ROOM

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Big science from small spacecraft

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Staying healthy on Mars

Kris Lehnhardt, p. 38

Searching for cosmic company

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Igor Ashurbeyli
Editor-in-chief

Clive Simpson
Managing Editor

Gateway to a world of future opportunity

Compared to even a few years ago there appears to be a growing shift in both the perception of and ambition for what can be realistically achieved by the global space industry.

Nations that eschewed a space presence in the past, perhaps because of cost, are now attracted by an increasing array of commercial opportunities and, in many cases, the absolute need to be up there with the rest.

Miniaturisation is playing no small part in this revolution as cubesats and nanosats begin to deliver ever more sophisticated payloads at the kind of affordable costs that were little more than a pipe dream a decade or more ago.

Articles in this third anniversary issue reflect the rapidly evolving global space scene, providing a unique and diverse perspective into the achievements, practicalities and visions of the future.

Nowhere is this better illustrated than by Anthony Freeman, of NASA's Jet Propulsion Laboratory, who dispels the view in 'Big science from small spacecraft' (p. 18) that planetary exploration is the domain of large multi-payload spacecraft.

Emerging markets are eager to make their mark, as Temidayo Oniosun, from Nigeria, describes in 'Africa is open for business' (p. 58), and Narayan Prasad, coordinator of the 'NewSpace India' digital platform, supports in his article 'India's dynamic ecosystem for space entrepreneurship' (p. 62),

In parallel, disruptive trends continue to shake up the accepted way of doing things and in 'On-orbit assembly will deliver major benefits in the coming decade' (p. 10) Iain Boyd, of the Washington-based Science & Technology Policy Institute, assesses how this might impact future space missions.

And, in the aptly titled 'Space invaders initiate disruptive EO trends' (p. 26), Gil Denis, of Airbus Defence & Space in Toulouse, views the convergence between defence needs and commercial capacities as a challenge to the paradigm of traditional leadership led by governments and public organisations.

Bigger and more distant dreams are afoot too. In 'Space nation set to mark its presence in orbit' (p. 33) Lena De Winne provides a report from Hong Kong on the announcement in June that the world's first space kingdom, Asgardia, is preparing to launch its inaugural satellite.

The Asgardia-1 nanosatellite will carry into orbit digital messages from around 250,000 Asgardian citizens and their families, marking the first stage in a long-term vision to provide orbiting bases and help protect Earth from space hazards.

Looking to deep space, Seth Shostak of California's SETI Institute suggests in 'Science searches for cosmic company' (p. 76) that the discovery of alien life is now more likely than ever before, whilst astronomers Manisha Caleb ('Telescope targets enigmatic deep space mystery' p. 80) and Robert Izzard ('Binary stars and their extraordinary lives' p. 84) push back the boundaries of cosmic astronomy.

This issue (number 12) marks the third anniversary of ROOM's publication, during which time the magazine has matured in reputation and global reach. Not only a valued source of information, ROOM is also a forum for informed comment and opinion. Its vision is to support the worldwide community of space engineers, scientists, students, post-graduates, entrepreneurs and visionaries who are all working towards common goals for the benefit of all humankind.

To all our readers, contributors and subscribers - thank you for your support over our first three years and we look forward to exciting times ahead!

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

Nations that eschewed a space presence in the past, perhaps because of cost, are now attracted by an increasing array of commercial opportunities

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Jupiter's vibrant beauty

A surreal world of vibrant colour, clarity and contrast captured by NASA's Juno spacecraft as it was racing away from Jupiter following its seventh close pass of the planet.

JunoCam snapped the stunning image on 19 May 2017 from about 29,100 miles (46,900 km) above the cloud tops. The spacecraft was over 65.9 degrees south latitude allowing a lovely view of the south polar region of the planet.

This image was processed to enhance colour differences and highlight the amazing variety in Jupiter's stormy atmosphere. Four of the white oval storms, known as the 'String of Pearls', are visible at the top right of the image. Interestingly, one orange-coloured storm can be seen at the belt-zone boundary, while other storms are more of a cream colour.

See page 102 for a further insight into the beautiful JunoCam imagery of Jupiter by NASA *astronaut and artist Nicole Stott.*

NASA/JPL-Caltech/SwRI/MSSS/Gerald Eichstadt/Sean Doran

On-orbit assembly will deliver major benefits in coming decade

Historically, the assembly of spacecraft on the ground and their integration into a launch vehicle places many constraints on the capabilities that can be deployed in space, including adding to the cost of launch. In contrast, on-orbit assembly offers a pathway to address such limitations in a variety of ways. Here, Iain Boyd and Bhavya Lal of the Washington-based Science & Technology Policy Institute (STPI), assess how on-orbit assembly is poised to dramatically change a number of key space missions within the next decade.

Iain D. Boyd
& Bhavya Lal
Science & Technology Policy Institute,
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The search for exoplanets is one of the most exciting space science endeavours and though NASA's James Webb telescope will cost about US$9 billion it may be too small to yield clear scientific conclusions on exoplanets.

To deploy a telescope with double the aperture of James Webb would impose an estimated cost increase to US$36 billion. Such monumental and ultimately unsustainable costs emerge from current concepts in spacecraft design and manufacturing, principally based on the need to fully assemble objects on the ground before launch.

Ground assembly and integration into a launch vehicle imposes significant limitations on the

▲ The 18-segment gold mirror of the James Webb Space Telescope is specially designed to capture infrared light from the first galaxies that formed in the early universe.

size, volume and design of payloads that can be accommodated within the fairing of a single launch vehicle, the largest of which is less than six metres in diameter.

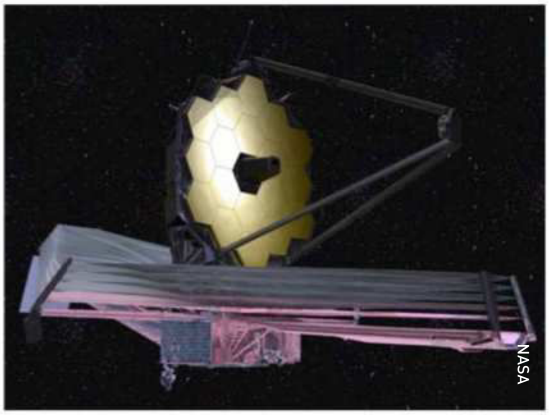
In particular, fairing diameter limitations restrict the size and number of instruments that can be fielded in orbit for science and national security missions which, in turn, constrain data that can be obtained from space-borne payloads.

Design of ground built spacecraft also requires components to undergo ‘ruggedization’ to withstand the harsh launch environment - severe vibration, acoustics, acceleration and thermal loads - which imposes mass and size penalties that ultimately limit payload capabilities and increase launch costs.

These are further compounded by the need for inclusion of redundant systems to provide contingency against damage during launch.

Communication satellites have similar constraints that limit flexibility and operations, and Figure 1 illustrates how these affect profitability and revenues.

On-orbit assembly can be defined as the aggregation onto an orbiting platform of ready-made structures that are manufactured on the ground (although they could also be manufactured on-orbit) and here we examine the potential implications of on-orbit assembly of science, exploration and commercial communication spacecraft for science and exploration and, and review the state of the art and future trends in the area.

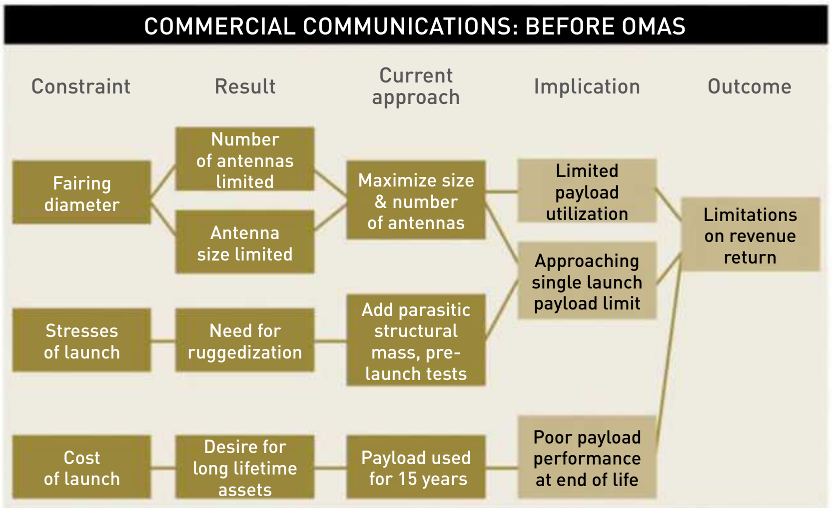


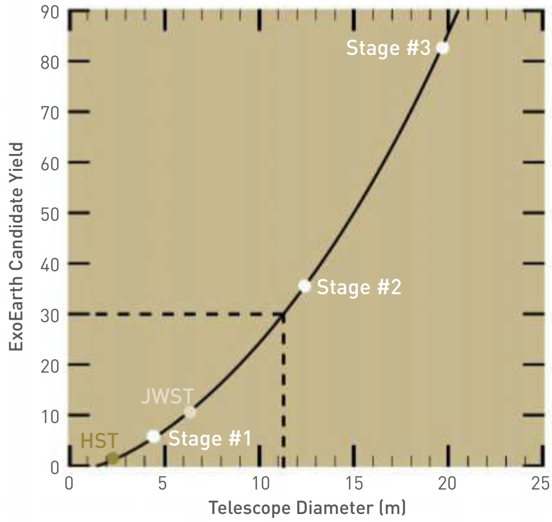
▶ Artist conception of the James Webb Space Telescope.

Benefits of on-orbit assembly

At a conceptual level, on-orbit assembly offers a number of advantages that may enable and enhance various types of space missions:

- An ability to deploy structures that cannot be launched from Earth because





▲ Figure 1. Illustration of how the current approach for deploying communications satellites places limitations on revenue return.

▲ Above right: Figure 2. Exoplanet yield as a function of telescope diameter (adapted from AURA, 2015).

of constraints imposed by launch vehicle fairing size and shape. The structures are packaged more efficiently into the launch fairing than can be accomplished with a fully integrated spacecraft

- An ability to achieve increased flexibility and resilience of spacecraft assets enabled by assembly involving additions, replacements and technology updates of payloads onto a compliant, orbiting platform
- An ability to create cost savings related to carrying more useful mass - less packaging material (structure) for ruggedization, and less platform material
- An ability to create cost savings through reduction in the number and intensity of ground-based tests of space-bound spacecraft and subsystems
- An ability to create structures that cannot be created on Earth at all because of constraints imposed by the terrestrial gravity.

These advantages, in turn, can provide dramatic benefits in a number of different ways to a variety of different space operations.

In astronomy, on-orbit assembly can enable the construction of telescopes too large to be fully built on Earth and launched into orbit. High definition space telescopes (HDST) are very large, space-based observatories with a number of primary missions, including characterisation of exoplanets and the search for life on exoEarths through the use of spectroscopic bio-markers.

An analysis performed by the Association of Universities for Research in Astronomy ('From Cosmic Birth to Living Earths: The Future of UVOIR Space Astronomy', 2015) showed that at least 30 candidates must be characterised in order to infer statistically meaningful conclusions about the prospects for biological life on other planets.

The same analysis revealed that telescope aperture diameter is the most important parameter in determining the number of candidates that can be characterised, and the relation is plotted in Figure 2. Data points are included for the Hubble Space Telescope (HST) and for the James Webb Space Telescope (JWST), the latter being the next NASA HDST mission planned for launch in 2018. With an aperture diameter of 6.5 m, it is estimated that JWST will identify about 10 exoEarths.

To advance the search for exoEarth candidates beyond JWST to a level of stronger scientific rigour, a significant increase in telescope aperture diameter is required on future HDST missions and Figure 2 shows that an aperture of 12 m would yield more than 30 candidates.

The JWST aperture is approaching the size limit for what can be accommodated within current launch vehicle fairings; even then, this size necessitates use of a complicated folding arrangement, with many associated risks and ground testing requirements.

While larger launch fairings are being considered in the development of future launch systems, significant growth beyond current capabilities is both technically challenging and extraordinarily expensive.

The idea is to assemble a large telescope in space using large hexagonal elements that are 4m across from one flat side to another

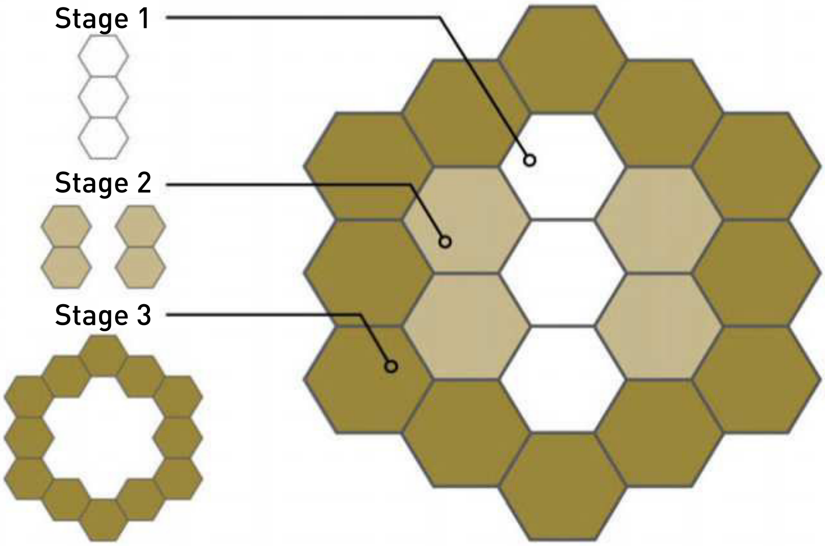
On-orbit assembly provides a potential pathway to address the size challenges of next generation HDSTs. For example, consider the three-stage evolvable space telescope concept described in Polidan et al., (Proceedings of SPIE, 9143, 2014) and shown schematically in Figure 3.

The idea is to assemble a large telescope in space using hexagonal elements that are 4 m across from one flat side to another. The telescope would evolve over three launches that are separated by budget cycles spread over several years. In the first stage, the central circular secondary mirror, and two hexagon elements that form the primary mirror assembly (PMA) are launched in a single stack and assembled on-orbit to form an asymmetric aperture of 4.5 m x 12 m.

In the second stage, four additional hexagon elements are launched in a single stack, and assembled to form a symmetric aperture of diameter 12 m. The third stage launches 12 additional hexagons that would be added to the existing structure to complete a telescope with an aperture diameter of 20 m. The exoplanet yields provided by the three stages are indicated in Figure 2.

In addition to enabling a scientifically important increase in information return for HDSTs by making it possible to evolve the construction of the telescope over multiple years, on-orbit assembly would likely provide significant cost savings.

For Earth science, on-orbit assembly can reduce the number of satellite launches for weather and climate observations through the creation of a persistent platform assembled in space. One illustration is the ability to use the persistent platform to replace the A-Train series of satellites that pass over the same spot on the Earth within a few minutes of each other collecting a variety of measurements. Sensors could be added to the platform regularly, enabling faster refresh than is currently feasible. Just as importantly, assembly of multiple payloads (as well as refresh) onto one platform would require fewer launches, and provide launch savings of several hundred million dollars.

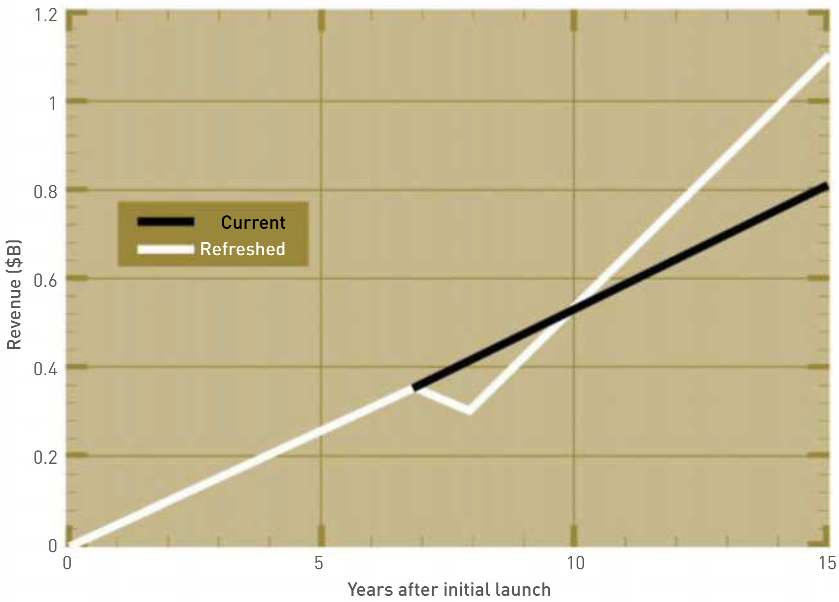


▲ Figure 3. Three-stage evolvable space telescope concept leading to 20 m aperture (Polidan et al., 2014)

Communications satellites

On-orbit assembly can also provide payoff for telecommunications in geostationary orbit (GEO).

◀ The International Space Station and the docked Space Shuttle Endeavour in May 2011 at the end of the main construction phase in LEO.



▲ Figure 4. Total revenue generated by a communications satellite over a 15-year lifetime.

Consider the data distribution sector where the satellite is used to move data from one central location to other regions of the world. Take a communications satellite with four antennas that allow it to distribute data to four different regions simultaneously. Due to the dynamic nature of end-user data distribution requests, these satellite systems typically achieve utilisation rates of only 60 to 70 percent. An increase in the number of antennas, without changing any other part of the satellite, would allow use to increase.

For illustration, we assume that increasing the number of antennas from four to eight would increase utilisation efficiency by 10 percent. The antennas are not assembled onto the spacecraft prior to launch but rather are packed efficiently into the fairing above the satellite platform. Once in orbit, the antennas are assembled robotically onto the satellite before transfer to GEO.

Assuming the satellite generates revenue at a rate of US$1.5 million per transponder per year (the recent historical average), a typical number of 36 transponders on the satellite, and a 10 percent increase in utilisation due to the use of on-orbit assembly to double the number of antennas from four to eight, the total increase in revenue would be US$5.4 million per year. Over the 15-year lifetime of a typical satellite, this yields a total revenue increase of US$81 million.

The JWST aperture is approaching the size limit for what can be accommodated within current launch vehicle fairings

Another important limitation of communications satellites fully assembled on the ground is that once deployed on orbit, the technological capabilities remain fixed for the lifetime of the spacecraft. This is an important consideration since the lifetime of most GEO satellites is 15 years.

The ability to reconfigure a telecommunications satellite through on-orbit re-assembly could provide valuable capability upgrades for operators, that may be especially important as GEO operators begin to gear up to compete with low Earth orbit (LEO) constellations expected to see refresh rates as low as 18 months.

The revenue generated by a communications satellite depends primarily on the rate at which information can be moved through the system, measured in bits per second. Similar to Moore's Law for computer processor speed, the historical data for the evolution of satellite bit-rate shows a predictable upward trend with no end in sight. Specifically, the bit-rate has been seen to increase by a factor of 10 every seven years or so.

When a new satellite is launched, in its first year of operation it provides the fastest bit-rate available in the market. However, each year that passes sees new satellites placed into orbit with a performance that exceeds that of the older asset. Thus, a seven-year old satellite is operating at a bit-rate that is a factor of 10 slower than the newest satellites in operation

Now consider the situation in which on-orbit assembly makes it possible to replace the entire communications payload on the satellite after seven years of operation. The new payload would refresh the technology and instantly increase the bit-rate of the asset. As an illustration, we again assume the satellite generates revenue at a rate of US$1.5 million per transponder per year, and 36 transponders on the satellite. We will further assume a factor of 10 increase in bit-rate enabled by on-orbit assembly of the updated communications payload.

However, this improved performance will be accompanied by a reduction in customer charge rate, and for our analysis we assume that the charge rate decreases by a factor of five. The cost of the second launch is assumed to be US$40 million and that of the new communications payload is estimated at US$100 million. Figure 4 shows the accumulation of revenue over the operational lifetime of the satellite under the current paradigm and for the new approach in which the technology is refreshed after seven years. The total revenue increase at end of life enabled by on-orbit assembly is about US$300 million per satellite.

Figure 5 shows how assembling more antennas onto a single platform, conducting on-orbit manufacture and assembly to eliminate the stresses of launch, and assembling refreshed payloads onto an existing platform, all contribute to increased system performance and revenue return for a communications satellite.

Technical capability status

Having identified the potential benefits of on-orbit assembly, it is informative to review present status and future prospects for the technical capabilities that can be expected. On-orbit assembly of spacecraft will require development of a number of technologies and processes involving sensing, robotics, automation and modular interfaces between payloads and platforms.

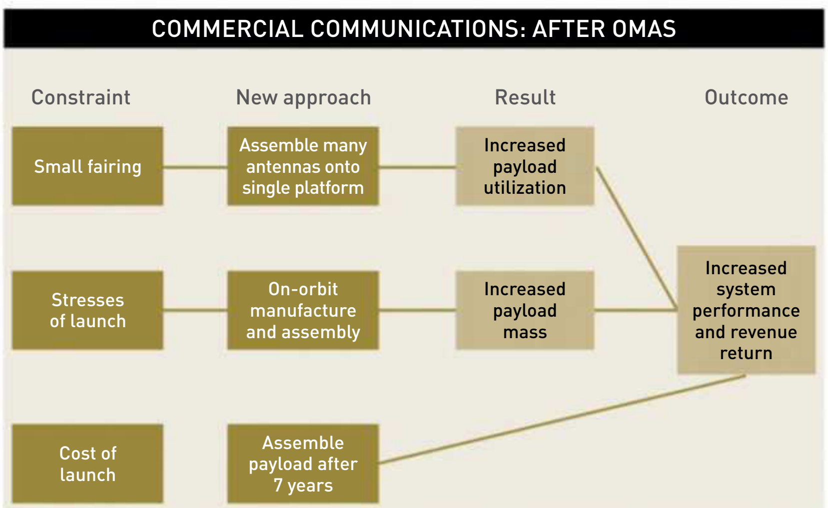
Relevant space activities that represent intermediate steps to full on-orbit assembly include on-orbit inspection and servicing of spacecraft. A significant heritage has been built up over the last 50 years by astronauts conducting on-orbit assembly and lessons learned from these activities will inform future missions and the development of new techniques.

Capabilities are being developed for automated on-orbit inspection of spacecraft. In the United States, the Air Force Research Laboratory (AFRL) Automated Navigation and Guidance Experiment for Local Space (ANGELS) spacecraft investigated technologies and procedures for manoeuvering and imaging within a few kilometres of an expended rocket body.

Concepts are also being developed using sensors for inspection of spacecraft. On-orbit servicing, including autonomous docking, was demonstrated by the US Defense Advanced Research Projects Agency's (DARPA) Orbital Express in 2007. The mission involved a surrogate next generation satellite and a prototype servicing spacecraft. The satellites docked several times, and the prototype servicer refuelled the satellite and exchanged modules.

The most impressive example of astronaut-assisted assembly is the construction of the International Space Station (ISS), which involved over 35 Space Shuttle launches and 160 spacewalks spanning 1,061 hours. The station is the size of a football field weighing over 400,000 kg and encompassing over 900 cubic metres of pressurised volume, and has been called home by over 200 people representing 15 countries.

A spectrum of robotic assembly techniques could be used to replace astronaut assembly, from robots as eyes, subordinates and sidekicks to robots as surrogates and specialists



▼ Figure 5. Illustration of how on-orbit assembly approaches can alleviate limitations associated with deploying communications satellites to enhance system performance and increase revenue return.

Robotic assembly

A spectrum of robotic assembly techniques could be used to replace astronaut assembly, from robots as eyes, subordinates and sidekicks to robots as surrogates and specialists.

United States' Orbital ATK's Mission Extension Vehicle (MEV) is one example of a servicing capability. The NASA Restore-L mission is scheduled for 2020, and involves the refuelling of Landsat-7 by a MEV. The MEV will autonomously rendezvous with the Landsat spacecraft and then tele-robotically cut wires, remove caps and refuel the satellite. Landsat-7, an unprepared 'client' built long before MEV technology was available, will be about 20 years old at that point.

Restore-L demonstrates the potential for robotic servicing to increase the lifespan and safety of current missions. The Space Dynamics Department of Germany's Institute of Robotics and Mechatronics runs a mission called Deutsche Orbitale Servicing (DEOS) which involves two satellites, a 'client' and a 'servicer'. Planned to launch in 2018, the servicer will chase and rendezvous with the client, demonstrate refuelling and module exchange, and then safely de-orbit the client.

DARPA is developing robotic servicing vehicles for GEO satellites as part of its Robotic Servicing of Geosynchronous Satellites (RSGS) project. Satellites in this high orbit will be able to be repaired and maintained over time, increasing their capabilities and value to their owners. Under development since 2016, the planned launch date is 2021.

On-orbit assembly has the potential to radically change the way in which spacecraft are deployed for a number of important space missions

In early 2016, ESA flew the Intermediate Experimental Vehicle (IXV); in 2020 it is expected to fly the Program for a Reusable In-orbit Demonstrator from Europe (PRIDE). IXV demonstrated many key capabilities for on-orbit manoeuverability; PRIDE will provide a platform for the experimentation with and development of on-orbit servicing capabilities.

Self-assembly, which involves small satellites with specialised capabilities self-organising to fulfill the objectives of a larger mission, is enabled by advances in formation flight. DARPA is pursuing the Phoenix Satlet concept whereby small autonomous modules incorporate key satellite capabilities and aggregate in various combinations to achieve different mission goals. The modularity of the Satlets increases mission resilience and re-configurability, reduces spacecraft design and integration time, and provides cheaper redundancies. In tandem with the Payload Orbital Delivery (POD) system, deployment costs are reduced. Satlets have been under development since 2012, and the first LEO flight is planned for 2017.

