less public investment in EO mission



◀ Shifting lines and new boundaries: evolution of EO data markets.

readiness to outsource service production is obviously a critical point. Typical markets and their maturity (use of EO data and services) are presented in tables 2 and 3.

Market disruptions

From a prospective point of view, future market development scenarios are useful tools to forecast possible impacts on the EO landscape and the following three 'science-fiction' scenarios are 'extreme' options.

Scenario 1: Solid revenues from the VHR data for the intelligence community

This is based on a steady continuity of the VHR market, with sustainable demand by the defence and intelligence community for high-end products. A significant market share comes from commercial customers, ready to pay a premium for high-class imagery. The main driving factors are: evolution of defence and commercial markets using VHR imagery; regulations and export control rules; and high performance distribution systems (e.g. OneAtlas by Airbus Defence & Space).

Main opportunities are related to global threats and instability (increasing GEOINT needs) and demand for accurate geo-information in the main vertical and export markets.

Threats are linked to the evolution of intelligence needs such as cybersecurity, electronic intelligence (ELINT), the use of other sensors (e.g. drones) and competitors entering this market beside their initial business. Some commercial customers could be satisfied with lower resolution (50 cm – 1 m), with impact on price sensitivity.

Services approach for GEOINT missions is not straightforward, as long as the readiness to outsource remains low. Institutional constraints (human resources and budget) can trigger innovative schemes involving private providers. The enabling conditions are integrity or confidentiality of information and new governance rules.

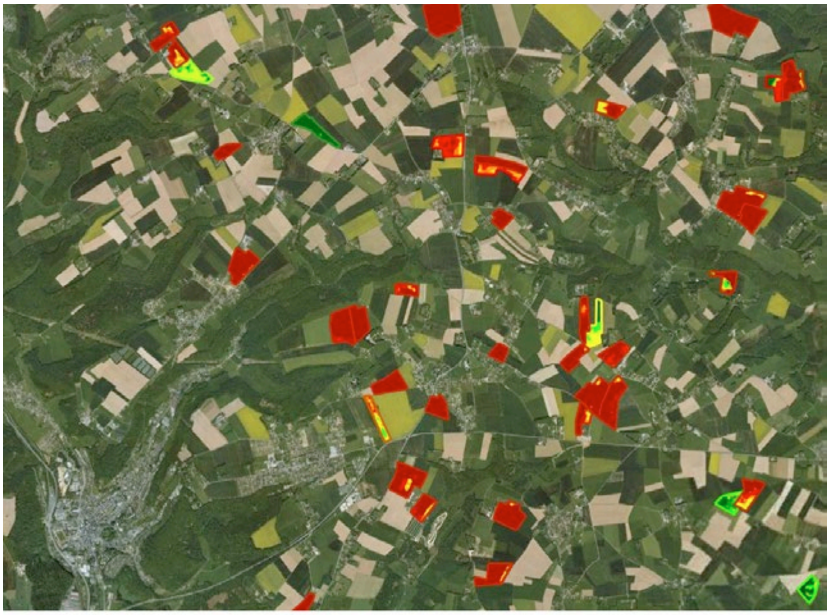
Scenario 2: A new Eldorado with EO-based services for commercial applications

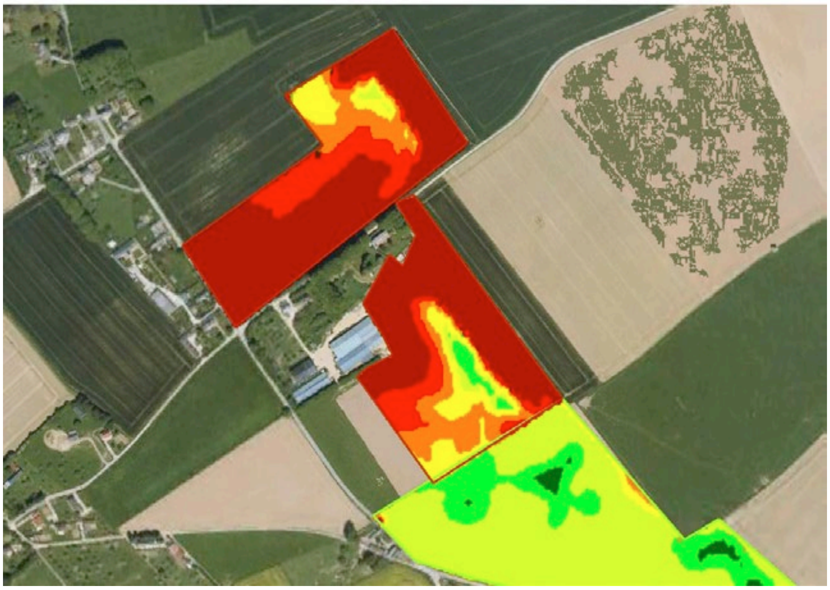
Here, NewSpace actors convert promises into tangible achievements, with a huge growth in geo-information services. This success depends on four conditions: some of the planned constellations are actually implemented; commercial demand materialises in key sectors; public demand is healthy, with institutional customers ready to outsource their geo-information needs; and EO data value in

More and more commercial EO satellites will be launched over the next decade, fostered by growing demand and new entrepreneurs

TABLE 2

IMAGE + SERVICES	SPECIALISED SERVICES AND NICHE MARKETS	VERTICAL MARKETS	HORIZONTAL APPROACH
• 'Image-only' services (real time, time series, etc.) • Automated processing **B2B or B2G rules** Close link with the satellite owner	• Thematic or geographic specialisation • High expertise • Customer intimacy **B2B or B2G rules** Tailor-made solutions Fragmented ecosystem of VAC and SME	• Defence • Agriculture • Oil and gas • Assurance, etc. **B2B or B2G rules** Ready-to-wear Standard product portfolio for families of customers	• Geo-marketing • Geo-Analytics • Monitoring • LBS) **B2C rules applied to B2B or B2G** One-size-fits-all Customer = consumer





▲ Precision agriculture: EO data from Farmstar, a service of Airbus Defence & Space and ARVALIS, using images acquired by the SPOT 6 and SPOT 7 satellites, can issue intra-field input recommendations for areas as small as 1 hectare, helping farmers make optimal use of their land and crops.

information production is demonstrated.

Two opportunities are the development of new services and new markets with game changers on the demand side, related either to global environmental issues (climate change, water and food security, insurance, etc.) or new commercial usage (geo-marketing, mapping and LBS, etc.), and successful implementation of services in areas where space data plays a major role and can't be substituted.

The main threat is the 'hype effect', with the collapse of new initiatives due to lack of funding or viable business models.

Scenario 3: EO becomes a commodity, competing with other sources of information

This is the nightmare version of scenario 2 - growth in geoinformation services without a corresponding growth in demand could oversupply the market. The main uncertainty is the actual role of space data in a big data world with data also coming from other information sources (drones, crowd-based and in situ in a connected world). For GEOINT, the need for real time information is often linked to tactical needs and response with security forces and first responders. In this case, in-field operators carry sensors (e.g. police helicopters, short range UAVs) and this model can be very efficient.

If EO data become a commodity with huge competition between data and satellite owners, there will be an opportunity for pure content aggregators or data brokers, without investment in proprietary data collection systems. An evolution towards source-agnostic service provision is also credible. End users are sensor/data agnostic: they want the information, not the data (GEOINT is a notable exception).

Consequences and opportunities

In a worldwide competition with disruptive offers mainly initiated in the US, access to market for European actors is a strategic issue, with commercial

TABLE 3	DEFENCE	CIVIL INSTITUTIONAL	COMMERCIAL	CONSUMER MARKET
TYPICAL ACTIVITIES	• Mapping • Intelligence • C2-ISR	• Cartography • Environmental monitoring	• Agriculture, oil and gas, insurance, etc.	• Mapping • LBS, etc, for web actors
MATURITY	High	High	Variable	Low
GROWTH POTENTIAL	Medium	High	High	High
CUSTOMERS/USERS	10-100	100-1,000s	1,000s-10,000s	Millions

and industrial consequences as well as issues related to sovereignty and non-dependence.

Market forecasts predict US$39 billion in manufacturing revenues over the period 2015-2024. There is a huge opportunity for European satellite manufacturers and their supply chain if they are competitive and ready to invest as partners in new ventures. Recent successes in the telecommunications domain (OneWeb, O3b or BlackSky) show that the European space industry is able to play the game.

The support of space agencies is mandatory for preparation for the future (non-dependence and critical technologies, disruptive technologies, etc.) and a contribution to 'de-risking' activities [3]. The relationship between space industry and space agencies will evolve from customer-supplier to a more cooperative approach.

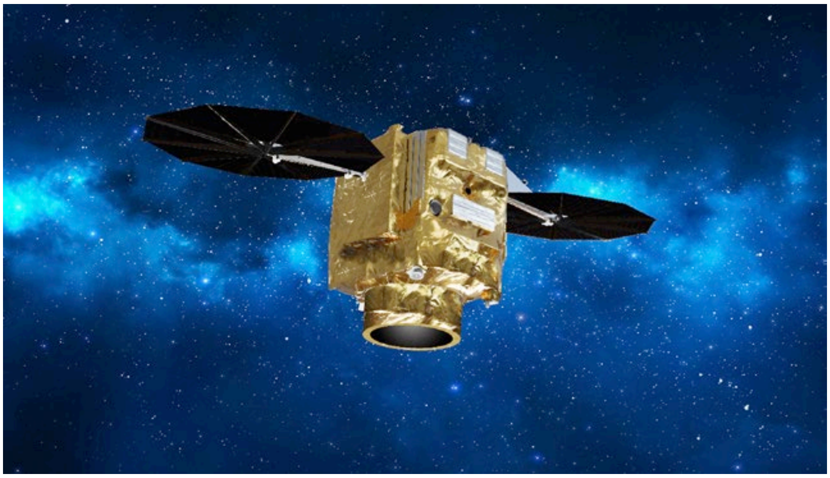
The big challenge

The European service ecosystem is fragmented and heterogeneous. In a study on the State and Health of the European EO Services Industry [4], the European Association of Remote Sensing Companies reports 451 EO services companies in Europe (and Canada) in 2014. The majority of companies (63 percent) have less than 10 employees (95 percent < 50 people).

The NewSpace context with new EO data sources brings new opportunities but also greater competition. The main risk is information dominance by a small number of worldwide champions or global service providers backed by the large web actors.

Europe's priority should be to secure the market position of the commercial VHR data providers. The public sector has a key role in helping its European champions: even if a European national geospatial agency will not be easily implemented, anchor-tenant contracts can be developed by national and European institutions as customers. It means a new balance between patrimonial assets or in-house activities and external services. In her report on 'Open Space' [5], Genevieve Fioraso recommends a 'Buy European Act'.

The consolidation of the supply chain leading to European champions is an option but fragmentation is not necessarily a weakness, with a closer link to final customers and a solid territorial footprint. This assumption is the rationale behind Eugenius (European Group of Enterprises for a Network of Information Using Space), an initiative started by Terranis, a French SME (small and medium enterprise), in cooperation with a set of European service companies. Targeting the development of Copernicus downstream services, the objective is to federate SMEs into a powerful network of providers serving their proximity customers.



▲ Pleiades NEO: a constellation of four VHR optical satellites developed by Airbus Defence & Space.

GEOINT community

Making the best use of future constellations for governmental and intelligence needs is part of the new US policy: the NextGen Tasking Initiative was launched in mid-2015 by the National Geospatial Intelligence Agency (NGA) in order to develop new methods using commercial information for intelligence purposes. Recently, the head of NGA confirmed that several tens of millions of dollars will feed the most prominent start-ups, in line with the Commercial Geoint Strategy published in October 2015 [6].

In the European Union (EU), some Member States have also expressed interest in these developments. In France for example, a recent report mandated by the French government [5] highlighted changes induced by the rise of the new commercial space sector and the need to adapt institutional practices. However, the level of readiness is far below what can be seen in the US with a number of obstacles to be overcome. The following trends can be foreseen:

- more dual systems used for security and defence needs (maritime surveillance, border control, monitoring international treaties, etc.) with investment shared between defence and civil entities
- more civil space assets owned and operated by private sector assuring guaranteed and secured access of data to military customers
- limitation of state owned systems to those strictly connected to national security and sovereignty: reconnaissance, signals intelligence (SIGINT), early warning, etc.

There is a huge opportunity for European satellite manufacturers and their supply chain if they are competitive and ready to invest as partners in new ventures

The main risk is information dominance by a small number of worldwide champions or global service providers backed by the large web actors

- enlarged cooperation between European member states
- more synergies with civil ICT technologies (big data, cloud, etc.) in order to deal with the increasing amount of space data.

In this context, high performance commercial imagery already plays a key role when intelligence procedures impede the sharing of intelligence produced by national systems. Commercial operators could become key providers of sensitive but sharable data on a collective basis.

Security and sovereignty

Independence is a key issue. Space is a sector of excellence for Europe. This is obviously an asset for autonomy and EU independence in terms of information gathering and processing.

The situation is more complex for the ICT component, as there is no European champion, able to compete with Google or Amazon on the mid-stream segment. Can we change this situation?

It is questionable but it raises many security and sovereignty issues: the growing control of the information chain by a small number of large US companies could create a monopoly situation. If GAFA (Google Amazon Facebook Apple) penetrate and conquer the EO sector with their end-to-end applications, the competitiveness of European actors is at risk. This risk calls for major awareness at Member State and EU levels and preservation of the European champions at the top of the EU political agenda.

New gold rush

The EO landscape will evolve significantly in the coming years. Can European industry secure its role and competitiveness with respect to the growing influence of the large US actors, the NewSpace companies emerging in Silicon Valley and worldwide?

Will the promise of a huge growth of the geo-information market fostered by the convergence between ICT and EO become a reality? Monitoring trends and key indicators should give a clearer picture:

- success of NewSpace initiatives and consolidation of the startups landscape
- evolution of the VHR market and relative shares of Digital Globe, Airbus Defence & Space, and newcomers
- development of EO services and profile of the top performers (SMEs, web actors, midstream actors)
- evolution of the ecosystem of innovative SMEs
- level of outsourcing by the public sector
- degree of consolidation of the service supply chain
- evolution of the European defence market and governance
- investment of new spacefaring countries in their own capacities for domestic and export markets.

The current picture looks a bit like the California gold rush of 1849 with lots of metaphorical 'gold miners' looking to strike it rich in EO data business. Alongside the development of service companies, satellite manufacturers have demonstrated they can become the new 'shovel sellers' in the analogy, proposing agile solutions and staying ahead with competitive products. OneWeb and Airbus, Terra Bella with SSL, and BlackSky with TAS are all examples of joint projects in this field. The big challenge is service development and the emergence of European champions for all layers of the value chain.

An obvious gap in Europe is the lack of world-class players in the big data and middleware infrastructure able to compete against GAFA. Despite the increasing influence of private investment, the public sector has a key role to play, not only at policy level but also as customer. ■

▼ EO services – A new gold rush... and opportunities for Europe

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Mapping the dark universe

ESA's Euclid spacecraft will allow scientists to investigate the nature of the dark universe and gravity. Measuring shapes and the distance-redshift relationship of distant galaxies it will look back on 10 billion years of cosmic history, covering the entire period over which dark energy and dark matter played a significant role in shaping the evolution of our universe. During a six-year mission, Euclid will survey more than 35 percent of the sky. Here, Andreas Rudolph describes specific challenges for the spacecraft and ground segment design team, including the demanding image quality and survey requirements, and the unprecedented data volume and transmission rate requirements compared to other science missions.

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European Space Agency, ESOC, Darmstadt, Germany

Euclid is due for launch on a Soyuz-Fregat from Europe's spaceport in Kourou, French Guiana, by mid-2021. The optical/near-infrared survey mission, which is part of ESA's Cosmic Vision programme, is designed to investigate the nature of dark energy, dark matter and gravity by observing their signatures on the geometry of the universe and on the formation of large structures over cosmological timescales.

Euclid combines several techniques of investigation, or cosmological probes, in a very large survey over the extragalactic sky. Among these cosmological probes, two play a major role in the Euclid mission concept - Weak Gravitational Lensing (WL) and Galaxy Clustering (including Baryon Acoustic Oscillations) to address the following questions in the area of cosmology and fundamental physics:

- Is dark energy merely a cosmological constant, as first discussed by Einstein, or is

NASA/ESA/ESO/W Freudling (ST-ECF)

it a new kind of field that evolves dynamically with the expansion of the universe?

- Is dark energy instead a manifestation of a breakdown of General Relativity and deviations from the law of gravity?
- What is the nature of dark matter and its properties?
- What are the initial conditions which seed the formation of cosmic structure?
- What will be the future of the universe over the next 10 billion years?

Thales-Alenia Space Italia, Turin, and its industrial team are building the Euclid spacecraft under ESA/ESTEC contract. The mission will be operated from the European Space Operations Centre (ESOC), in Darmstadt, Germany.

Mission architecture

The architecture of the mission is strongly driven by the requirements for the sky survey in the areas of its speed, depth, precision and imaging quality. To fulfil its science objectives, the mission performs the following observations:

A survey of a large fraction of the extra-galactic sky of some 15,000 deg² (i.e. around 35 percent) of the sky. During this survey Euclid images billions of galaxies out to a redshift of 2 (around 10 billion years) and to an AB magnitude of 24.5 (visible) and 24.0 (near-infrared) depending on the type of celestial object

A deep field survey will cover some 40 deg² to lower magnitudes. During this part of the survey several million galaxies will be imaged.

Regular observations for instrument calibration and sample characterisation

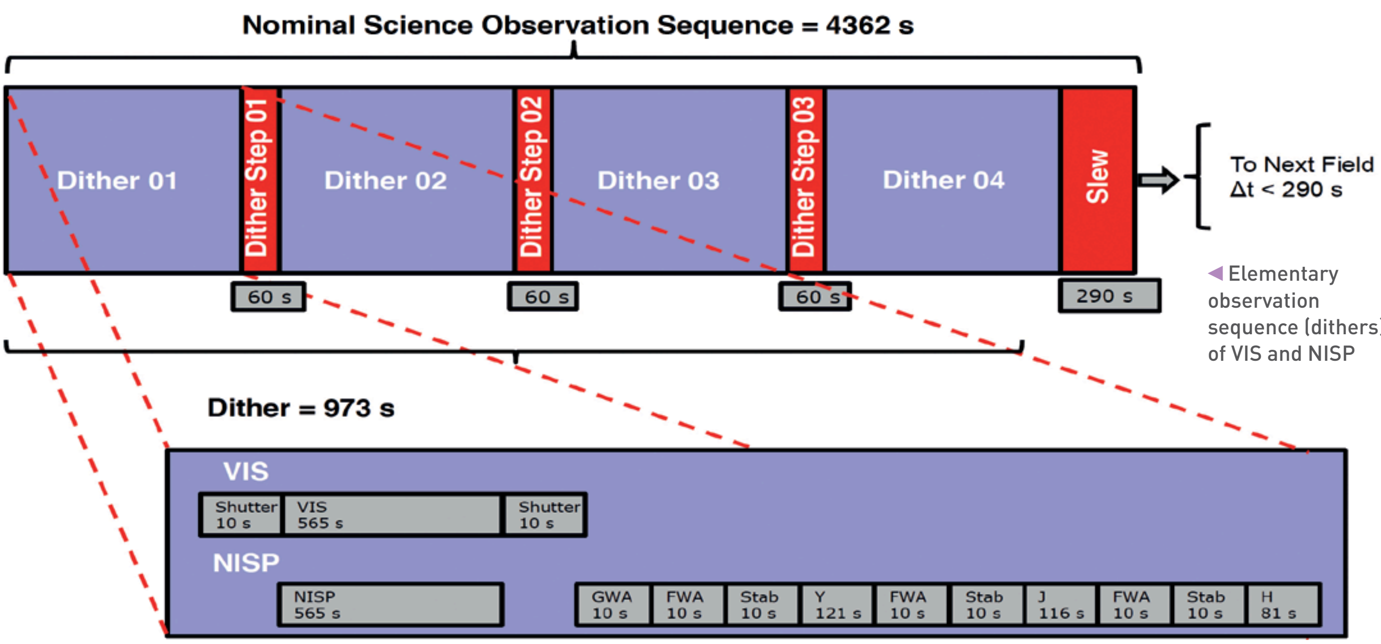
The Euclid spacecraft is equipped with a 1.2 m three-mirror Korsch-type telescope and two instruments, a visible imager, VIS, and the Near Infrared Spectro Photometer (NISP), for slitless spectroscopy and imaging photometry.

The survey consists of elementary observation sequences of around 73 minutes duration. Each sequence consists of four frames covering approximately 0.54 deg² of common area of the sky and dither steps in-between. During the first part of each frame both VIS and NISP instruments are observing. In the second part the NISP instrument carries out exposures for photometric imaging interspersed with filter wheel rotations. The VIS instrument shutter is closed during this rotation due to the disturbing noise of the NISP filter wheel movements. After a dither step the next frame is taken. At the end of the sequence the spacecraft slews to the next observation field.