▼ Artist impression of Restore-L servicer extending its robotic arm to grasp and refuel a client satellite on orbit.


Space Systems Loral

Operational challenges

Many on-orbit assembly capabilities face space environment challenges, such as microgravity, atomic oxygen (in LEO), radiation and micrometeoroid impacts. It may therefore be necessary to deploy a protective shell structure in orbit, in which assembly can proceed free from many of these environmental concerns. For LEO operations, there is also the continual significant variation in the lighting environment caused by going in and out of eclipse, which may negatively impact vision-based operations.

Tele-robotic missions are impacted by communication latencies and therefore require tasks such as rendezvous and docking to be entirely automated. When not supervised by an astronaut, on-orbit assembly requires a robotic system with high reliability and a high degree of 'trust' between human and robot. New operational steps must be developed to verify that the assembly procedures have been executed as planned.

Some of the challenges faced by robotic, autonomous on-orbit assembly can be addressed by learning and benefiting from the much more extensive worldwide activities of terrestrial-based applications of the same technologies. Use of automated, robotic assembly of complex machines is widespread and growing in capability on the ground across many industries. Important examples include large industries such as automotive and micro-electronics, as well as assembly of components directly related to spacecraft such as antennas and solar-cells.

Future impact

On-orbit assembly has the potential to radically change the way in which spacecraft are deployed for many important space missions. The already long history of astronaut-assisted on-orbit assembly combined with ongoing progress in on-orbit inspection and servicing will have a significant impact on on-orbit assembly in the next decade, especially if the space sector is able to leverage investment in terrestrial activities in robotics and automation. ■

About the authors

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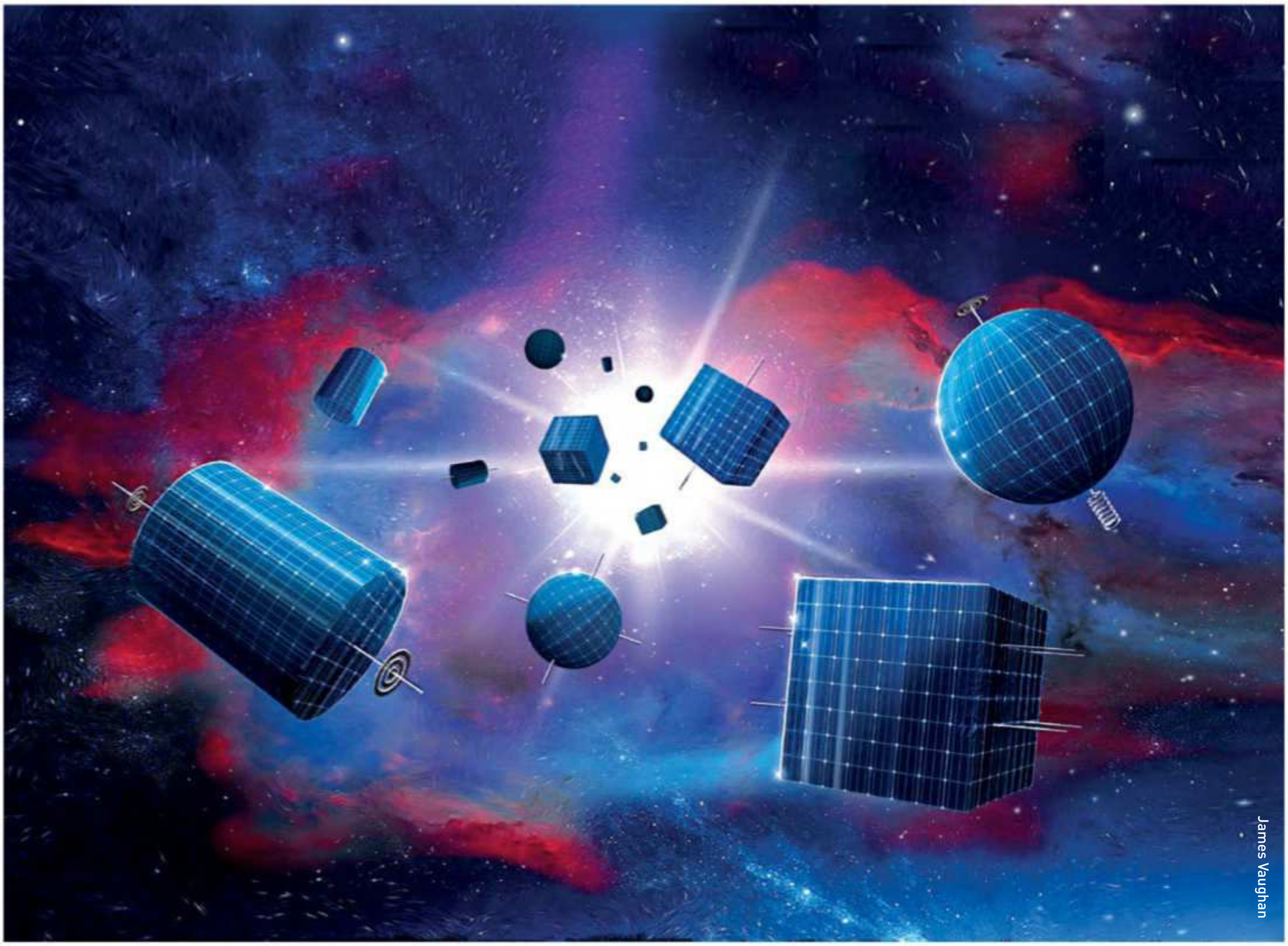
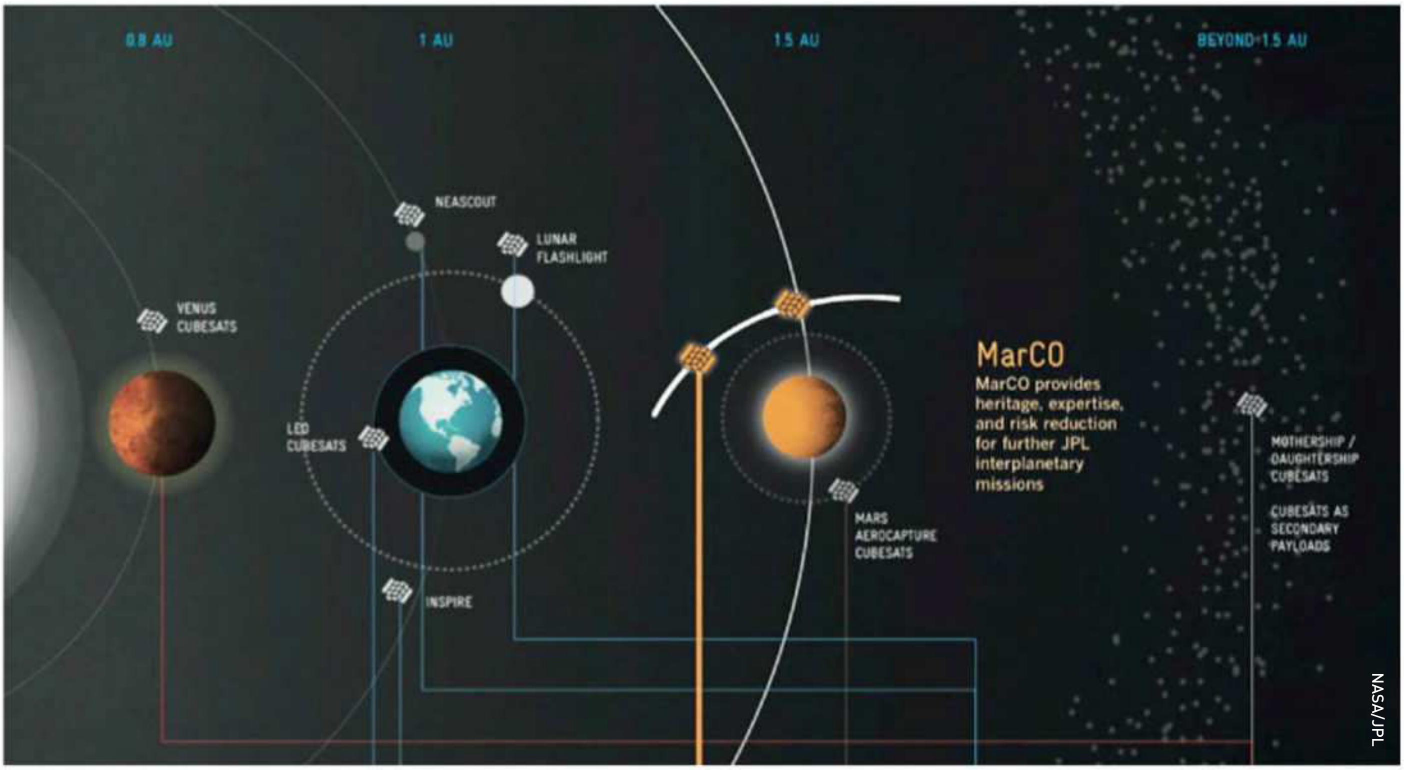


Big science from small spacecraft

Anthony Freeman
NASA Jet Propulsion Laboratory,
California Institute of Technology, USA

When planetary scientists and engineers at NASA's Jet Propulsion Laboratory (JPL) get together to plan the next steps in exploring our solar system, the result is usually something fairly massive - but exploring space and seeking to do science on the cutting edge raises the question: is it possible to get the kind of results we want with smaller spacecraft? Since 2012 a small group of like-minded enthusiasts (the 'cubesat kitchen cabinet') at JPL has helped to conceive some new, exciting science missions using deep space cubesats and nanosats to accelerate growth in this field. They hope that once the barriers to flying small space missions have been broken down, and the cost of entry reduced, universities and research institutes across the world will be empowered to join them in this great endeavour to explore our solar system.



▲ Exploring our Solar System with cubesats and nanosats.

NASA's Curiosity rover, currently exploring the Gale crater on Mars, weighs in at 899 kg and the Europa Clipper spacecraft will probably tip the scales at over three tonnes. Mass generally drives the cost of each mission – so bigger spacecraft usually cost significantly more than smaller ones.

At the other end of the scale in both size and cost, cubesats and nanosats could, in theory, fly more missions for the same budget. But could smaller spacecraft deliver in the space science arena? The answer, as suggested by a recent National Academy of Sciences report is a qualified 'yes': small spacecraft such as cubesats can take on unique science missions but are not a substitute for the larger 'flagship' missions like Curiosity or Europa Clipper.

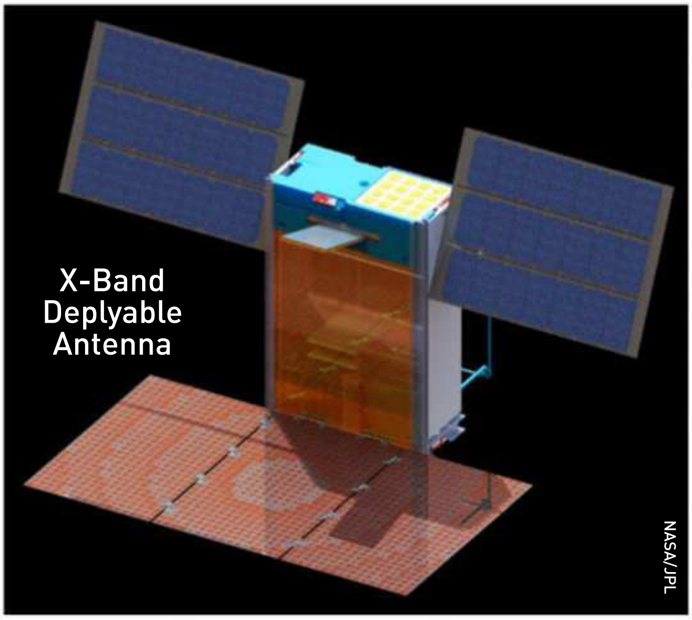
Destinations

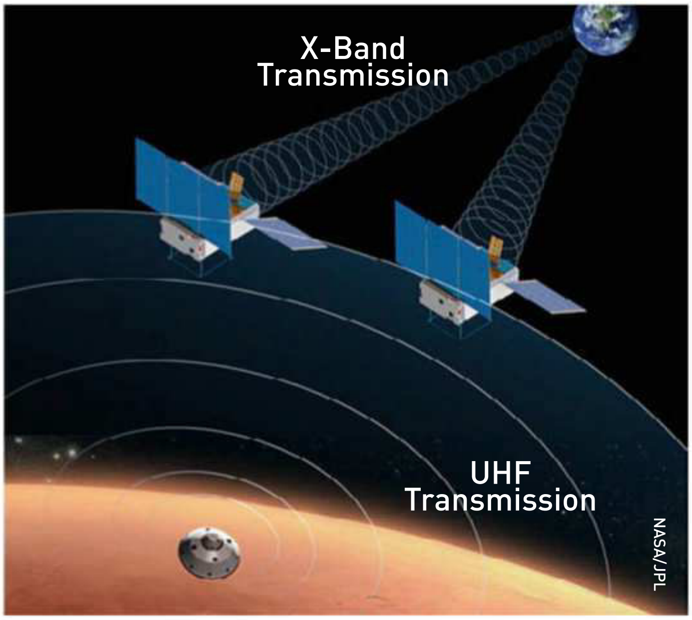
So where can we reasonably expect to explore in our Solar System with smaller spacecraft? The Sun is an obvious target, since we can cost-effectively send cubesats and nanosats to places that provide a unique vantage point to view solar phenomena. The inner solar system is fairly easy to reach, being accessible to both free-flying and 'hitch-hiker' cubesats/nanosats, while the outer solar system is currently compatible with just hitching a ride on a larger spacecraft. Without a suitable, compact radioisotope power system, deep space nanosats heading out to Jupiter and beyond will have to rely on their host spacecraft to get to their destination, run on energy stored in batteries after their release from their storage/hibernation container, and relay data back to Earth through the primary spacecraft.

It is common enough for deep space missions to use a gravity assist manoeuvre at Venus to provide a boost in velocity to propel them on their way to their primary mission target. NASA missions that have used this slingshot effect include Galileo (Jupiter), MESSENGER (Mercury), Cassini (Saturn), and Parker Solar Probe (the Sun). Now, imagine that every time a mission executes a gravity assist at Venus, it drops off a small nanosat probe that could sample and analyse part of Venus' atmosphere, relaying the data back to Earth via the vehicle that dropped it off, or be captured into a stable orbit that allows longer-term study of our nearest neighbour. Straight shot, independent trajectories to Venus are also possible for nanosats.

The Moon is an attractive destination for nanosats, since it is so close to home,

The 'cubesat kitchen cabinet' has helped to conceive some new, exciting science missions using deep space cubesats and nanosats





▲ The two MarCO cubesats will execute a flyby of Mars and relay UHF telemetry received from the InSight lander directly back to Earth using an X-band communications link.

which makes communication distances very manageable. Near Earth Asteroids (between 0.98 and 1.3 astronomical units (AU) distant from the Sun) are another rich target set, with their number estimated at over 14,000, and ~1000 of them larger than a kilometre in diameter. By the end of this century, we will probably only visit a handful with larger spacecraft like NEAR Shoemaker, or Japan's Hayabusa. But nanosats could be sent in large numbers to examine hundreds of asteroids close up within a generation, at a much lower price tag than the larger missions.

A launch window for energy-efficient trajectories to Mars opens up at intervals of about 26 months and, in recent times, most windows have one or more spacecraft taking advantage of a fast transit to the red planet. Nanosats could ride along as ballast to make up the launch mass on larger Mars missions, or make their way there as free-flying spacecraft. With a few km/s of Delta-V (propulsion) capability, free-flying nanosats could be placed into orbit around Mars, opening up the potential for science from orbit, and adding to the communications and navigation infrastructure.

The main asteroid belt, situated 2.2 to 3.2 AU out from the Sun, contains 0.7-1.7 million objects with a diameter of greater than 1 km. Thus far, spacecraft passing through the asteroid belt en route to the outer planets have given us a closer glimpse of only a few; and NASA's Dawn mission has provided detailed examination of just two of the largest, Ceres and Vesta. This is definitely rich hunting ground for nanosat missions – the asteroid belt is close enough to the Sun that solar power generation is practical, and close enough to Earth that communication distances are manageable. It can take a long time to get out to the main asteroid belt though – Dawn arrived at its first target, Vesta, nearly four years after launch – so reliability and longevity will need to be demonstrated over several years before we send nanosat explorers to the Belt.

We know of 5000 comets to date whose orbits take them close enough to the Sun that their tail is visible from Earth. Again, our spacecraft have visited less than a dozen: Halley's comet, 21P/Giacobini–Zinner, 26P/Grigg–Skjellerup, 107P/Wilson–Harrington, 19P/Borrelly, 81P/Wild, 9P/Tempel, 103P/Hartley, 2P/Encke, and 67P/Churyumov–Gerasimenko. That leaves plenty of possibilities for nanosat mission flybys and encounters of future comets.

We know enough about comet trajectories to plan and quickly execute flyby missions, but rendezvous missions where we catch up with a comet take a little longer and will require a higher standard of reliability: ESA's flagship Rosetta mission took 10 years to rendezvous with comet 67P/Churyumov–Gerasimenko. Such long mission durations are not unusual when we plan missions to chase the so-called 'short-period' comets.

The inner Solar System is fairly easy to reach, being accessible to both free-flying and 'hitch-hiker' cubesats/nanosats

Exploring Mars

In the last couple of decades, through the Mars rovers and other spacecraft, scientists have learned a lot about Mars' history, but there is still plenty to discover. In 2018, NASA plans to launch the InSight spacecraft, led by Bruce Banerdt at JPL, to probe the interior of Mars using a seismometer. In parallel, JPL has developed the MarCO (Mars Cube One) spacecraft as the first interplanetary cubesats, intended as pathfinders for the space science community. Two MarCO spacecraft are scheduled to launch on the same rocket as InSight in May 2018, but will make their own way to Mars.

A small propulsion system has been designed to adjust their flight path en route. The two spacecraft will execute a close flyby of the red planet and relay engineering telemetry from InSight as it lands, when it will be out of direct line of sight from Earth.

MarCO's mission objective is not science – its relay function serves an engineering purpose – but it is easy to imagine how it could be turned into a science orbiter. If we had added a bigger propulsion system to provide that extra few km/s of Delta-V, and a miniature spectrometer to characterise the Martian atmosphere by looking at the absorption of sunlight, just-like-that we would have had a science mission in a cubesat form factor.

Prof David Spencer of Purdue University aims to go one better in formulating a mission concept that uses a drag skirt to place a 12U cubesat (a U is a measure of volume of about 1 litre) in an orbit at Mars that provides close-up encounters of Phobos and Deimos. The origin of the martian moons is unknown and they are therefore ripe for scientific discovery. Prof Spencer's 'Chariot' mission was recently awarded a NASA grant to mature his concept.

Exploring the Moon and asteroids

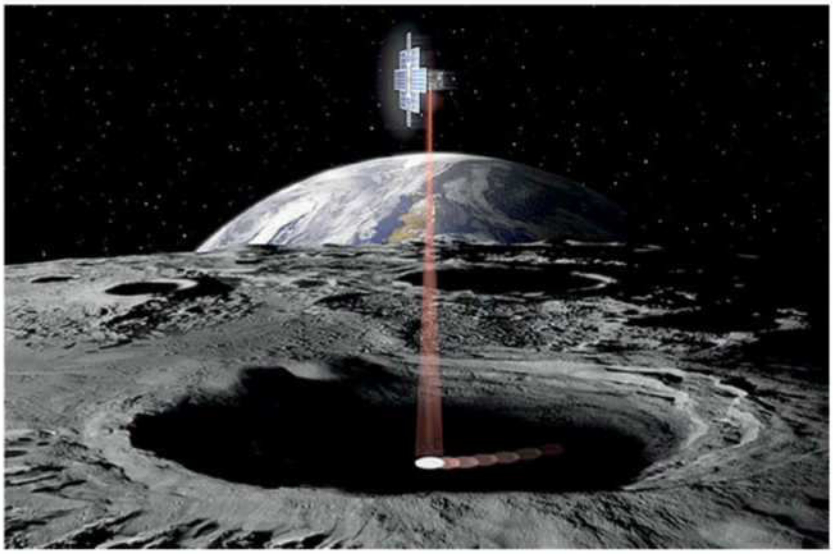
The Moon is so tantalisingly close that you would think we'd understand all there is to know about our celestial companion. You could think that, but our lunar scientists would tell you you're wrong. A cubesat currently under development to explore the Moon is Lunar Flashlight, a mission that will use lasers to shed light on the permanently darkened craters of the Moon's poles, to probe the composition of the lunar surface within. Lunar Flashlight will also be the first planetary cubesat mission to use 'green' propulsion.

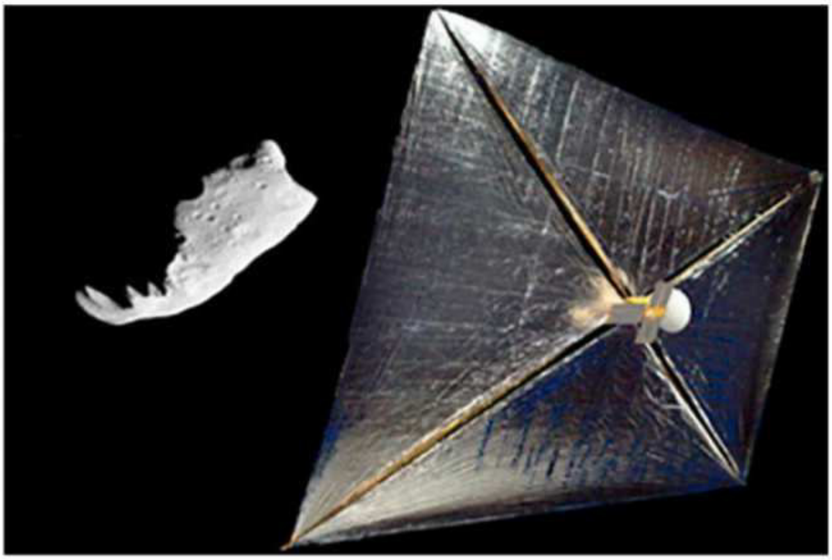
Another project under development is the Near-Earth Asteroid Scout, which will deploy a solar sail that catches sunlight to steer a flight path taking it from a lunar trajectory to a rendezvous with a Near-Earth Asteroid. JPL is working with NASA's Marshall Space Flight Center on both Lunar Flashlight and NEA Scout.

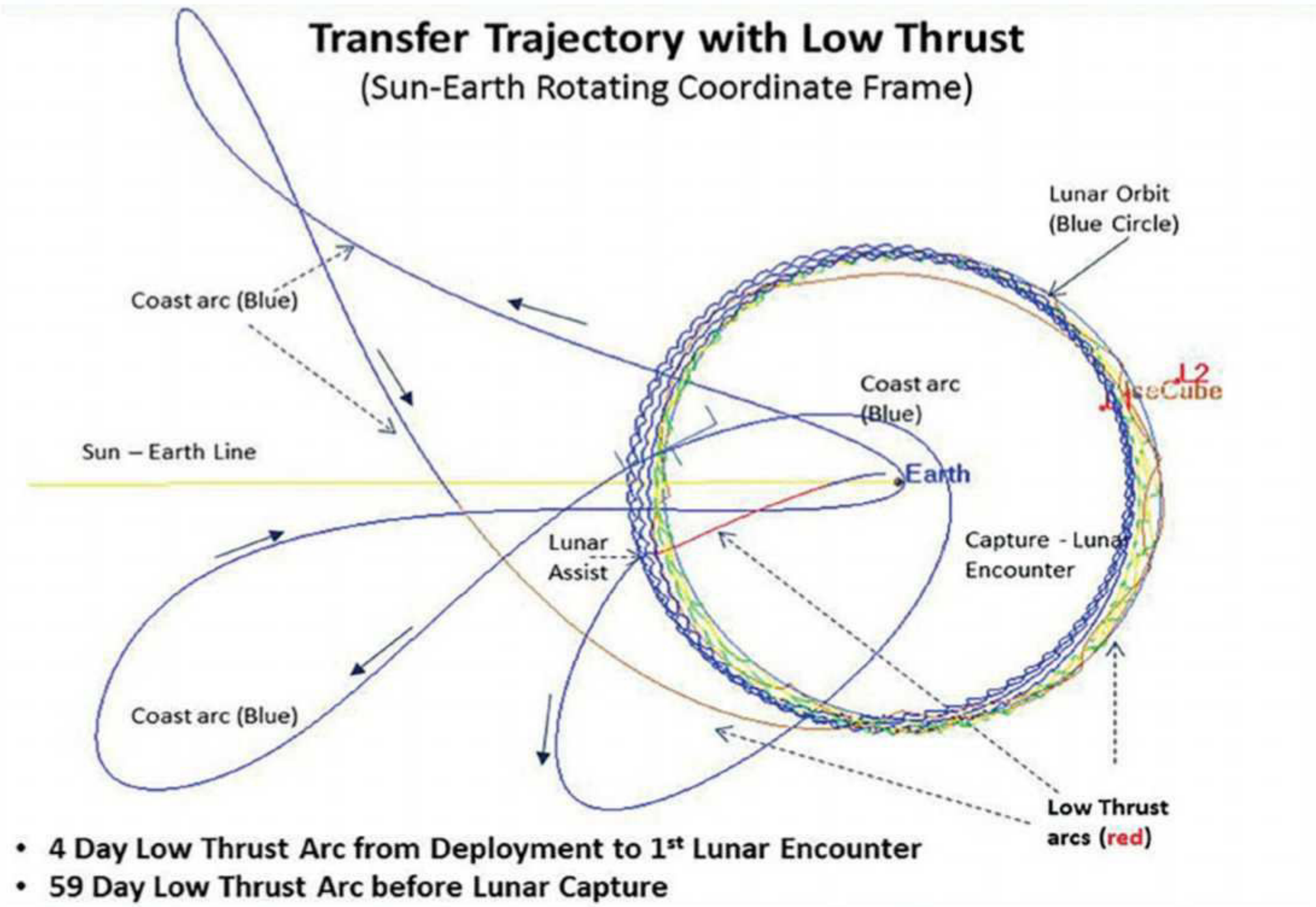
Lunar Flashlight, NEA Scout and a third spacecraft, LunarIceCube, will all be dropped off near the Moon as part of a 'swarm' of up to 13 cubesats, hitching a ride on the first flight of NASA's new heavy lift rocket, the Space Launch System (SLS), planned for 2018.