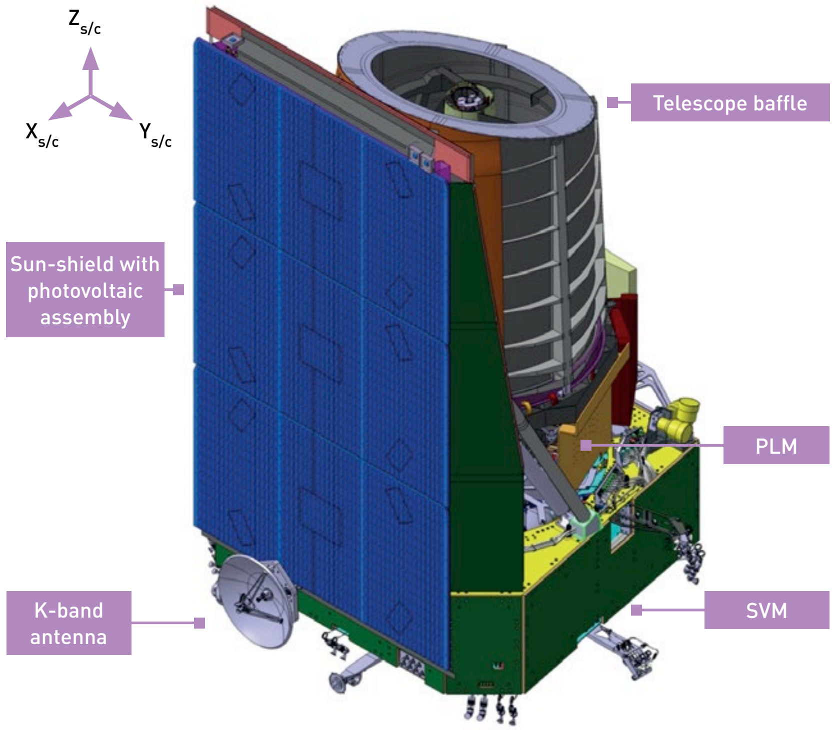
The spacecraft comprises three main elements: a service module (SVM), a payload module (PLM) and the two scientific instruments, VIS and NISP. The PLM includes the 1.2m Silicon Carbide telescope with three folding mirrors and a total focal length of 24.5m. It accommodates the instruments' focal planes and cold electronics.

Timeline and concept

The Euclid operations phases can be broken down into the standard mission phases, i.e. Launch and Early



◀ Elementary observation sequence (dithers) of VIS and NISP



▲ Euclid spacecraft overview.

Euclid combines several techniques of investigation, or cosmological probes, in a very large survey of the extragalactic sky

Operations Phase (LEOP), commissioning, routine operations with an optional mission extension, and end of mission operations (see Table 2).

The individual sky survey observations are planned many months to weeks in advance and executed at a pre-programmed time. The main difference between Euclid and previous ESA science missions is that all payload data and most other operational data is organised and stored in files in the Mass Memory Unit (MMU) on-board. Because there is no need to cut science data into telemetry packets (and to reconstruct and consolidate them on ground afterwards) the new approach will simplify the task of science data processing on-ground.

Drivers and design choices

The characteristics of the Euclid mission pose a number of important challenges on the design of the ground segment and its operations:

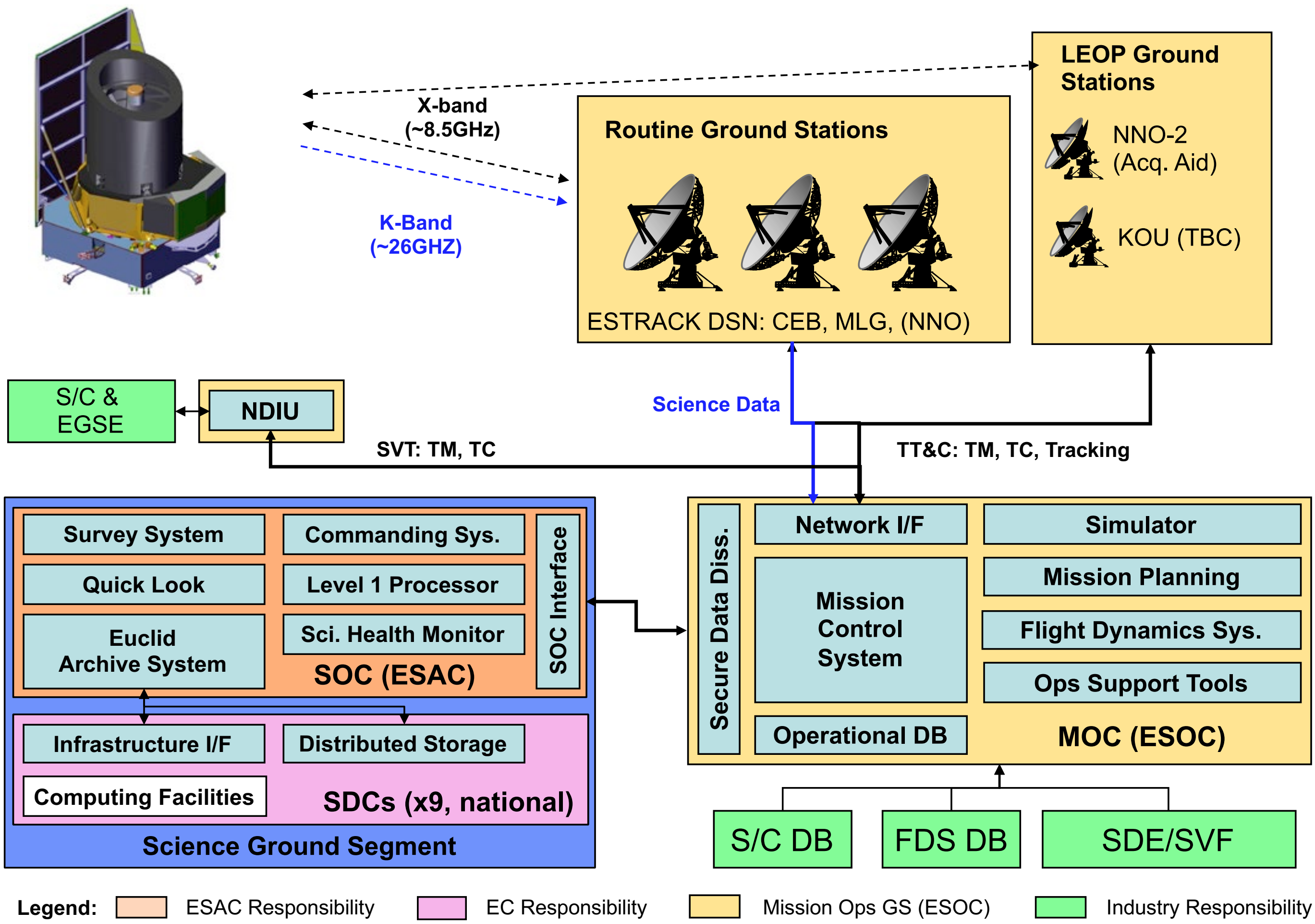
- Euclid will be placed and maintained on a large amplitude Halo orbit around SEL2. The orbit is eclipse free and ensures a maximum sun-spacecraft-earth angle of 33 deg, ensuring space-to-ground communications. For this type of orbit radio frequency regulations mandate the use of the 8.45-8.5 GHz (X-band) and 25.5-27.0 GHz (K-band) frequency bands for downlink, which are different from the frequencies used for deep space missions to avoid interference.
- The spacecraft is autonomous for 72 hours of nominal operations and has very stringent pointing requirements for fine pointing mode, which necessitate a custom-built fine guidance sensor with a star catalogue that needs to be updated from ground regularly.
- To image the high number of galaxies, which are needed to achieve the science objectives, the mission produces about 850 gigabits of science and ancillary data per day. This is around four times more than originally planned for ESA's Gaia mission and around 3.5 times more than the estimate for NASA/ESA's James Webb telescope. In terms of data volume and downlink rates Euclid is therefore the most demanding ESA space science mission to date and for the foreseeable future.
- The data is stored in files on-board and downlinked during four hours of ground station contact each day in K-band. This frequency band is much more susceptible to atmospheric, weather induced attenuations than the X-band links used for other ESA SEL2 missions like Herschel, Planck and Gaia.
- To ensure the completeness of science and ancillary data files downlinked via K-band the CCSDS file delivery protocol (CFDP) class 2 is implemented. The protocol requires a tight and timely handshake between the on-board and ground systems for each file transfer.
- The need to circulate the large volume of data on-ground between ESA's 35m stations in Malarguë and Cebreros and the MOC, and then the Science Ground Sehment (SGS) in a cost-efficient manner drives the design of the ground communications architecture, which in turn becomes a driver for the overall design of the ground systems for network sizing, local data storage at the stations and timely closure of the file delivery protocol with the spacecraft.

Ground communications

The Euclid spacecraft will produce a high volume of science and housekeeping data, which has to be transmitted back in a timely manner to free

Table 1: Key spacecraft characteristics.

ITEM	CHARACTERISTICS
Overall launch mass	2,160 kg[1] of which ~946 kg for PLM and instruments
Solar array power	1,780 – 2,430 Watts depending on the spacecraft/sun to sun-shield angle
Data volume (instrument + ancillary data)	850 Gbit/day down-linked during 4 hours of ground contact/day
Mass memory unit capacity	4 Tbit (end-of-life)



▲ Ground segment overview.

space for observational data. Tracking, telemetry and command data required to support real-time operations of the spacecraft (when visible) has to be transmitted in real time from the ground station to the control centre. Science data and other ancillary data acquired during a pass have less stringent timeliness and availability requirements.

Traditionally, high capacity MPLS ground communication networks are used for real time critical operations and science data transfer but this would not be affordable for Euclid. Therefore, the routing of the Euclid data traffic on ground has to be split:

- time critical real-time operations data (including CFDP protocol instructions to the spacecraft) will still be routed via commercial redundant MPLS networks (at 2 to 10 Mbps), which provide a service with ensured availability and bandwidth
- affordable academic/national research networks will be used to transfer the large volume of science data.

The proposed setup introduces a number of challenges that have to be addressed. In particular

Table 2: Operations Timeline overview.

PHASE	DESCRIPTION
LEOP (~ 4 days)	Launch and separation from Fregat; automatic sequence execution and first acquisition of signal; perigee velocity correction and trim manoeuvre(s)
Commissioning (~ 3 months)	Transfer to Halo orbit around SEL2 (~ 30 days); Commissioning of the spacecraft and instruments
Routine operations (6 years)	Sky survey (large and deep survey); instrument calibrations; routine spacecraft activities (orbit maintenance ~1/month, etc.)
Extended operations (0.75 yrs)	Spacecraft consumables are sized to support (at least) an additional 9 months of mission if required
End of mission (~1 month)	De-orbiting into a helio-centric orbit minimising the probability of return to the Earth/Moon system; end of mission configuration of the spacecraft (venting of remaining fuel, transmitters off, etc.)

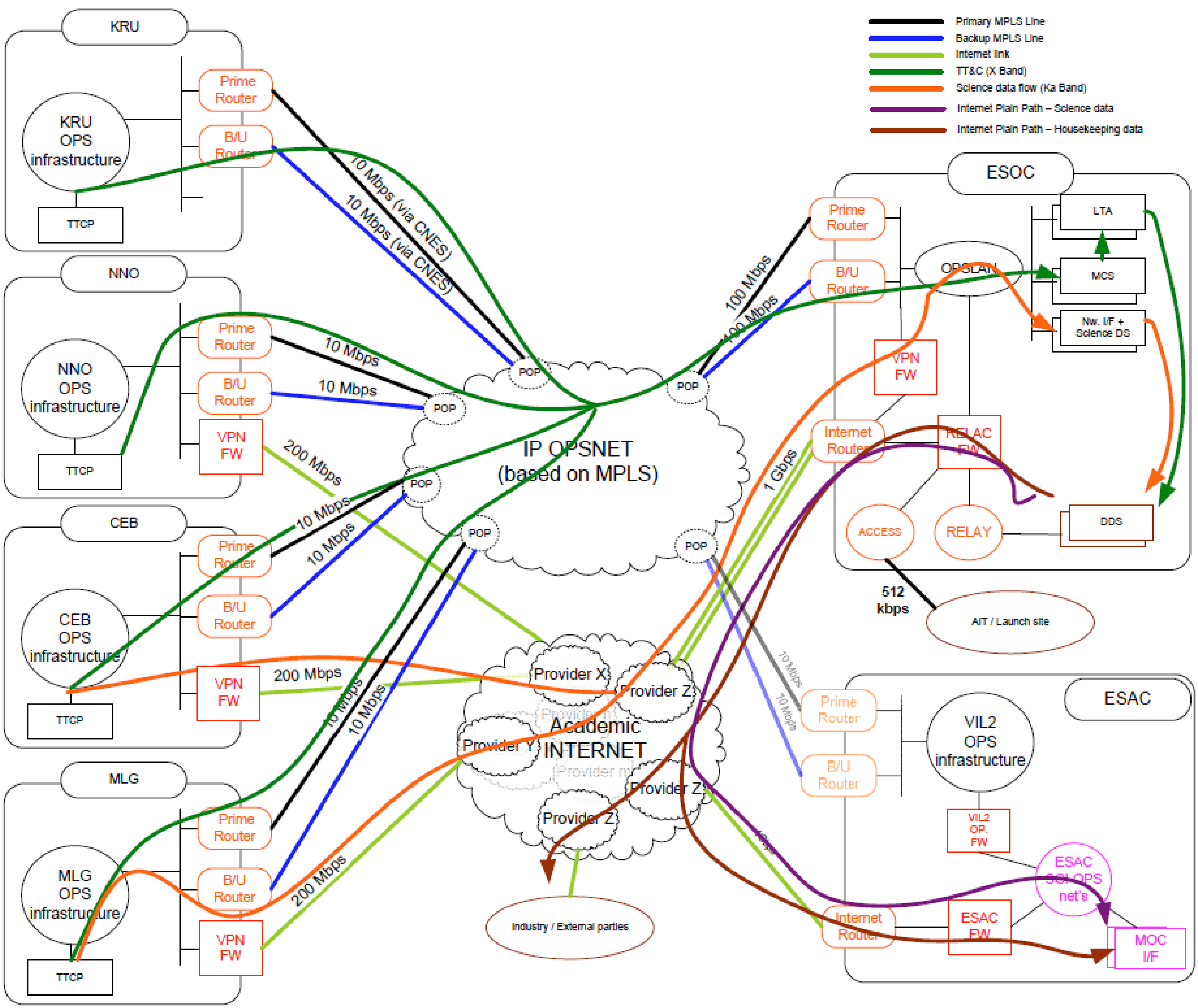
the fact that the availability and 'end-to-end' performance (in terms of delay and throughput) of academic/research networks cannot be guaranteed at all times. The links have to be sized to enable the timely transfer of the 73.9 Mbps data stream from the spacecraft and also to cope with backlog recovery of seven days of data within three days in parallel to nominal operations in case of a temporary outage of the research network.

Therefore, 200 Mbps internet access links to the Malargüe and Cebreros stations will be implemented. Providing spare bandwidth capacity in combination with enough local storage at the ground station can alleviate the availability issues, however this alone is not enough to solve all the challenges.

File-based operations

The key element for Euclid's new file-based operation concept is the central On-Board File Store in the Mass Memory Unit. It will store all on-board generated data as files (science files, telemetry files, diagnostic files and memory dump files) and will receive and store all uploaded files (TC-Files, On-Board Control Procedure-Files and memory images for patching from a file). This allows decoupling of data transfers and operations, e.g. for on-board software updates.

The file-based operations concept is currently being implemented in ESA's generic mission control system SCOS-2000.



▼ Euclid ground communications architecture.

However, due to the ground communications architecture described above this alone is not sufficient for Euclid. A concept has been developed to install an additional CFDP entity in the ground station for reconstructing the science files in real-time.

For closing the class 2 file transfer protocol, which ensures completeness of data reception also in case of intermittent data losses, all necessary protocol requests (negative acknowledgements in case of missing file data, acknowledgement of end-of file, transaction finished, etc.) are sent to the mission control system in real time, which then issues the required protocol instructions for uplink to the spacecraft. Thereby, all information required for real-time operations is available centrally in the mission control system at the MOC.

The CFDP Assembly at the ground station receives file data encapsulated in telemetry frames. Protocol requests from the CFDP Assembly are provided to the mission control system for uplink via the standard uplink chain.

As these protocol requests are few and small in size compared to the overall volume of the science data files they can be routed comfortably through the existing redundant MPLS network between ground station and MOC. The bulk of files can then be transferred off-line through the academic research networks. This design allows to re-use existing interfaces without requiring changes to the infrastructure.

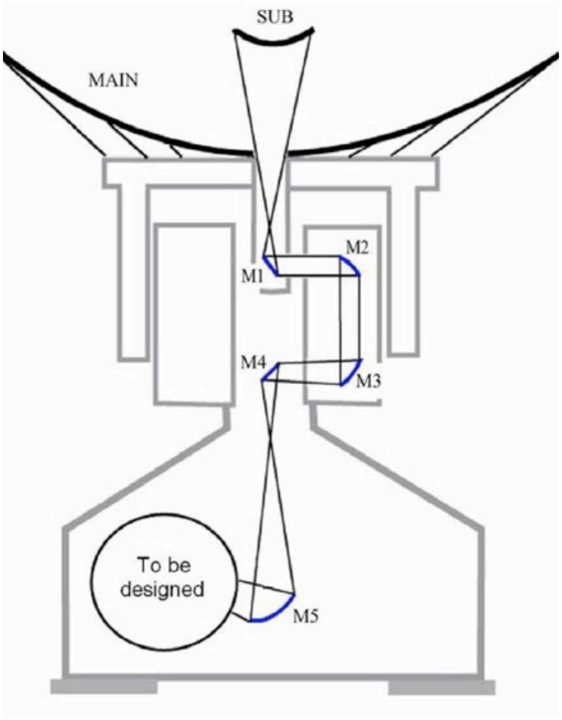
Deep space ground stations

ESA's tracking network (ESTRACK) includes three deep space ground stations, which currently support different RF bands at 2GHz (S-band), 8GHz (X-band) and 32GHz (Ka-band). Euclid requires reception capability in the 26GHz band (K-band). Therefore, the Cebreros and Malargüe Deep Space stations will be upgraded and will be able to operate in either a 'Deep Space mode' (X- and Ka- bands), or a 'Near-Earth mode' (X- and K- bands).

ESA's deep space antennas have a beam waveguide structure. For the upgrade the mirrors M1 to M4 will not be modified. M5 will have the capability to rotate the several feed positions: either to the existing X- and Ka-band feeds or multiband X/K feed.

Overall, the ground station antennas will meet the following performance:

- G/T (gain to noise temperature ratio) at X-band above 50.4 dB/K at 25° elevation (clear sky)
- G/T at 26 GHz Band above 56.6 dB/K at 20° elevation (clear sky)
- EIRP (effective isotropic radiated power) at X-band above 107 dBW.



◄ ESTRACK deep space antenna waveguide structure.

Next steps

Euclid will be ESA's next cosmology mission in the quest for a better understanding of dark energy, dark matter and gravity and their role in the past and future evolution of our universe.

The operations ground segment relies strongly on heritage from previous astronomy and other science missions (Herschel/Planck, Gaia, etc) but there are a number of specific challenges and new developments required to manage the wealth and high volume of scientific data that the mission will produce and that needs to be efficiently dealt with on-board and on-ground.

Introducing the concept of file-based operations and using a file delivery protocol (CFDP class 2) addresses the challenges in the design of the space and ground segment.

The next steps for the Euclid ground team will be the implementation and validation of the concepts in the ground segment itself. ■

There are a number of specific challenges and new developments required to manage the wealth and high volume of scientific data that the mission will produce

About the author

Andreas Rudolph joined ESA in 1991 working first at ESTECin the Netherlands and then (from 1993) at ESOC in Germany. Since 2008 he has been responsible for the ground segment and mission operations of ESA's astronomy and fundamental physics missions including Herschel & Planck, Gaia, Lisa Pathfinder, Euclid and Plato.

▶ A newly formed star lights up the surrounding cosmic clouds in this new image from ESO's La Silla Observatory in Chile.

Exploring the extreme universe

With a multitude of astronomical phenomena shining their light in one of the most unexplored electromagnetic windows on the Universe, a proposed breakthrough observatory mission aims to look where no one has looked before and capture the secrets of some of the brightest objects known to us. Known as e-ASTROGAM, the programme will study non-thermal processes produced from sources such as supernovae, pulsars and even gravitational waves, to learn more about the high-energy Universe with unprecedented sensitivity and resolution.

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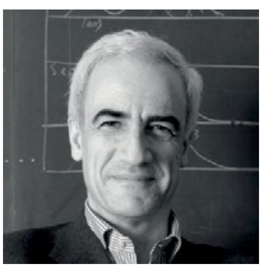

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The night sky has been a source of wonder and mystery for millennia. The Universe contains objects producing a vast range of radiation with wavelengths either too short or too long for our eyes to see, instead needing dedicated astronomical instruments with which to view them. It has only been in the past few decades that we have been able to look at the Universe over the entire electromagnetic spectrum - the keyword for this recent field of investigation is 'multiwavelength' astronomy.

Fortunately, from the perspective of life on Earth, our atmosphere blocks a large part of harmful radiation from space. This however is not such good news for anyone wanting to study astronomical phenomena that emit high-energy photons, as these are absorbed by the protective cloud layers that make up our skies. It has thus only been possible to study photons with infrared, ultraviolet, X-ray and gamma-ray wavelengths in the wake of the rocket era, when scientists could send instruments above the Earth to get a view from space.

Photons at the higher end of the electromagnetic spectrum, i.e. gamma-ray wavelengths that have an energy range above a Mega electron volt (MeV), are one million times more energetic than visible light. As such they are able to create an electron-antielectron pair consistently with the well-known Einstein's relation $E=mc^2$. They are therefore particularly important in multiwavelength observations as they are the highest energy emissions that we know of and, subsequently, they allow astronomers to sample and probe the most energetic (non-thermal) processes in the Universe.

Helping to uncover these processes is e-ASTROGAM ('enhanced ASTROGAM') - a breakthrough observatory mission dedicated to the study of the non-thermal Universe in the gamma-ray photon energy range from 0.3 MeV to 3 GeV (six to nine orders of magnitude more energetic than visible light). The mission is based on an advanced space-proven detector technology, with unprecedented sensitivity, angular and energy resolution, combined with polarimetric capability.

While the measurement of linear polarization (the preferential direction of the electric field vector of detected electromagnetic radiation) is an established technique at other wavelengths such as those of radio and optical astronomy, it has been little exploited in high-energy astrophysics to date. However, polarization analyses with e-ASTROGAM will reveal many details about the geometry, magnetic fields and radiation processes of the high-energy astrophysical sources.

Big hopes for extreme objects

The MeV-GeV domain, which covers the range of wavelengths that e-ASTROGAM will observe, is presently the most unexplored electromagnetic window on the Universe. e-ASTROGAM will bridge the gap between the current generation of hard X-ray satellites - like NuSTAR, INTEGRAL, SWIFT, Chandra, RXTE, XMM-Newton - and NASA's Fermi Large Area Telescope, making pioneering observations of the most powerful Galactic and extragalactic sources and elucidating the nature of their relativistic outflows and their effects on Galactic ecosystems.

From the extreme physics of compact astrophysical objects to a large population of unidentified objects, fundamental questions can be addressed that in many of these sources, mark the transition from thermal astrophysics, i.e. the study of hot plasmas, to non-thermal astrophysics, which deals with the study of relativistic particle populations and of the output of nuclear and subnuclear interactions.

e-ASTROGAM will also study extreme acceleration mechanisms from compact objects such as neutron stars and black holes, ranging up to billions of solar masses (supermassive black holes). Its polarimetric capabilities and its continuum sensitivity will solve the problem of the nature of the highest energy radiation. In addition, the MeV range characterises the nuclear energy transitions of unstable atoms in the same way that the visible wavelength spectrum is identified with the atomic energy transitions, or put another way, MeV observations are for nuclear physics what optical observations are for atomic physics.

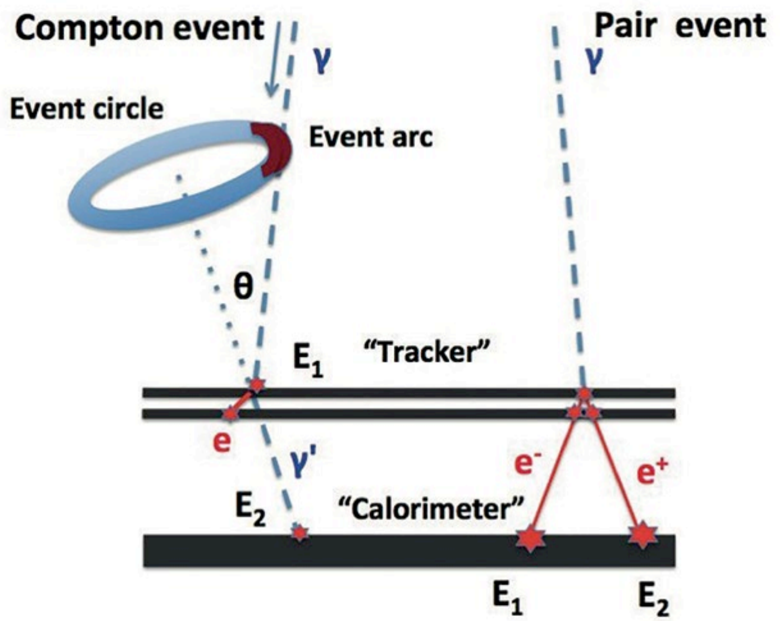
By detecting nuclear gamma-ray lines from cosmic radioactivity, e-ASTROGAM will shed light on the synthesis of new isotopes in stars, on the mechanisms of supernova explosion, and on the resulting continual chemical enrichment of our galaxy. By sampling daily the relative abundance of elements through the study of emission lines, e-ASTROGAM will help us understand how core-collapse supernovae (CCSNe) explode, and the recent history of CCSNe in the Milky Way. Core-collapse supernovae mark the final stage of evolution of massive stars and, although these events are common, the physics of CCSNe is still not well understood even today.

Not only that but the evolution of chemical composition in CCSNe is a key factor to understanding the diversity of elements in the Universe. The cycle of matter proceeds from the formation of stars through nuclear fusion reactions, towards the ejection of stellar debris into interstellar space via winds and supernova explosions.

Interstellar gas, enriched with newly produced nuclei, will eventually cool down to form new stars, hence closing and starting the cycle again. The cooling down of hot nucleosynthesis ejecta and their trajectories towards new star formation have not yet been observed due to the lack of instruments sensitive to gamma-ray radiation in the MeV range; nonetheless, once again, e-ASTROGAM will be on hand to fill this gap and study the cycle.

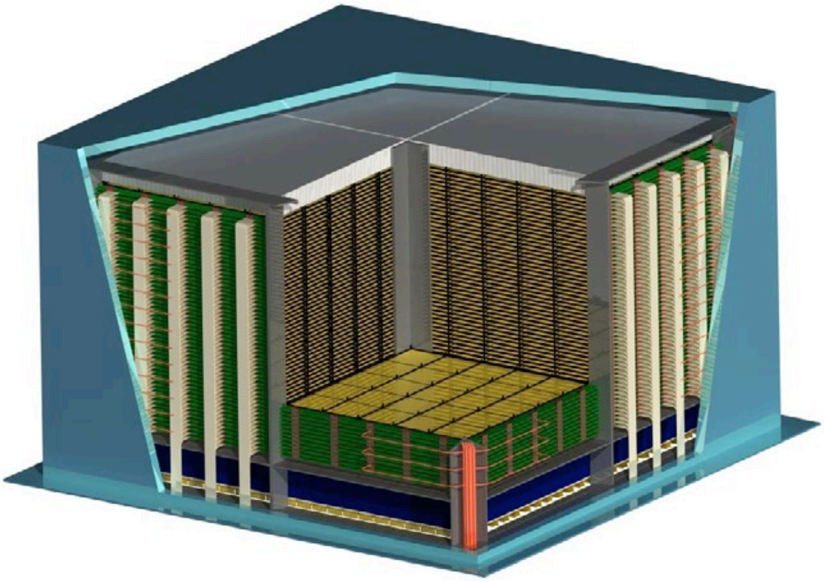
And there's more

e-ASTROGAM will also enable a detailed spectro-imaging of the high-energy emissions from the



▲ Figure 1 - Principle of operation of e-ASTROGAM. Representative topologies for a Compton event (left) and for a pair event (right) are shown. Photon tracks are shown in pale blue, dashed, and electron and/or positron tracks in red, solid.

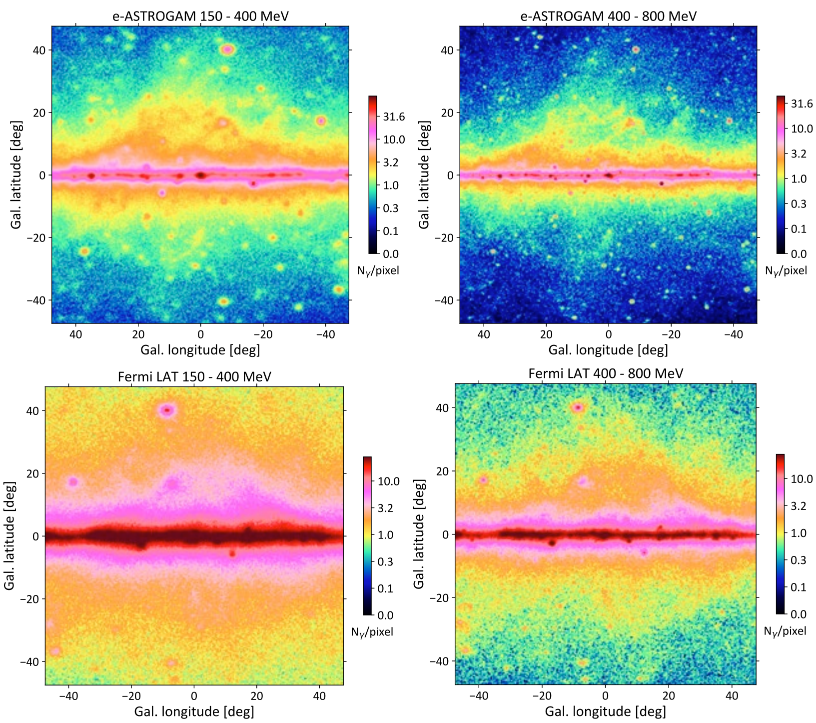
e-ASTROGAM will bridge the gap between the current generation of hard x-ray satellites and NASA's Fermi Large Area Telescope



▲ Figure 2 - Overview of the e-ASTROGAM payload showing the silicon tracker, the calorimeter and the anticoincidence system.

central regions of the Milky Way, allowing scientists to understand at last the origin of the positrons (the antimatter counterpart of the electron).

This particle accumulates in the galactic bulge and within gigantic gamma-ray bubbles - the so-called Fermi bubbles, which extend tens of thousands of light-years above and below the Milky Way's disk. Reprocessing of cosmic rays in the Galaxy due to interaction with molecular clouds is also a source of photons in the MeV range, and e-ASTROGAM will be in the best position to study the processes related to this phenomenon, and its influence on the high-energy photon background.



▼ Figure 3 - Imaging the inner galaxy region: simulated performance of e-ASTROGAM in one year of effective exposure (upper panels) compared to eight years of Fermi (lower panels) for the energy ranges 150 MeV - 400 MeV (left) and 400 MeV - 800 MeV (right).

The observatory is therefore ideal for the study of high-energy sources in general, and its ability to uncover the mysteries of the Universe also extends to the search for elusive dark matter. e-ASTROGAM will have an unprecedented sensitivity to detect a possible cosmic gamma-ray signal from the annihilation or decay of suspected dark matter particles, such as Weakly Interacting Massive Particles (WIMPs) - a theory proposed in many extensions of the Standard Model of particle physics.

In doing so, it will help explain the discrepancy between the motion of stars in the haloes of galaxies with respect to the prediction of the law of gravity in the framework of general relativity.

Multi-messenger

With the recent discovery of high energy astrophysical neutrinos by the IceCube detector buried in the ices of Antarctica and the first direct observation of gravitational waves by the LIGO interferometer, we are at the dawn of another new revolution in astronomy; the so-called `multi-messenger era'.

Multi-messenger astronomy is the study of different particle types as well as photons of different wavelengths. e-ASTROGAM is extremely well placed, again, to assist in these new scientific endeavours, as the one characteristic of the electromagnetic counterparts of both gravitational waves and high-energy neutrino bursts is detectable with our observatory. The expected detection rate of electromagnetic emission by e-ASTROGAM in coincidence with a gravitational wave event detection is between two and nine events a year.

e-ASTROGAM's large field of view will maximise the detection probability and provide accurate sky localisation (better than one square degree), thus allowing the follow-up of the gravitational wave events by other telescopes. This capability will be crucial for the identification and the multiwavelength characterisation of the sources of high-energy gravitational collapses.

Advanced space technology

The detection of photons at MeV energies is challenging. This is mainly due to the strong background noise induced in space instruments by the numerous energetic particles propagating in near-Earth orbit, and by possible radio activation of the satellite.

In addition, two processes of photon interaction compete in this gamma-ray energy domain; Compton scattering and pair production. These two interaction processes require different approaches both in the detection and in the data analysis, and consequently in the instrument concept, thus complicating the design. However, this goal can be achieved at reasonable cost with the technology based on positron-sensitive silicon detectors that have recently reached a high state of readiness, and have been tested on several satellites already. Following on from these advances, e-ASTROGAM will be equipped to use the largest surface of silicon detectors in space.

The instrument itself consists of three main constituents: a silicon tracker, a calorimeter and an anticoincidence system (see Figures 1 and 2). The tracker detects the secondary electrons and positrons produced by the interaction of the incoming gamma-rays. It is made up of 56 planes of double-sided silicon strip detectors, whereby each plane has a total area of about one square metre. The calorimeter is used to measure the energy of the secondary particles by absorbing them, and the anticoincidence system will be used to cancel out any unwanted charged particle background signal.

Many of the high-energy photon emissions in the Universe are transient, i.e., they last a limited amount of time, from fractions of seconds to a few hours. For example gamma-ray bursts - the brightest electromagnetic events which can typically outshine the rest of the high-energy Universe - can last from ten milliseconds up to several hours at a time and are currently detected almost daily.

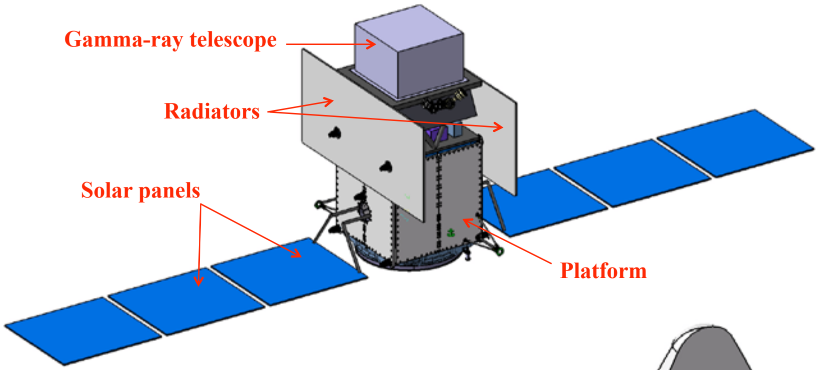
The large field of view of e-ASTROGAM, more than one quarter of the total solid angle, will be ideal to detect transient sources and in particular hundreds of gamma-ray bursts, and to trigger observatories all around the world. e-ASTROGAM will detect thousands of astrophysical objects; the discovery space of this mission for new sources and source classes is very large. The accuracy with which high-energy emitters in the galaxy will be imaged is unprecedented (Figure 3).

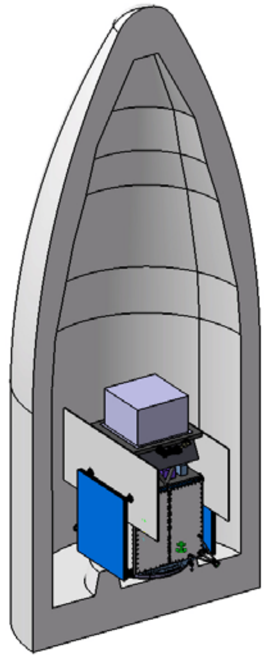
e-ASTROGAM has been proposed as a response to the European Space Agency (ESA) call for the fifth medium-size mission (M5) of the Cosmic Vision Science Programme. When complete and ready for launch, e-ASTROGAM will be launched by an Ariane rocket to a low equatorial orbit of altitude 550 - 600 km, with an inclination of less than 2.5 degrees, and eccentricity smaller than 0.01 (Figure 4), as these characteristics optimise particle background properties.

The overall data generation rate will be about 8.0 Gigabit per orbit, and this amount of data can be transmitted using two ground stations at a downlink rate of about 6.6 Megabit per second; the orbit allows making use of the ESA ground-station at Kourou as well as of the Malindi station from Agenzia Spaziale Italiana in Kenya. The planned launch date, if the project is approved, is 2029, however the construction of pre-mission demonstrators is underway now.

A very large community of astronomical users will benefit from e-ASTROGAM data available for multifrequency studies through a Guest Investigator programme managed by ESA: in addition to the astronomical objects that have been discussed above, e-ASTROGAM will observe with serendipity a large class of phenomena consisting of objects such as pulsars, magnetars, novae, and binary objects. And of course, since it will focus on a relatively unexplored region of the electromagnetic spectrum, it might observe something unexpected. The data will be of great interest to many, either way.

The international collaboration working on e-ASTROGAM involves more than 400 scientists from Argentina, Brazil, Bulgaria, China, Czech Republic, Denmark, Ireland, Italy, Finland, France, Germany, Japan, Norway, Poland, Portugal, Russia, Spain, Sweden, Switzerland, Turkey, United States. The bulk of the construction is going to be mostly handled by European industries, and several industrial partners are already developing parts of the instrument. ■





▲ Figure 4 - e-ASTROGAM diagrams showing deployed configuration and as it would fit under an Ariane 6.2 fairing.

The accuracy with which high-energy emitters in the Galaxy will be imaged is unprecedented

About the authors

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When it comes to water Mars may not be the promised land

Controversy has always surrounded the water content on Mars and while some claim it is responsible for carving out the largest canyon in the solar system, others have a more fiery explanation as to how many, if not all, of the great valley systems came about. If water is not as abundant as once thought, should we give up our plans to colonise the red planet?

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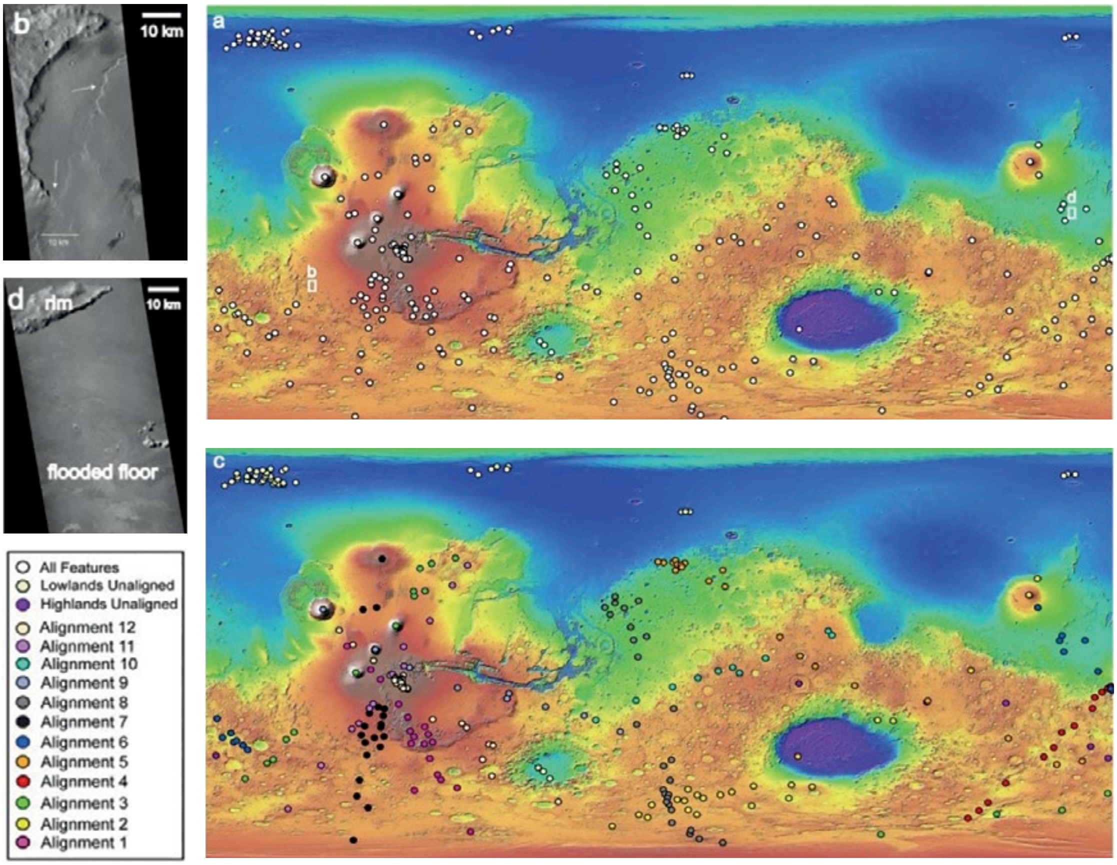
The formation of the solar system was a chaotic period characterised by, amongst other things, impacts between planetesimals and growing planets. These impacts were somewhat random and occurred not only along the orbit that each planet swept but also in their polar regions.

Large southern polar impact basins such as the Aitken-South Pole on the Moon, Rheasilvia on Vesta, and the Martian dichotomy on Mars reveal that an important flux of impactors came from the southern side of the inner solar system. The collision responsible for the southern polar giant impact that formed the Martian dichotomy is the most peculiar because it did not leave a large depression, but instead produced a unique topography and volcanism never seen before in the whole solar system.

The large impactor that changed the face of the planet just four million years after Mars fully accreted - around 4.5 billion years ago - struck the red planet's south pole at a speed of ~5 km/sec. It is surmised that the object fits one of two descriptions; it either had a radius of approximately 1600 km (for comparison the radius of the Moon is about 1737 km) with an iron content of around 80 percent, or it was larger at 2000 km radius with a lower iron content (around 50 percent).

Either way, its sheer size meant that the impactor reached the core of Mars which resulted in the

▲ Diffuse, water-ice clouds, a hazy sky and a light breeze. Such might have read a weather forecast for the Tharsis volcanic region on Mars on 22 November 2016, when this image was taken by the ExoMars Trace Gas Orbiter. Clouds, most likely of water-ice, and atmospheric haze in the sky are coloured blue/white in this image.



▲ Map (a) of all the volcanic centres of Mars, the small white rectangles indicate the location of the black and white panels b and d. Impact crater in Daedalia Planum (b) half buried by lava flows coming from Arsia Mons. The volcanic centres are indicated in (c) by coloured dots to make the volcanic alignments more evident; and (d) the remaining rim of a buried crater in Elysium Planitia. [Journal of Volcanology and Geothermal Research 309, 78-95]

planet heating up to 2300 degrees Kelvin and turning the whole southern hemisphere of the planet into a magma ocean. The re-equilibration, cooling and subsequent solidification of this magma ocean deleted every trace of the impact and formed the Martian dichotomy that is seen today; a southern hemisphere characterised by highlands and a northern hemisphere identified by its lowlands. The cooling process also formed a thick crust in the southern hemisphere under which hot mantle plumes migrated towards the south pole giving origin to 12 alignments of volcanoes still visible on the Martian surface.