LunarIceCube will use a compact broadband infrared (IR) instrument (BIRCHES) to investigate the origin of volatile gases on the Moon, their distribution, and ongoing processes at the lunar surface. To operate the infrared spectrometer

▼ The Lunar Flashlight (top) and NEA Scout (bottom) cubesat missions.







▼ LunarIceCube's elaborate low-thrust trajectory (diagram above) places it into a final mapping orbit at the Moon.

at its required temperature of 120 K, the mission will demonstrate the first use of a compact cryocooler on a cubesat platform.

The LunarIceCube project is led by Morehead State University, with significant contributions from NASA's Goddard Space Flight Center and Busek Corporation. The science lead is Pam Clark of JPL.

Exploring Venus

Although spacecraft from Earth have visited Venus many times, our nearest neighbour is still shrouded in mystery. Cupid's Arrow, a mission concept for a free-flyer nanosat probe, launched directly from Earth towards Venus, was recently funded for study by NASA to unravel some of those mysteries. The mission study is led by JPL scientist Christophe Sotin. It targets very high priority science – measuring the relative abundances of neon, argon, helium, krypton and other 'noble' gases to understand how Venus' atmosphere formed and has evolved.

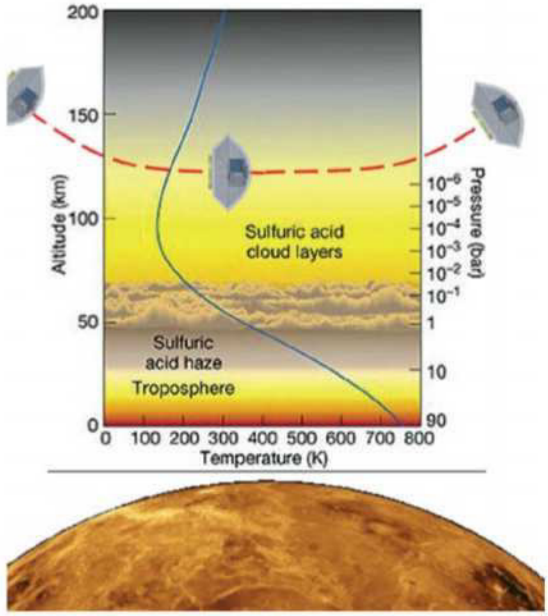
To be truly representative of these noble gases and their isotopic ratios, a sample of the atmosphere has to be acquired where the atmosphere is well-mixed: which for Venus is below 120 km altitude.

Cupid's Arrow samples Venus' atmosphere using a compact, yet very precise, gas analyser known as an ion-trap mass spectrometer contained in a small (60 cm diameter) probe that skims through the atmosphere. After acquisition, the gas sample is analysed to generate estimates of noble gas concentrations. The results are returned to Earth via a communications relay routed through the carrier spacecraft, similar to the architecture developed for MarCO.

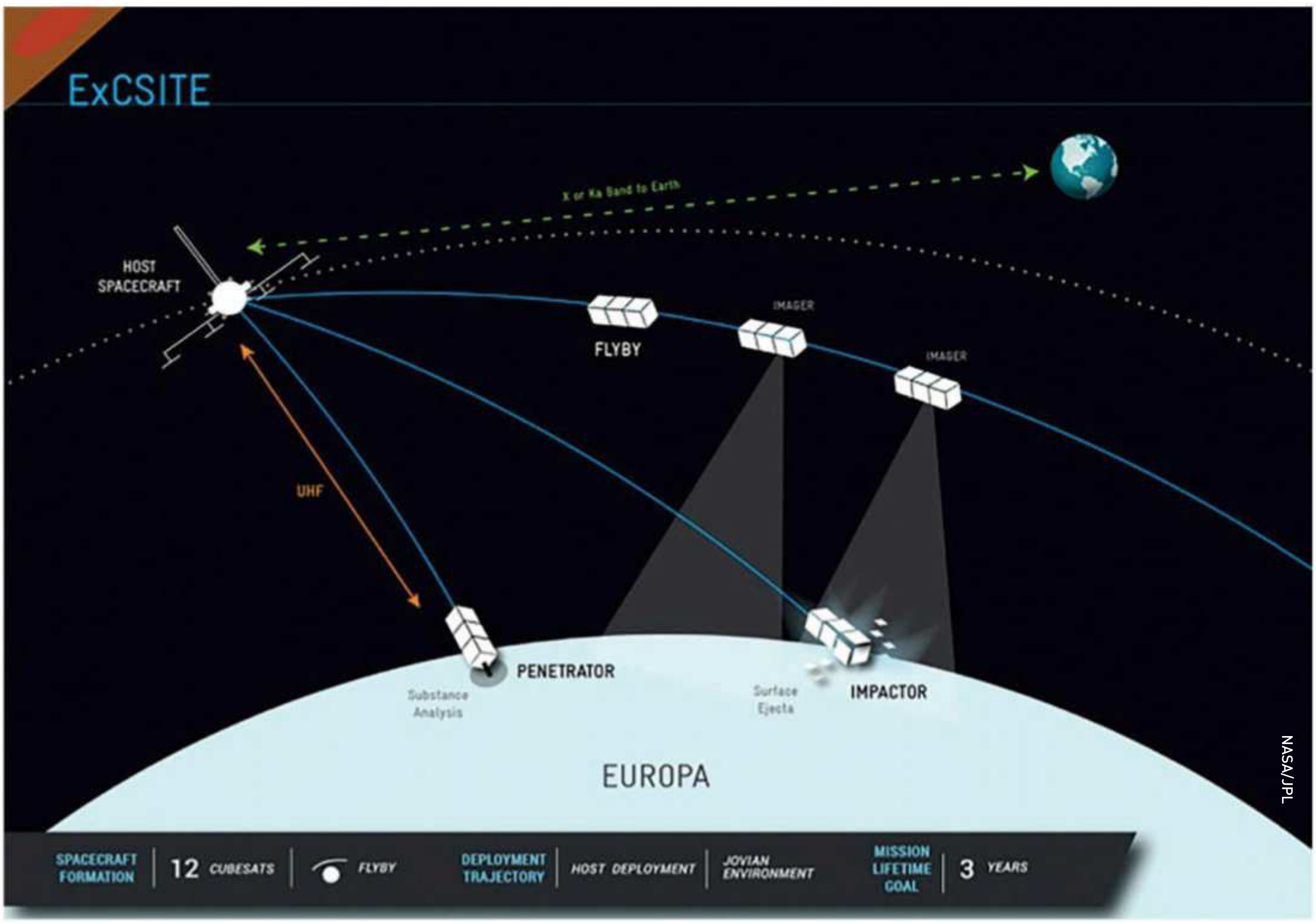
The current design of the probe and its companion carrier spacecraft both make extensive use of cubesat spacecraft components and their combined mass adds up to less than 55 kg.

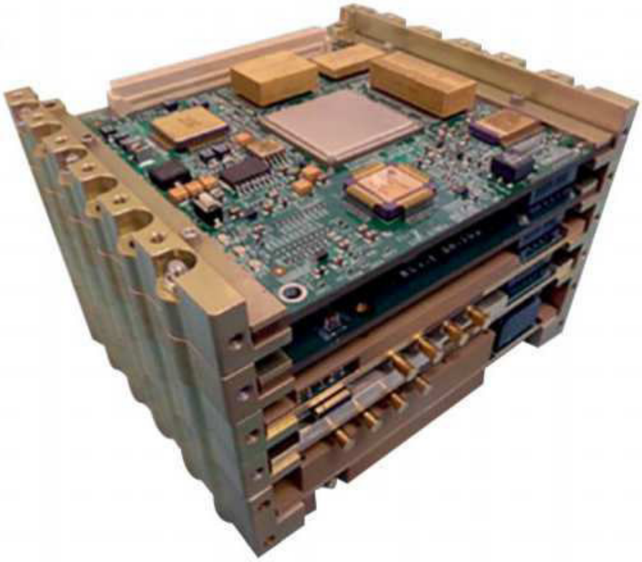
Another high-priority science objective for planetary scientists is to improve our understanding of the dynamics of Venus' atmosphere. Prof Valeria Cottini from the University of Maryland, College Park, was recently funded to address this under a NASA grant to study the CubeSat UV Experiment (CUVE), a 12U CubeSat orbiter concept that measures ultraviolet absorption and nightglow emissions.

▶ Venus atmospheric sampling probe skims through the atmosphere to sample noble gases at less than 120 km altitude.



▼ Cubesats being deployed from the Europa Clipper mission.





The Moon is so tantalizingly close that you would think we'd understand all there is to know about our celestial companion - but our lunar scientists would say you're wrong

Exploring ocean worlds

Europa is one of the 'ocean worlds' in our solar system that planetary scientists believe may be a suitable place for life to have arisen independently. JPL's Europa Clipper project is planning to head there in 2022 and has supported the maturation of cubesat concepts that have the potential to enhance the science achieved at Europa. These cubesats would be carried to Jupiter by the host spacecraft and then released on approach to execute their assigned mission. In this hitch-hiker architecture, the cubesats can get much nearer to the surface of Europa than the primary spacecraft, enabling unique science observations.

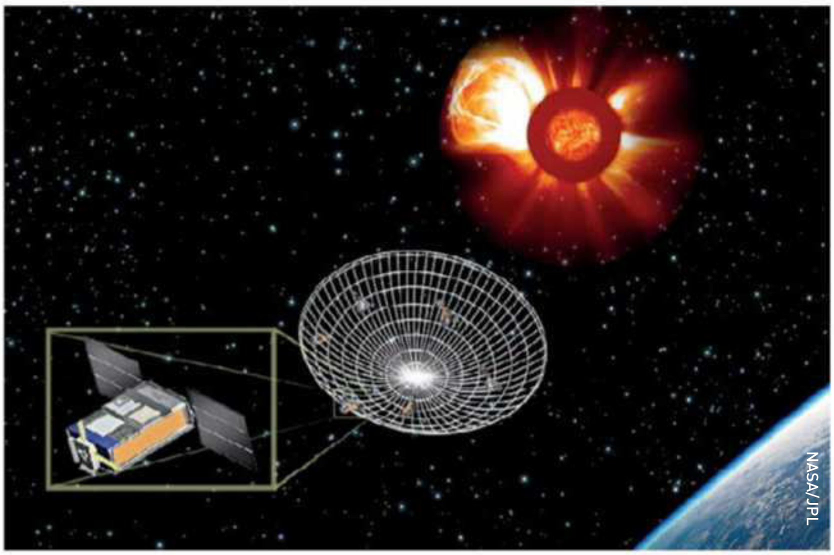
One concept proposed by the University of Michigan would use multi-frequency magnetic induction sounding from a compact magnetometer to characterise the subsurface ocean of Europa. Another proposed by Robert Ebert of the Southwest Research Institute is the JUpiter MagnetosPheric boundary ExploreR (JUMPER), a SmallSat to study Jupiter's magnetic field, including its interaction with the solar wind.

Observing our Sun

The Sun is a massive, roiling, dynamic object at the centre of our solar system. Energetic solar flares, known as Coronal Mass Ejections, shoot out beams of high-energy electrons that can go out far into interplanetary space. As they interact with the Sun's magnetic field, the electron beams generate bursts of radio frequency signals. They are in a frequency range (less than 15 MHz) that can't be seen by radio telescopes on Earth because they are blocked by our ionosphere. If we could position a radio telescope up at geostationary orbit (GEO) or higher, well above the ionosphere, we could observe and characterise these short-lived phenomena, a long-standing goal of the solar physics community.

With Prof Justin Kasper of the University of Michigan leading the science, and the Space Dynamics Lab at Utah State designing the spacecraft, JPL has proposed the SunRISE mission to NASA. The SunRISE mission concept is a constellation of six cubesats, each carrying a radio frequency receiver, deployed just above GEO orbit. Signals collected by individual cubesats are combined to form a 'synthetic aperture' in space, a tried-and-tested technique that allows multiple radio telescopes to coordinate to resolve signal sources such as Coronal Mass Ejections with improved resolution.

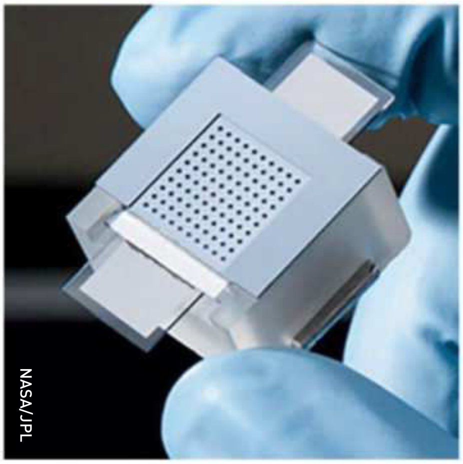
▼ The SunRISE cubesat constellation observing Coronal Mass Ejections from the Sun.



Developing technologies

If you're trying to do big science with small spacecraft, there is no point in arriving at an exotic destination in the solar system if you can't make useful, science-grade measurements. If it's an object we haven't visited before a simple optical snapshot may add to our scientific knowledge, but if we've been a few times already we need more capable sensors.

Not all the instruments we need for deep space exploration can be miniaturised to fit within the constraints of a cubesat or



▲ JPL spacecraft technology development for cubesats/nanosats, and the corresponding mission they will be demonstrated on. From left to right – the deep space transponder (INSPIRE and MarCO), micro-electric spray propulsion (TBD), compact, deployable 0.5 m diameter reflector (RainCube), and onboard data reduction board (M-Cubed/COVE-2).

nanosat volume, but the list of those we can accommodate is surprisingly long. It includes: magnetometers; optical/IR cameras; UV/optical spectrometers; IR radiometers and spectrometers, from the near-IR to far-IR; microwave radiometers; sub-mm-wave spectrometers; short wavelength radars; GPS radio occultation; mass spectrometers; gamma ray and X-ray spectrometers; and optical communication lasers that can be used for occultation. That's quite a rich suite of science instrumentation that reflects the investment the science community has made in reducing instrument size.

There are also some critical spacecraft technologies that JPL and others within NASA are investing in with high payoff for deep space cubesats/nanosats, including: a low mass radio transponder; reflector array antennas for X-band and Ka-band telecommunications; a compact, deployable Ka-band 0.5 m diameter reflector antenna; Micro-Electric Propulsion (MEP) that can provide up to 1 km/s of Delta-V; the design of a standard attachment container to deploy cubesats as hitch-hikers; and onboard data reduction and data handling to significantly reduce science data volumes.

Other technology developments that will greatly enhance or enable deep space nanosat missions include: low-power modes and duty cycling; efficient, lightweight solar arrays; greater energy storage capacity; on-board data compression; delay-tolerant networking; autonomous operations; terrain relative navigation; radiation-tolerant avionics; and multi-layer structures for more efficient packaging and improved thermal balancing. Looking ahead, compact radioisotope power systems may eventually open up the outer solar system to free-flying nanosat missions.

Looking forward

The future for space science using small spacecraft looks bright. We are clearly at the bottom of the growth curve but the pace of change in this area is accelerating, and a lot of innovation is happening across the community. The two factors that will have the most influence on this future from outside the cubesat/nanosat community are whether launch costs can be kept low (and in particular whether dedicated, low cost launch vehicles make it to market), and whether hitch-hiker ride-along opportunities can be created on all planetary missions flown by NASA, ESA and other space agencies. ■

About the author

Anthony Freeman joined NASA's JPL in 1987 and is now manager of JPL's incubator of new ideas, the Innovation Foundry, working on many mission concepts across Earth Science, Planetary Science and Astrophysics. He also teaches Aerospace Engineering (with a focus on nanosats), Systems Engineering and Program Management at the California Institute of Technology (Caltech).

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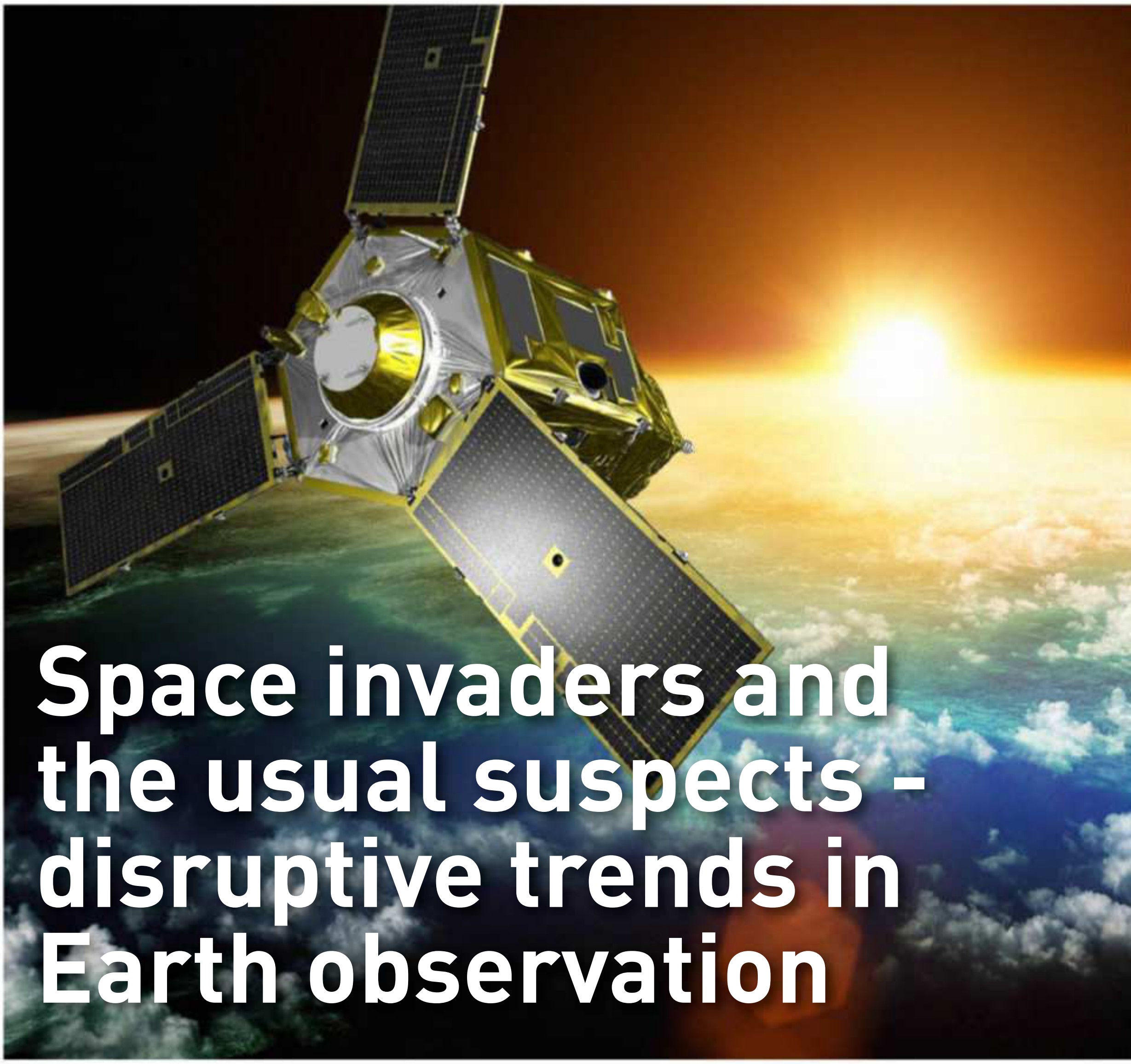
There is no point in arriving at an exotic destination in the Solar System if you can't make useful, science-grade measurements once you get there



Space invaders and the usual suspects - disruptive trends in Earth observation

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Earth observation systems for the most critical institutional needs, including defence intelligence, have historically been dedicated assets predominantly owned and operated by governments or public organisations. Now, the high degree of convergence between defence needs and commercial capacities, together with the NewSpace revolution, is challenging this paradigm and affecting all stakeholders, from established commercial operators to NewSpace actors and nations with new ambitions in space.

Since the launch of Landsat 1 in 1972 and the failed attempt at privatisation of the Landsat programme by EOSAT (Earth Observation Satellite Company), different types of Earth observation (EO) models have been developed and several disruptive events have shaped EO history, bringing significant changes in paradigms.

France's decision, in 1986, to use a commercial model for the distribution of SPOT (Satellite Pour l'Observation de la Terre) system for distribution of EO imagery was a revolution. Two months after its launch, SPOT 1 was tasked with acquiring the first 10 m images after the explosion of Reactor 4 at the Chernobyl nuclear plant in Ukraine. SPOT 1 demonstrated one of the main benefits of commercial

remote sensing for intelligence missions: that it can be shared with anyone. The US newspaper, USA Today called SPOT satellite 'the ultimate skycam'.

In the 1970s US President Carter's administration identified an opportunity for the US to develop a commercial market in order to capitalise on the nation's huge investment in space. Successive US administrations built on that foundation of US policy, as expressed in the Clinton Policy on Remote Sensing Licensing and Exports (1994) and Bush's US Commercial Remote Sensing Policy (2003).

An important milestone was the launch of Ikonos-2, the first commercial EO satellite to collect images with a ground sampling distance below 1 m (0.82 m) GSD at nadir in panchromatic mode, in September 1999. Ikonos imagery began to be sold in January 2000 and the US took the lead in the race for higher resolution. [1]

▲ The area of the 1986 Chernobyl disaster as viewed by SPOT 1.

Innovative framework programmes adopted by the US National Geospatial-Intelligence Agency (NGA), such as Clearview, NextView and Enhanced View, awarded to DigitalGlobe and Space Imaging in 2003, were the first Private Public Partnerships (PPP) in EO.

US administrations have, for the two last decades, favoured commercial services aimed at minimising the proliferation or uncontrolled dissemination of very high resolution (VHR) images. US players, such as DigitalGlobe, offer the best resolution to deter countries who could plan to acquire their own EO satellites.

Defence cooperation

The France-led Helios programme remains a unique prototype example of international military cooperation in space imagery.

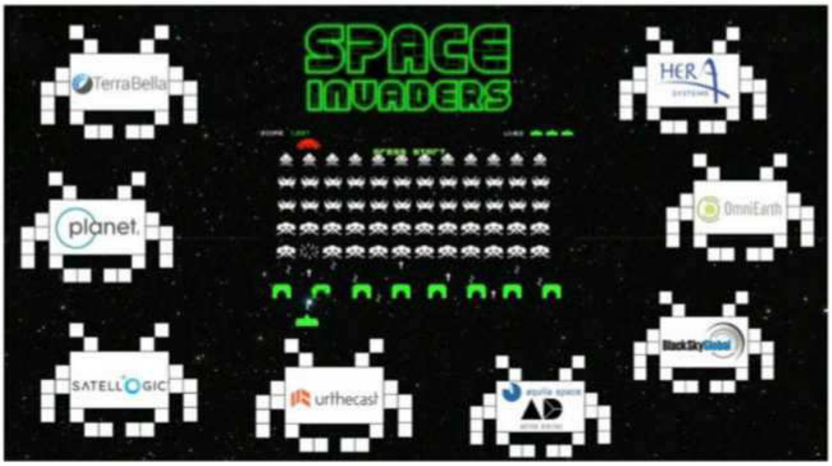
Spain and Italy partnered with France for Helios 1, with the addition of Belgium and Greece for Helios 2. Italy and Germany had separate image-exchange agreements with France for access to Helios 2 in return for giving France access to the Italian COSMO-Skymed and German SAR-Lupe radar reconnaissance spacecrafts.

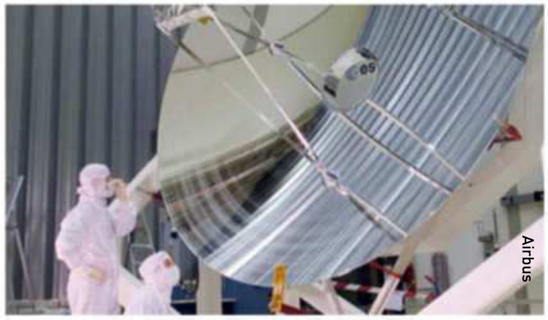
Fifteen years after Helios, the Pleiades system was designed as a full dual system, able to provide imagery to both commercial/civil and military users with appropriate security and priority rules.

In parallel, in the mid-90s, France and the UK developed EO satellites for the export market. The rationale was to offer remote sensing technologies as instruments of sovereignty by providing integrity of the image (no modification by third parties), full access and control of satellite resources, and confidentiality of national areas of interest.