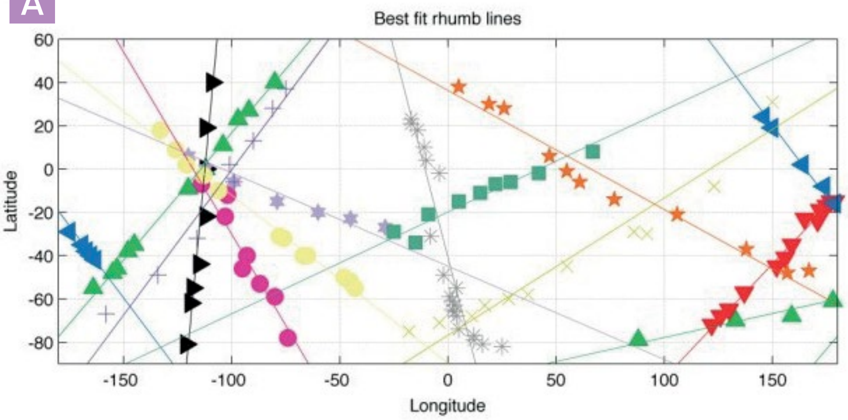
Perhaps more amazing still, is that all of these alignments followed loxodromic trajectories - an arc crossing all meridians of longitude at the same angle - a feature unique to Mars and not seen elsewhere in the solar system.

The giant impact also triggered the internal dynamo processes that formed the transient magnetic field of the planet. Once the internal heat flow fell below a threshold value (between 40-20 milliwatt per square metre) the magnetic field declined and ended at around 4.1 Gy (one giga-year = one billion years) ago at the beginning of the Noachian age.

This data is supported through the study of the magnetic anomalies found by the Mars Global Surveyor on the surface of Mars. Similar values of heat flow between 22-14 milliwatt per square metre are still observed today and estimated through studies of the lithospheric flexure; it is hoped that the forthcoming Mars InSight mission might give better estimates for such a value. The low heat flow coincided with the end of the paroxysmal phase of volcanism, which formed the largest volcanic centres of Mars, followed by a decline that likely ended every activity well before but no later than 3.5 billion years ago (the Hesperian age).

Another important consequence of the giant impact that formed the Martian dichotomy is the fate of the atmosphere and of the water resources of the planet. It has been estimated that 10^{29} joules of energy released by a giant impact could remove as much as 50 percent of the original Martian atmosphere.

A



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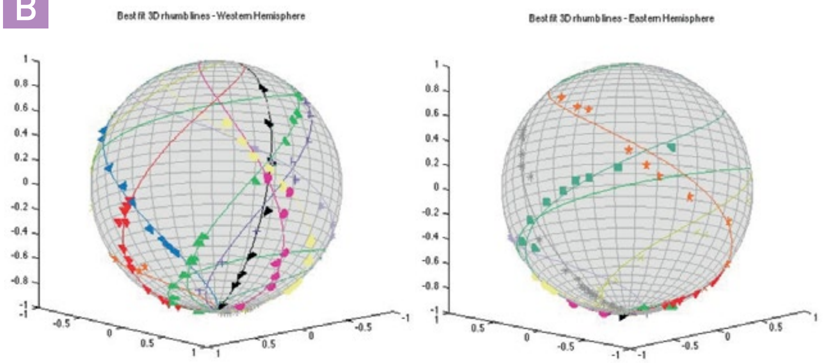


[Journal of Volcanology and Geothermal Research 309, 78-95]

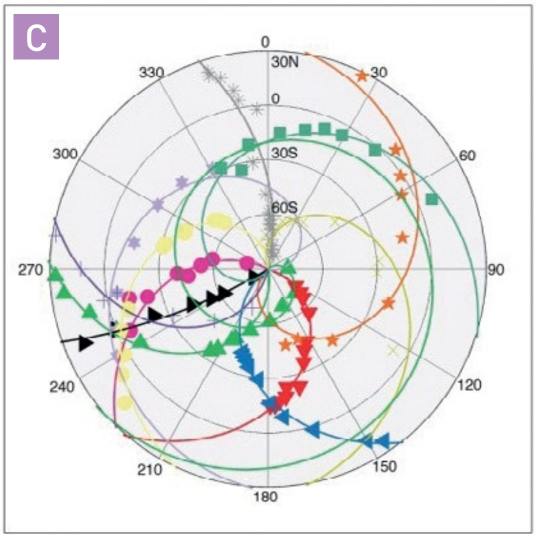
A. Matlab planisphere map of volcanic alignments with best fit loxodromes.

B. Loxodromes of volcanic alignments in the western (left) and eastern (right) hemisphere of Mars.

C. Convergence of the volcanic alignments towards the south pole as predicted by the model of the Southern Polar Giant Impact of Mars.

Southern polar view

C



An important consequence of the giant impact that formed the Martian dichotomy is the fate of the atmosphere and of the water resources of the planet

Coincidently, this is exactly the order of magnitude of energy estimated for the Northern Giant Impact hypothesis which, according to some researchers, did not produce any volcanism and did not melt the northern hemisphere. This figure is significantly lower than the energy released by the Southern Giant Impact hypothesis that did produce volcanism all over the southern hemisphere. It is therefore reasonable to assume that the original atmosphere may have undergone a loss well above the 50 percent initially estimated for Mars. In addition, the heating and melting processes of the southern hemisphere immediately following the giant impact may have seriously dehydrated the planet down to the core.

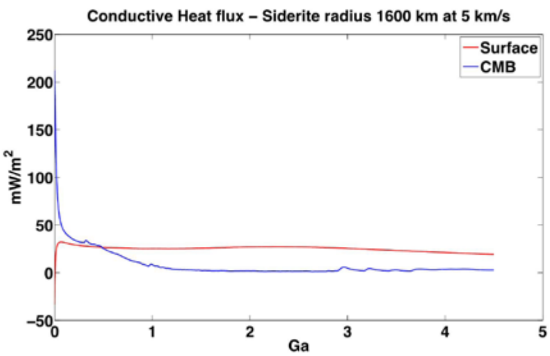
Water loss event

Several studies of the part per million remnants of atmospheric water (H_2O) and its deuterated form (HDO) across the Martian globe agree on a major water loss event early in Mars' history (4.5 billion years ago).

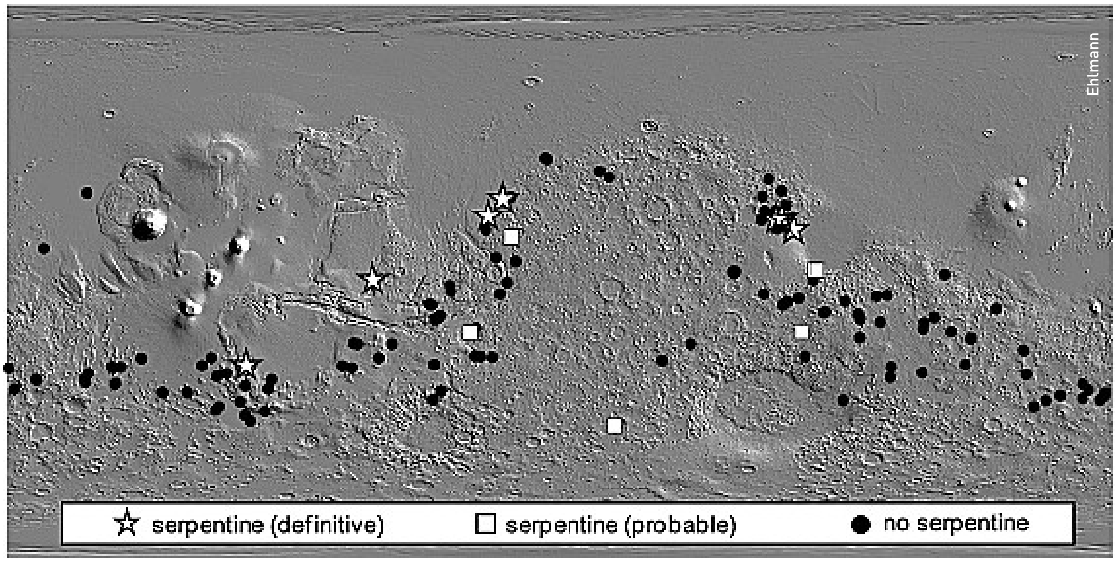
Further significant losses of the remaining water continued for the next half a billion years, at a time that coincided with the strongest phase of volcanism that Mars had ever witnessed. The energy released by the giant impact produced massive volcanic eruptions which built the highest volcanoes and the largest volcanic provinces of the solar system.

While the consequence of these huge eruption rates seem obvious from a volcanic perspective, it also helps to explain other features of the Martian surface. Volumetric studies of the canyons and of the 'fluvial' valley networks have shown that the total global inventory of water for the whole history of Mars would not have been sufficient to carve Valles Marineris.

With a volume of 9.85 million cubic kilometres, Valles Marineris is the largest canyon on Mars. But if water was not capable of carving it out, what was? Lava. Nonetheless, it still means that 98.5 million cubic kilometres of lava was needed



▶ Conductive heat flux of Mars following the southern polar giant impact. The blue line indicates the Core-Mantle Boundary (CMB) heat flux whereas the red line indicates the surface heat flux. [Geophysical Research Letters 41 (24), 8736-8743]



◀ Olivine map of the equatorial belt between ± 40 degrees of latitude. Unaltered olivine is even located on the lowlands where the putative ocean of Mars should have been. [Geophysical Research Letters 37, L06201]

to create this canyon system; and this is not the only outflow channel present on the red planet. Mangala Valles, the eleventh largest outflow channel on Mars, would have required 180,000 cubic kilometres of lava - more than the total volume of lava of all the known historical eruptions on Earth - to carve this sizeable canyon out. And that is just the eleventh largest, so it means that there are at least 10 larger eruptions, including Valles Marineris, that scientists are aware of.

It is reasonable to suggest that throughout Mars' history, the total remaining water inventory - an optimistic estimate of 5 million cubic kilometres concentrated mainly in both polar caps - would not be enough to carve out the biggest canyon of all. It has previously been theorised that the underground circulation of water from the poles to the equator was a route to feed putative aquifers. However, this would mean that the hydraulic heads of the outflow channels are located on high volcanic centres where water must be pumped up to heights of at least 10 km.

Accordingly, this hypothesis seems quite unlikely. Only the huge lava fields erupted by the volcanoes in the provinces of Tharsis, Elysium, and Tyrrhenum match the volumes of lava required to carve all the canyons and the valley networks. Not only that, but the combined thermal and mechanical erosion of lava rivers is able to explain the observational fact that the largest canyons start only from the slopes of the largest volcanoes and the valley networks are located only along their lava fields.

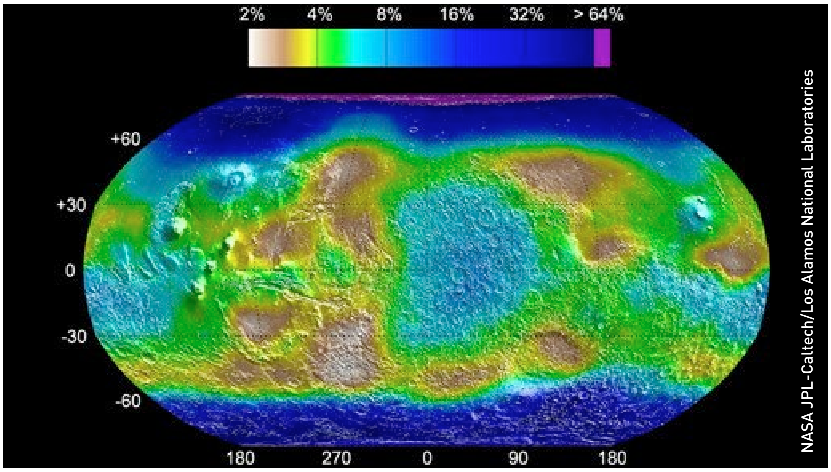
No canyon or valley network was ever observed elsewhere outside the volcanic provinces of Mars as it would be expected if water/rain was the cause. It is also well known that olivine erupted with lava becomes serpentine upon contact with liquid water in a timescale between 100 and 10,000 years. Aside from a few spots of serpentine formed in underground hydrothermal systems, where water was still kept stable by lithostatic pressure, all the olivine observed along the equatorial belt of Mars (where all the 'fluvial' valley networks and canyons are located) never turned into serpentine.

Water inventory

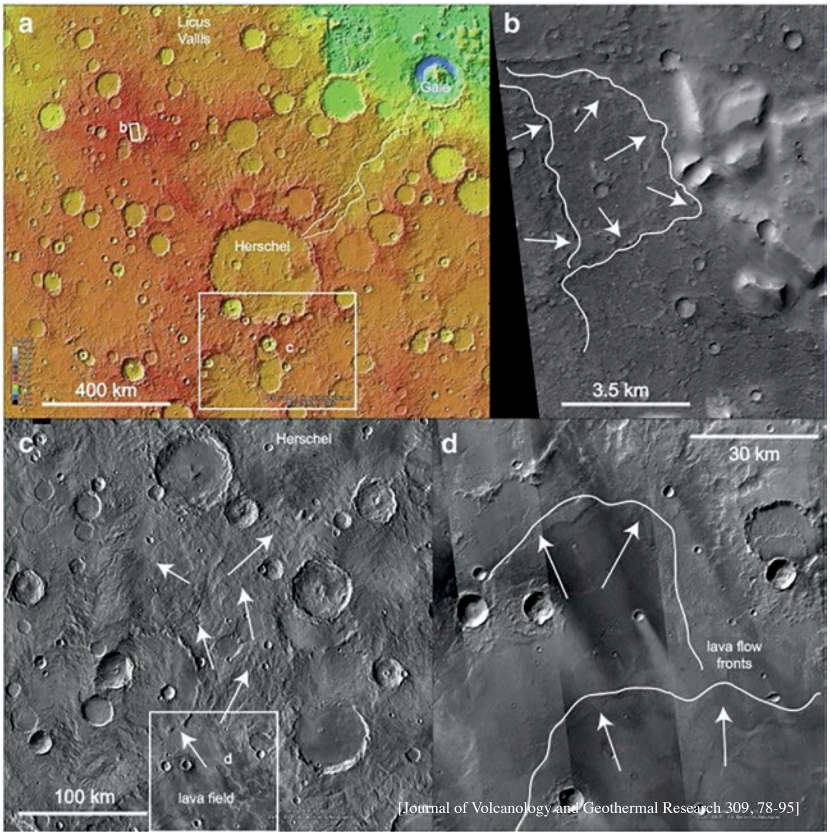
These observations and the fact that the olivine present in erupted lava was never altered on a global scale lead to the obvious conclusion that it may never have rained across Mars at all in its entire history. The arid and cold planet that we see today could thus be a consequence of the events that followed the formation of the martian dichotomy and despite the optimistic views of many scientists, the water inventory of the planet may not be as much as anticipated.

Assuming that all of the hydrogen observed through the Mars Odyssey data today is linked to oxygen to form water, all of the remaining water inventory mentioned before could be divided as follows - 64 percent mass of water equivalent hydrogen (WEH) trapped in the CO_2-rich northern polar cap; 32 to 50 percent mass WEH in the

Only the huge lava fields erupted by the volcanoes in the provinces of Tharsis, Elysium and Tyrrhenum match the volumes of lava required to carve all the canyons and the valley networks



▲ Mars Odyssey epithermal neutron map.



▲ Alignments of volcanic features in the southern hemisphere of Mars produced by migrating mantle plumes. MOLA context image (a) for the region where the Herschel crater is located and an unnamed crater at the source of Licus Vallis. The unnamed crater is located on a topographic high and thus cannot receive supply of lava flows from the Tyrrhenum Mons lava fields; the white curvy lines indicate an unnamed lava channel that flooded Gale crater starting from the lava overflows of the Herschel crater. Crop of the CTX image (b) covering the floor of the unnamed crater. Infill of lava flows is visible in the image, the white arrows indicate the direction of movement of the lava flows, the white solid lines indicated the fronts of the lava flows. The THEMIS mosaic (c) shows the area south of the crater Herschel. The white arrows indicate the direction of movement of the lava flows on the surface, the white rectangle labelled d refers to the next panel of the figure; several craters appear flooded and some of them, including Herschel, have the southern rim eroded confirming the direction of provenance of the lava flows. A mosaic of images (d) shows the lava flow fronts indicated by the curvy white solid lines; the white arrows indicate the direction of advancement of the lava flow fronts.

No canyon or valley network was ever observed outside the volcanic provinces of Mars as it would be expected if water/rain was the cause

CO_2-rich southern polar cap; 16 to 32 percent mass WEH at latitudes ±60 degrees; two to eight percent mass WEH at latitudes ±45 degress; and two percent mass WEH exactly along the equatorial belt, where the outflow channels and the valley networks are located.

This would leave very small traces (up to 200 parts per million) in the atmosphere that is mostly the result of the interchange with the polar caps. This is also taking into account that all of the hydrogen is linked to oxygen, which is unlikely as methane has also been detected on Mars and might be trapped in the polar caps along with CO_2.

If this is the case, then these numbers represent a significant setback for many scientists and wealthy space enthusiasts who have ambitious plans of human exploration and settlements on Mars. The daily drinking water need for an astronaut is at least one or two litres per day and, even with the current recycling systems, water is still consumed for the production of breathing oxygen while hydrogen is dumped to space.

A study of the water needs per astronaut on the International Space Station (ISS) has estimated a daily consumption of 14.2 litres with a specific mass consumption varying from 10 to 20 percent of the total. If, for example, a mission lasted one year the total need per astronaut is 5,183 litres, excluding mass consumption and excluding the same amount needed again to account for the six months travel time there and back. Such a volume of water would also have weight implications for the payload at launch.

It is clear that if no significant amounts of water are found in situ, or transport problems solved, NASA's ambitions for Mars might be crippled. Furthermore, the important mineral resources for a permanent outpost are located in the volcanic terrains of the equatorial regions where the amounts of groundwater are even scarcer than those observed at higher latitudes. The claims of shallow underground water detected by radar are tenuous at best - even radar has a limited range underground.

One solution would be to dig deeper and deeper into the unknown underground in search of the expected water resources. However, this would require a great expense of energy with no guaranteed results.

The only viable option might be the construction of very long pipelines from the (sub)polar regions to the equator. But this would require absurd logistics for astronauts and materials and high operational costs. Of course, robotic methods remain the most economical and safest options for the exploration of Mars.

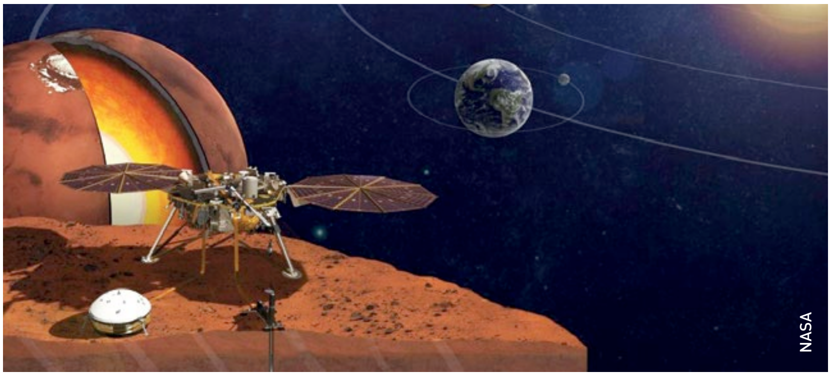
It would appear then, that the current US exploration plans for Mars are not well supported by a careful study of available and secure water resources.

In addition, the search for life on Mars does not seem based on a well-grounded preliminary analysis from orbit. The landing sites of the latest rovers were chosen on the hypothesis that impact craters were once filled by water.

However, high-resolution Mars Reconnaissance Orbiter images clearly show that lava flows from Tyrrhenum Mons head into the Gale crater via Herschel crater and Farah Vallis - features that do not seem to be taken into account before Curiosity touched down on the Martian surface. And this is not the only example of lava filled craters. Indeed, the majority of the impact craters on Mars are filled by lava and/or by basaltic sands of volcanic origin transported by the wind.

When viewed from this perspective Mars is not at all a new promised land waiting for human colonisation, but a cold and arid world that does not contain or support life. Despite this, it is still a world rich in mineral resources and we must continue our exploration to understand which is the best and most cost-effective way to exploit them.

This might be easily accomplished by robotic miners, which do not need expensive life support systems and so alleviate the risk posed to human life. Future programmes would benefit from taking this into consideration and, although unlikely, if life is found during the search it would be an unsurpassed bonus to say the least. ■

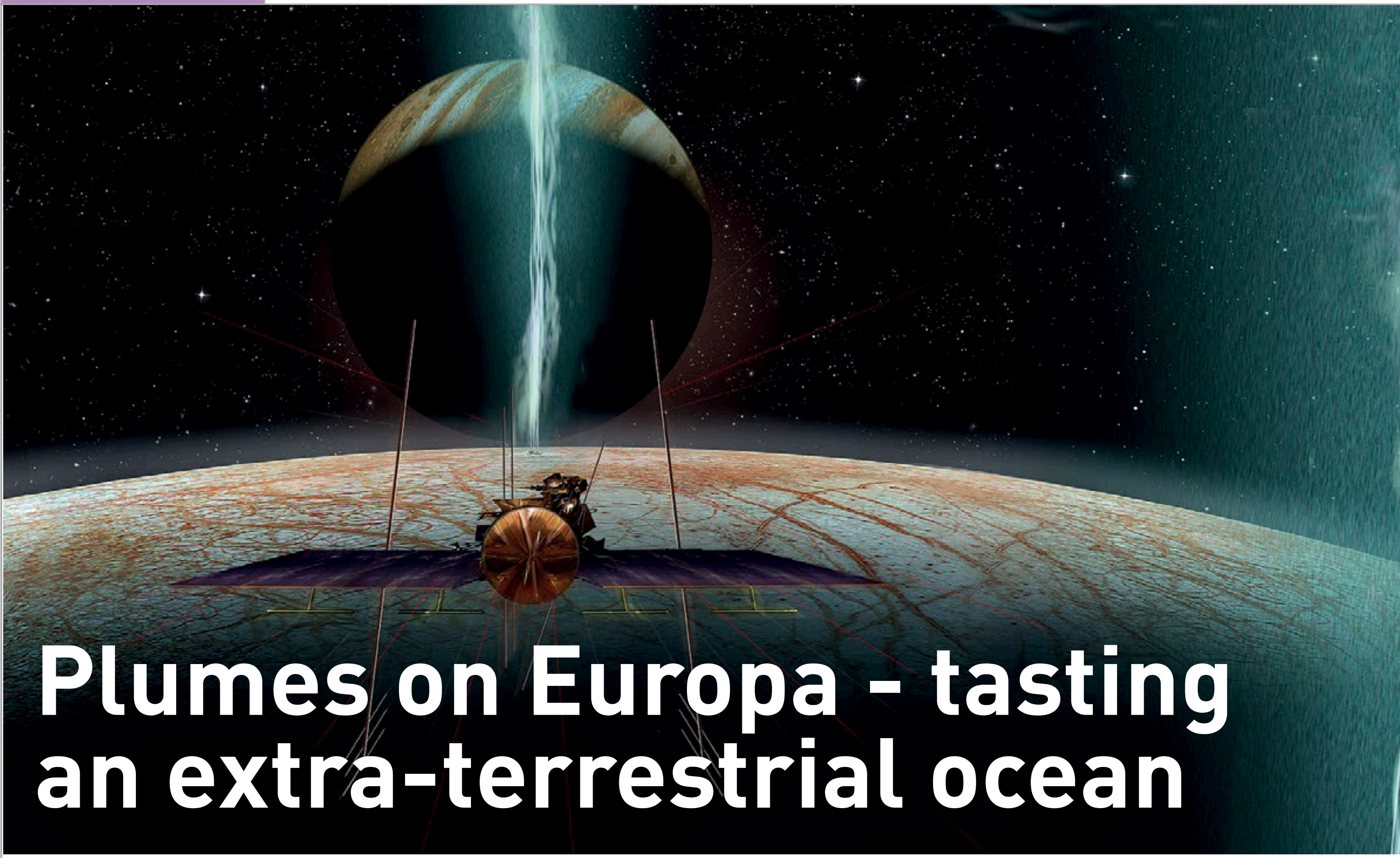


▲ NASA's InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) lander will be the first mission to explore the deep interior of Mars. Launch is scheduled for May 2018.

About the author

Dr Giovanni Leone graduated from Eidgenössische Technische Hochschule (ETH), Zürich, and Lancaster University, UK. His areas of expertise include volcanology, geochemistry, geophysics and modelling, and he also offers consulting services on earthquake, volcanic, and hydrogeologic risk assessment for insurance and business industry.

◀ The solar arrays on NASA's InSight lander are deployed in this test inside a clean room at Lockheed Martin Space Systems, Denver. This configuration is how the spacecraft will look on the surface of Mars.



Plumes on Europa - tasting an extra-terrestrial ocean

▲ An artistic interpretation by James Vaughan of NASA's proposed 'Europa Clipper' lining-up to make a pass through one of Europa's enigmatic plumes.

Europa has captured the imagination of scientists and enthusiasts alike with its intriguing features that hint at a hidden ocean beneath its icy surface. So what does lie beneath? And if it is a vast ocean, does it have the right ingredients to support life? Life that is perhaps similar to the creatures found at the depths of our own oceans far away from light and the Sun's influence? ESA's JUICE mission will soon be en route to sample, amongst other things, the chemical ingredients of vast plumes shooting up from the moon's surface, to give scientists more knowledge of how habitable any sub-surface seas might be.

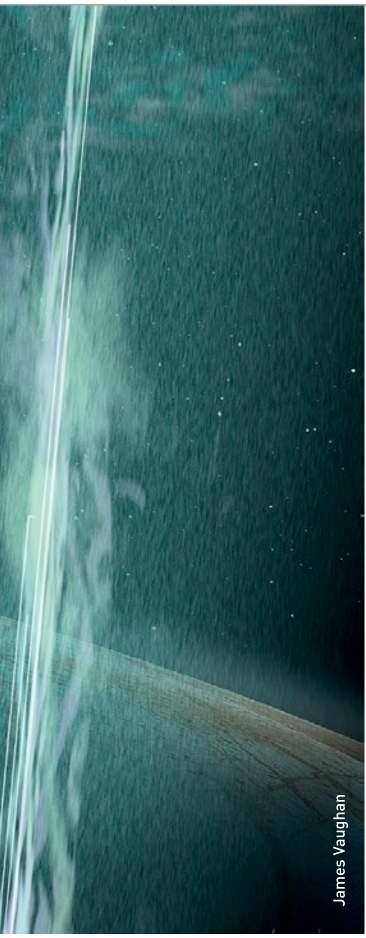
Hans Huybrighs
Max Planck Institute for Solar System Research, Göttingen, Germany

Slightly smaller than our own Moon, Europa is the smallest of the four Galilean moons orbiting Jupiter and its distinguishing surface features have led scientists to suggest that beneath its icy exterior lies an ocean of liquid water. What makes Europa's ocean interesting compared with other similar moons, is not just that it exists, but that this ocean might be able to support life. Until recently the idea of studying this ocean directly seemed something for the distant future; landing on the surface of Europa and penetrating several kilometres of ice is not an easy task.

Nonetheless, observations taken with the Hubble Space Telescope (HST) seem to indicate that liquid water might be escaping into space from beneath the ice in the form of giant plumes. Flying through those plumes and taking samples might give us direct access to the contents of the ocean, without even having to land on the ice moon's surface.

The first mission that might be able to exploit this opportunity is the Jupiter Icy moon Explorer (JUICE), comissioned by the European Space Agency (ESA). Scheduled for launch in 2022, JUICE is expected to arrive in the Jovian system in 2029 and head to Europa in the early 2030's. It will also visit and spend time analysing Jupiter's other large icy moons, Ganymede and Callisto.

For the study of the plumes on Europa, simulations show that during the flybys, water (H_2O) and ionized water (H_2O+) from an active plume should be detectable with the on-board particle detector instruments.


James Vaughan


Airbus Defence & Space

◀ Testing a model of the JUICE spacecraft 16 m antenna system in September 2017.

Europa's ocean

The presence of water on Europa has been known about for some time, as the spectroscopic analysis of light reflected from the surface shows that it is made of water ice. Other measurements of the moon, made mostly with the Galileo spacecraft, indicate that there is a global ocean of liquid water hidden underneath a thick layer of ice and although it cannot be viewed directly, there are strong indications it is there. The moon's surface geological features, for example, suggest that there is at least a 'slushy' ice layer under the surface as some craters appear to have been 'refilled' with ice after the initial meteorite impact.

In addition, measurements of Europa's magnetic field by Galileo also show that the moon has its own magnetic field, the strength of which varies continuously. This variation is linked to Europa's movement relative to Jupiter's magnetic field. It is possible therefore that Jupiter's magnetic field is inducing a corresponding magnetic field via a conductive layer - made from a salty ocean - under the moon's icy surface.

Finally, measurements of the gravity field also taken by Galileo on the interior composition of Europa, suggest a liquid layer could be there.

Estimates of the thickness of the ice-ocean layer range from 80-150 km, of which the ice layer is thought to be between a few and 20 km thick.

Having a source of liquid water on a moon is not an automatic guarantee that life is present; other factors have to be considered too

Habitability

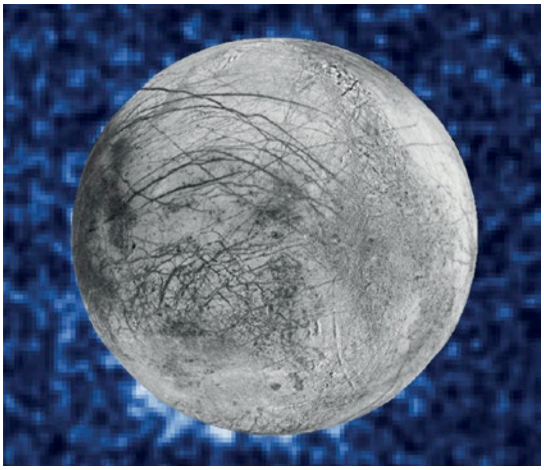
Having a source of liquid water on a moon is not an automatic guarantee that life is present; other factors have to be considered too, such as a stable environment (liquid water has been present for an extensive period of time?) and access to essential elements - the basic elements needed for life as we know it: sulphur, phosphorus, oxygen, nitrogen, carbon and hydrogen. All of these criteria are met for Europa.

One further fundamental ingredient that is also required is a source of energy. For example, Earth-like life largely depends on photosynthesis. Europa's ocean will be very dark, because it is sealed off by the ice. Hence in this instance, photosynthesis is not a likely source of energy. However, unlike the other Galilean moons, Europa's ocean is in direct contact with the rocky interior. Thus, geothermal vents at the bottom of the ocean could release reducing substances into the ocean that could fuel chemosynthetic metabolism (comparable to the black smokers on Earth's ocean floor). Furthermore, oxidising substances that are formed at the surface of Europa (by charged-particle bombardment) and transported back into the ocean could also contribute to chemosynthetic metabolism.

Water vapour plumes

The existence of cryovolcanism with accompanying plumes on the surface of Europa has been hypothesised in the past. However, up until 2014 no evidence of any current activity had been reported. Observations made with the HST in December 2012 and reported in 2014, hinted for the first time at the occurrence of a transient plume of water vapour near Europa's south pole.

The method that led to this first pivotal plume detection is worth explaining in more detail. Europa has a thin atmosphere, referred to as exosphere, which is continuously bombarded by high energy plasma particles from Jupiter's magnetosphere,



▶ A composite image showing suspected plumes of water vapour erupting at the 7 o'clock position off the limb of Jupiter's moon Europa. The plumes, photographed by NASA's Hubble Space Telescope Imaging Spectrograph, were seen in silhouette as the moon passed in front of Jupiter. NASA/ESA/W Sparks

Unlike the other Galilean moons, Europa's ocean is in direct contact with the rocky interior

which results in an auroral glow. Observing this auroral glow in visible light is difficult, since there are much brighter sources of light in this environment. However, in the ultraviolet (UV) these emissions can be identified more easily. It was during an observation of these UV emissions that a surplus of oxygen and hydrogen spectral lines were detected near Europa's south pole. The emission was characteristic of water vapour being dissociated by the impacts of high energy electrons. If this emissions surplus is indeed caused by a water vapour plume energised by the plasma bombardment, it implies the plume is 200 km high and expels 7000 kg of water per second. Attempts were made to repeat this observation but out of 20 attempts in total only the one, in December 2012, proved to be successful.

Then in late 2016, a new observation was reported by a second team who used a different method to study the plume. Their new approach was to observe the limb of Europa (the 'edge' of the planet) while it moves in front of Jupiter. If a plume was present during such a observation, the plume would block out part of the sunlight being reflected by Jupiter. The method proved to be more successful and out of 12 observations, between 2014 and 2016, four possible plumes were detected. However, this method only tells us that there could be a local exospheric density increase; it does not tell us anything about composition.

Although plumes on Europa have potentially been observed five times now, both of the applied methods offer only indirect evidence and, as yet, an unambiguous detection of the plume has still to be reported. It is likely that we will have to wait for such a confirmation until either JUICE or NASA's Europa Clipper mission arrive at the ice moon in the early 2030s.

▼ Artist's concept of JUICE at Jupiter.

Airbus Space & Defence

Particle detector

ESA's JUICE will make flybys of Europa and Callisto, and also enter orbit around Ganymede. As currently planned, it will make two flybys of Europa, with a closest approach planned at 400 km. Together with NASA's Europa Clipper mission, it will be the first opportunity to study this enigmatic world from close-quarters since the Galileo mission.

One of the 11 JUICE experiments is the Particle Environment Package (PEP), comprising six instruments designed to study the particle environment in situ. These instruments detect particles (electrons, ions and neutral particles) in the vicinity of the spacecraft and give information about their energy, the direction they are coming from and their mass (and thus their composition). In our study we have investigated the feasibility of detecting H_2O (water) and H_2O+ (ionized water) from the plume with two PEP instruments - the Neutral gas and Ions Mass spectrometer (NIM) and the Jovian plasma Dynamics and Composition analyser (JDC).

NIM is designed to study the density and mass of neutral particles, while JDC is an ion-detector that gives information about the direction and energy of the particles, along with the flux (density times velocity).

To be able to simulate the detection of H_2O and H_2O+ from the plume, we need to know how these particles distribute in space and we have developed a model that simulates the trajectories of the particles in the plume. Looking first at H_2O, these particles in our model originate from a source on the surface of Europa and propagate through space as influenced by Europa's gravity.

The velocity of the particles derived from the first observation (700 m/sec) implies that particles will mostly fall back on the surface of Europa, since this velocity is well below the escape velocity (2 km/sec). However, due to the temperature of the gas, the velocity of the particles will vary and our model shows that some of them will reach the altitude of the spacecraft before falling back.

Europa resides deep inside Jupiter's magnetosphere where there is a high flux of high energy plasma that will interact with the neutral plume particles. The interaction with high energy electrons and ions from Jupiter's magnetosphere will ionize some of the H_2O into H_2O+. These H_2O+ ions will propagate in a very different way from the neutral H_2O as their trajectories are no longer dominated by gravity but rather by electric and magnetic fields.

In its orbit about Jupiter, a flow of plasma moving in the same orbit as the moon, but faster than Europa itself can be distinguished. This plasma flow is co-rotating with Jupiter's magnetic field and constantly overtakes Europa. The H_2O+ ions start moving with this plasma flow, away from the moon. They do this while moving in trajectories that are referred to as 'cycloid trajectories'. So although the neutral H_2O particles mostly fall back to the ice moon's surface, the H_2O+ ions are transported away from Europa.

Using this model, we can simulate the distribution of H_2O near the spacecraft and the results show that the number of particles reaching the vicinity of the spacecraft is high enough to be detected by NIM. The model also gives the density and velocity distribution of H_2O+ needed for the JDC simulation and again, the flux is sufficiently high to detect the particles. Detection is possible even though we have restricted the simulation to plumes that expel 1 kg of water per second, which is significantly less than what could be derived from the observation (7000 kg/sec).

The mission is not without its problems, however, and some will be more easily overcome than others. 'Noise' generated from the high energy electrons in Jupiter's magnetosphere, for example, is likely to penetrate the instruments and generate false counts though the high signal to noise ratio for the two instruments should be sufficient to overcome this problem.

What is likely to cause some consternation is separating the mechanisms that create H_2O+; the high energy plasma in Jupiter's magnetosphere causes the release of H_2O from Europa's surface ice and unfortunately (for us) this H_2O will also be ionized into H_2O+.

The instruments can't in principle discriminate between the H_2O/H_2O+ originating from the plume or from the surface ice. Detecting the plume is only possible because it creates a local and not global enhancement. Thus, accurate knowledge is needed of the distribution of H_2O/H_2O+ in the exosphere which can hopefully be gained from remote sensing instruments on board JUICE.

Opportunity

The plausible, but not conclusively proven, existence of water vapour plumes on Europa creates an interesting opportunity to 'taste' Europa's ocean and JUICE should be able to detect such plumes, even if they expel significantly less material than has been observed.

If JUICE is not as successful as we anticipate, then NASA's Europa Clipper mission could pick up where JUICE leaves off. Europa Clipper is scheduled to make 45 flybys of Europa coming as close as 25 km compared to the 400 km for JUICE. ■

About the author

Hans Huybrighs is a PhD student in space physics at the Max Planck Institute for Solar System Research, The Swedish Institute of Space Physics and the Technical University of Braunschweig. The goal of his current research project is to find evidence of Europa's plumes in particle detector data collected by NASA's Galileo mission. Additionally, he works on predictions for future measurement campaigns of Europa's exosphere and plumes.

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Though plumes on Europa have potentially been observed five times now, an unambiguous detection of the plume has still to be reported

▼ Jupiter's moon Europa.

ROOM is an open forum for comment and opinion - and actively encourages contributions. To promote debate, discussion and inspiration we regularly publish commentaries and opinions by space leaders and those involved directly or indirectly in aerospace and space exploration. If you have something to say and would like to contribute, please get in touch - editor@room.eu.com

Are we asking the right questions about space debris?

▲ Many tens of thousands of man-made debris objects are in Earth orbit posing a dynamic collision risk to operational satellites and other debris.

Darren S McKnight
Technical Director, Integrity Applications, Chantilly, Virginia, USA

The aerospace community has rightfully spent significant resources considering how to prevent a potential cascade of catastrophic collisions leading to an exponential growth in the debris environment (i.e., the Kessler Syndrome) that was identified decades ago [1]. The typical proposed response is the steady, long-term removal of abandoned rocket bodies and payloads (i.e., five objects a year for 100 years) [2]. Active debris removal (ADR) analysis assumes that we are unable to determine which events might occur first; the overall effect is that one must remove 35-50 objects on average to prevent a single collision and around 15 collisions are estimated to occur in this 100-year scenario. These collisions would likely erode spaceflight safety significantly in the near-term even while possibly preventing environmental instability over the next century. The psychological inertia of this scenario as a community norm has created two trends: one, policymakers see ADR as a non-urgent, cost-prohibitive option and two, engineers are fixated on a traditional, statistical ADR concept of operations.

In the paper 'Preliminary Analysis of Two Years of the Massive Collision Monitoring Activity' presented at the International Astronautical Congress (IAC) in Adelaide, Australia, in September 2017, I reported on an ongoing space monitoring and characterisation experiment that is investigating alternatives for controlling the growing orbital debris hazard.

Cluster name	Cluster member	Mass (kg)	Number	Apogee (km)	Perigee (km)	Inclination (deg)	Collision Rate/Year	Debris Produced Catalogued/lethal non-trackable
C775	SL8 RB	1,434	44	793	733	74	~1/400	~4,000 / 60,000
	SL8 PL	850	44	802	742			
C850	SL16 RB	8,300	18	860	814	71	~1/800	~16,000 / 200,000
	SL16 PL	3,250	18	868	823			
C975	SL8 RB	1,434	144	1020	935	83	~1/90	~4,000 / 60,000
	SL8 PL	800	142	1024	934	83		
	Other PL	1500	15	997	905	64		
C1500	SL8 RB	1,434	17	1660	1330	74	~1/1300	~5,000 / 75,000
	SL14 RB	1,407	24	1530	1363	83		
	SL14 PL	2,477	24	1507	1381	83		
TOTAL	~756k	490	-	-	-	-	-	-

RB = rocket body; PL = payload.

▲ The four clusters monitored in MCMA are the 'hot spots' in LEO as the collisions will be the most consequential and the collision rate is significant.

I hypothesise that it is more important to examine immediate space safety risks rather than long-term environmental stability. Scrutinising a limited subset of the debris population that will create the most consequential events (i.e., clusters of massive abandoned space objects) provides clarity in risk calculations that may help to prove or disprove this hypothesis.

Assurance of immediate spaceflight safety as the primary objective has encouraged us to examine the possible short-term, highly consequential events (rather than trying to determine the average collision hazard across the entire catalogued population over the long term), a refocus which led us to examine debris 'hot spots' in Earth orbit where the most massive objects might interact with each other at hypervelocity speeds (i.e., above 6 km/s).

In summary, we are striving to break out of the cognitive bias of studying 100-year evolution models, waiting for someone to develop ADR solutions, or hoping that massive collisions will not occur.

In contrast, I suggest we follow a sequence of monitoring (examining interactions amongst clusters of massive objects) and characterising (determining cluster dynamics relevant to collision risk determination and debris remediation prioritisation) to provide a basis for responsible action (e.g., remove the 'worst offenders' or create an emergency response capability to prevent imminent collisions). This experiment is called the Massive Collision Monitoring Activity (MCMA).

~~Study, wait and hope'~~

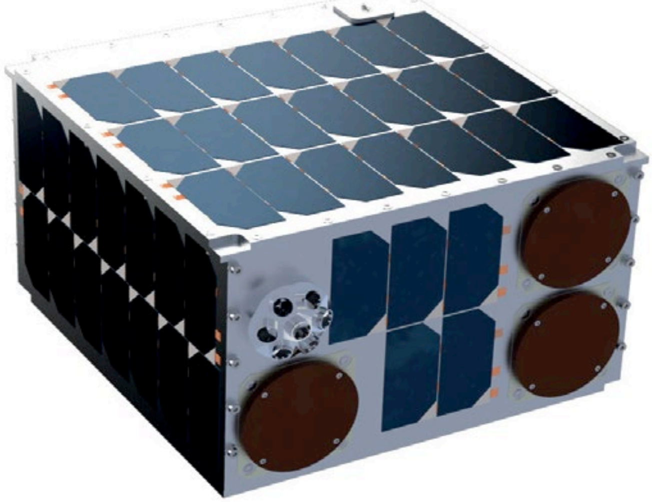
Monitor, characterise, and act

Massive Collision Monitoring Activity

The MCMA has been designed to challenge us by asking several questions. What are the most consequential events that can occur in low Earth orbit (LEO)? What does the 'average' collision event within the satellite catalogue really mean? Can we predict the most likely next massively catastrophic collision? Can we enhance the utility of ADR operations? And, can we respond to an individual potential collision?

The clusters identified for the initial MCMA effort were selected by considering (1) proximity of apogees and perigees (i.e., clumped in altitude); (2) common inclination values (speculated to cause

It is more important to examine immediate space safety risks rather than long-term environmental stability



SSTL/ASTROSCALE

▲ ASTROSCALE and Surrey Satellite Technology Ltd (SSTL) are working on a first joint demonstration mission to simulate orbital debris capture to validate key technologies for end-of-life spacecraft retrieval and disposal services.

greater interaction rates); (3) total mass involved in a potential collision; and (4) altitude of the centre of the cluster (i.e., high enough so that debris produced would be long-lived).

It should be no surprise that the riskiest clusters identified are in LEO due to faster orbital velocities, higher mutual inclinations and a bigger concentration of debris.

These criteria resulted in the selection of four clusters that contain nearly 500 objects that have an aggregate mass of nearly 800,000 kg. The accompanying table provides the characteristics of the four clusters. The clusters are named by their centering altitude; C775 is centred at roughly 775 km altitude, etc. All of these clusters were largely populated between 1990 and 2007 by the deployment of payloads to long-lived orbits and abandoning the rocket stages that deployed them into similar orbits.