This trend confirmed the soft power dimension of space and opened new opportunities for international co-operation or commercial agreements.

Google Earth opened the door to full private investment from non-space players




Airbus

▲ Space invaders!

▲ Above right: Space telescope or spysat: both have large mirrors.

Private funding

The introduction of Google Earth in June 2005, based on a virtual globe created by Keyhole Inc, also triggered a disruption, in democratising access to satellite imagery. Google Earth opened the door to full private investment from non-space players.

Another major innovation was the 2012 launch of SPOT-6. While the two Pleiades spacecraft were publicly funded, SPOT-6 and SPOT-7 started a new era: for the first time in the remote-sensing industry, satellite development costs were financed entirely with private funds provided by Airbus Defence & Space.

NewSpace was the most recent and most visible disruptive trend, [2] starting in the US Silicon Valley and spreading worldwide, arousing our expectations, sometimes excessively.

This new model involves not only start-ups but also big web actors with substantial investment capacity. Both aim at transforming space into a commodity. Beside the massive constellations for broadband Internet access, some initiatives have been launched for EO markets, targeting high resolution and high revisit.

Although less publicised than the NewSpace ventures, more and more countries are investing in EO capacity, opening up opportunities for international or regional cooperation, and some already active participants such as Russia, India, China and South Korea are becoming involved in new projects, including private initiatives, to ensure independent access to imagery or to develop their own industry.

In terms of EO data and services, the two 'champions' are DigitalGlobe (US) and Airbus Defence and Space (Europe). DigitalGlobe is currently the worldwide leader. It offers the sharpest imagery (30 cm GSD) with WorldView-3 and WorldView-4 (launched in November 2016). DG's first market is the US government with 55 percent for NGA as anchor customer (framework contract).

Since June 2014, DG has been allowed by the US government to collect and sell imagery at the best available resolutions (up to 25 cm panchromatic and 1.0 m multispectral GSD). In February 2017, DG entered into a merger agreement with MacDonald, Dettwiler and Associates Ltd.

Airbus Defence & Space is the second champion and first commercial operator. Its uniqueness is its capacity to offer both VHR optical (Pleiades-1A and Pleiades 1B) and X-band radar imagery (TerraSAR-X and TanDEM-X). There is no major anchor tenancy contract but the twin Pleiades satellites have been funded by the French government, in a dual use scheme. The first market for SPOT-6 and SPOT-7 is the commercial market. The company is currently designing and building a new constellation of very high performance optical satellites, to replace the Pleiades satellites.

Despite their differences, DigitalGlobe and Airbus Defence & Space share similar elements of profile: they deliver high quality VHR imagery (down to 30 cm), with a focus on acquisition capacity and powerful distribution services, based on a fleet of agile satellites, direct receiving stations and networks of distributors. Most of their revenues come from image sales, direct access and delivery services, targeting both domestic and export markets. They propose information services, mainly through vertical markets, including defence.

The other established commercial actors are Imagesat International (Israel) and e-GEOS (Italy). Imagesat International operates the family of EROS satellites. EROS-B delivers 0.7m GSD at nadir from 510 km. The swath is 7 km. EROS-C is expected to be launched in 2019. It will deliver 0.4 m GSD from 500 km. e-GEOS operates the Cosmo-Skymed SAR constellation and distributes DigitalGlobe imagery in Europe.

The massive use of high-performance commercial off-the-shelf technologies has already proved the feasibility of constellations of several tens of cubesats

Space invaders

Also known as 'aliens' or 'barbarians' [3], these companies do not belong to the regular crowd of the 'space club'. They have their own rules, coming mainly from the IT world and are fast and agile, with a fresh look on entry barriers.

Several private companies have emerged, first in the US and now in Europe and worldwide, such as Satellogic in Argentina [4] and NorStar Space Data in Canada. Their ambition is to develop and operate space systems and services with disruptive commercial objectives.

Rise of NewSpace

These firms bet on low-cost technology to provide more affordable space systems and services based on EO data. The massive use of high-performance commercial off-the-shelf (COTS) technologies has already proved the feasibility of constellations of several tens of cubesats weighing around 5 kg and costing a few thousands of dollars per unit. But NewSpace is not always orientated to 'small is beautiful' - some initiatives are based on medium-sized or even large satellites.

The big players of the web sphere are increasingly interested in space and able to invest massively. With a huge cash capacity, their assumption is the disruption will be triggered by the convergence between advanced information technologies and EO: in June 2014 Google surprised space remote sensing experts and traditional players when it bought Skybox Imaging for US$500 million.

NewSpace actors have scalable business models (i.e. the capacity to start business before the full deployment of the system). They believe they can lower or break the market entry barriers. They target the final user in a B2C (business to consumer) approach with aggressive and agile solutions. 'Democratising' access to space imagery is usually a key element of their business strategy. Nearly all promote information freshness, apps or web platforms, data analytics tools and subscriptions via the Internet.

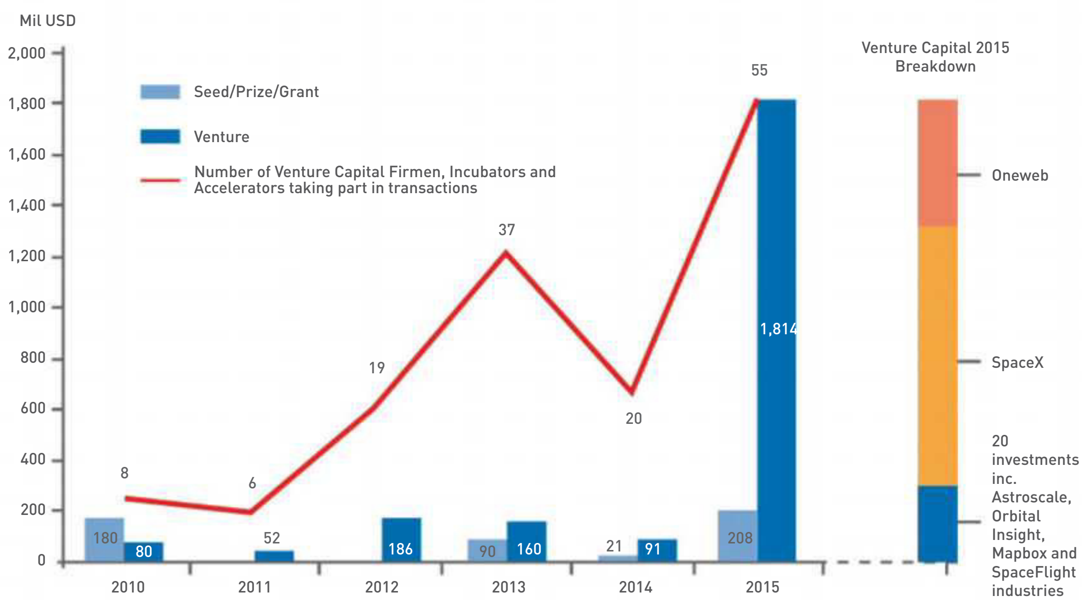
Space nations

Whether they are veterans in space activities (China or India) or newcomers deciding to have their own EO capacities, more and more nations are becoming active players in EO. This affects both the competition and the accessible market.

For example, since mid-2016, SI imaging Services (South Korea) has been distributing VHR imagery (GSD <50 cm) acquired by Kompsat-3A. Another

▲ High resolution on small satellite: like squaring the circle.

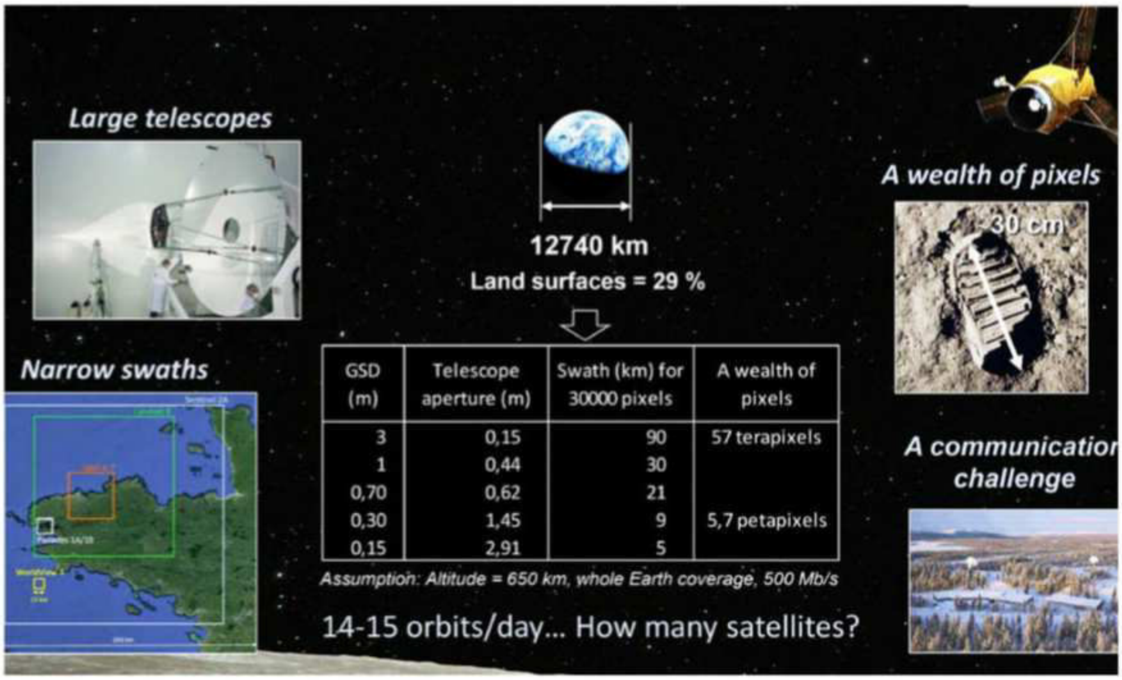
New Space is not always orientated towards 'small is beautiful'



◀ 2015 was a record year for venture capital investment in space.

Spacetec Analysis/Tauri Group data

▶ The digital Earth challenge.



example is the drastic reduction of EO data imported by China since it began operating its own high and very high resolution satellites. Sooner or later, China will enter the worldwide EO market as a new provider.

Key initiatives

Over the past decade, more than 33 projects for new EO satellite constellations have been announced. Although experts may remain sceptical of the capability of these projects to become operational, some initiatives are led by serious players.

The main technical challenge remains the size and mass of the satellites: high resolution means large imaging instruments.

Planet, (formerly Planet Labs) has put into orbit nearly 150 cubesats with GSDs of between

▶ Integration of an optical instrument on AstroBus-S platform.


Airbus

Main EO providers focus on acquisition capacity and powerful distribution services

3 and 5 m. While modest in terms of pure performance (when compared with 0.30 m resolution from the best commercial satellites), the main feature of these new initiatives is the high number of platforms in orbit. This allows very high revisit rates and makes space sensors much more reactive than when placed on a few satellites only.

Terra Bella (formerly Skybox Imaging) plans to put up a constellation of around 24 satellites in the next few years. Seven have already been launched (the last four in September 2016). Their mass is around 100 kg. They acquire images with a ground resolution of about 0.90 m.

BlackSky Global, located in Seattle, plans to put into orbit 60 imaging satellites allowing a performance of around 1 metre ground resolution by 2019. Six satellites are under preparation and the first 'Pathfinder' was launched in September 2016.

UrtheCast, based in Vancouver, plans to serve the governmental market with its eight optical and eight radar satellites in preparation. It targets a high-quality phased optical and radar product with 0.50 m and 1 to 5 m resolution respectively in the optical and radar domains (OptiSAR).

In 2015, Planet and Urthecast raised sufficient funding to acquire the space assets of established competitors Blackbridge and DEIMOS, re-enforcing their business model with a 'traditional' satellite constellation and a client portfolio. These first buybacks are observed with interest by satellite EO experts and venture capitalists to understand the dynamic of this new economic ecosystem.

Many other projects [5] exist as of today, with different mixes regarding the number of satellites, mass, complexity and performance, but with a common objective to reap market shares using innovative dissemination practices.

Private financing

According to a recent study [6] by Bryce Space and Technology (formerly Tauri Group), the space start-ups (all activities included) raised almost US$13 billion of private investments between 2000 and 2015. In 2015, a record US$2.3 billion was spent on more than 50 investments in space start-ups in the US.

Investments by business angels, venture capitalists or major industrial groups can be highly rewarding. In the case of Skybox, Google paid more than US$480 million, while only US$91 million had been invested in the start-up by venture capitalists. The benefits for them were well worth the initial effort. Planet has been through five rounds of investments, representing in 2016 about US$206 million contributed by 17 investors. It recently bought Terra Bella, highlighting that some consolidation in this new sector is starting.

More and more countries are becoming active players in Earth observation

US government support

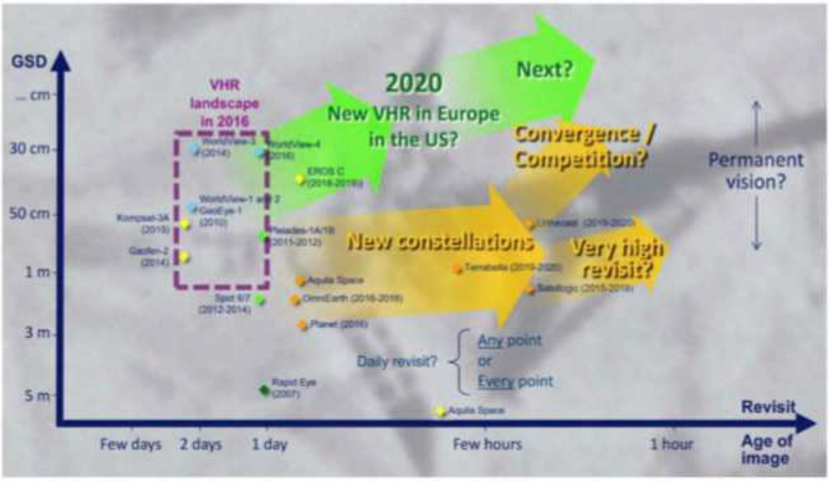
In the US, public institutions support this new economy. A bit like the early support to DigitalGlobe, the US government (through the NGA) has declared many times its enthusiasm for the NewSpace entrepreneurs in EO.

In 2015, a first initiative known as the 'NextGen Tasking Initiative' was announced to sustain these new commercial activities, especially to help with the development of new methods for the collection, processing and dissemination of commercially generated data.

The global picture is depicted in the Commercial GEOINT Strategy, published the same year by the NGA [7]. Six months later, the creation of an 'Outpost Valley' close to Silicon Valley start-ups was announced with the reinforcement of the NGA California branch.

More recently still, a new Commercial Initiative to Buy Operationally Responsive GEOINT (CIBORG) was publicised with the explicit goal of supporting the new space imagery industry for federal users [8]. Terra Bella, UrtheCast, Planet and BlackSky Global have been identified as the first potential interested parties. The first CIBORG contracts are being signed this year with a budget increasing over the period 2018-2022.

▼ Pleiades image iof the Silicon valley.



▲ Trends in commercial imagery - resolution versus revisit.

Space without satellites

Some start-ups do not plan to fly their own satellites: Orbital Insights, based in Palo Alto, recently received US$20 million in new investment, including US$5 million from In-Q-Tel, the investment arm of the US intelligence community. Orbital Insights gathers its data through contracts with EO data owners and the start-up develops software to extract insights from satellite and aerial imagery.

Another example, SpaceKnow, also based in Silicon Valley, uses space imagery and other data sources to track global economic trends through its Analytics-as-a-Service products. SpaceKnow SMI (China Satellite Manufacturing Index) is the first trading index based on satellite data to be featured on the Bloomberg Terminal.

Next steps

The EO landscape may radically change in the coming years. While some experts warn about a possible new internet 'bubble', two considerations moderate the relevance of this analogy.

First, technology has evolved and new small satellites have improved in terms of performance/cost and performance/size ratios. Some (although not all) technological obstacles tend to disappear or to be of less crucial importance for the design of space and ground systems.

Second, comparing support from the web industry in the 1990s with today gives a clear indication of the huge progress made and the financial and industrial strategies regarding its massive requirements for broadband telecommunication, location-based services and information dissemination worldwide.

The usual suspects and the new entrants implement specific, non-exclusive strategies:

- The 'high end approach', with increased imagery resolution for customers acknowledging the value of these products: a significant percentage of revenues come from EO image value
- The 'service-based strategy' is not only a low-cost approach. It assumes that the value will be the information and the services created from the EO data and from other data sources. The main focus is data freshness (revisit).

It is too soon to say for sure if the promise of huge growth in the geoinformation market fostered by the convergence between IT and EO will become a reality but EO markets and the related industrial landscape will evolve significantly in the coming years and may even be disrupted by newer technologies. ■

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James Vaughan/Asgardia

Space nation set to mark its presence in orbit

▲ A rotating-wheel space station alongside an interplanetary rocket.

The world's first space nation announced its first small step towards a giant leap into the future at a press conference in Hong Kong on 13 June 2017 when a team of international scientists, academics and entrepreneurs revealed concrete plans for the launch this fall of Asgardia-1, the fledgling state's inaugural satellite. The announcement was made by Asgardia's Founding Father and Head of Nation, Dr Igor Ashurbeyli, one of the world's most distinguished rocket scientists. The satellite launch will mark the first significant tangible step in the foundation of Asgardia, which is planned to be independent of any Earth-bound country but subject to international law.

Lena De Winne
NGO Asgardia,
Vienna, Austria

Whilst it eventually plans to operate a futuristic Earth orbiting space complex, Asgardia's first satellite will store data for the nation's newly selected citizens- up to the first one and a half million people who adopt the Constitution of Asgardia.

Asgardia-1 will be deployed from Orbital ATK's Cygnus OA-8 resupply spacecraft due to launch this autumn to the International Space Station (ISS). The nano satellite is 10 x 20 x 20 cm and has eight batteries and four deployable solar arrays, and it will orbit at up to 500 km above Earth.

▲ Asgardia's first satellite, Asgardia-1, will launch this fall on Orbital ATK's Cygnus spacecraft, which will be delivering supplies to the International Space Station.

The satellite is a first step to fulfilling his plans to create a planetary-defence constellation to help protect Earth against asteroids, solar flares and human-made space debris

Texas-based space services firm NanoRacks is the satellite's prime contractor and operator.

Speaking in Hong Kong to 36 journalists representing broadcast, print and social media, as well as hundreds from around the globe who logged into the live broadcast, Dr Ashurbeyli said the satellite is a first step to fulfilling his plans to create a planetary-defence constellation to help protect Earth against asteroids, solar flares and human-made space debris and other space threats.

He also described plans for a space complex and lunar colony. "We plan to have this station in space and on the Moon," he said. "It will be a four-level orbital constellation and the technical details will be defined by the country's Ministry of Science, which I hope we will have in place by the autumn of this year."

All approved applicants for Asgardian citizenship were invited to vote on a constitution for the space-based nation on 18 June for the prompt formation of the admistrative organs of the proposed state - parliament, government, etc.

Anyone can register as prospective Asgardians on the website - www.asgardia.space

In the autumn of this year, Asgardia's first satellite will be laucnhed, which will be a marker for the nation and become the foundation stone of a permanent presence in space. It will contain data from up to 1.5 million Asgardians which will be stored in orbit for free - 300 kB for each of the first 100,000 citizens of Asgardia, the next 400,000 people will receive 200 kB each, and another one million people will receive 100 kB.

Dr Ashurbeyli said: "Asgardia will now demonstrate that space is within our grasp. Last year in Paris when we launched Asgardia many people were sceptical that we would ever put anything in space. But I can confidently announce today, that we will be launching a space satellite, Asgardia-1.

"Asgardia-1 is our first, small step which we hope will lead to a giant leap forward for humankind. It will be our foundation stone, from which we will look to create an entire oribtal, terrestrial and lunar constellation that will help protect our planet and all humanity against threats from outer space and move on to the borders of the infinite universe."

Asgardia is working to establish a legitimate, independent first space nation, which will be recognised by states on Earth and the United Nations. Whilst "facing towards space and its own future development", Dr Ashurbeyli explained Asgardia required its own constitution, a draft of which had been developed over the previous six months with the help of legal experts and others in the community.

The news followed last October's announcement in Paris of the creation of Asgardia and the launch of the citizenship process. In the first 48 hours following that announcement over 100,000 people

▼ Dr Igor Ashurbeyli addresses the press conference in Hong Kong which was broadcast live via social media.

■ Dr Ashurbeyli meets with local Asgardians in Hong Kong.

Asgardia-1 will primarily be a data storage satellite. It is scheduled for launch into orbit this autumn by an Orbital ATK Antares rocket carrying the ninth Cygnus cargo freighter, which will be on its eighth operational cargo delivery flight to the International Space Station.

on Earth registered as Asgardians, rising to above 500,000 registrations in the first 20 days.

So many registered that Asgardia stopped taking in new applications and switched to a second level of verification which excluded minors who registered without the permission of their parents, duplicate applications, those who did not provide additional information, and various 'bots'.

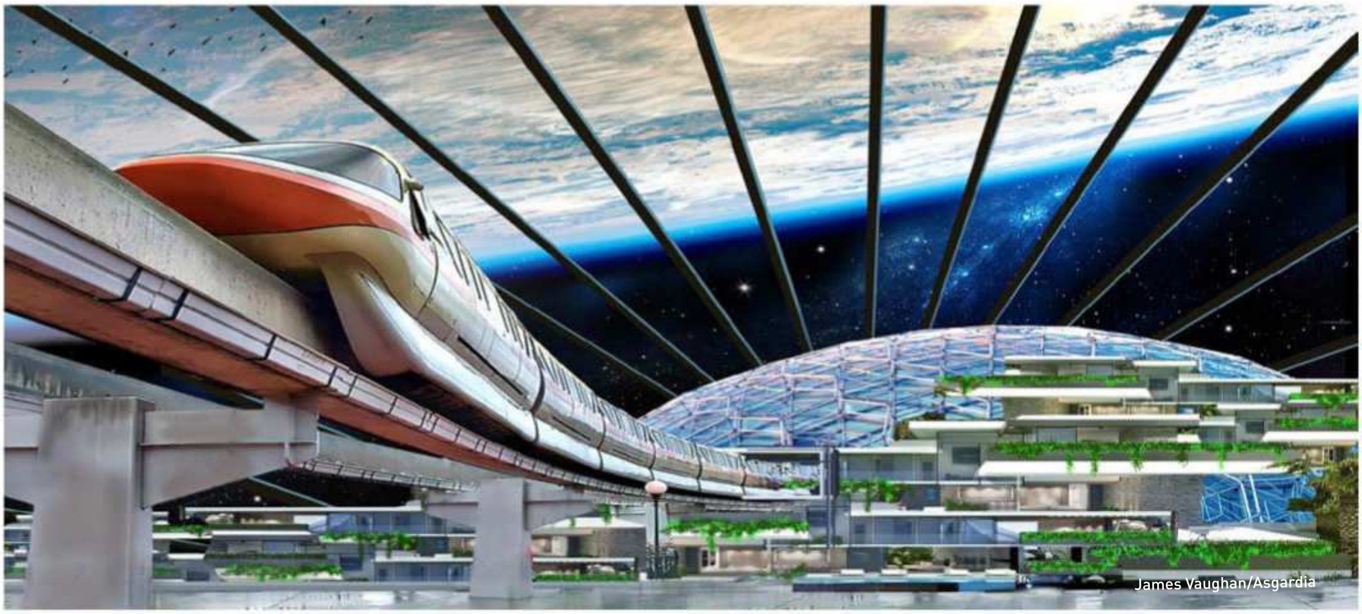
After removing ineligible candidates, more than 200,000 Asgardians from all over the world remained. All endorsed candidates provided their personal data and received personal certificates of Asgardia, allowing them to vote in order to approve the constitution developed by lawyers.

Prof Ram Jakhu, Director of the Aerospace Law School at McGill University in Montreal, Canada, who was on the press conference panel, said: "Law is necessary for certainty

The nanosatellite will be a marker for the nation and become the foundation stone of a permanent presence in space

Landmarks of Asgardia's first eight months

- Asgardia registered as non-governmental, non-profit organisation in Vienna, a prototype of the future state where officials will begin work in 2018.
- The entity will be the legal owner of all Asgardia property and this will remain the case until Asgardia becomes a UN recognised nation. Immediately after that all the NGO Asgardia property will be transferred to the state of Asgardia.
- Vienna selected because Austria is a neutral state and does not belong to a military political alliance, it is the location of the UN branch responsible for Space matters, and is the base of the Aerospace International Research Centre (AIRC) founded by Dr Ashurbeyli as the initial stage in the launch of Asgardia.
- Asgardia's national calendar approved and first three national holidays (in Gregorian calendar 12 October - the Birthday of Asgardia; the 31 December - Year Day; and 18 June - Asgardia National Unity Day) installed.
- The Asgardia trademark is registered in the appropriate classes in Europe and the USA, and in other countries. Work is on-going.
- A joint stock company Asgardia AG has been registered in Vienna and, subject to certain conditions, any Asgardian can become a shareholder. The main goal of the company is to collect, analyse and fund any ideas and start-ups in the space technology development domain for the benefit of Asgardia - the country of space ideas; and for the benefit of all humankind.
- New updated www.asgardia.space website launched on 13 June.



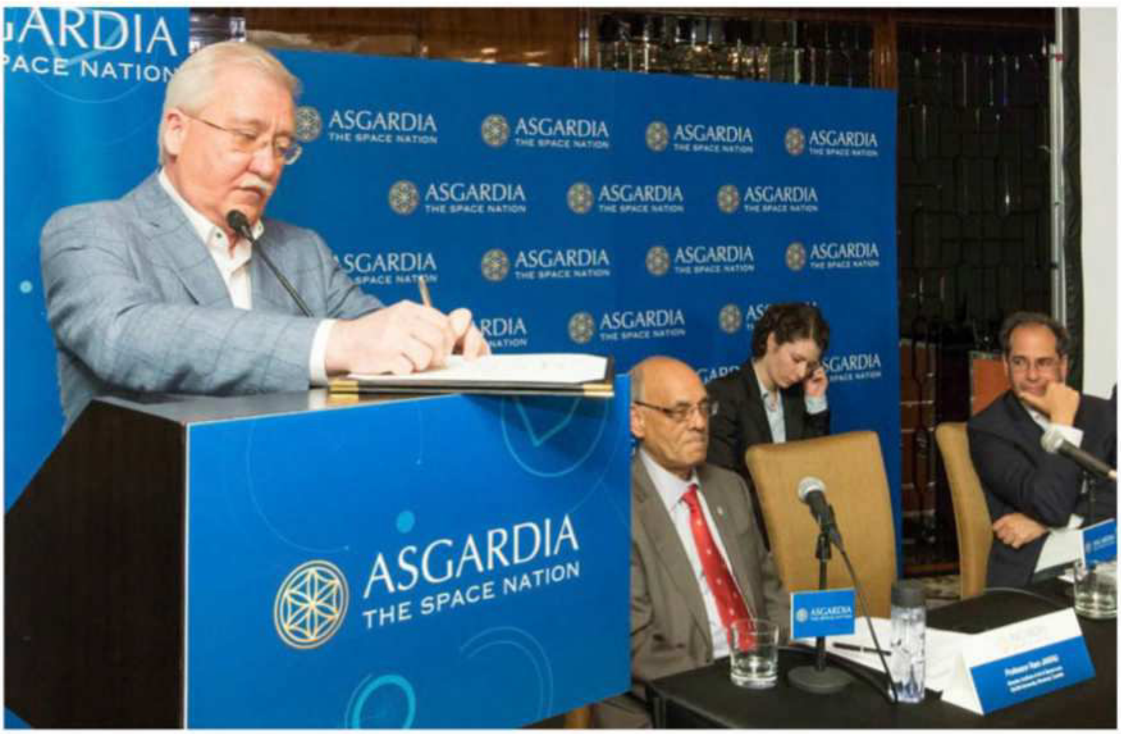
▲ An imaginative interior of an orbiting space colony as visualised for the space-based nation Asgardia.

in human behaviour and for supporting innovations in human progress. Progressive adaptations and new developments in law are indispensable for facilitating technological and entrepreneurial advances for the betterment of humanity not only on our mother planet, Earth, but also for humanity's migration to the universe."

The implementation partner for Asgardia's first satellite is the US-based private company NanoRacks which develops products and offers services for the commercial utilisation of space from its base in Houston, Texas.

Jeffrey Manber, Nanoracks CEO and co-founder said: "We are delighted to be providing a turnkey solution to Asgardia's in-space needs, from locating the satellite to the launch and final deployment in space. Asgardia is a creative and exciting new chapter in our eternal questioning of how humanity will live and work in space. We're excited about its future."

Asgardia partnered with NanoRacks, a leading provider of commercial access to low-Earth orbit, to



▶ Signing of the declaration in front of a live global audience.

Asgardia aims to establish a legitimate, independent first space nation, which is recognised by states on Earth and the United Nations

"There is nothing and nobody standing between us apart from the idea of creating the space kingdom of Asgardia!"

manufacture and oversee the satellite mission that will enable its debut in space. In turn, NanoRacks has selected NearSpace Launch (NSL) of Indiana to build the satellite based on previous mission success, integrity and quick turnaround time.

NSL says the satellite is designed to carry a payload of energetic particle sensors and a 512 GB hard drive which contains the beginnings of an Asgardian space presence. Its payload will enable regular communication between Earth and the Asgardian satellite through NSL's EyeStar S2 Simplex and Duplex radios and Globalstar's 30 satellite constellation, regardless of the satellite's position in orbit.

Marcia Blount, director of operations for NanoRacks in Houston, said: "NSL has been a strategic vendor to NanoRacks in the Asgardia-1 programme. Its services align with the turnkey solution we offered to Asgardia, and we look forward to bringing the first space nation's satellite to orbit in near record time."

After launch on an Orbital ATK rocket to the ISS, Asgardia-1 will be deployed from the External Cygnus NanoRacks CubeSat Deployer, mounted on the outside of the Cygnus spacecraft. The satellite will be deployed from Cygnus after the vehicle departs from its primary mission at the Space Station. ■

▼ Dr Ashurbeyli pictured with Ram Jakhu (left) and Jeffery Manber.

Highlights from the speech of Dr Igor Ashurbeyli

In his presentation to the press conference Dr Ashurbeyli said Hong Kong had been chosen because it is one of the biggest international financial and commercial centres in the world, and also represented the largest population of Asgardians living in the People's Republic of China.

He went on to state: "We want to build a serious, legitimate, independent first space nation, which is recognised by the Earth states and the United Nations, and which is facing towards space in its development.

"Of course, the baseline documents which were prepared in such a short period of time may and will cause serious debates. This is the reason why I have constitutionally limited my own authority to a five-year period. This will allow Asgardians to thoughtfully define how they see their future, and to incorporate necessary changes into the Constitution and the laws of Asgardia.

"Today I am calling upon everyone to vote for this Constitution as it is presented. It may change many times, the same as our Asgardian space humanity will change. But today we must not waste time.

"According to our Constitution in only six months, we have to form the Parliament of Asgardia based on the language representativeness principle. And in the three months after - the Government, the Court, the Prosecutors Office, etc.

"We, Asgardians, have a unique advantage. As the Founding Father of Asgardia I do not know any of you personally. And none of you knows me personally. This means that there is nothing and nobody standing between us apart from the idea of creating the space kingdom of Asgardia!

"Let's do it together!

"I am declaring the voting open right now on the new Asgardia web-site asgardia.space. And in front of you, in this live event, I sign a Decree.

"You do not need to go to an election booth now. You just stay in the comfort of your favourite gadget and make a couple of clicks - a few on your device, and mostly important, one in your heart.

"One humanity one unity! We are not the best. We are the future. I embrace you all and everyone of you."

▲ Medic on Mars by artist Phil Smith.

The vast distance to Mars and its inhospitable environment mean it is imperative for the first colonists in any future settlement to be independent particularly when it comes to treating medical emergencies, as well as for general and mental health, and many other things we take for granted. Drawing on existing studies for long-duration space missions and related medical research, this article seeks to identify potential countermeasures to many of the human risks to living on Mars and suggests avenues where more research is needed.

The concept of humans living on Mars is shifting slowly from the realm of science fiction into technological reality. NASA intends to take humans to Mars in the 2030s and SpaceX founder Elon Musk is working towards a full-time human presence on the red planet by 2040. Even more ambitiously, Musk intends for this Martian colony to grow eventually to a population of 80,000 people.

As a relatively small outpost located in a hazardous environment far from Earth, a Mars colony could not afford to have many sick or

Planning for health, sex and sleep on a future Mars colony

injured members. Treatment requires the use of limited medical and human resources and prolonged illness, injury or even death would impact designated tasks. The human health challenges of a Martian colony calls for pragmatic planning at a basic level.

A well-functioning Martian colony would need to address numerous issues related to human health and well-being in space. While many of these areas may be fascinating - such as human reproduction in space - their discussion at this time is almost entirely speculative. Clearly, the ability to reproduce is essential for the health and sustainability of any colony but it is an area of that still needs considerable study. Here we will focus on 'immediate' health needs of the first generation of Martian colonists - radiation, gravity, circadian dysrhythmias, life-support systems, mental health, and public health.

Radiation

Radiation is a major challenge for human space travel. Away from Earth's protective magnetic field, two key types of radiation are of concern: solar particle events (SPE), which largely consist of low-energy protons and originate from the Sun; and galactic cosmic radiation (GCR), which is composed of high-energy protons plus heavier nuclei and originates from beyond the solar system.

Known consequences of radiation exposure include cancer, reduced fertility, cataracts, cardiovascular and central nervous systems problems, and inheritable genetic mutations. Particularly intense exposure at one time can result in acute radiation syndrome (ARS), which can lead to nausea, vomiting, skin damage or even death within a matter of days. Radiation exposure may also aggravate the effects of bone loss due to reduced gravity conditions.

Since Mars lacks a magnetic field or protective atmosphere comparable to Earth, countermeasures against radiation would be needed. Certain consequences of radiation - ARS, cataracts and cardiovascular effects, for example - occur predictably and correlate with the severity of the radiation exposure. Even space radiation exposures of less than two weeks without adequate protection have been shown to increase the long-term mortality from heart disease.

A basic countermeasure is to simply establish limits for maximum acceptable doses of radiation but this alone will not be sufficient to protect the colonists, so

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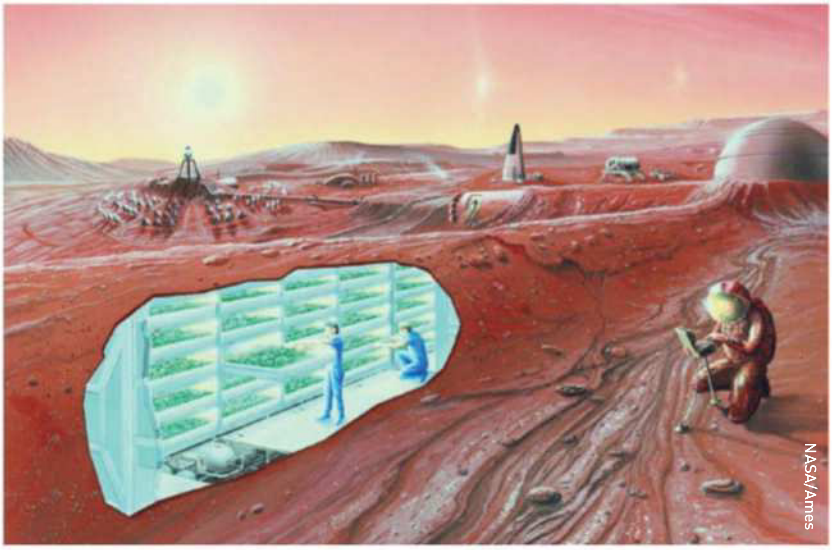
The concept of humans living on Mars is shifting slowly from the realm of science fiction into technological reality



▲ Future Mars settlements may be partially buried to reduce radiation impact, as this cutaway view shows.

shielding technology will also be necessary.

Shielding against SPE radiation, due to its relatively lower energy, can be achieved with existing technology. Aluminium or regolith (Martian soil) could be used to protect habitats on the Martian surface; the use of caves as habitats that reach sufficiently deep underground has also been proposed.

In general, short-duration human extra vehicular activities (EVA) of a few hours at a time outside of the habitat would not likely result in significant radiation exposure, though anyone working on the Martian surface would need to remain close to appropriate shelters in case of solar storms or an intense SPE, for which a deep space SPE alert warning system would need to be created.

Higher energy GCR is more challenging and research examining shielding effectiveness suggests that only small reductions to GCR are possible using current technology.

Pharmaceutical countermeasures against symptoms of radiation may also prove useful, although no drugs currently exist that mitigate long-term effects.

Some medications may reduce radiation-associated symptoms like nausea and vomiting while other drugs with radio-protective properties, such as amifostine or antioxidants in general, can serve as direct countermeasures, although they may have side effects. Research on mice has suggested that a class of drugs called bisphosphonates may be used to address bone loss caused by radiation and microgravity exposure.

Interestingly, there is little to no information available on the long-term effects of a partial gravity environment on the human body

Reduced gravity

The consequences of prolonged microgravity on the human body - osteopenia and osteoporosis (the long-term loss of bone mass), muscle atrophy, reduced healing, changes in fluid distribution throughout the body, intervertebral disc expansion and reduced sensorimotor function - have been studied extensively.

Frequent exercise and pharmaceuticals offer mitigation while in space. Some effects, such as the loss of bone mass, can be permanent while other effects, such as changes to the distribution of fluids within the body, are temporary and will resolve upon return to a gravity environment.

Interestingly, there is little to no information available on the long-term effects of a partial gravity environment on the human body. There have only been 12 humans who have travelled to the surface of another celestial body and those missions were all relatively short. All long-duration human habitation space missions have occurred in space stations in low Earth orbit (LEO), which can only support research in microgravity, not partial gravity.

The relationship between gravity and health is not necessarily a linear one and computer modelling suggests the reduced gravity of Mars is, for the purposes of human health, more similar to Earth-level gravity than it is to microgravity. This research suggests that any negative effects of Martian gravity on human colonists could be relatively manageable and current countermeasures should be sufficient. However, until long-duration human research is conducted in a true partial gravity environment this is simply an educated guess.

Circadian dysrhythmias

Sleep is essential for human health as well as for human performance. In a Mars colony, optimal functioning will be crucial for maintaining critical systems and performing operations - fatigue would become a threat to overall health.

The term 'circadian rhythm' describes the natural biological clock of organisms; on Earth, that cycle is approximately 24 hours long. Disruptions can result in fatigue, decreased alertness and performance failure; in space, those disruptions can include an intense workload, confinement, and the loss of the light/dark cycle that comes with experiencing day and night.

While the Martian day (sol) is only 39 minutes longer than an Earth day and so within the likely range tolerated by the human circadian rhythm, the general need to remain inside the Martian habitat for most hours of the day will limit the ability of colonists to align their circadian rhythms with the Martian sol. Scheduled day and night periods inside the colony would therefore be necessary to prevent circadian disruptions.

It would also be necessary to develop reasonable schedules and workloads for colonists. Operating the colony and its systems will require constant, around-the-clock work and observation, and consequently it will be necessary to maintain at least two shifts with inverted work/rest schedules. If those assigned to a particular shift were unpredictably transferred to the other shift, or made to work beyond their regular shift, the resulting circadian disruptions would very likely cause them to perform below their optimal level.

Life support

Life support systems for human spaceflight have historically been relatively simple and requirements for a Mars colony will include power, environmental support, clean water, waste disposal, food production and medical treatment facilities. Any permanent Mars colony will need to use resources available in situ or recycle, as regular deliveries of food and water will not be practical.

Arguably, power systems will be the most critical system in the Mars colony because, without it, other systems needed to support human life would fail. Solar power is one option, although due to Mars' distance from the Sun and environmental conditions, the surface area of the requisite solar arrays would need to be impractically large.

Nuclear power, either through fission or radioisotope emission, would likely be more efficient in terms of mass than solar power and more reliable, although it clearly presents other challenges. In practice, a combination of both nuclear and solar power might be prudent for a Mars colony.

Multiple systems will be needed to monitor and maintain the colony's internal environmental conditions. The native Martian atmosphere is largely composed of carbon dioxide and it maintains a pressure only one percent of Earth's; atmospheric systems would therefore need to maintain Earth-like internal conditions, approximately 78 percent nitrogen and 21 percent oxygen, at roughly 101 kilopascals of pressure, in spite of the external environment.

Local resources could be used to extract oxygen and other necessary atmospheric components in situ from the Martian environment instead of bringing them from Earth.

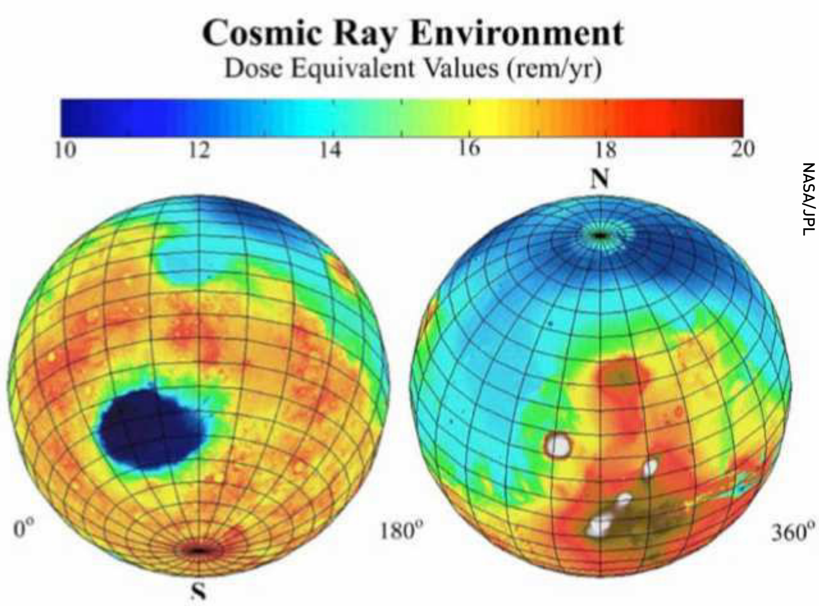
Water is not only naturally available on Mars but is relatively abundant

Recycling air would be a good supplement to in situ resource utilization (ISRU) but refinements in recycling technology would be necessary as current technology is impractical on very long-duration missions. The average temperature on Mars is -63C so there would also be a need to maintain Earth-like temperatures inside habitats.

Unlike on previous human space missions, which have operated almost exclusively in vacuum and therefore were more concerned with radiating excess heat than retaining it, the Mars colony would require systems to distribute heat throughout the habitat as well as insulate the environment to maintain a comfortable temperature for human living. The environmental support system would also need to be capable of filtering micro pollutants, such as dust from outside, trace amounts of synthetic compounds, etc, out of the colony's air and water.

The amount of water necessary to support a permanent human colony on Mars would be prohibitively heavy if brought from Earth. Fortunately, water is not only naturally available on Mars, and not exclusively at its poles, but is relatively abundant; frozen water comprises between 1.5 and three percent by mass of the Martian regolith, and this water can be extracted simply by heating it up. It could very well be easier for the Mars colony to produce water than to recycle it.

As mentioned, the technology needed to recycle sufficient volumes of water for a permanent Mars colony would require significant further development; as an example, current water recycling and waste disposal systems used on the International Space Station (ISS) are not designed to handle menstrual



▼ Global map of Mars showing estimated radiation dosages from cosmic rays reaching the surface, based on cosmic-radiation measurements by the Mars radiation environment experiment on NASA's Mars 2000 Odyssey spacecraft, plus information about Mars' surface elevations from the laser altimeter instrument on NASA's Mars Global Surveyor.

Arguably, the power system would be the most critical system in the Mars colony - without adequate power, nearly all the other systems needed to support human life would fail

blood, which would certainly be an issue for a permanent human Mars colony.

In addition, human discomfort with drinking recycled urine might also increase the attractiveness of ISRU over recycling. The issue of disposing wastewater products might be as simple as sequestering it and eventually relocating it away from the colony, though this would likely be considered an inefficient use of resources and energy. A partial water recycling system, such as greywater recycling, might therefore be useful for other water-intensive purposes such as agriculture and industry.

In fact, waste disposal systems and agriculture on Mars would be tightly linked. While traditional outdoor agriculture on Mars would likely be impossible, some form of food production would be necessary to supply the colony with adequate nutrition to sustain itself. And unlike air and water, which can be produced from local Martian resources, food and vitamins would need to be recycled from human waste in order to support crop growth.

Beyond the challenge of linking those systems, there are other questions about the practicality of agriculture on Mars. For instance, plants respond to low atmospheric pressure by drying out so, due to lower pressures on Mars, crops might need to be grown hydroponically in water rather than in soil. Furthermore, while plants have been successfully grown in microgravity, it is unknown how they will develop in a partial gravity environment.

Medical systems are obviously critical for human health. Unlike traditional spaceflight missions, which frequently use telemedicine and resupply technologies to supplement onboard medical resources, it would be desirable for a Mars colony to invest heavily in its own medical supplies and personnel.

Medical facilities would need to be able to address any illness or injury, and be able to support ongoing care. While most supplies for medical facilities would need to be brought from Earth, perishable or consumable supplies like medicines could be produced on Mars.

For example, bioreactors - which use microorganisms to generate biological products - could be used to replenish antibiotic supplies. While bioreactors have been demonstrated to work in space, there are some questions about their efficacy and so the efficacy of bioreactors on Mars is speculative and could be affected by differences in gravity and radiation exposure.

Mental health

There is a substantial body of research concerning the psychological health of astronauts while in space.

▶ NASA astronaut Karen Nyberg in the Cupola module of the ISS - studies have shown that windows and the ability to view 'home' are a great benefit to crew members.

Not all of it will be applicable to a Mars colony but some lessons from Earth orbiting space stations can be applied.

For instance, it is broadly agreed that the simple idea of having windows to allow the colonists to look outside is likely to be salutary. The challenge with this on the surface of Mars will be that it will be very difficult to see Earth, which is considered one of the great psychological benefits of current space missions.

It is also known that unrealistic work schedules can be a major source of stress. In 1973, the crew of Skylab 4 'mutinied' after they had been made to work during three consecutive scheduled rest days and were then asked to work through the fourth; they decided to take the day off. It would therefore be prudent to build 'slack' in the schedule to allow colonists enough time to rest, for their health as well as for public order.

On the other hand, the Mars colony would be such an unprecedented undertaking that it is difficult to predict with certainty how its participants might behave; while astronauts on the ISS have clearly defined mission durations, Mars colonists would be living permanently away from Earth. Current astronauts are, in an emergency, only a matter of hours away from reaching Earth's surface; Mars colonists would be months away, even assuming that travel back to Earth was possible.

Today's Space Station crews are carefully selected and then train together for years to help them work as a coherent team; the proposed scale of the Mars colony would make such team-building and detailed selection strategies impractical. These are challenges that will be difficult to address until human missions to Mars begin.

Public health

The first generation of Mars colonists would need to be carefully screened for infectious pathogens before leaving Earth but there are still risks posed by contagious diseases.

Spaceflight tends to cause reduced immune response - as does stress in general - and alters the virulence of some pathogens; consequently, colonists may be susceptible to infection from their own microbiomes, the microorganisms that typically exist within the body.

Given the close quarters in which the colonists would have to live, this could result in epidemic-like events. Careful monitoring of colonists' health would therefore need to be a priority and sick colonists who are contagious would need to be isolated and treated promptly.

Because all Mars colonists would be living and working in an artificial habitat, with relatively few opportunities to go outside on EVA, the habitat itself would need to be designed with safety and human health in mind.

Some of the issues to consider would include: incorporating redundant life support and airlock systems; avoiding fall and electrical hazards, such as loose cables and exposed wires; ensuring that residential areas are quiet enough to sleep in; and dedicating enough space for storage, etc.

The need for exercise to mitigate bone loss and muscle atrophy is critical in microgravity. While those symptoms may be less severe in the partial gravity Mars environment, the confined nature of the colony's habitat would also make physical exercise crucial for maintaining mental health. Journals kept by astronauts on the ISS suggest that their time spent exercising also proved a valuable aid to mental relaxation, and they disliked it when their workloads kept them from scheduled exercise periods.

Profound risks

The risks to human health from spaceflight are significant but the risks to human health from establishing a permanent human settlement on another planet are even more profound. Located in an extremely dangerous environment, such a venture will be unprecedented, uniquely independent and technologically challenging.

The long-term survival of a Mars colony will rest upon the health and wellbeing of its inhabitants; if such an audacious venture is to be attempted, it is absolutely essential that the threats to human health are identified early and prepared for aggressively. ■

A full list of references supporting this article is available on request.

About the authors

William West graduated from the Space Policy Institute within the Elliott School of International Affairs at the George Washington University, USA, where he earned a master's degree in International Science and Technology Policy. He has a Bachelor of Arts in Geography and has worked as a contractor for the US Geological Survey and is currently a consultant in the space policy community in Washington, DC.

Dr Kris Lehnhardt is an Attending Physician and Assistant Professor in the Department of Emergency Medicine at The George Washington University (GWU) School of Medicine and Health Sciences. At GWU, he is the Director of the Fellowship in Extreme Environmental Medicine (FEEM) and the Director of the Introduction to Human Health in Space graduate course. Dr Lehnhardt has served as the Chair of the Human Performance in Space Department for the International Space University Space Studies Program, where he is currently an Adjunct Professor.

It is absolutely essential that threats to human health are identified early and prepared for aggressively

Radiation protection for space colonists and travellers

When space crews travel beyond the protection of Earth's atmosphere and magnetic field, space radiation becomes a serious hazard. Radiation permeates empty space and most of the places we would like to colonise, and surviving the high radiation environment in space will be a vital part of human effort when it comes to colonising the solar system. Here, in the second of two articles, Joseph Parker suggests some ways that extreme radiation risks might be managed and mitigated for crews travelling and living beyond Earth.

When stem cells are severely damaged we can no longer repair radiation injury

L. Joseph Parker MD,
Arkansas, USA

Dreams of colonising space may be drawing closer to reality with plans now under development in different parts of the world for humans to move beyond Earth and low Earth orbit to explore and live in space, on the Moon, on Mars or in orbiting colonies. But leaving home is never easy, and space travellers moving out of the shelter of Earth's atmosphere and magnetic field will have to contend with high levels of solar and galactic radiation.

Space agencies take measures to limit the time astronauts spend exposed to radiation, such as scheduling spacewalks so that they do not occur during times of intense solar activity and limiting the amount of radiation they are exposed to during their careers - but for humans in the future intending to spend many years in space, prolonged exposure will be unavoidable.

Scientists and engineers will have to find creative ways to deal with this danger and unless it ever becomes possible (or desirable) to alter human genetic make-up sufficiently to create in-built protection, the only way to provide radiation protection in space will be with different kinds of external shielding technology.