Within these LEO clusters, 85 percent of the interactions exceed hypervelocity speeds. The typical observation that the average encounter speeds in LEO are 10 km/s is somewhat misleading since for these clusters the median is around 12 km/s and the mode is well above 13 km/s.

Data in the table show that a collision is most likely in C975 as there is a ~1/90 probability each year that any two of the objects within C975 will collide with one another.

However, the most consequential collisions will occur in C850; if two SL-16 rocket bodies collide it would produce around 16,000 trackable fragments which would double the catalogued population in LEO.

In addition, it would create around 200,000 lethal but non-trackable (LNT) fragments (i.e., 1-10 cm size). These LNTs would in turn result in the reduction of the operational lifetime of all satellites in the 650-1050 km altitude range by an average of 10 percent [3]. An examination of the satellites residing within this altitude range suggests at least US$10-15 billion [4] so even 10 percent of this asset pool is significant.

We need to do a better job of expressing these risks and explaining the limitations of these models

Explaining risk

While the Poisson probability distribution is often used to determine probability of collision and collision-rate for orbital debris applications, the gamma distribution [5], that predicts the probability of when the first event is likely to occur, is enlightening and produces the following two observations:

- for C975, within which a collision would produce around 4,000 catalogued fragments, there is approximately an 11 percent chance that statistically such a collision could have already occurred
- and similarly, for C850, within which a collision would generate some 16,000 trackable fragments, there is around a one percent chance that statistically such a collision could have already occurred.

These numbers are significant since these are the statistics that 'experts' will quote to people after an event occurs justifying that we understood the debris population and our models are correct. They are correct. However, we need to do a better job of expressing the risks and explaining the limitations of these models.

There are two main issues about these statistics that we need to be clear about. First, the average value is not always the typical value, and the average only provides a small part of the answer. The variance (i.e., possible spread in values about that average) and shape of the probability distribution is critical to understanding the range of possible outcomes.

When it comes to on-orbit collisions, the variance about the average value is very large because of measurement limitations and the limited amount of historical data (i.e., we have only had one accidental catastrophic collision in space).

Second, the sad truth is that since the probability of any one event is so small, even the most likely event will probably not be the next event.

At a more cognitive level, it is instructive to listen to experts who have stated that for aerospace and business catastrophes, 'multiple near misses preceded (and foreshadowed) every disaster and business crisis [we] studied and most of the misses were ignored or misread'.

Their research also suggests that cognitive biases serve to desensitise managers to near misses. This behaviour is captured in the cognitive biases of normalisation of deviance (i.e., over time accept anomalies) and outcome bias (i.e., focus on results more than, often unseen, complex processes) [6].

As a matter of fact, the experts in the psychology of anomaly reporting and risk acceptance state that 'viable approaches to preventing [such] catastrophes are to observe near-misses and use them to identify and eliminate problems before they produce large failures' [7].

MCMA is an attempt to provide this information; while advanced modelling techniques can be applied to collision risk calculations, it is all for naught if risk communications and risk awareness are neglected.

In C975, over the last 18 months, there have been five recorded conjunctions with miss distances under 100 m. These encounters are within the positional uncertainty of these objects' orbits so we can reasonably consider ourselves 'lucky' that we did not have a collision; these are near misses. Now that you are reading this article, you cannot say that you do not know about them. However, without MCMA there is no monitoring and reporting of conjunctions between two massive debris objects. Are these the types of close calls that the experts have told us not to ignore?

In C850, we have had five encounters less than 500 m over the last two years. While these encounters are less likely to have been official 'close calls', these events would have resulted in a doubling of the LEO catalogued population instantly. Are these misses 'too close for comfort', serving as a harbinger for an impending massive breakup event, or are they meaningless as a future indicator for debris growth? These are the sort of questions we continue to pursue answers for with the MCMA.

Interestingly, the risk values for these two primary clusters (as determined by the product of probability and consequence) are within a factor of two of each other and are orders of magnitude greater than the other two clusters. Further, encounter data from MCMA over the last two years were analysed to identify the top four 'worst offenders' (i.e., determined to have the highest debris-generating risk in any of the clusters); two are from C975 (satellite numbers 15056 and 32053) and two from C850 (satellite numbers 31793 and 22285).

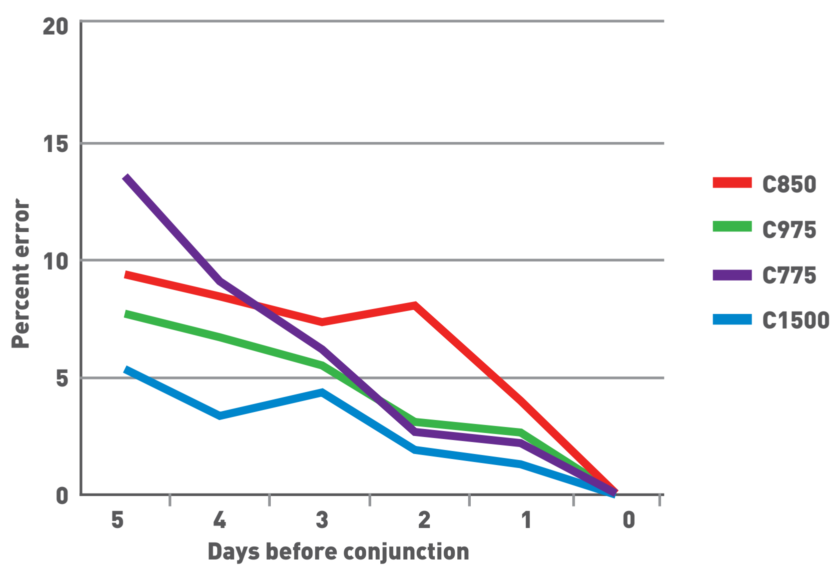
Predicting conjunctions

As part of the MCMA, it has been shown that we are capable of predicting the conjunction of these massive abandoned objects to within five to 14 percent of the miss distance five days before the encounter as shown in the accompanying figure. These curves are based upon over 20,000 conjunctions between massive objects in 'high-LEO' orbits. As you might expect, generally the higher altitude clusters have smaller errors as atmospheric drag is less influential at the higher altitudes.

This capability to predict close encounters days in advance may provide a mechanism to improve the return on investment from ADR operations by possibly making an ADR mission as an emergency response (e.g., just-in-time

Are these misses 'too close for comfort' or are they meaningless as a future indicator for debris growth?

▼ The accuracy of predicting conjunctions improves as we increase altitude and as we get closer to the conjunction date/time.



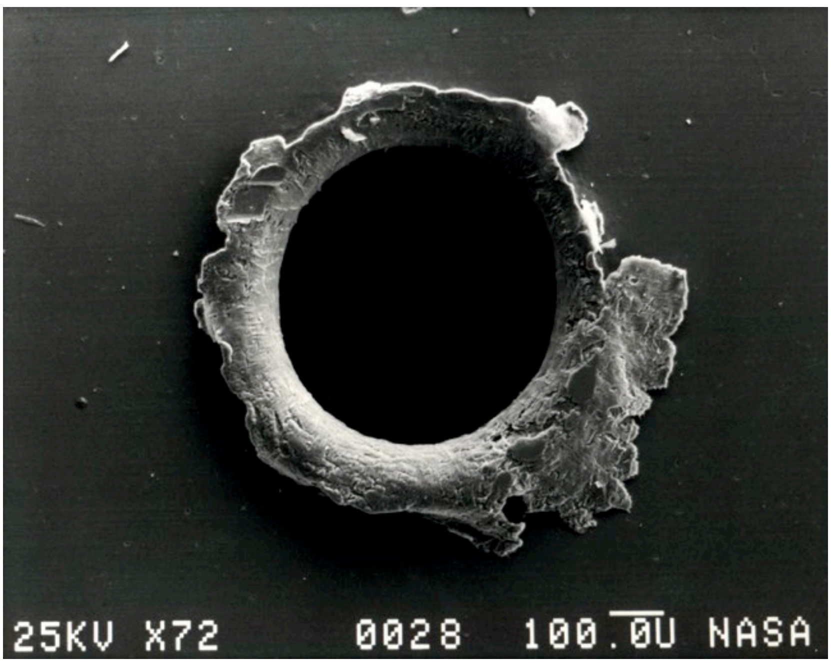
It would be prudent to capture more of the massive derelict population that could contribute to significant debris-generating events

ADR or JADR) rather than a strategic clean-up process expected over decades implied when ADR is mentioned.

In addition, the ability to predict close approaches accurately five days in advance may enable the use of Just-in-time Collision Avoidance (JCA) to prevent collisions. JCA's mission is to deposit a 'puff of talc' (on a ballistic trajectory) in front of an orbiting derelict object on a potential collision course in order to nudge it away from the impending collision. Analyses have shown that existing sounding rocket technology is responsive enough to support this solution, however, there are still some challenges related to the accurate placement (in time and space) of a nudging cloud [8].

The motivation for MCMA is to monitor and characterise a small, but consequential, subset of the catalogued population with the hypothesis that they pose the majority of the risk for large debris-generating events. Indeed, it is without doubt that encounters within the four clusters monitored within MCMA produce the vast majority of the most consequential collision events possible in Earth orbit. This monitoring process provides both a quantitative accounting of potential near misses that should not be ignored and insights that might enable new remediation options (such as JCA and JADR). It is hoped that the results from the MCMA will help to spur the aerospace community to take tangible steps to remove massive derelict objects from LEO.

▼ View of an orbital debris hole made in a panel of the Solar Max satellite.



Next steps?

While the four clusters that account for around 500 massive derelicts amounting to approximately 800,000 kg of mass (i.e., one third of derelict mass in LEO) provides a compelling representation of a very important subset of the debris population, it is incomplete.

Since we have already learned that the most likely event is likely not the next event to occur, it would be prudent to capture more of the massive derelict population that could contribute to significant debris-generating events.

The MCMA experiment has recently been expanded to include a total of ~800 massive derelicts amounting to ~1,600,000 kg of mass which now includes all derelict objects with a mass over 2,000 kg that reside in or transit through LEO (i.e., perigee less than 2,000 km).

This monitored population now includes the hundreds of massive transfer rocket stages that pass through LEO at their lowest altitude while transiting to altitudes as high as 20,000-36,000 km. These transfer orbits create another interesting, potentially cross-contaminating hazard that is now being studied very carefully. ■

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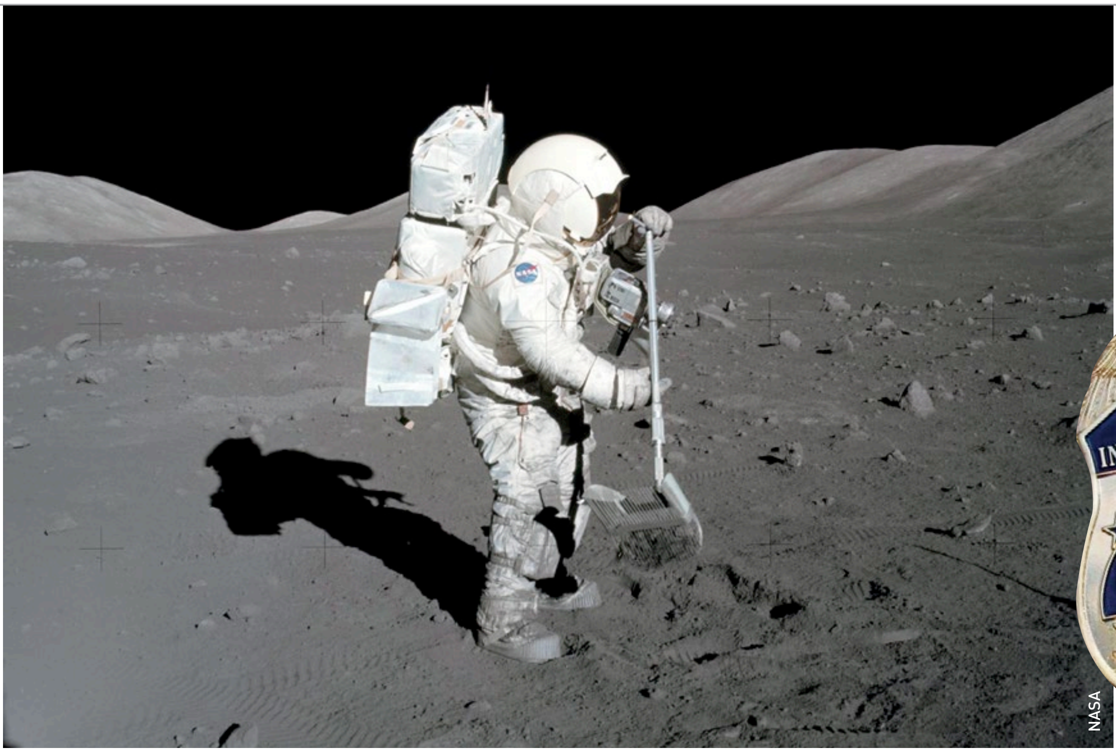
About the author

Dr Darren S McKnight is Technical Director at Integrity Applications, Inc. (IAI). He leads teams to develop creative solutions across widely disparate domains including space systems, renewable energy, predictive awareness for infectious disease outbreaks, bioterrorism and orbital debris. He is a member of the International Academy of Astronautics' (IAA) Space Debris Committee and has Bachelor's Degree from the US Air Force Academy in Engineering Sciences, a Master's Degree in Mechanical Engineering from the University of New Mexico, and a Doctorate in Aerospace Engineering Sciences from the University of Colorado.



◀ Scientist-astronaut Harrison-Schmitt collects lunar rake samples ranging in size from 1.3 to 2.5 cm during the Apollo 17 mission in 1972. The rake was used to collect rocks and rock chips

NASA's space police wield full force of law to protect Moon rock and dust

Zero tolerance for unlawful possession is generally viewed as the mantra for the United States' war on drugs and this approach has spawned a web of bureaucratic entities dedicated to uncovering and seizing unlawfully possessed controlled narcotics. What is not generally known is that the US employs a similar zero tolerance stance for unlawfully possessing what is now known as an 'extracted space resource'. This zero tolerance regime, like the war on drugs, has its roots in the late 1960s, is still in force, and engages in zealous seizure operations. Unlike the war on drugs, the supply source for extracted space resources is extremely limited thereby making transactions in minuscule amounts very lucrative. While the supply source may change in light of the US law allowing for the commercial extraction of space resources by licensed private ventures, it is doubtful that the zero tolerance regime will dissipate. A glance at the current deployment of the policy may offer a glimpse into a potential space age American law enforcement regime.

George Anthony Long
Managing Member,
Legal Parallax, LLC,
Nevada, USA

In 2015 the United States enacted a law defining 'space resource' to mean an 'abiotic resource in situ in outer space', which includes but is not limited to water and minerals. This definition is considered to include abiotic or non-biotic resources located on the Moon, planets and other celestial bodies. There was no legal definition for 'space resource' prior to 2015, but that does not mean space resources were non-existent.

Between 1969 and 1972, the Apollo programme conducted six crewed Moon

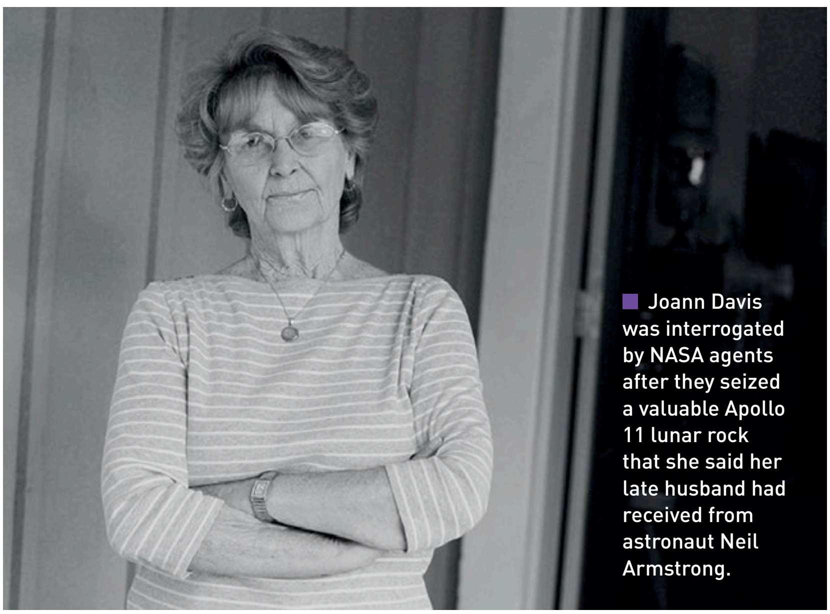
▲ Apollo 16 lunar sample weighing 128 grams, collected by astronaut John W. Young about 15 m southwest of the landing site. There is a strong unofficial market for extracted lunar material like this.

▲ Above right: Moon rock replicas are available to purchase from NASA.

missions that garnered about 382 kilograms of rocks, core samples, pebbles, sand and dust extracted from the lunar surface. The US has consistently maintained that it owns all lunar material collected during the Apollo missions unless it knowingly transferred title to another. It does not base its ownership claim on a specific unambiguous law passed by Congress, but instead asserts its title claim through a series of administrative directives issued by NASA. Apparently, no foreign government has ever protested or objected to the United States claiming ownership over the extracted lunar material.

In conjunction with its ownership claim, the US has adopted a policy that no one can own or possess any portion of the lunar material extracted during the Apollo missions unless it has formally transferred possession of or title to the material. However, as with any precious, rare and lucrative commodity, an unofficial market developed resulting in the disappearance of small quantities of extracted lunar material. The US has been vigilant in seeking to retrieve any unlawfully held lunar material and the case of United States v. One Lucite Ball Containing Lunar Material, 252 F.Supp.2d 1367 (S.D. Fla. 2003) is one such instance.

In 1973, the US distributed a small speck of lunar material extracted during the Apollo missions as a goodwill gift to 135 countries, with Honduras being one of the countries. Each goodwill gift weighed about 1.1 grams. In the mid-1990s, a retired Honduras colonel was offering to sell the Moon rock Honduras had received. Rosen, an American citizen in Honduras on business, became aware of the offer and, following some negotiations, acquired the Moon rock and its accompanying plaque from the retired military officer. Rosen then obtained two independent verifications that the item he possessed was in fact lunar material.



■ Joann Davis was interrogated by NASA agents after they seized a valuable Apollo 11 lunar rock that she said her late husband had received from astronaut Neil Armstrong.

Undercover

In 1998, NASA formed an undercover company as part of a sting operation to snare dealers in lunar material. The undercover company placed an ad in a national newspaper soliciting the purchase of lunar material. Rosen apparently

The United States has adopted a policy that no one can own or possess any portion of the extracted lunar material without its authorisartion

experienced a momentary lapse of reason as he thought this presented a viable commercial opportunity for a transaction involving a rare, precious and extremely unique resource.

Rosen responded to the newspaper ad and spent two months negotiating with undercover federal agents posing as representatives for the interested purchaser, asking US$5 million for the Moon rock and accompanying plaque. Although he harboured some concern that the representatives might be federal agents, Rosen's reason and good sense were trumped by an apparent desire to consummate the transaction.

After convincing Rosen to designate a site where they could inspect the Moon rock and the accompanying plaque, federal agents appeared at the designated inspection site and seized both. The US then successfully instituted civil forfeiture procedures against the Moon rock and accompanying plaque, claiming the items were stolen property that it had previously transferred to Honduras. The Moon rock and plaque were subsequently returned to Honduras.

While the One Lucite Ball case displays the accepted subterfuge of an undercover sting operation, the investigation and facts underlying Davis v. United States, 854 F.3d 594 (9th Cir. 2017) reveal a disturbing darker side.

Joann Davis and her husband worked for a NASA contractor during the Apollo programme. Joann's husband was considered a brilliant engineer and eventually became a contract manager for the Apollo programme. According to Joann, her husband received memorabilia associated with the first Moon landing mission, Apollo 11, which included two encased paperweights. One of the paperweights contained a small fragment of the Apollo 11 heat shield with the other containing a small piece of Moon rock extracted from the lunar surface during the mission. The Moon rock was about the size of a rice grain. Joann's husband died in 1986 and she said the Apollo 11 memorabilia passed to her as part of her deceased husband's estate.

Joann subsequently remarried in 1991. In 2011, she began to experience financial difficulties. Her monetary problems developed because her son suffered from a medical condition which necessitated more than 20 surgeries and extensive medical supervision and care. To further complicate her financial struggles, Joann was also raising several grandchildren following the untimely death of her youngest daughter.

◀ In 1973, the US distributed a small speck of lunar material embedded in a ball of Lucite acrylic glass as a goodwill gift to 135 countries.

Paperweight auction

To cope with the financial strains, Joann decided to determine the value of the Moon rock memorabilia in hope that it had some value and could assist in defraying her son's medical expenses. She contacted several public auction houses to market the paperweight but did not receive any positive responses. She also attempted unsuccessfully to utilise the internet to locate someone to assist in selling the Moon rock. On being unable to find a market outlet for the Moon rock, Joann emailed NASA on 11 May 2011 requesting its assistance in selling the Moon rock her first husband received as memorabilia for his association with the Apollo programme. Immediately upon receipt of Joann's email, NASA authorised a criminal investigation into the claim that she possessed an Apollo 11 Moon rock. The investigation included the prompt institution of an undercover operation.

Within hours of NASA receiving her email, a NASA undercover agent posing as a 'broker' named Jeff telephoned Joann. 'Jeff' told Joann that he had worked on the Space Shuttle programme, was well known at NASA and had been informed of her email. 'Jeff' and Joann engaged in several telephone conversations during the next few days

As with any precious, rare and lucrative resource, an unofficial market developed, resulting in the disappearance of small quantities of extracted lunar material

NASA formed an undercover company as part of a sting operation to snare dealers in lunar material

and NASA recorded all of the conversations except for the first one.