To understand radiation shielding we must first review different types of radiation – photonic (electromagnetic wave) and particulate.

Photonic radiation

Photons have no rest mass and their impact, and the degree of damage they can cause, is determined by their energy levels. With sufficient energy photons become ionising, converting atoms or molecules into ions by stripping them of one or more electrons, breaking molecular bonds and damaging cells.

At the lowest end of photonic radiation energy are radio waves, microwaves and visible light. These are referred to as non-ionising and they aren't normally harmful to us.

Ultraviolet (UV) light is more powerful than visible light and it is the weakest form of photonic radiation that can cause us harm. It doesn't penetrate more than a few millimetres through the skin but, with high exposure, can cause skin cancer because, when it ionises atoms in a covalently bonded molecule, it breaks those bonds and damages the molecule. In the case of cancer, the damaged molecule is DNA.

◄ A computer-generated visualisation of the Apollo 8 spacecraft in orbit around the Moon, with Earth rising over the horizon. The thin metal shell of the Apollo capsules protected the astronauts from most types of radiation on their way to the Moon.

The most harmful energy waves are X-rays, which most of us are familiar with, and gamma rays.

X-rays can be stopped by the atmosphere, by heavy metals such as lead, or by sufficient volumes of water. Gamma rays can also be halted by the atmosphere, by water and, for the most powerful photons, by several metres of lead. Because the wavelength of a particle is inversely proportional to its frequency the short wavelength gamma rays have the highest frequency and energy.

Passive shielding

The Apollo spacecraft were incredibly well designed for their time, though some parts of the outer skin were as thin as 0.03 cm, no more than a modern soda can. This thin metal shell was enough to partially protect the astronauts from most of these types of radiation on their way to the Moon, although enough X-rays and gamma rays got through to give them a dose of between 1.8 and 11.4 millisieverts.

The average annual dose of radiation exposure on Earth is around 3 millisieverts, making the Apollo 11 crew's dose of 11.4 millisieverts about three years' worth in nine days. This seems high, but they suffered no immediate ill effects, although there is some question of increased heart disease and cataracts in these men.

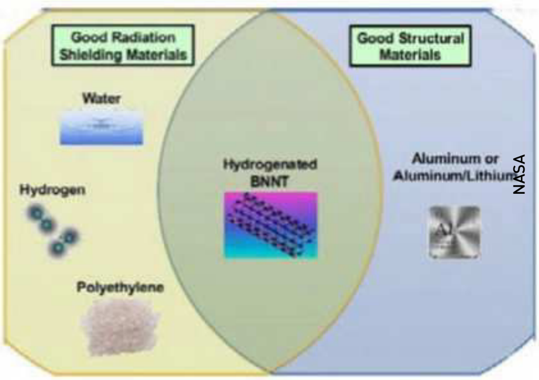
A thicker metal shield is more effective at stopping photonic radiation, especially when materials that have a high concentration of hydrogen atoms, such as water or plastic is layered with the metal as is the case with modern spacecraft. This raises an odd issue, however. When these photons impact the metal, or to a lesser degree water, they come in contact with the electron clouds around other atoms and can produce a type of secondary radiation called Bremsstrahlung or 'braking' radiation. Layers of metal and water or metal and plastic should be able to absorb most of this if it is thick enough.

Particulate radiation

The second type of radiation we have to worry about is particulate radiation, which will usually be in the form of free high-speed electrons, protons (the simplest hydrogen nucleus) or more massive atomic nuclei.

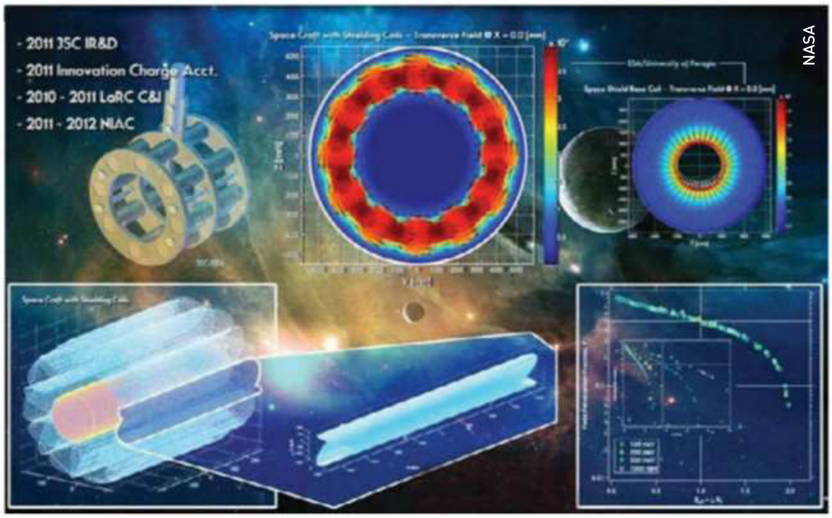
These nuclei are usually hydrogen or helium and their isotopes (as produced by our Sun) but they can be much heavier nuclei, iron or even uranium if they come from more energetic events such as supernovae and black holes. High-speed atomic particles produced by supernovae and other energetic deep-space events are referred to as galactic radiation and, while solar radiation comes from the direction of the Sun, galactic radiation comes from all directions in space.

These particles have a tremendous amount of energy and can cause serious damage to human cells, penetrating into metal shielding and sending out



◄ Structural radiation shielding systems.

Space travellers moving out of the shelter of Earth's atmosphere and magnetic field will have to contend with high levels of solar and galactic radiation



▲ Active radiation shielding using high temperature superconducting magnets.

showers of secondary radiation, including neutrons. They are also best absorbed by materials with a high hydrogen content, the best being liquid hydrogen, then water, plastics and perhaps liquid methane. Neutrons are particularly hard to stop because, being chargeless, they are not affected by electromagnetic fields generated by other atoms and can penetrate deep into tissues and cause a great deal of damage.

There are several ways to mitigate and block these particles, also called 'high-energy, high-charge' or 'HZE' (high atomic number and energy) particles in some literature.

Designed to protect

A spaceship with a metal skin that uses plastic interior walls and supports, with all possible supplies and fuel tanks arranged to surround the crew quarters, is the best option to start with. It adds no extra power requirements; the mass is already necessary to the structural integrity of the craft and the supplies are necessary for crew survival needs. Water for the crew can be distributed through a second hull to surround the habitable areas of the ship.

These interventions will shield the crew from all but the most powerful gamma rays and most but not all of the galactic radiation. They will also help mediate the effects of secondary radiation, where a high speed atomic particle strikes a nucleus in the ship materials causing a cascade of radiation particles and photons, including neutrons.

The Orion spacecraft will use the mass that is already on board to protect the crew of long-distance missions to Mars. Supplies, equipment and launch and re-entry seats, as well as water and food will be used to protect the crew by creating a temporary shelter in the aft bay of the spacecraft, which is the inside portion closest to the heat shield.

Active shielding

Engineers are working on several ways to protect future space crews or colonists from very high energy galactic radiation. One method that could be very useful is generating a powerful magnetic field, which could cause the charged particles approaching the ship to curve around it - much as the Earth's magnetic field protects us here.

This would be done by producing two rotating magnetic fields with opposite orientation. One would be larger than the other with the second field cancelling out the effects of the first except outside the second smaller field. This would create a magnetically neutral bubble around the ship, so as not to interfere with equipment etc. with a larger bubble of high magnetic strength farther out.

This shield system would run at low power during normal radiation levels but could be made much stronger during high radiation events by redirecting all available ship power to this shield system when a surge of radiation is detected.

Some engineers have looked at this type of system and voiced concern about synchroton radiation, which is produced when charged particles travel on a curved path, but all of the synchroton radiation would be photonic and in the wavelength of radio waves and microwaves, and possibly visible light causing a 'Northern lights' effect. Even if a severe event produced some X-rays or gamma rays it would be a lot better than letting the high-energy particles through. A system such as this would also provide the added bonus that some captain somewhere would be able to order, "Shields Up!".

▼ Active radiation shielding using 6+1 expansion coil architecture.

The crew could also, of course, use a storm shelter, like that on the International Space Station, to wait out any major radiation storm. The active magnetic shielding method could be effective for individual buildings or even large settlements that generate lots of power but would not be very practical for space-suited colonists in the open on the Moon, Mars or elsewhere in space.

The power requirements and mass required would limit mounting such a system on a space suit until our batteries are much smaller and more powerful. Unprotected time in space will always have to be carefully monitored and limited to prevent radiation sickness or early cancer.

Wearable radiation protection

Space suits create a protective environment for the wearers providing essential air pressure and oxygen in the vacuum of space and give protection from extreme temperatures and from small pieces of space dust. But they provide only limited shielding against radiation

Most of the damage from acute radiation exposure is produced in the bone marrow. This is the source of stem cells that we need to repair damage elsewhere in the body and is one of the most vulnerable organ systems to radiation exposure, because the limited life-span of blood cells requires continuous cell divisions of hematopoietic stem cells in the bone marrow. If the bone marrow is severely damaged we can no longer repair radiation damage, leading to medical conditions that can be fatal.

▲ The AstroRad Radiation Shield vest developed by StemRad will be tailor-made for individual astronauts. It was on show at the 33rd Space Symposium in Colorado Springs earlier this year.

◀ A cutaway illustration of NASA's Orion capsule.

One cutting-edge technology that may help future astronauts has been devised by an Israeli-American company called StemRad. The AstroRad Radiation Shield is a multi-layered vest that will be tailor-made of non-metallic shielding materials which will be positioned to protect the bone marrow and other organs from radiation.

Only about five percent of the bone marrow needs to survive a high radiation event in order to replace the rest and provide healing stem cells, and shielding the entire body would be too bulky and inflexible to allow freedom of movement. Creating a vest that shields the body's core while allowing normal movement is a great balance of protection and functionality.

The vest is due to be tested on the Orion mission scheduled to orbit the Moon in late 2018. It will be attached to a 'phantom' torso dummy, a device used to monitor radiation absorption, and a second phantom will fly unprotected so that the comparative results can be analysed after they return to Earth.

Almost certainly a combination of these technologies will be needed to successfully protect future astronauts and colonists as they venture into deep space. ■

Unprotected time in space will always have to be carefully monitored and limited to prevent radiation sickness or early cancer

About the author

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Spaceflight studies support geriatric health on Earth

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Understanding the links between spaceflight physiology and the aging process can lead to improvements in human health not only for astronauts living in microgravity but also for older people living on Earth. This article provides a general overview of important physiological consequences of spaceflight, the aging process in humans on Earth, and important connections between these physiological states.

Ever since our ancestors started walking upright, the human body has adapted to the effects of gravity. For example, during standing the human heart - despite being located below the brain - is able to pump enough blood to the brain against the force of gravity to maintain proper brain function. The pooling of blood in the legs - which occurs due to gravitational forces - is counteracted by the muscle pump in the lower limbs by one-way leg venous valves as well as by the action of breathing.

Additionally, the weight-bearing bones and anti-gravity muscles have adapted during evolution to ensure adequate support during standing. Thus humans can stand up without any real problems.

The real importance of gravity on physiological systems is, however, seen when gravity is reduced or taken away, as in the microgravity environment

▲ Right: Astronauts exercising on the ISS, with NASA's Ron Garan in the foreground.

of spaceflight. Here, the impact of microgravity is seen on many physiological systems including cardiovascular function, cerebral autoregulation, musculoskeletal and sensorimotor systems.

For instance, cardiovascular deconditioning remains a persistent problem associated with the time spent in microgravity during spaceflight (Antonutto et al., 2003). In addition, the re-entry to Earth has many important effects including increased heart rate, dizziness symptoms upon standing up (decreased orthostatic tolerance) and a reduction in exercise capacity (Buckey et al., 1996).

Physiological deconditioning as seen in spaceflight also occurs on Earth, especially as a consequence of the aging process and also due to bed-confinement and/or immobilisation. A variety of conditions and diseases such as cerebral or peripheral vascular disease, metabolic or endocrine disorders, autonomic neuropathy, or cardiac arrhythmias may result in syncope (dizziness and loss of consciousness), especially during changes in posture from lying/sitting to standing up.

Illness or injury in older people frequently requires hospital-based care and the immobilisation that occurs during hospitalisation is itself a major factor in physiological deconditioning and functional decline which, in older people can further contribute to a downward spiral of increasing frailty, dizziness upon standing up and increased risk and incidence of falls (Mühlberg and Sieber, 2004).

Bedrest is used as a ground-based analogue for studying the effects of weightlessness on physiological systems as seen during spaceflight (Goswami et al., 2015; Jost, 2008; Pavy Le Traon et al., 2007). The bedrest study protocol, in which subjects lie in supine position over variable time periods, is a highly controllable experimental setup routinely used by space agencies and providing excellent possibilities to investigate physiological function changes during lowered gravitational stress (Arzeno et al., 2013; Cvirn et al., 2015; Oshea et al., 2015).

As older people spend up to 80 percent of their time in hospital confined to bed, bedrest studies can also help in furthering our understanding of the deconditioning process during hospital stays.

Astronauts in space spend a substantial amount of time doing physical training to counteract the deconditioning due to the effects of microgravity and to alleviate orthostatic intolerance on return to Earth. They also complement their training regimes with nutrition and other measures to ensure optimal health. Pedersen and colleagues (2016) recently reported that since the advanced resistive exercise device (ARED) was introduced on the International Space Station (ISS) eight years

The real importance of gravity on physiological systems is seen when gravity is reduced or taken away

▶ ESA astronaut Thomas Pesquet is carried to a waiting helicopter after six months in space. He returned to Earth in June 2017, landing on the steppe of Kazakhstan with Russian commander Oleg Novitsky.

A high protein diet increases lean tissue mass and muscle strength when it is complemented with resistive training in older women

ago the resistance exercise component of total in-flight exercise has increased.

Could such physical activity programmes carried out by astronauts in space be used during bedrest immobilization in older people to counteract deconditioning on Earth as well? Early intervention in bed-confined older people is vital as, without it, a rapid decline in muscle mass, bone mass and functionality occurs (Singh et al., 2008).

Started early enough, re-mobilisation interventions can overcome the decline of physiological function, leading to complete recovery. If intervention is started later, then recovery is usually incomplete and patients can be left with reduced physiological functionality. Unfortunately, remobilisation is started too late in many cases and patients permanently lose their functionality, independence and autonomy, leading to increased risk of mortality (Singh et al., 2008).

Intervention combinations in older people confined to bed could incorporate physical exercise and/or nutrition. While there is some evidence that physical activity is beneficial for maintenance of both physical function and mental health in older people (Olanrewaju et al., 2016), there is limited literature that has examined the effects of physical activity to counteract the effects of bed-confinement.

Recent data generated from bedrest campaigns related to space research suggest that resistive vibration exercises can maintain muscle strength and function. Even though these data were obtained in young subjects confined to bedrest, resistive vibration exercise could be of great value in addressing the problems of deconditioning in bed-confined older people. This illustrates how data generated from ground-based analogues of spaceflight could be used in geriatrics.

▼ Six degree head down bedrest immobilisation in an ESA facility.

Nutrition

There is growing evidence that there is a strong association between risk of frailty and inadequate intake of food in elderly people (Martone et al., 2013). Malnutrition results in functional decline, increased morbidity, preterm dependency, more frequent readmission after hospital discharge, early dependency and institutionalisation, and finally, increased mortality.

Spaceflight data have shown that resistance exercise, together with proper nutrition, including Vitamin D, is effective in maintaining physiological functionality in astronauts during spaceflights of up to six months' duration (Smith et al., 2012).

The evidence regarding the beneficial role of nutrition alone in older people, however, is limited (Muscaritoli et al., 2016). Strandberg et al. (1985) reported that nutritional therapy, along with resistance training, improves muscle mass in older people. A further study showed that high protein diet increases lean tissue mass and muscle strength when it is complemented with resistive training in older women (Daly et al., 2014).

These observations indicate that knowledge obtained from space research can provide guidance towards optimising/supplementing the effects of physical exercises via additional nutritional supplements and/or pharmacological interventions, which could represent key innovations in tackling bed-confined deconditioning, especially in older people (see Hackney et al., 2015).

Future perspectives

The intersection of understanding of human physiology under microgravity conditions and during the aging process allows for each of these physiological conditions to provide insight into the other and allows for development of new insights and strategies of intervention.

As we have seen, bed rest studies in addition to simulating spaceflight-induced deconditioning can be designed and used for investigation of the various physiological conditions that arise due to bed-confinement that occurs frequently in older people due to surgery, injury or chronic debilitating diseases.

◀ A person doing resistive vibration exercise while in six degree head down tilt position.

Strategies that apply spaceflight technology to help life on Earth, especially in relation to bed-confined older persons, should be further explored

Thus, there exists a potential for developing a powerful synergy of information between microgravity-induced deconditioning and bed rest induced deconditioning in older people, which could be useful in the development of countermeasures in both conditions.

The parallels between the consequences of aging and microgravity, and strategies that apply spaceflight technology to help life on Earth, especially in relation to bed-confined older people should be further explored and recommendations made that take into account key factors such as (mal-) nutrition, (de-) conditioning, muscle loss, cardiovascular and vestibular effects, which arise in aging and/or long term bed confinement. ■

A full list of references supporting this article is available on request.

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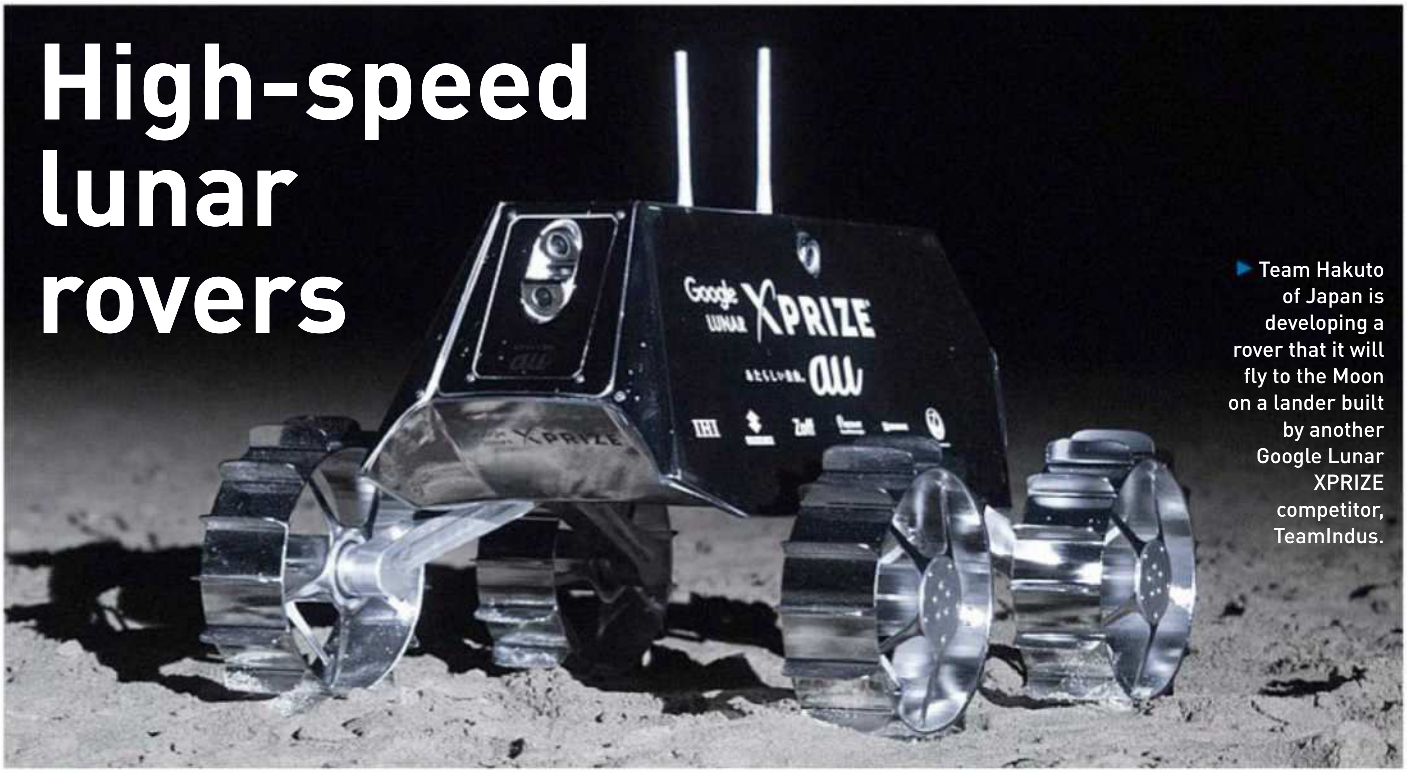
High-speed lunar rovers



Team Hakuto of Japan is developing a rover that it will fly to the Moon on a lander built by another Google Lunar XPRIZE competitor, TeamIndus.

It has been said many times before that to become a multi-planet species, we must first be able to conquer the Moon and use its resources effectively before making the leap to other worlds. To achieve this aim, a team based in the Space Robotics Lab at Tohoku, Japan, are working on a high-speed, improved-mobility rover to help identify regions of interest on the lunar surface. Could this be the start of a journey that will eventually help humans get to Mars in the 2030s?

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Dr Kazuya Yoshida
Space Robotics Lab, Tohoku University, Sendai, Japan

With many of the present and future space exploration missions revolving around the exploitation of the Moon, there is a need to gather the knowledge and to develop the technology that will eventually make these missions affordable and sustainable. Unlike life in low Earth orbit (LEO) where resources can be brought form the ground, for humans to thrive beyond LEO resources have to be found, extracted, processed, managed and used directly at the place of exploration. Characterising the local environment in the search for specific resources is the first necessary step of the voyage that humankind is already undertaking to explore and inhabit the Solar System.

In this endeavour, robots are set to play a key role by working side-by-side with humans and the objective of our mission at the Space Robotics Lab at Tohoku University in Sendai, Japan, is to develop the capabilities for planetary robots to be more efficient in reaching positional targets, more effective in the selection of regions of interest, and more reliable in overcoming the obstacles and withstanding the risks of performing in outer space. Our plan to develop a high-speed, improved-mobility rover is just the beginning of a journey that will take humans farther into the Solar System than ever before.

Gateway to exploration

Concrete plans to develop a cis-lunar outpost in a Near-Rectilinear Halo Orbit (NRHO) around the Moon are beginning to take shape [1]. This outpost will allow human and robotic exploration of the Moon, giving the chance to further study some of the most compelling questions about the formation of the universe and to unveil its potential in terms of availability of resources for use in future exploration, commercial activities and habitation.

The Moon and cis-lunar space are considered crucial in the development of the technologies that will eventually bring humans to other planetary bodies. Besides serving as a proving ground for

Current rover designs are not suited for accomplishing many of the goals envisaged in future exploration missions

future human and robotic missions to Mars, the lunar vicinity is a key area for the development of an affordable and sustainable space economy that would completely transform the current landscape of space exploration [2].

High-speed lunar rover

Successful robotic systems currently operating on the surface of Mars, such as the Mars Science Laboratory 'Curiosity' and the 'Opportunity' Mars Exploration Rover, were provided with locomotion systems all designed based on the same principles: a six-wheel, self-propelled chassis with a rocker-bogie type of suspension system.

Despite the difference in weight (185 kg for Opportunity and 899 kg for Curiosity) and the use of a slightly different version of the rocker-bogie suspension (differential for Opportunity and hinged-lever for Curiosity) the properties that characterise the performance of both robotic systems are very similar [3].

Rocker-bogie suspension systems have proved to be simple and highly reliable when traversing rough and uneven terrains without compromising overall stability. However, some important limitations can be found with regards to its mobility and locomotive performance, such as the maximum traverse speed that a rover is capable of attaining.

Mobility could be defined in broad terms as the capacity of a rover to traverse between two distance points of an uncharted or unprepared region [3]. This capacity is merely characterised by the relief and the variation of the physical properties of the terrain [4].

Current rover designs are not suited for accomplishing many of the goals envisaged in future exploration missions [5]. Aspects such as the uneven distribution of torques between the wheels, the maximum operational speed (i.e., 2.5 cm/s for Curiosity and 5 cm/s for the Mars Exploration Rovers, Spirit and Opportunity), and the issues experienced by several rovers on past and present exploration missions (mainly related to skidding, which causes the sinking of the wheels) raised the need to develop the mechanics of a future generation of planetary rovers.

As part of our mission at the Space Robotics Lab we are developing a locomotive system for an improved mobility rover. This includes the mechanical design of the suspension, wheels and drive systems together with the improvement of mobility-related control algorithms. In addition to the mechanics of the locomotive system, other aspects related to the navigational ability of a rover, such as path planning, sensing and localisation, have a direct influence on the overall performance of planetary robots.

Our work is oriented towards the design of the mechanics and the development of traction control algorithms for a lunar prospecting rover intended for the exploration and characterisation of the lunar south polar region. Due to limited illumination, irregular topography together with the need to avoid the use of radioisotope thermal heaters, a long-range, high-speed prospecting rover is required.

▶ Artist's concept of a future lunar habitation.

The term ‘high-speed’ describes velocities two orders of magnitude greater than the operational velocities of current rovers, which means an operational speed greater than 1 m/second. Benefits of a faster mobility include:

- Exploration, mapping and characterisation of geological features located far from the landing area, including exploration of regions currently dismissed by today’s planned lunar prospecting missions due to low operational speeds
- A faster return from shadowed areas to the polar highlands
- Gathering of critical information in less time is vital for the assessment of the scientific value of a given region and exploration-based decision making processes.