The recorded conversations revealed that Joann wanted US$1.7 million for the Moon rock and that she would never voluntarily give the Moon rock to NASA. The recordings also disclosed that Joann had discussed the tax implications of the memorabilia sale with her accountant because she wanted the sale to be 'above board'. The conversations also revealed that Joann knew that NASA could confiscate the Moon rock paperweight if she could not prove lawful possession. 'Jeff' acknowledged Joann's desire to lawfully sell the items, but informed her that selling the lunar material could not occur in a public forum. The NASA operative never told Joann that the lunar material was US government property or that her possession of the material was illegal.

Based on the recorded conversations, NASA obtained a search warrant targeting Joann and authorising seizure of the paperweight containing the rice grain sized lunar rock. NASA executed the warrant on 19 May 2011, eight days after receiving Joann's email. Preparation for executing the warrant involved the undercover operative arranging to meet Joann at a Denny's restaurant around noon, producing the Moon rock paperweight for inspection and finalising the transaction details.

Joann arrived at the restaurant with her husband, a retired employee of the Federal Bureau of Alcohol, Tobacco, Firearms and Explosives. Upon meeting and exchanging pleasantries with 'Jeff', Joann placed the Moon rock and Apollo 11 heat shield paperweights on the table. Unknown to Joann, there were at least two NASA criminal investigators and three undercover local police officers sitting at nearby tables. Upon Joann placing the paperweights on the table, the NASA agents approached the table and identified themselves. The officials secured Joann and her husband and seized the Moon rock paperweight. Joann and her husband were then escorted to separate locations in the restaurant's parking lot where Joann was interrogated by the NASA agents for between one-and-a-half to two hours.

At the time of the warrant's execution, Joann was 74 years' old and stood four feet, eleven inches tall. Upon being confronted by the NASA agents, Joann experienced an immediate need to evacuate her bladder. She requested permission to relieve the pressure of her biological urge. The NASA agents declined and Joann urinated on herself in her clothes in public. This did not deter the NASA agents who proceeded to interrogate Joann while she stood in the restaurant parking lot in urine-soaked clothes. After concluding their interrogation, the NASA agents informed Joann she was free to go home.

NASA subsequently verified the authenticity of the Moon rock Joann had in her possession and proceeded to take steps to criminally prosecute her but the US Attorney assigned to handle the prosecution exercised the prosecutorial discretion not to pursue a criminal prosecution. Joann's son died about seven months after her encounter with the NASA agents and Joann did not recover the Moon rock paperweight because she could not prove her first husband lawfully received it as a gift for his work on the Apollo programme.

Zero tolerance

In addition to Davis, another instance of zealous pursuit of zero tolerance is demonstrated by United States v. Ary, 224 F.Supp.3d 1186 (D. Kan 2016).

The Kansas Cosmosphere and Space Center is a space museum that displays space artefacts, many of which are on loan from NASA. Following the resignation of Cosmosphere's President and CEO, it was discovered that over the course of several years, the former museum executive had sold artefacts on loan from NASA for his personal enrichment. A federal search of the executive's residence resulted in the seizure of many items, which included artefacts NASA had loaned to Cosmosphere. The former executive was subsequently charged, convicted and sentenced for various violations of federal criminal law such as fraud, theft of government property and money laundering. His appeal was denied in 2008.

In 2014, the United States obtained an order forfeiting the items seized during the raid of the former executive's home and authorising their auction. The US then made arrangements with a private auction house to sell the forfeited items. A Lunar Sample Return bag was among the items forfeited and listed for auction, though the bag was not sold during the initial online auction as no bid was submitted for it. Another online auction was held in 2015 and the bag, together with a mesh cushion, sold for US$995 to Nancy Carlson.

▲ Sotheby's auction (above left) in July 2017 of the NASA Lunar Sample Return bag.

After receiving the bag, Nancy began wondering if it contained any traces of lunar material. Nancy subsequently contacted a NASA official about her curiosity and was informed that if she sent him the bag he could determine if it contained any lunar material. Nancy did so and a NASA analysis indicated that the bag contained Moon dust. A follow-up investigation revealed that the bag Nancy purchased was the outer decontamination bag for the first lunar samples collected during Apollo 11's Moon landing. NASA further determined that lunar dust was 'intrinsically mixed' with the bag's fabric. The determinations triggered deployment of the zero tolerance enforcement policy.

NASA declined to return the bag to Nancy. It then requested the court to set aside the forfeiture and rescind the sale of the bag on grounds that it remained the lawful owner of the bag and the lunar material. In support of its judicial request, NASA asserted that (1) it was not given direct notice of the bag's sale, (2) the bag was a unique cultural item that could not be replicated or replaced, (3) the bag was mistakenly allowed to go to auction, and (4) it did not knowingly relinquish ownership of the bag or the lunar material.

The Court noted that, at the time of seizure, NASA and not the former museum executive owned the bag; and that the forfeiture and auction of the bag were products of mistake and error. However, the Court could not find any legal authority to grant the government relief since Nancy was a bona fide purchaser at a court-sanctioned auction requested by the United States. Accordingly, the government could not deprive Nancy of title to the bag or the intertwined Moon dust. Nancy subsequently regained possession of the bag and in July 2017 sold the bag with the intertwined lunar dust for US$1.8 million.

Eventually a collective awakening may surface that 'space police' exist with zero tolerance for the unauthorised possession of a controlled space resource

Enforcement regime

The zero tolerance enforcement efforts demonstrated by the above cases may very well signal the genesis of a bureaucratic enforcement regime that can coalesce and expand under the statutory scheme establishing the commercial extraction of space resources.

Indeed, the development of a space resource extraction industry may eventually necessitate a specialised government unit tasked with enforcing the applicable federal regulatory provisions and shielding the investment and profits of the licensed commercial extractors from unlicensed merchants.

Such a development will probably not be an obvious occurrence but will stealthily emerge. Then eventually a collective epiphany will surface that 'space police' exist and that they have zero tolerance for the unauthorised possession of a controlled space resource. ■

About the author

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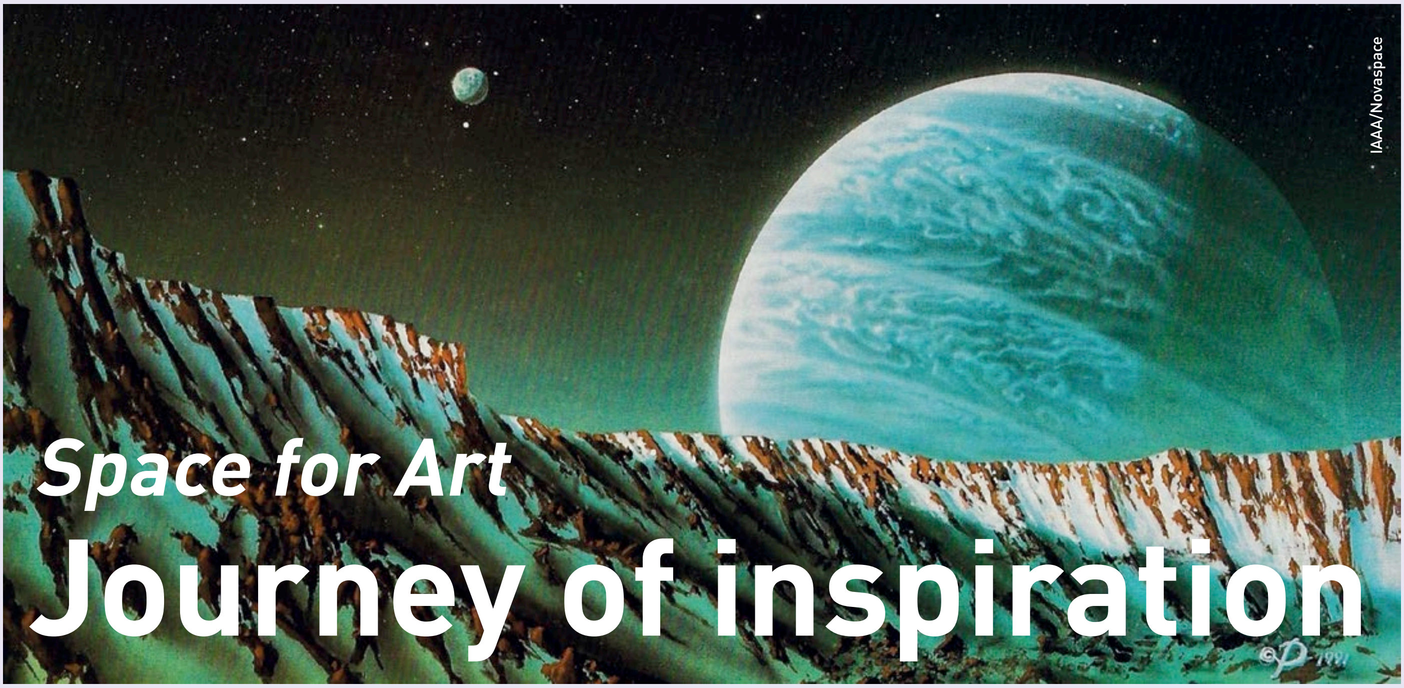


Space for Art
Journey of inspiration

▲ 'Pistachio Crater' by Kim Poor. An idea inspired by the artist's late-night craving for pistachio ice cream - Dawn breaks on a hypothetical planet with ice the colour of pistachio ice cream. From the base of a crater, we see a giant gas planet looming on the horizon.

As I grow older, time of course seems to fly, and I find myself reflecting more on the opportunities I've had through my life. It's funny how while we're actually experiencing something we don't, or maybe we can't, always appreciate all aspects of it. It's kind of like when I looked at Earth from space – physically more separated from the planet and all the people on it than I would ever be, but feeling more connected than I do when I'm right here in the middle of it. So now, as I look back on my journey to space, I think mostly of the people who supported and inspired me along the way - people who shared with me their passion for what they loved, who saw things in me I might never have seen in myself, who encouraged me when my own self-confidence was low, who supported me when it might have even scared them a little, and who inspired me to believe that nothing is impossible.

Nicole Stott
Artist, Astronaut and SciArt Advocate

My parents were first to inspire me, although I don't think I really realised it at the time. They always included me and my sisters in the activities they enjoyed. Mom sewed our clothes, macramed plant hangers, made pottery and hooked rugs; and Dad taught us how to boat and water ski, and he loved to build and fly small airplanes. We grew up at the local airport and I had my first exposure to flying, separating from our planet and being presented with a whole new perspective. Through these early life experiences, I developed my own life-long love of creativity and flying.

Growing up like this, it just seemed natural for me to earn my private pilot's license, study aeronautical engineering at university, learn how spaceships fly, enjoy painting and woodworking and other crafts, and one day to work at NASA.

NASA mentors

Shortly after graduating from college I started a job at the Kennedy Space Center (KSC) working with the NASA Space Shuttle team. This group of people loved the work they were doing, believed in the amazing Space Shuttle and the value of our space programme, and were passionate about the care of these space vehicles and their crews. These were a people and place that inspired before you even went through the gate and once you got inside the inspiration was overwhelmingly wonderful.

Through these early life experiences, I developed my own life-long love of creativity and flying

At KSC I met and worked with people who I considered to be mentors and who ultimately encouraged me to submit my application to become an astronaut. For as long as I could remember, the idea of being an astronaut seemed completely unreal - really cool but something that other people do. But the encouragement of the people closest to me, who maybe saw something in me that I didn't, gave me the self-confidence to actually fill out the application. Believe me, the words 'thank you' are frequently and enthusiastically used whenever I encounter these people!

Astronaut selection

In 2000, I was selected into the 18th class of NASA Astronauts – something that's still very surreal. Our class was made up of 17 people from all over the US and with very different backgrounds. Each of us dreamed of being an astronaut but not one of us got there in the same way or with the same experiences. To me, it's wonderful that there isn't a single path or checklist for becoming an astronaut, and that inspiration can come from so many different places.

During my time in space, I was inspired by the wonderful mix of personality and professionalism of my crewmates and by the people who supported us even through things that are much more difficult to watch than to do yourself, like watching someone you love strapping into a rocket ready for launch.

Nicole Stott

▲ Sharing the love of flying with my young son.

Painting in space

I love how photography and music have always been a part of human spaceflight. Other art forms occurred more rarely during the early missions - like cosmonaut Alexey Leonov's coloured pencil sketches of orbital sunrise and charcoal portraits of his Apollo/Soyuz crewmates – although, as we've spent more time as humans working and living in space, the number of astronauts creating something artistic during their missions has continued to grow.

My crew support rep and friend Maryjane Anderson encouraged me to think about how I might spend some of my spare time living for months in space and thanks to her I packed a small watercolour kit and had the opportunity to paint in space. That painting has

Nicole's mom and sisters before the launch of Discovery, STS128.

NASA

▼ Best kind of crew - wonderful mix of personality and professionalism in all of these people, ISS Expedition 20.

▲ Looking out the window at our beautiful home planet is absolutely one of the highlights of any spaceflight. Photo capture by Steve Bowen during an STS-133 spacewalk.

been a significant source of inspiration for my post-NASA life and how I've chosen to share the spaceflight experience with others.

Kindred spirits

Part of my decision to retire from NASA involved a need to share the experience I had in space with as broad an audience as possible. The inspiration from my spaceflight experience and the opportunity I had to paint in space were the foundation for choosing art as the way to do this.

I knew that art would allow me to communicate with audiences that might not even know there is an International Space Station (ISS), and through my artwork I would be able to encourage them to learn more about all the amazing things we're doing every day in space to improve life on Earth, and maybe even provide a little lesson in Earth appreciation.

But retiring from a job like a NASA astronaut to become an artist was not a normal path - only one other person had done that before, Alan Bean. He is one of my heroes; spaceflight and art all wrapped up in one awesome person! Shortly after retiring from NASA I had the opportunity to meet him after an introduction via my friend and fellow astronaut, Anna Fisher.

Alan welcomed our visit to his studio and I can't say enough about his enthusiasm for his art and his humble nature, or his willingness to answer all of my questions about his experience as an artist and his transition from astronaut to artist.

He is a hugely talented painter and his artwork presents his spaceflight experience like a beautiful gift he wants to share. If you haven't already, be impressed and inspired yourself, and check out his website - www.alanbean.com

Spacesuit Art Project

My own art has certainly been a big part of the work I'm doing now - but I believe that the love I have for both space and art has put me in a place to support projects with an even more meaningful mission. One of these projects is the Spacesuit Art Project. I've shared some details about this project in an earlier issue of ROOM's Space for Art column, and I'm happy to say that the inspiration of space and the power of art and healing continues to spread further around our planet through these spacesuits and the children that paint them.

We now have four completed art suits - HOPE, COURAGE, UNITY & VICTORY. COURAGE and UNITY have both flown to and from the ISS. UNITY was modelled after the peaceful and successful relationships of the ISS programme and created from the artwork of children in our ISS partner countries.

VICTORY is a suit created under the leadership of our Russian partners with artwork from children in Russia and the US, and it is currently onboard the ISS with the Expedition 53 crew. Two additional suits, EXPLORATION and DREAM, are being created from artwork produced by children around the world and they will join all of the suits on their global mission of art and healing.

▶ An amazing visit with son Roman, Anna Fisher, and Alan Bean at his beautiful art studio, sharing the love of space and art!

▶ Right: Meeting up with Kim Poor at Spacefest.

Pennies from heaven

As an astronaut and an artist, I feel blessed. I am thankful for the very special experiences I've had and continue to have, and for the people who have supported me and shared those experiences along the way; and I'm thankful that I continue to enjoy special and sometimes unexpected experiences and people in my life. One of my closest friends calls these 'pennies from heaven'.

Even with my experience I have to admit that I was pretty ignorant of the history and the artistic legends of space art, a world occupied by some extremely talented and creative people. And here's where I say 'thanks' again to Alan Bean who introduced me to the International Association of Astronomical Artists (IAAA), and to the most awesome space and art event on the planet called Spacefest; one of the wonderful things that these two had in common was the one and only Kim Poor. Pennies from heaven!

Kim was one of those extremely talented and creative space artists, and a co-founder of the IAAA and the creator of Spacefest where I met him in 2016. Unfortunately, we weren't really able to have a conversation but he listened and smiled as I showed him my artwork and explained my impressions from space and what I hoped to share with my paintings.

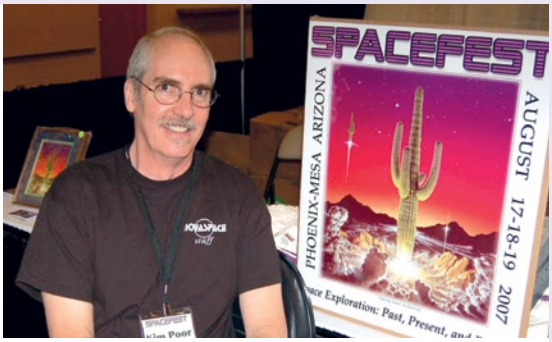
When I thanked him for creating such an incredible space and art experience as Spacefest, I'm thankful that he listened and smiled - and I'm saddened that the world has lost such a pleasant and inspirational man.

I hope that my own journey of inspiration never ends and that all of you who have taken the time to read this will also take the time to reflect and look for similar experiences and people in your own lives on your personal journey of inspiration. ■

▼ Art and space inspiring this young lady to look up and imagine her future.

Eyes on the skies

Kim Poor (1952 – 2017)



Kim Poor always loved the sky. He grew up in Phoenix, Arizona, before heading south to Tucson for college studies in 1974, which provided him with a panorama of stars, planets, and galaxies overhead, and a neighbourhood of people dedicated to studying them.

Tucson is the home of the Planetary Science Institute, Kitt Peak National Observatory, Mount Lemmon Observatory, and the University of Arizona, where advanced space research takes its place among other areas of scientific endeavour. One of the 'heavenly bodies' he ran across (his words) was Sally, who became his wife, confidant and business partner. Kim and Sally had two children, Kelsey and Nathan, and raised their family in their home among the mountains outside Tucson, where they founded Novagraphics, an art gallery and fine-art-print company now known as Novaspace.

Kim's fascination with all things astronomical expanded beyond the canvas when he took the reins as one of three leaders of the International Association of Astronomical Artists (IAAA) along with Rick Sternbach and Michael Carroll in 1983.

That relationship actually began in 1981 in Pasadena, California, when Kim joined Carroll and a dozen other artists to put together an art exhibition billed as the first international space art show. It represented artists who had worked on science magazines along with the core group who had brought vision to Carl Sagan's *Cosmos* TV series.

Under Kim's leadership of the IAAA, a delegation of North American space artists was also invited to the Soviet Union under the auspices of the Planetary Society. The international delegation, led by Carl Sagan and Louis Friedman, was invited to Moscow by the Soviet Institute of Space Research (IKI) to celebrate the thirtieth anniversary of Sputnik. At the conference, Kim gave a guest speech about the spirit of art, and the inspiration of space exploration, in an international context. The conference was the beginning of a long and fruitful relationship between the IAAA and the Planetary Society, a relationship that flourishes even today.

With his use of colour, dramatic compositions and imaginative-yet realistic vistas, Kim's art stood out even in this illustrious crowd. His painting style netted numerous awards and he received the IAAA Lucien Rudaux award for lifetime achievement in the astronomical arts. In 1997, Kim was diagnosed with ataxia, a degenerative nerve disorder and with painting already becoming difficult, he faced giving up his own art altogether. But in typical Kim Poor fashion, his dreams of space exploration and passion never faded and he refocused his energies on Novaspace which grew to become the largest dealer of astronaut autographs and memorabilia, often hosting events with astronauts, authors and artists.

Kim Poor's legacy includes rich friendships with many of the moonwalkers. His business remains a leader in the field under the capable and creative guidance of Sally and daughter Kelsey Poor. The IAAA artists group has grown to include 152 members representing over a dozen countries dedicated to scientifically-informed depiction of astronomical subjects, something Kim supported with great vigour. In addition to the IAAA and Novaspace, Kim leaves behind a long train of friends who count themselves lucky to have known such a creative, funny and talented individual.

Michael Carroll

Cosmic cocktails and galactic moonshine

Alcohol will almost inevitably travel into the expanse with future settlers and will eventually be manufactured at their new interplanetary homes

Chris Carberry
Explore Mars,
Washington DC, USA

Astronauts may currently be prohibited from drinking alcohol in space but Chris Carberry argues that as humanity establishes permanent colonies in orbit and settlements on other planets, the consumption and production of alcoholic beverages is inevitable. After all, with evidence of deliberate fermentation of alcohol going back more than 9,000 years, drinking for pleasure and ceremonial purposes has long been a staple of human culture.

A bottle of Dom Perignon, vintage 2265, tumbles through space on a seemingly endless voyage. Unless this fine Champagne is somehow intercepted along its path, its inertia may carry it onward for millions of years. The bottle grows ever larger on the screen and then, without warning, it explodes on the surface of what appears to be the off-white hull of a ship, with the camera panning out to reveal the name, 'USS Enterprise: NCC 1701-B'.

Perhaps no other scene depicts more literally the phrase 'alcohol in space' than this opening scene of the 1994 film, *Star Trek Generations*. In this 23rd century ship christening ceremony, we see a new Starship Enterprise entering service in a fictional, futuristic society where alcoholic beverages are as ubiquitous in space as they are on Earth today.

While we have no true idea what future spaceships will actually look like, for better or for worse alcoholic beverages will almost inevitably travel into the expanse with future settlers and will eventually be manufactured at their new interplanetary homes.

Space will present a whole raft of challenges for alcohol production. When European settlers arrived in the Americas they found a continent teeming with life, where crops could be plentiful without new techniques or technologies. In contrast, perfecting agricultural techniques in space will be far more difficult and challenging - and alcohol certainly will not be the first priority. As the author, Andy Weir, commented, "Alcohol is just about the least-efficient use of crops. It takes a huge amount of otherwise edible food to make a small amount of alcohol. So, while it would certainly be a produced item in future space colonies, it wouldn't come about until they had a very plentiful food production capability."

Science fiction

All too frequently, NASA and other 'official' depictions of future colonies have a utopian almost antiseptic feel to them with, for example, images of happy settlers in hydroponic gardens or heroic explorers gazing into massive canyons on Mars. It is entirely possible that more realistic depictions of the future - particularly future societal habits - may come instead from the world of science fiction.

Indeed, booze in space is far from a new concept. Science fiction has incorporated interplanetary bars and saloons, as well as exotic spirits and cocktails, in storytelling for decades. Many tales depict the future of human civilization

in more realistic terms than the 'official' portrayals that tend to focus more on technology rather than on sociology and culture.

Even the near utopian human future of the *Star Trek* television franchise does not shy away from the fact that Star Fleet officers may indulge in a drink from time to time. To avoid the perception, however, that members of Star Fleet are potentially exploring the final frontier while inebriated, the producers came up with the concept of 'synthehol' - a beverage that is supposed to simulate the taste and effects of alcohol. According to *Star Trek* creator Gene Roddenberry, synthehol "...acts just the same as alcohol. It makes you feel that you can be a lover or wise or all the things that alcohol does, but it's only temporary. With force of will you can shove it aside and be as sober as you ever were..."

Rodenberry believed that humanity would be too smart for real alcohol in the future but, in his lifetime, alcohol plays a role in the *Star Trek* universe. Crew members would also occasionally partake in illicit products like Romulan Ale or have a chalice of Klingon blood wine.

Creators of science fiction clearly have difficulty imagining a world without alcohol and science fiction novels have a multitude of treatments for space drinks, interplanetary beer and colourful saloons in space. Whether it is drinking a Pan Galactic Gargle Blaster from *Hitchhiker's Guide to the Galaxy* - described as 'like having your brains smashed out by a slice of lemon, wrapped round a large brick' - or Melange, often referred to as 'the spice' in *Dune* with addictive mind-altering effects, the prospect of exotic galactic libations has provided science fiction authors with an abundance of material for creative inspiration.

Alcohol is also a part of life at the lunar surface facility in Andy Weir's new novel *Artemis*. According to Weir, "Artemis is a vacation destination. So, they import alcohol from Earth and sell it at a huge mark-up. But they're still in an era where sending mass from Earth isn't cheap. So, they tend to have reconstituted beer and spirits..."

Teetotal in space?

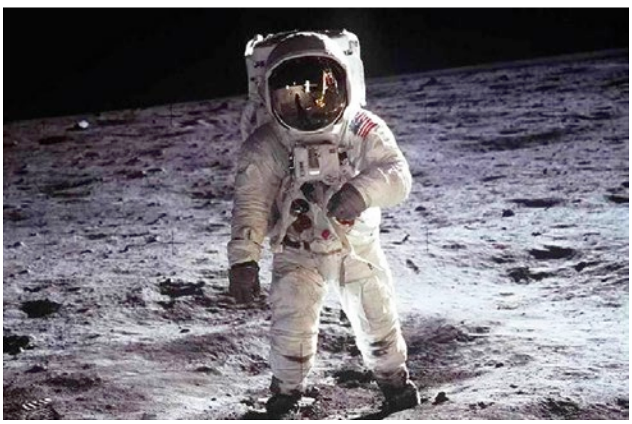
Historically alcohol and space exploration have had a complicated relationship. The world's space agencies, including NASA, have largely prohibited astronauts from consuming alcohol in space - although this has not always been the case.

▲ Left: A bottle of Dom Perignon, vintage 2265, used in a film sequence to christen the 'Enterprise' in the 1994 film *Star Trek Generations*.

▲ Above: The notoriously strong Romulan ale in the *Star Trek* fictional universe had a reputation for getting humans instantly drunk.

▼ Below left: Buzz Aldrin, the second person to set foot on the Moon, consumed wine as part of a communion ceremony that he performed whilst in the lunar module.

▼ Cosmonauts gather for a cognac on the Mir space station in 1997, hours after a flash fire nearly killed them.



▶ One of the bottles of Paul Masson Rare Cream Sherry that was supposed to have been sent to Skylab .

▶ Right: *The Martian* actress Kate Mara and retired astronaut Clay Anderson joined Budweiser in March 2017 to unveil the brand's long-term commitment to be the first beer on Mars.

Perhaps the most notable example of this occurred during the Apollo 11 Moon landing in 1969 when Buzz Aldrin consumed wine as part of a communion ceremony that he performed while on the surface. Aldrin stated in *Guideposts* magazine that, "In the one-sixth gravity of the Moon the wine curled slowly and gracefully up the side of the cup. It was interesting to think that the very first liquid ever poured on the Moon, and the first food eaten there, were communion elements."

Even though it was the first time in human history that alcohol was consumed on a planetary body other than Earth, the ceremony was not widely publicised at the time, in part because there had been complaints several months earlier when a Bible passage had been read from the book of Genesis by the crew of Apollo 8 while in lunar orbit.

A few years later, alcohol was almost added to the menu for the Skylab space station crews. Skylab was intended to be a 'home away from home' and as such, nutritionists investigated whether wine would be a suitable beverage for crews. It became clear that any wine being sent to Skylab would need to be repackaged, and would be subject to an extreme level of shaking that could impact its overall taste and quality. Sherry was determined to be the most suitable form of wine because it is extremely stable - thus, the ideal official alcoholic beverage of the United States space programme. Paul Masson Rare Cream Sherry was ordered for a Skylab mission.

In the end it never flew because NASA became concerned about the prospect of negative publicity. In addition, when asked, most of the astronauts did not seem to care whether they had alcohol on board because they felt that they would be too focused on their mission.

Space presents a whole raft of challenges for alcohol production never experienced on Earth

Prohibition for American astronauts, however, does not mean that no drinking at all has occurred in space. While Russia officially prohibits drinking by cosmonauts, there are many stories of Russian cosmonauts consuming alcohol on both the Russian Mir space station and the International Space Station (ISS). According to cosmonaut Alexander Lazutkin, "During prolonged space missions, especially at the beginning of the space age, we had alcoholic drinks in the cosmonauts' rations." Russian doctors had recommended cognac to stimulate their "immune systems and on the whole to keep our organisms in tone".

Space farming

Despite the current restrictions on consuming alcohol in space, there are dozens of projects under way, with some already completed, examining methods for manufacturing or testing alcohol in space.

One example of this is a group of engineering students at the University of California, San Diego, USA, who are working on an experiment to brew beer on the Moon. They call themselves 'Team Original Gravity,' vying for a spot to have an experiment sent to the Moon aboard the Indian TeamIndus spacecraft.

Bioengineering student Neeki Ashari states, "We all appreciate the craft of beer and some of us own our own home-brewing kits. When we heard that there was an opportunity to design an experiment that would go up on India's Moon lander, we thought we could combine our hobby with the competition by focusing on the viability of yeast in outer space." In theory, this experiment might not only help to show the possibility of beer production on the Moon, but Ashari stated, "Yeast is a prevalent microorganism. It's in our food (bread), beverages, and pharmaceuticals (insulin)... so understanding yeast viability in space may have consequences and clinical applications for the future of space exploration and colonisation."

Beer-loving students are not the only ones thinking about the prospects of producing drinks in space. In 2011, Ardbeg, the Scottish single malt whisky distiller, became the first Scotch producer to send whisky samples to the ISS to investigate whether microgravity impacts the aging process of whisky. The experiment showed a clear difference between the control sample on Earth and the sample that went to the ISS. A white paper produced by Ardbeg described the aftertaste of the ISS samples as, 'pungent, intense and long with hints of wood, antiseptic lozenges and rubbery smoke'.

Not to be discouraged or outdone, in 2015, Japanese whisky producer the Suntory Group also shipped whisky samples to the ISS to investigate whether microgravity impacts how whisky mellows with age. They sent samples that range from newly distilled whisky to 21-year-old single malt whisky.

In 2017, American beer producing behemoth, Budweiser, entered the fray at the South by Southwest (SXSW) festival in Austin, Texas, when it announced plans to become the first company to brew and sell beer on Mars. It remains unclear if Budweiser is serious or if this was a publicity stunt but there may be commercial value for a company like Budweiser to test the waters of a new space business.

Even when humanity finally reaches Mars, the first permanent settlers will not be successful, or produce alcohol, unless they are able to reliably grow food on the surface. Research projects are underway to investigate whether certain crops could be grown on the Moon or Mars. The primary purpose for such crops would be to provide food for crew members but, as astro-farming becomes more efficient, some of the agricultural products will inevitably be converted into consumable alcohol.

One group investigating the prospect of Martian agriculture is called 'Potatoes on Mars', based at the NASA Ames Research Center

As astro-farming becomes more efficient, some of the agricultural products will inevitably be converted into consumable alcohol.

in Mountain View, California. According to planetary scientist Dr Chris McKay, a team member of the initiative, "It is known that potatoes can grow in cold conditions and we certainly think they will grow on Mars if given Earth-like pressure and temperature."

Assuming McKay and the Potatoes on Mars team are correct there is no reason to think that alcohol cannot also be produced. The real question is how quickly and successfully humanity will explore and settle space.

Once humanity establishes permanence anywhere - and probably before that - brewing, distillation and fermentation will inevitably follow. In a recent interview astrophysicist Neil deGrasse Tyson, said, "After we find space aliens, my next question might just be, is there Burgundy wine elsewhere in the universe?"

We can only speculate about the possibility of finding space aliens but our descendants who become the first settlers of Mars will certainly make their own wine, beer and spirits. ■

About the author

Chris Carberry is the Chief Executive Officer of Explore Mars, a U.S. based non-profit organisation created to advance the goal of sending humans to Mars within the next two decades. Prior to joining Explore Mars, Carberry served as Executive Director of The Mars Society.

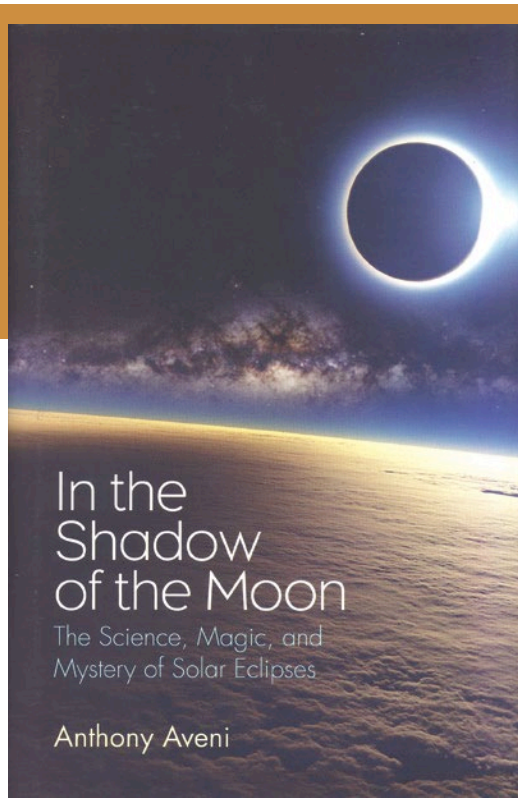
▼ Dr Bill Lumsden, Ardbeg Director of Distilling and Whisky Creation, with the sample of Ardbeg distillate from space. The experiment demonstrated that gravity has a very real effect on the maturation of spirit.

Mark Williamson
Space Technology Consultant, Cumbria, UK

Reviews

In the Shadow of the Moon: the science, magic and mystery of solar eclipses

Anthony Aveni,
Yale University Press, 2017, 312pp, hardback
£20.00
ISBN 978-0-300-22319-4



Viewing a total eclipse of the sun is almost a rite of passage among astronomers (and others too), and no amount of vicarious narrative and TV viewing can substitute for actually being there. This book comes at an opportune time for me, given that I lost my own total eclipse 'virginity' as recently as August 2017 on a bridge across the Snake River in Idaho.

The author is an astrophysicist and anthropologist, the "fortunate witness" of eight total solar eclipses which have taken him from the South Pacific to the Egypt-Libya border. Having been trained as a scientist, he admits he didn't "think much about how different cultures might interpret the cosmos" until he took a group of students to measure the celestial orientation of pyramids in Mexico. He and archaeologists there "created a new interdisciplinary field variously called astroarchaeology, archeoastronomy, and cultural astronomy"- and this is the main subject of his book.

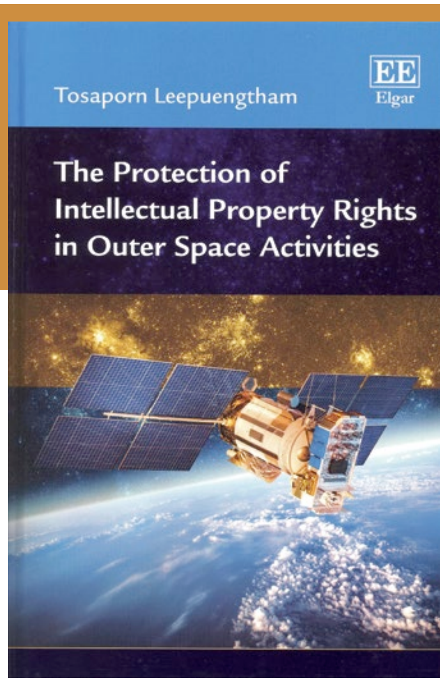
Observing that most explanations of how people around the world understand natural phenomena are "a bit short-sighted", the author says his book represents an attempt to "broaden our collective vision". His personal narrative is presented in four main sections (introduction, eclipses in the ancient and modern worlds, lessons, and personal eclipses). The volume concludes with chapter notes and an index, and there is a brief chronology of solar eclipses, which includes future eclipses up to September 2099 (for those who expect to be around).

Of course, there is science in this book but it is cleverly interweaved with history, culture and the social aspects of eclipses, which makes it both accessible and fascinating to those already familiar with the science of astronomical alignments. It includes quotes from the Bible, excerpts from poems and references to 'rave' culture. And there is also humour: noting the narrowness of the band of totality and the limited chances of ever seeing a total eclipse, the author writes "you could opt to stay put and see a partial eclipse, but that's a bit like being in the stadium the day before the Super Bowl".

I couldn't agree more: it was surprising how light it was even one minute before totality with just a sliver of the sun still visible. For me, the most surprising effect was the distinct sense of foreboding that accompanied the final seconds before totality and I suddenly understood how the ancients – less schooled in astrophysics than today's observers – might have felt as the sun was devoured by a black disk. This book will help eclipse virgins and the more experienced alike to appreciate the social context and impact of the total solar eclipse.

The Protection of Intellectual Property Rights in Outer Space Activities

Tosaporn Leepuengtham, Edward Elgar,
2017, 249pp, hardback
£80.00
ISBN 978-1-78536-961-2



With interest in asteroid mining on the increase and bases designed to acquire lunar water resources in the offing, a book on the legal aspects of property is timely. The subject of who owns the Moon and other celestial bodies has been under discussion, by space lawyers at least, since the signing of the Outer Space Treaty in 1967; the typical answer has always been 'no-one owns outer space' because it is part of the 'heritage of mankind'.

This view has evolved in recent years, because the space law treaties are increasingly understood to apply to states as opposed to individuals; of course, it was once only states and their agencies which explored space, but that paradigm is shifting towards private industry.

This is clearly a legal text - as indicated by its formal style, voluminous footnotes and total lack of illustrations – but it provides a good introduction to the issues of Intellectual Property (IP) property in space. After a section on principles and definitions, it covers IP rights, patents, the application of copyright law and aspects of private international law in relation to space activities. The volume concludes with a substantial bibliography and index.

As is often the case with discussions of space law, the broaching of a subject generates more questions than answers. Indeed, the final chapter features four key questions and explains the extent to which they are answered by the preceding chapters. The author concludes with a nod towards future challenges. Most scholarly discussions of IP rights in space relate to patent and copyright protection, he says, but 'a whole new space tourism industry' will generate 'trademark issues relating to souvenirs and advertising in space, which scholars will be required to address'. So, plenty more legal discussions and textbooks to come.

Worlds Fantastic, Worlds Familiar: A Guided Tour of the Solar System

Bonnie J Buratti,
Cambridge, 2017, 239pp, hardback
£19.99
ISBN 978-1-107-15274-8

At first glance, the contents list of this book appears to cover the planets of the solar system one by one but a second glance shows that the gas giants are missing. Instead, the author substitutes some of the better known moons of the solar system, such as Titan and Enceladus… and despite its downgrading by the International Astronomical Union, which she refers to as its 'dethronement', Pluto is also there.

In her introduction, the author explains that she 'decided to talk just about the [bodies] I've worked on or that I find most interesting' and, consequently, the coverage is more personal than encyclopaedic. It is also, unashamedly, aimed at the layperson, with 'no prerequisites beyond high school science'. As a result, those who have read a book or two on space and astronomy will probably not get much out of this one.

The text, interspersed as it is with science fiction references and other popular story-telling devices, is well-written and should be accessible to those already interested in space and astronomy. The glossary and index add value and should help with their enjoyment of the volume. However, the design of the book appears somewhat old-fashioned in its use of black-and-white photos and a glossy insert that repeats selected images in full colour. This makes it much more of a considered purchase than an impulse buy.

That said, its author – as a senior research scientist at JPL – has plenty of expertise in the subject (and even has an asteroid named after her), so there are unlikely to be many mistakes in the science.

Australia in Space

Kerrie Dougherty

ATF Press, 2017, 196pp, softback, AUS

$64.95

ISBN 978-1-925309-64-5

One might think Australia has two main claims to fame in the space arena: its historic launch base at Woomera and the fact that the remains of the deorbiting Skylab space station fell within its territory. This is, of course, a gross misrepresentation of the nation's activities in space, as Australian space historian Kerrie Dougherty reveals in her new book.

Although Australia only recently inaugurated a space agency, it has a long heritage in space technology and related services. Unsurprisingly, Dougherty begins with rocketry: "While Australia cannot claim any significant contributions to the early development of rocketry", she admits, "local inventors, dreamers and entrepreneurs were inspired by overseas developments to undertake their own rocketry experiments."

This 'catch-up' mode soon turned to 'cutting edge' research, however, when the UK began a programme to test its Black Knight and Blue Streak rockets at Woomera. This later morphed into the European Launcher Development Organisation's programme for Europa, the first stage of which was the Blue Streak.

Arguably more important for Australia's reputation in what the author calls 'the space club' was the launch of its first satellite, WRESAT, from its own territory. Here, Dougherty proves that professionalism trumps patriotism with an unbiased analysis of her nation's ranking: "it is often claimed that Australia was either the third or fourth country to launch its own satellite," she says, but she places it fifth after the USSR, USA, France and Italy. This is because some nations launched their own satellites on foreign vehicles while others launched foreign vehicles from their own facilities – as she says, it's a "complex matter".

Subsequent chapters cover Australia's tracking facilities (including the story of its role in the Apollo missions); the use of space for defence and security; space science; engineering; and Australian space policy. The book is well-designed and illustrated throughout in colour and concludes with a list of acronyms, a timeline of space events and a useful index.

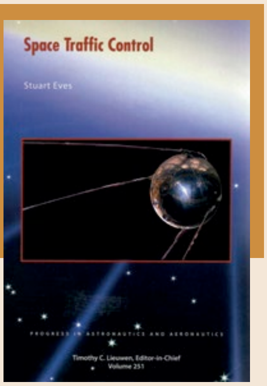
Space Traffic Control

Stuart Eves

AIAA, 2017, 129pp, hardback, US

$119.95

ISBN 978-1-62410-400-8



Space traffic control – the title of this book – has become a space-related catch phrase of the early 21st century. Its earthbound sister is the far-better-known air traffic control (ATC), which evokes airports, radars and controllers staring into screens displaying a plethora of aircraft tracks across the globe. But how does STC compare?

This relatively brief volume begins by describing the main reason a system of control for space traffic is required – the burgeoning space debris population. Making a deliberate analogy with ATC, the author points out that 'a system of standards and regulations was necessary to enable international air travel' and that 'we have now reached that juncture in space'.

In eight chapters, the book describes space situational awareness and tracking systems, debris mitigation techniques, the threats and hazards themselves and how to improve the situation in future. It is illustrated, fairly sparsely, with monochrome images and line drawings, and has an index.

The book provides a useful introduction to this increasingly important topic but perhaps lacks the level of detail required by space practitioners and implied by its generic, catch-all title. Anyone with a good general knowledge of the space field will fail to discover much that is new in this volume and so they may find the level of content does little to justify the eye-watering price.

Overall the book, part of the AIAA Progress in Astronautics and Aeronautics series, is well-researched and written on a subject of great future importance. readers might do well to await a more comprehensive and definitive text.

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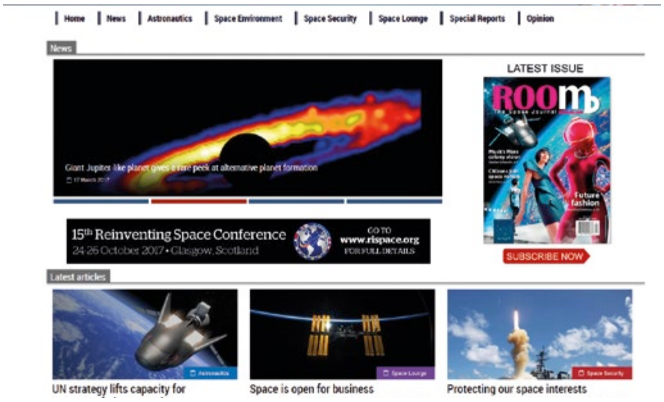

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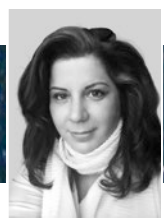

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Published by
The Aerospace International Research Center GmbH,
Stubenring 2/8-9, 1010,
Vienna, Austria.
AIRC tel: +43 664 230 9614 (Austria)
www.airc.at

ISSN 2412-4311

Printed in the USA by Creel Printing

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