From DEM to prototyping

The first step towards the design of an advanced locomotive system is to understand the micro and macro-mechanics of lunar regolith. In line with our aim to follow a step-by-step process, we first need to study the effects of increased traversing velocities on the behaviour of lunar regolith, i.e. the variation of its properties: deposition, compaction, erosion, etc.

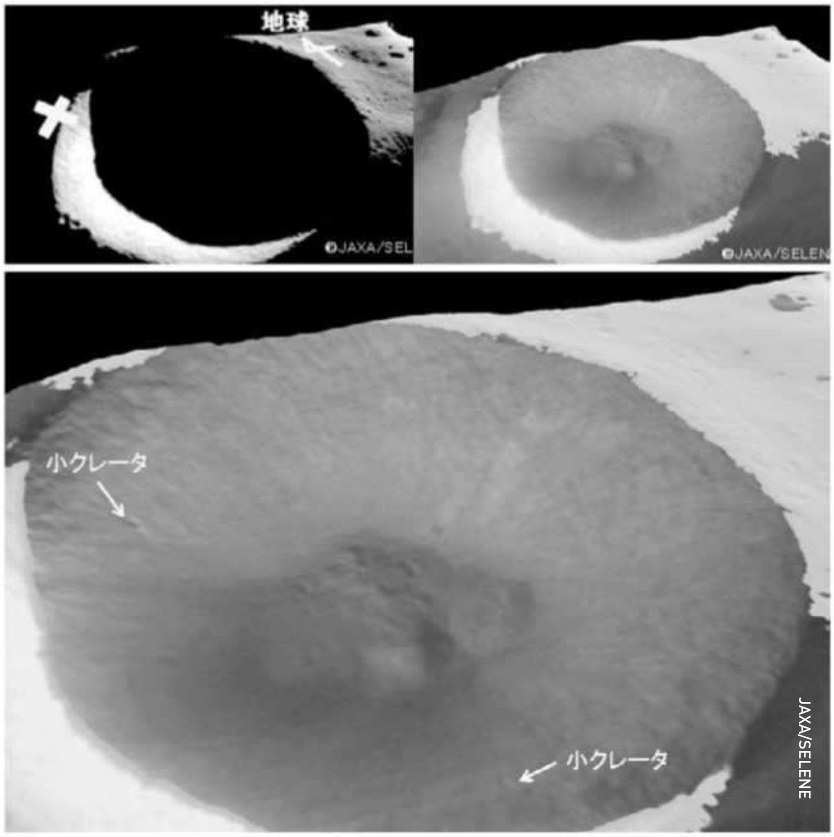
Understanding the implications and limitations of traversing at different velocities is crucial for the assessment of the overall performance of a rover locomotive system. This initial study is encompassed both within the fields of soil mechanics and lunar-oriented terramechanics, in which the Space Robotics Lab has been specialising in for more than 20 years [6, 7, 8, 9].

An initial objective is to improve current numerical algorithms for the simulation of soil behaviour and its interaction with the driving system. This is being approached by investigating the capabilities of Discrete Element Modelling (DEM) in simulating the behaviour of regolith as compared to the results obtained by other numerical techniques.

DEM models consider a physical discretisation of the material, which allows for the simulation of the motion of a group of particles colliding and interacting with each other. This will provide us with the much-needed information to better understand the mechanics governing how a high-speed rover will traverse the lunar surface.

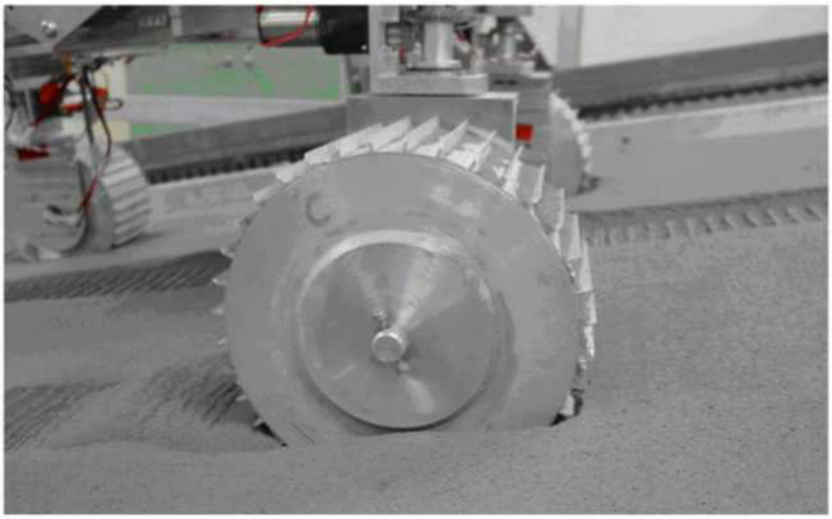
Together with odometric measurements, i.e., data on the change in position over time obtained from motion sensors and environmental mapping, the outcome of these numerical models provides the basic input for the rover’s navigation, localisation and control schemes. Results obtained from simulations will be verified by the performance of a single-wheel test and a particle image velocimetry (PIV) test.

This initial stage of the project will help us to define the best approach in the production of innovative rover suspension and chassis concept designs. Our aim is to provide potential design concepts that enable the production of a rover locomotive system capable of achieving a high



▲ SELENE TC images of the interior of Shackleton Crater on the Moon. The upper left image is the original view of the crater, while the large and upper right images are enhanced pictures based on the original. In the large image, impact craters of hundreds of metres in diameter, located along the crater rim, are marked by arrows.

◀ The front wheels of the NASA’s Spirit rover sunken in Martian soil on mission Sol 2126.



The Japan Times/KYODO

▲ Top: 'Traction performance test of Space Robotics Lab/Tohoku University rover wheels using lunar regolith simulant.

▲ Above: The Space Robotics Lab has actively participated in the development of Team Hakuto's rover. Hakuto is one of the five teams currently taking part in the Google Lunar XPRIZE. Their rover is expected to be launched towards the Moon by the end of 2017.

traversing velocity across the lunar surface while still being compliant with different types of mission architectures. To this end, we will give special attention to the requirements governing actual lunar exploration missions such as stowage and deployability, payload accommodation and wheel adaptability. The different designs proposed will be assessed by means of all-wheel and multi-body dynamics simulations.

These 3D simulations will bring us closer to the development of a 10 to 20 kg class rover prototype. Field tests and further indoor testing resembling different aspects of the lunar environment will be performed. The objective will be to completely characterise different parameters of the locomotive ability of the rover such as steering, horizontal traversing and slope climbing.

Besides locomotive-oriented experiments, the production of a small-class prototype opens the door to the realisation of future testing activities on the different aspects of a lunar mission. For instance, the level of dexterity of space robots could be largely increased by the addition of human factors. Experiments such as reduced-visibility tests that measure the driving ability of humans involving a teleoperated, high-speed, prospecting rover on an environment resembling the lunar south pole could be conducted.

The assessment of the potential of a teleoperated, improved-mobility rover to assist future lunar exploration missions would be of tremendous benefit in the accomplishment of current and future plans for human space exploration. ■

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About the authors

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Africa is open for space business

Filled with rich history, cultures and resources, Africa is the one of the most populous continents on Earth and there is a saying that if Africa closes its borders, other parts of the world will go out of business. Despite being the second largest continent in the world, it is filled with mostly third world countries still developing after colonial independence. All industries thrive in Africa with multinational, commercial giants trying to make a home within its lands - and the US$250 billion space industry is no exemption.

Temidayo Isaiah Oniosun
Regional Coordinator, Space Generation Advisory Council, Nigeria, Africa

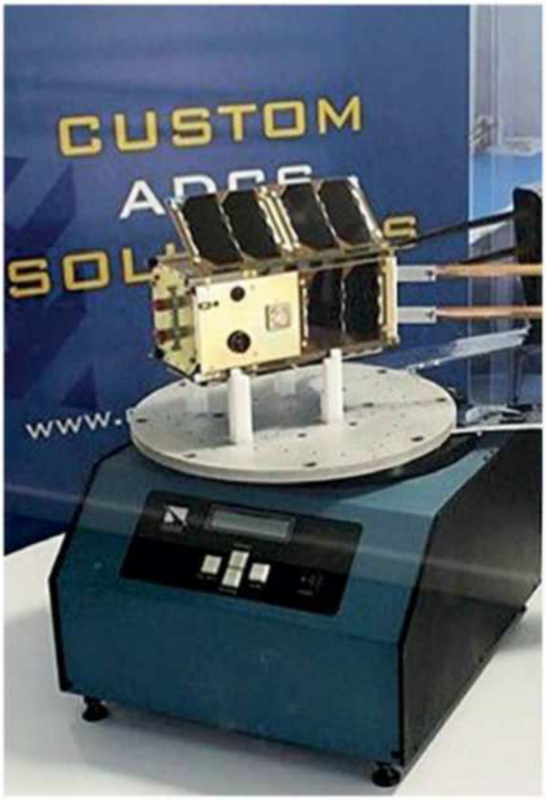
According to Euroconsult, a consultancy focused on high-tech industries including space, Africa's emerging space market is about to make a significant contribution to the global space sector.

The journey began in February 1999 when South Africa's first satellite, Sunsat-1 launched. It was built by Stellenbosch University, South Africa, and this first step toward space technology for the African continent eventually led to a giant leap forward. In November 2002, Algeria joined the big players by launching her first satellite, Alsat-1, built by UK-based Surrey Space Technology Limited (SSTL) and the Algerian Centre National des Techniques Spatiales (CNTS).

In September the following year, Nigeria - representing the biggest economy and most populous country in the region - launched its first satellite NigeriaSat-1, also built by SSTL. In April 2007, Egypt launched MisrSat-1, built by Egypt's National Authority for Remote Sensing and Space Sciences together with the Yuzhnoye Design Bureau in Ukraine.

Eighteen years after the first venture into space, the African space industry has progressed with millions of dollars invested and about 21 satellites launched by six nations. The growing space industry contributes to the continent's objectives of smart, sustainable and inclusive growth.

As well as driving scientific progress, space activities boost growth and employment in other areas such as telecommunications, navigation and Earth observation where systems and services guarantee independence and security for the continent, whilst also helping to address major societal challenges including climate change, resource scarcity, public health and an ageing population. The largest national investors are Nigeria, South Africa, Algeria, Angola and Egypt,



◀ South Africa Za-AeroSAT.

◀ Map showing distribution of the space industry across Africa, showing the major and minor players and number of missions.

with other key players including Morocco, Kenya, Tunisia and Gabon.

Funding is always an important determinant of space technology development - and the lack of funding has been a major problem for the fledgling African space industry. As such, attention has been diverted to small satellite development (nano-satellites) with countries like South Africa, Nigeria, Ghana and Kenya investing heavily in this. On 21 November 2013, South Africa made history by becoming the first African country to launch its own cubesat, the TshepisoSAT, into space. Another South African cubesat, named ZA-AeroSat, was launched in April 2017.

The University of Nairobi, Kenya, is working on a cubesat project called IKUNS-PF, which is to be used for monitoring agriculture and coastal areas. This huge project has been accepted into the United Nations Office of Outer Space Affairs KiboCube programme.

The Joint Global Multi-Nation Birds Satellite project, or the 'BIRDS Project', is a cross-border interdisciplinary satellite project supported by Japan with participation from countries including

Africa's space industry has progressed with millions of dollars invested and about 21 satellites launched by six nations

▼ The South African TshepisoSAT Team.

▶ Nigeria EduSAT-1.

As the second largest continent, Africa leaves a very big market open for commercial space start-ups to maximise profit on investment

Mongolia and Bangladesh, and within Africa, the Federal University of Technology, Akure Ondo State, Nigeria and All Nations University College, Koforidua, Eastern Region, Ghana. The BIRDS Project has yielded two cubesats for both Ghana and Nigeria, named Nigeria EduSAT-1.

The world needs to understand that such a revolution in the space industry for this part of the world will require working with African nations as a whole. Gone are the days of regional monopoly - each region depends on technologies from other regions of the world for space exploration, and Africa has to be a part of this.

Africa is now developing the knowledge and technology to ensure the success of future space missions. For example, all five cubesats developed in the region were built by Africans - and more revolutionary projects are coming from the region soon.

One example is the development of the world's largest radio telescope, the Square Kilometre Array or SKA project, which is currently being built in South Africa, Botswana, Ghana, Kenya, Madagascar, Mauritius, Mozambique, Namibia and Zambia.

The existing infrastructure and skilled workforce, both inside the burgeoning space industry and in supporting industries, will enable Africa to position herself as a regional hub of space science and technology. This can be used as a basis for strengthening ties with industries in established spacefaring nations, and for developing links with other emerging national space initiatives across the world.

As much as the space industry in other parts of the world focuses on exploring other planets, including trying to make Mars like Earth, the space industry in Africa is focused on not making Earth more like Mars - this is evident in the goals and objectives of her space missions. Most of the investments in the region focus on Earth observations, using space technology to tackle challenges in security, telemedicine, climate change, agriculture, disaster monitoring, and communications. For example, one of Africa's key players in the space industry, Nigeria Communication Satellite or NIGCOMSAT, is a pioneer in providing improved internet access to every part of the continent including rural areas.

Recently, Elon Musk elucidated SpaceX's plan to colonise Mars and planets in the Trappist system, and discover solar systems that could support human life. This seems to be the latest exciting project in the global space industry. Then, there is the African Space Policy, which could be the next big thing. The African Union (AU) Heads of State and Government, during their Twenty-Sixth Ordinary Session on 31 January 2016 in Addis Ababa, adopted the African Space Policy and Strategy as the first of several concrete steps to realise an African Outer Space Program.

It has been suggested that one such avenue through which African regional cooperation can be encouraged is the establishment of an African-led regional space programme managed by an African Space Agency.

In August 2010, the African Union Ministers of Communication and Information Technology called for the AU Commission to conduct a feasibility study for the establishment of such an agency, called AfriSpace. Through funding from the European Union, a European consortium

▼ The BIRDS project.

undertook the feasibility study, highlighting the current use of space applications in Africa, making recommendations and creating a roadmap for the establishment of an agency.

Egypt and potentially Sudan have indicated interest in hosting an African Space Agency to coordinate a regional response to the space policy. Work is already underway to bring this to reality as it will foster cooperation among African states in space research, technology and applications.

Through the launch of an African Space Agency, Africa will be able to negotiate better offers for satellite construction, space launches and technology transfer; and coordinate the sharing of data, limited facilities and infrastructure much more than individual small countries can do on their own.

According to Timiebi Aganaba-Jeanty, a keen observer of the African space industry, in a paper presented at the 2016 International Astronautical Congress (IAC) in Mexico, a number of challenges have been identified with an African Space Agency:

- lack of political will on the continent
- dependency on external support
- regulatory restrictions
- insufficient coordination, and awareness of indigenous capacity.

Although no space project is currently ongoing that leverages this level of regional cooperation - except the SKA project which involves about nine African countries - some regional projects are anticipated in the years to come.

This is a good time to invest in the space industry in Africa, with Nigeria's National Space Research and Development Agency (NASRDA), the South African National Space Agency (SANSA) and their counterparts in other countries pursuing a proactive agenda.

Africa has decided to take charge of its space matters and collaboration will be essential in building the next generation of technology in the space industry and maximising it for sustainable development of the region. As the second largest continent, Africa leaves a very big market open for commercial space start-ups to maximise profit on investment. ■

About the author

Temidayo Isaiah Oniosun is a graduate of Meteorology at the Federal University of Technology, Akure (FUTA) and the African Regional Coordinator for Space Generation Advisory Council of the United Nations (SGAC). He works with the Centre for Space Research and Applications, FUTA, and is currently working on SpaceTeD; a start-up committed to empowering the minorities with space technologies for sustainable development.

Lack of funding has been a major problem in the African space industry

▼ Artist's impression of the Square Kilometre Array at night featuring all four elements. The SKA-mid (front left) dishes and precursor MeerKAT dishes (background left) will be located in South Africa, with some remote stations in other African partner countries. The low frequency aperture array antennas (bottom right), and precursor ASKAP dishes (background right) will be in Western Australia.

▶ The first developmental flight (GSLV MkIII-D1) of India's heavy lift launch vehicle GSLV Mk-III was successfully conducted on 5 June 2017 from Satish Dhawan Space Centre SHAR, Sriharikota, with the launch of GSAT-19.

India's dynamic ecosystem for space entrepreneurship

Narayan Prasad
Satsearch.co, Delft, The Netherlands

India's blossoming NewSpace movement is slowly beginning to synch with the firebrand entrepreneurs starting companies around the world and targeting commercial opportunities for innovative space products/services. In a global context they are being backed mainly by private risk capital (mostly venture firms) with an expectation that the innovation pursued by these entrepreneurs will integrate into the economy here on the Earth, creating value towards a meaningful exit. Narayan Prasad analyses the industry trends across the world and looks at how India is jumping onboard.

Today, NewSpace companies are springing up almost on a weekly basis and there is strong reason to believe that there are over 1,000 such companies spread around the world. They are embedding themselves across the value chain from upstream to downstream, with each attempting to bring a new layer of innovation by different methods such as low-cost, commercial off-the-shelf (COTS), agile-mass manufacturing, and data fusion combined with machine learning.

With a possible success rate of five percent in startups across tech industry, the world could potentially see a cultural shift in space business through a community of entrepreneurial space ventures who target their customers with global business-to-business and consumer-to-consumer models.

Most of the NewSpace ventures orient the innovations they are bringing into space products/services towards establishing capacities across verticals where there could be network effects that can be exploited.

There are new services emerging across the world that are not charted into the current roadmap of ISRO

For example, the vertical integration of upstream with downstream done by Planet gives it control over the entire supply chain of production (agile methods of construction of satellites) to provide the four Vs (volume, velocity, variety and veracity) of medium-resolution imagery.

One of the strong pillars of NewSpace is the dynamism around integrating space-based products and services into traditional industries such as energy, agriculture, retail, transport, internet/connectivity, etc. NewSpace companies are planning to pick up the buck where traditional space companies have flattened in technology and growth.

There is, for example, a whole new ecosystem of Earth observation (EO) downstream applications ventures that want to go beyond traditional Geospatial Information Systems (GIS) but using satellite data with ground based sensors in creating data stacks that can add specific industry and decision intelligence to an array of industries.

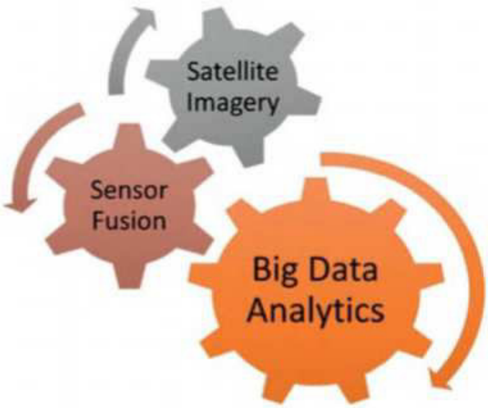
The low Earth orbit (LEO) constellation-based satellite services - including Internet, IoT, AIS, ADS-B, GPS-RO - integrate into different B2B or B2C offerings that are primarily agnostic to what happens in the government procurement realm. There is no doubt that a large percentage of NewSpace ventures will fail and ultimately the market size of several of these services may be limited to a few players even though many of these services are required today and can complement or integrate into industries on the ground.

A step beyond

The proof of availability of several reliable and scalable (hardware/software) platforms, trends towards low-cost access to space, integration into industry 4.0, and global business models are some of the key reasons for new actors to consider investing.

Initially fuelled by private investors, NewSpace has arguably alerted states to opportunities which, in turn, is leading to some states actively pursuing investments and creating regulatory frameworks to promote, for example, space resource utilisation.

The latest prime movers on this front are states such as Luxembourg and the United Arab Emirates which intend to offer an attractive overall framework for space resource utilisation related activities, including but not limited to the legal regime. These governments are pushing dedicated research and development (R&D) funding into technologies related to space resource utilisation, in line with the ambition to become if not international, then regional hubs for the exploration and use of space resources.

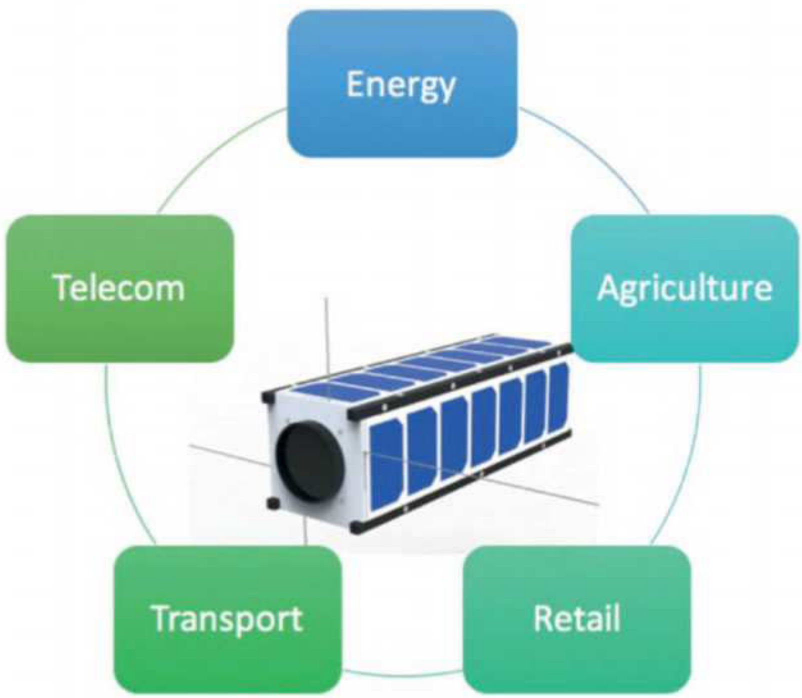


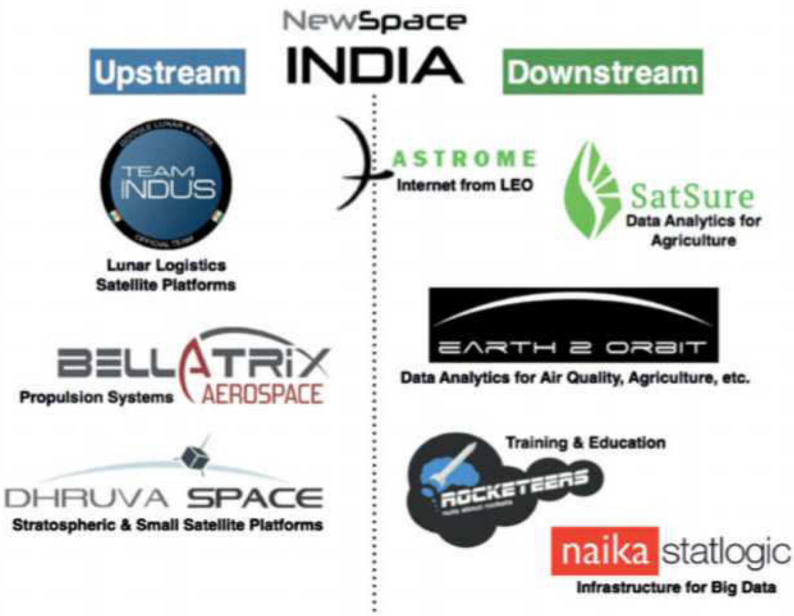
NewSpace India

India's space programme dates back to the early 1960s and today stands in the midst of major achievements including having homegrown reliable rockets and satellites providing applications serving the needs of society. However, the entire value chain from upstream to downstream is mostly occupied by the government ministries/organisations. There are no independent verticals (EO, navigation, communication) in which there is an upstream to downstream connection that is entirely private sector driven.

Due to the sheer increase in the space-based services required in the country that has expanded its footprint in EO, navigation and telecommunications, the private sector is now being engaged in creating an Assembly, Integration and Testing (AIT) consortium of industries to produce navigation satellites and a Joint Venture (JV) for producing the Polar Satellite Launch Vehicle (PSLV). These strategies are possibly the next

India's entire value chain from upstream to downstream is mostly occupied by the government ministries/organisations





step in closing the gap between state-led initiatives in areas of use of geospatial data, navigational services and telecommunications.

While such measures are a welcome step in satisfying the current requirements, there are new services that are emerging across the world that are not charted into the current roadmap of the Indian Space Research Organisation (ISRO).

These include providing low-latency, high-bandwidth internet using LEO satellites, integration of a wide array of communications services including AIS, ADS-B, IoT, etc. and small satellite constellations in EO for bringing in the four Vs of satellite big data. These services are already being planned by several NewSpace players around the world and, given the demand and the growth trajectory of India, such services would play a meaningful role if integrated into the Indian consumer and industry ecosystems.

The question really is about approach. There is no doubt that a successful space agency such as ISRO can plan and provide all of these services over the course of time. However, it would require thorough planning, appraisal for budgets by the Government of India and effective execution. Given that ISRO has already charted a roadmap up to 2021 to develop over 70 satellites to meet the current demands, any additional requirements of satellite services may not fit in the execution plan within timelines of the next three to five years (unless there is a substantial commitment by the Indian government to expand the budget of the space programme).

Therefore, while there is substantial movement towards production of more launch vehicles and expansion of services driven by ISRO, there is enough room for NewSpace to act via development of complementary products and services.

A transparent regulatory framework has a strong effect on attracting large scale investments especially from private risk capital

We now see a beginning of NewSpace in India where entrepreneurs are for the first time risking the development of space-based products and services which are primarily targeted at B2B and B2C markets. The space landscape in India is now moving in both upstream and downstream, and has the potential to expand over the next few years.

Several of these NewSpace companies, backed by private capital at various stages, have now been operating for up to five years. The emergence of NewSpace in India is occurring despite the absence of any dedicated or formal start-up incubation/acceleration programmes in the country with entrepreneurs mainly looking for support in terms of consultancy and access to facilities based on the heritage established within the space programme (both in terms of manpower and infrastructure).

New landscape

It should also be noted that there are no institutional risk capital investment cases in India for any of the NewSpace companies. Most of the NewSpace companies have been primarily funded by grants and high net-worth individuals (HNIs), who can relate to synergies created in technology sectors like information technology (IT) and bio-technology (BT) to be replicated in the space sector and would like to be a part of the ecosystem creation in the nation.

Therefore, there are significant differences in the nature of the ecosystem when one compares the NewSpace entrepreneurial dynamic in India with that from across different geographies. Despite the inherent challenges in the foundation of a commercial space ecosystem, India's NewSpace entrepreneurs have identified possible commercial opportunities to create a niche for themselves by creating proprietary technologies that they can possibly scale to users across the world.

Policy framework

NewSpace in India brings along challenges in the governance of the private sector that is attempting to create independent capacities in both upstream and downstream. The current framework for administration of space is mostly government-to-government, where most of the regulatory requirements for licensing, launch, operation and distribution of spacecraft and space-based services are performed within the realm of organisations in the Government of India.

For example, frequency allocation and coordination is done by the Wireless Planning Commission of the Department of Telecommunications for ISRO. Similarly, EO data distribution to Indian users is performed by the National Remote Sensing Centre (NRSC), an arm of ISRO dealing with remote sensing data reception, processing and dissemination to users.

However, with NewSpace companies planning to build their own satellite platform capabilities in the upstream and with space-based services and big-data platforms emerging on the downstream, there are a host of challenges for issues such as frequency allocation and fleet operations (setting up ground stations), licensing of remote sensing satellites (including data distribution), launch authorisation of spacecraft in line with the Outer Space Treaty (especially when a foreign launcher is procured by an Indian company), among others.

Regulatory framework

It has to be noted that India does have a defined framework for participation of the private sector in the commercial communications services realm. A SatCom policy was made almost two decades ago that allows making an application to the Committee for Authorising the establishment and operations of Indian Satellite Systems (CAISS). This permits private Indian companies with a foreign equity of less than 74 percent to establish Indian satellite systems.

Under this policy, the CAISS is responsible for private operators to be provided with authorisation to operate the satellite and notification/registration of the orbit and spectrum thought the Department of Telecommunication and the Ministry of Information and Broadcasting will provide the operating licenses for services.

Given the recent proliferation of upstream EO private sector activities across the world, the potential participation of Indian private companies was possibly over-looked. There is still a gap, however, in authorising (frequency allocation, operations, launch, data distribution) where the private sector wants to establish a complete capacity to sell EO services.

A transparent regulatory framework has a strong effect on attracting large scale investments especially from private risk capital. Given the nature of the space industry, high sums of capital investment remain one of the fundamental requirements for expansion of upstream capabilities for NewSpace India companies seeking to establish end-to-end platform capabilities. Similarly, a transparent data policy on using different sources of data (national and foreign high-resolution satellites and ground-based data) is to be rolled out to create a vibrant geospatial services ecosystem.

Therefore, it becomes necessary that an ecosystem perspective is taken to encourage NewSpace in India by creating an independent, single-window led, transparent and time capped framework taking into account both upstream and downstream requirements across the value chain.

Creating dynamism

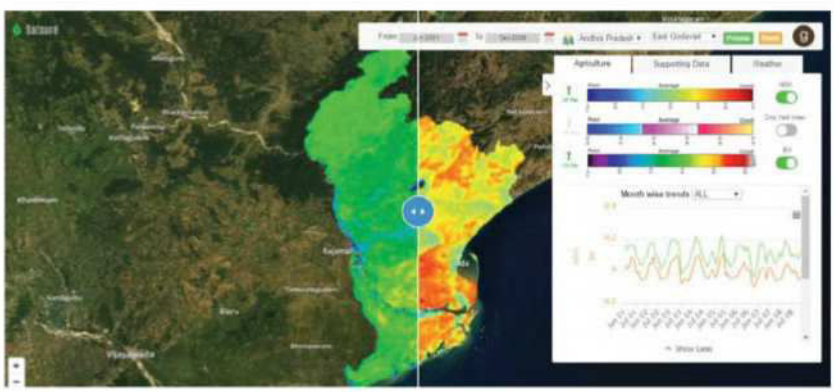
There is no doubt that India's NewSpace entrepreneurs can leverage the infrastructure and the capacity created over five decades of investments into the space sector by the Government. The country stands in a realm of several complementary and convergence technologies that is enabling several new space-based services that are waiting to be tapped for economic and societal benefits. Within India's own ecosystem, there are significant opportunities for NewSpace to complement the efforts of ISRO and provide new and innovative services.

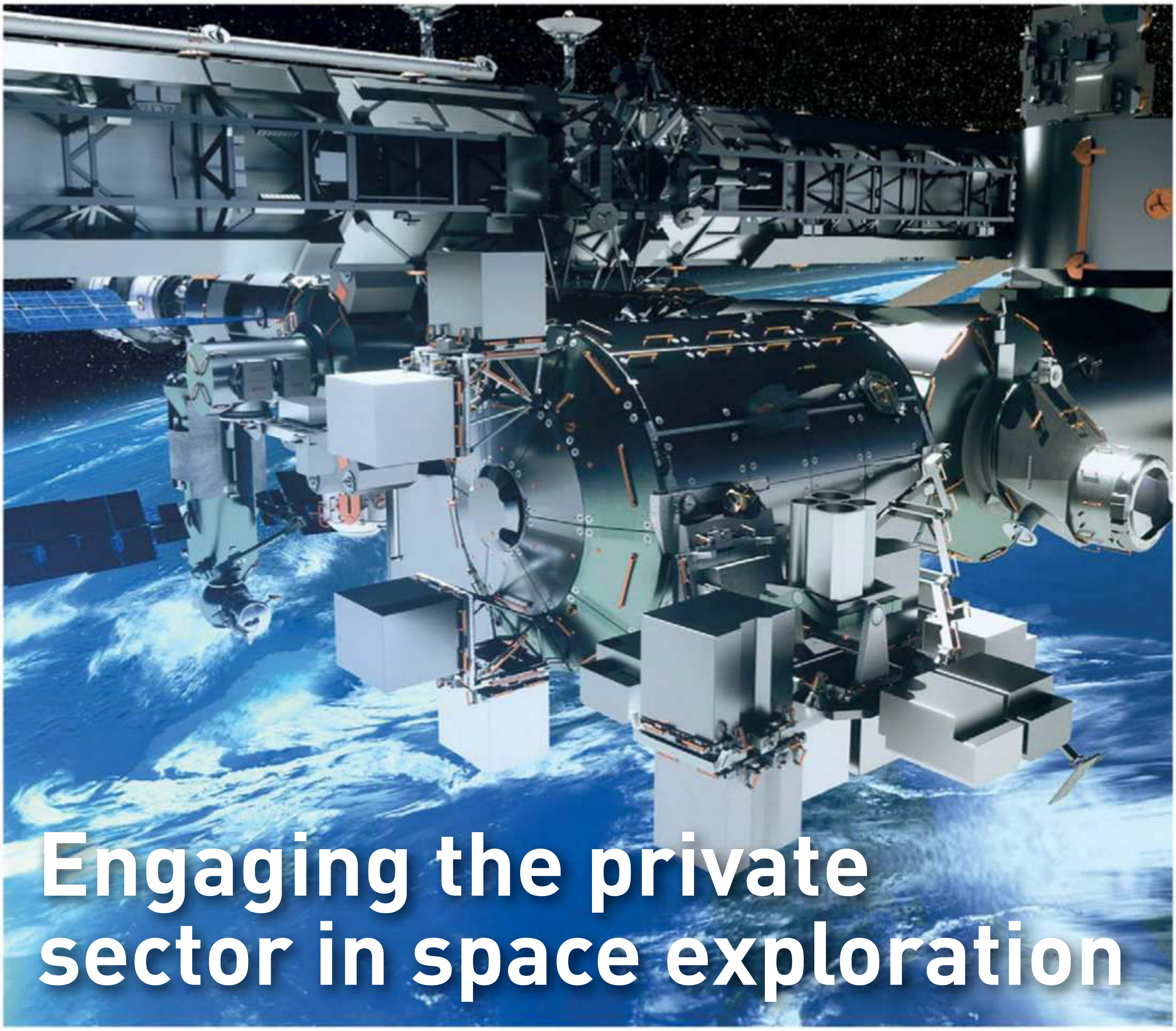
Today, there is a combined responsibility for the NewSpace entrepreneurs in India to come together and create a community to pursue the expansion of the space economy of the country. A community creation drive should work towards benefiting everyone within the ecosystem (across the value chain) and lead to creating a holistic environment for triggering changes in the policy realm, bringing in investor confidence (especially from an institutional investment perspective) and possibly opening up the drive for foreign direct investment (FDI), which can ultimately lead to a greater global integration of India's space supply chain. ■

New space-based services are waiting to be tapped for economic and societal benefits

About the author

Narayan Prasad is co-founder of satsearch.co and curator of NewSpace India, a digital platform providing analysis of issues in technology, policy, economics, commercialisation, geo-politics and defence around the Indian space programme. He has a Master in Space Technology (Erasmus Mundus, Sweden), a Master in Space Techniques and Instrumentation (France) and a Master in Space & Telecom Laws from the Center for Air & Space Law of NALSAR Law University, Hyderabad, India.





Engaging the private sector in space exploration

Bernhard Hufenbach
ESA Directorate of Human Spaceflight & Robotic Exploration, ESA ESTEC, Noordwijk, The Netherlands

Fostering open technology innovation is not only about promoting broader use of the International Space Station (ISS) but could also have a positive impact on future missions to the Moon and Mars. ESA is committed to participating in the development of a market-driven economy in low Earth orbit and here Bernhard Hufenbach explains the agency's step-wise approach to partnering with private companies that are ready to share risks. He also highlights pilot projects that are aiming to demonstrate their feasibility and commercial viability.

In 2015, the European Space Agency (ESA) launched a process for setting up strategic partnerships with the private sector to facilitate its exploration ambitions - and to foster growth and competitiveness of the European space and non-space industrial base. The initiative is nurturing the gradual establishment of private sector services, led by European companies for low Earth orbit (LEO) exploitation in support of lunar exploration. It aims to strengthen the competitiveness of European industry, stimulate research and development and integrate innovative solutions into ESA space exploration missions.

ESA's role in these commercial partnerships is to act as a business partner in developing new services or products on a non-exchange of funds principle, where the agency provides technical support, and reviews, business development support, co-funds technology development, and grant access to ESA facilities.

The first results are already in: ESA has just signed the first commercial partnership agreement with Space Applications Services (SpaceApps) to provide quick, easy and low-cost access to the Space Station in less than a year using its International Commercial Experiment Cubes service.

'ICE Cubes' could allow access to a large number of users, including educational institutions, small and medium-sized enterprises, and research and development organisations.

Boosting business

European space industries have traditionally carried out most of their activities for space and defence purposes within a governmental procurement frame and their business footprint is just starting to emerge in non-space market sectors, such as materials, pharmaceuticals, bio-engineering, nanotechnology, oil and gas.

ESA Member States are getting more sensitive to the current ecosystem of 'Space 4.0', transitioning from a government-run laboratory in orbit to an increasingly commercially driven human spaceflight economy.

ESA is promoting brainstorming activities with space and non-space actors in order to agree on potential ways forward and is seeking to establish marketable commercial space exploration initiatives and to boost the spill-over effects in terms of socio-economic growth, job creation and added welfare. The goal is to make the European market place attractive for newcomers.

A key action includes the 'Space for Inspiration' event to communicate opportunities for integrating space exploration with society at large and create opportunities for new actors to engage in space exploration, either as a contractor, user or partner of ESA.

In addition, it aims to create partnerships via Innovation Exchanges by bringing together in splinter sessions people from different fields and backgrounds to elaborate synergies and common activities driven by the goal to develop synergetic solutions addressing both space exploration and global societal challenges. ESA is also partnering with business accelerators and maintains a network of brokers throughout Europe. Industry days are helping commercial partners to consolidate the industrial consortium.

New opportunities

Around 60 ideas were submitted in response to the first call for commercial partnerships, and nearly 10 have been selected to enter a pilot phase to demonstrate their programmatic and technical feasibility and to consolidate the business plan and partnership model.

This initiative, fully supported by ESA Member States, is currently in its inception. Next year's maturation of the pilot phases will have to demonstrate the willingness of all partners to share risks as well as benefits, before entering into a full implementation phase.

Each partnership idea is evaluated by an ESA panel of experts, following consultation meetings where companies have been invited to present their proposal. Those consultation meetings were paramount for ESA to better assess the viability of the partnerships.

The range of ideas is broad and includes applications, products and services related to utilisation of the International Space Station, post-ISS exploitation, lunar exploration and ground analogue tests.

Each partnership offers opportunities for additional partners, interested users and potential customers to participate in the partnership development and benefit from the final products and services.

◀ The Bartolomeo external research platform to be attached to the Columbus module on the ISS in late 2018 could facilitate access to the orbital laboratory for commercial users.

Fostering open technology innovation will boost future ESA missions to the Moon and Mars

▼ The primary objective of a European version of Dream Chaser will be to provide affordable, reliable and flexible space services for autonomous European access to LEO.

▶ Open and closed configurations of the ICE Cubes facility.

There is a huge need to stimulate market demand in space exploration

Some of the partnership ideas will focus on establishing potential Earth application spin-outs, enabled by developing products and services that will serve both future space exploration missions and the global economy.

On the launch pad

ICE Cubes is the first commercial partnership with ESA. It will provide rapid, simplified and low-cost access to the ISS. The cubes are small replaceable boxes in which customers could place their experiments under space conditions. SpaceApps, the company behind it, expects the service to be operational in the first quarter of 2018.

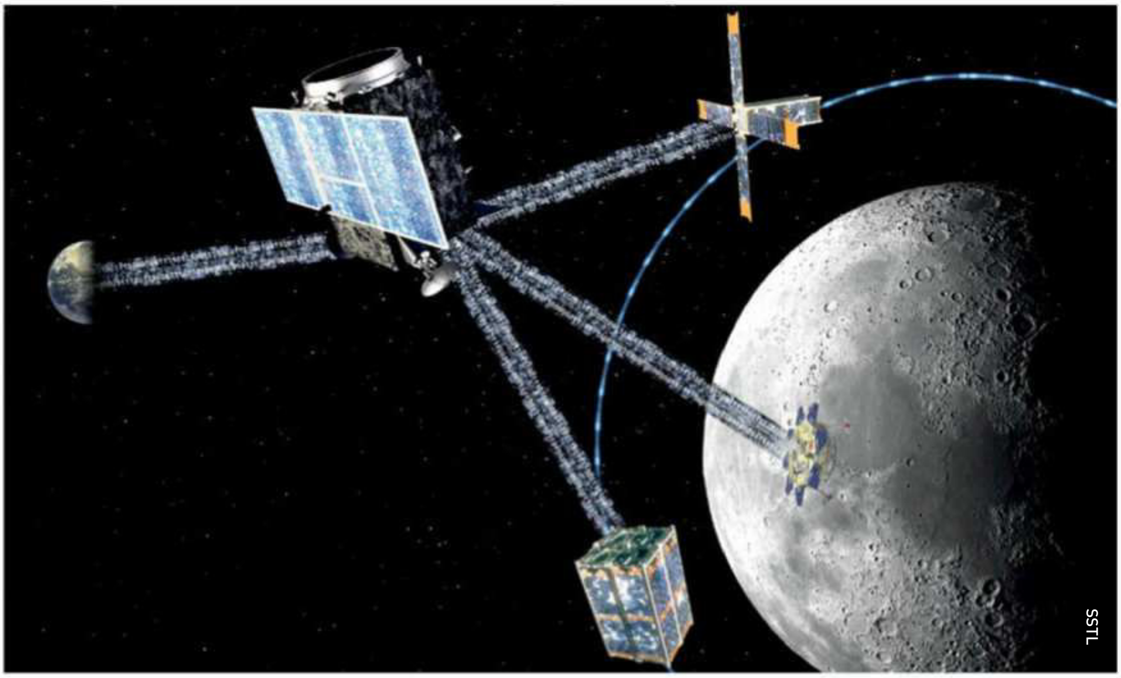
Other ideas currently being considered by ESA as commercial partnership pilot projects:

- Bartolomeo: Airbus DS proposes to operate an unpressurised platform on the ISS to host external payloads. The platform would be installed outside ESA's Columbus space laboratory offering an unconstrained view of Earth and space, and provide stable pointing to the instruments. Bartolomeo would attract new commercial users, as companies could piggy-back off existing resources to reduce cost.

- TELDASAT: A system prototype, designed to demonstrate global satellite-based 'machine-to-machine' data services from the ISS. TELDASAT would enable monitoring of future space-based infrastructure, such as large-scale electricity grids in remote areas, by connecting millions of sensors around the globe. The project would prepare the ISS to act as the future host of a 12-satellite constellation to open-up a novel Internet of Things market with several million sensors. The SAT4M2M consortium is responsible for the design, development and breadboard of the payload.

- Dream Chaser: is a free-flight space vehicle for multiple missions including scientific research, technology development and operational demos such as in-orbit assembly

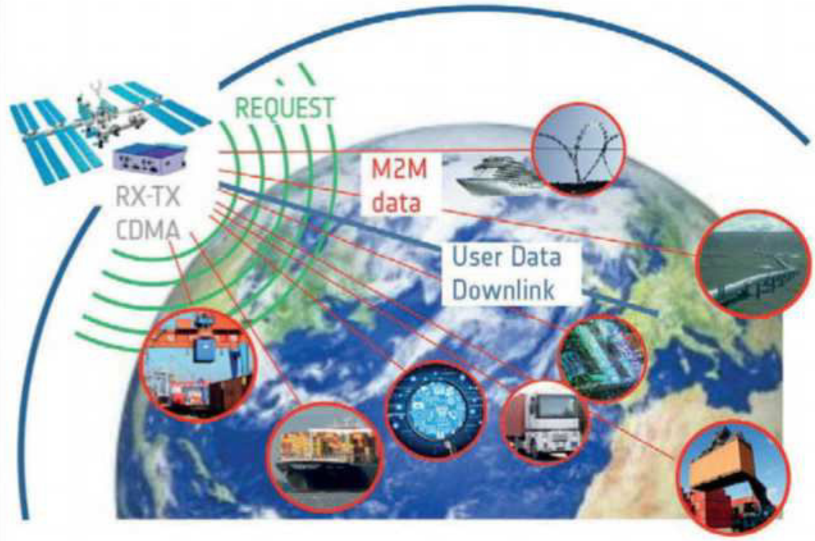
▶ Lunar Communications Pathfinder system.


SSTL

and repair. The primary objective of a European version of Dream Chaser would be to provide affordable, reliable and flexible space services for autonomous European access to LEO. The US company Sierra Nevada Corporation leads the project, supported in Europe by OHB System AG, Germany, and Telespazio, Italy.

- Lunar Communications Pathfinder: this proposal would deliver customer payloads to lunar orbit and provide them with communications services. It would become the first commercial deep-space data relay mission, using commercial ground stations to provide communications to cis-lunar space. The system would connect with the far side of the Moon, its southern hemisphere and the South Pole. Surrey Satellite Technology Ltd (SSTL) is developing this idea in cooperation with Goonhilly Earth Station.

- European Private Lunar Surface Mission: PTScientists, Germany, in partnership with Audi AG, propose a European privately-funded Moon surface mission. This Moon mission is a promising opportunity to establish a commercial lunar transport service in Europe. Such capability would enable the testing of new technologies and the delivery of scientific payloads to the Moon, leading the way for a future of prolonged space exploration. The private spacecraft would be able to deliver up to 100 kg payload to the lunar surface with each flight. ■



About the author

Bernhard Hufenbach is head of ESA's Strategic Planning and Outreach Office for Space Exploration, responsible for supporting ESA-wide strategic plans for space exploration and enlarging the stakeholder community engaged in space exploration. He is involved in the definition of future ESA space exploration missions, the development of strategic partnerships, and the stimulation of commercial activities related to space exploration.

ESA is open to continue receiving ideas from the European space or non-space private sector for additional partnerships. Proposals can be submitted to strategic.planning.office@esa.int. Further information is also available at the ESA Partners for Space Exploration website.

ESA is promoting brainstorming activities with space and non-space actors in order to agree on potential ways forward

◀ The Audi lunar quattro soon to land on the Moon. Equipped with a 4-wheeled electrical drive chain, tiltable solar panels, rechargeable batteries and science-grade high-definition cameras, the rover will deploy and operate a series of technological payloads.

▶ While awaiting sample return missions from Mars, our only way to study martian rocks in the laboratory is with meteorites. Although Tissint meteorite (909 g sample - NHMV-N9388) was recovered shortly after its fall on 18 July 2011, it was already contaminated with terrestrial elements.


Kracher/NHMV

Europe needs facility to handle extra-terrestrial space material

Aurore Hutzler
Post-doctoral researcher, Natural History Museum Vienna, Austria

Ludovic Ferrière
Co-curator of collections, Natural History Museum Vienna, Austria

Exploring our solar system has been keeping humankind busy for more than 100 years - from the theoretical work of 'The Exploration of Cosmic Space by Means of Reaction Devices' by Konstantin Tsiolkovsky in 1903 to the launch of the first artificial satellite Sputnik 1 in 1957 to the recent sample return mission OSIRIS-REx launched in 2016. Although orbiters and landers are equipped with ever more accurate instruments and with increased capacities to study planets, moons, asteroids and comets, analyses are still somewhat limited in comparison to what can be done in laboratories on Earth. Here, Aurore Hutzler and Ludovic Ferrière argue the case for Europe to develop its own curation facility so it can be more involved in future sample return missions.

The typical constraints of spaceflight mean that the mass, the volume, the power supply and the data feed of pieces of equipment must be kept as low as possible. Some analytical instruments routinely used in research laboratories on Earth - such as Inductively Coupled Plasma Mass Spectrometry (ICP-MS) - cannot be used in space because it involves preparing a liquid solution out of the sample.

Even if instruments on spacecraft have allowed significant advances in a number of different fields, to obtain high-precision analyses, it is necessary to bring samples back to Earth. Sample return

Sample return missions have enabled extraordinary discoveries

missions have enabled extraordinary discoveries that fundamentally improved our understanding of the Moon with the Apollo missions and their 382 kg of lunar rocks; of comets with the Stardust mission; and of asteroids with the Hayabusa mission.

Until now, sample return missions have been led mostly by NASA in the US, by Roscosmos in Russia and by JAXA in Japan. Europe is a main actor in space exploration but has lacked the goal of claiming part of the samples brought back by these missions.

One possible explanation is that there is currently no dedicated curation facility for pristine extra-terrestrial samples on European territory, similar to those at NASA's Johnson Space Center, Houston, or at JAXA, Sagamihara, Japan.

Unrestricted or restricted samples

The two facilities cited above have been designed to keep the samples protected against a range of contaminants which may affect the scientific analysis of returned samples. The main requirements rely on technologies routinely used in cleanroom environments (i.e., by keeping the rooms under positive pressure, with a range of High Efficiency Particulate Air (HEPA) and Ultra-Low Penetration Air (ULPA) filters to scrub the air of any particles) and on the rigorous selection of materials allowed to be in contact with the samples.

Samples are typically kept under an inert atmosphere, usually dry nitrogen gas. However, all the samples which have been returned to Earth so far are from celestial bodies known to be devoid of any potential present or past form of life.

The Committee on Space Research (COSPAR) [1] defines five planetary protection categories with subcategories dependent on the target of the mission and the type of mission (fly-by, orbiter or lander). Category I missions do not have planetary protection requirements, e.g., for missions to undifferentiated, metamorphosed asteroids or Io.

Category V missions include the most stringent planetary protection requirements. All missions which will return extra-terrestrial samples to Earth for further analysis belong to category V. Dependent on the origin of the extra-terrestrial material, a category V mission can be an unrestricted Earth return mission (e.g., in the case of samples from the Moon) or restricted Earth return mission (e.g., in the case of samples from Mars or Europa).

NASA/Glenn Benson

▲ NASA's OSIRIS-REx spacecraft during its preparation for encapsulation in its payload fairing prior to launch in September 2016. It is the first US mission to sample an asteroid, retrieve at least two ounces of surface material and return it to Earth for study.

▼ Aurore Hutzler in front of an X-ray diffractometer inside JAXA's Hayabusa-returned sample curation facility in Japan. The lab coat (a class 1,000 gown) is specifically designed to reduce contamination from workers.

There are no special requirements for sample containment for unrestricted missions. However, for restricted missions, where there is thought to be a chance of life, the requirements include absolute prohibition of destructive impact upon return, containment of all returned hardware which directly contacted the target body, and containment of any unsterilized sample returned to Earth.

Considering the Mars sample return missions planned for the future, it is imperative to start now to plan a facility able to receive and host these potentially biohazardous samples, especially knowing that the design, construction and certification of such a facility can take a decade to be up and running [2].

Study and long-term curation of extra-terrestrial samples, either unrestricted or restricted, require the samples to be protected


Ferrière/NHMV

There is currently no dedicated curation facility for pristine extra-terrestrial samples on European territory

▼ Ludovic Ferrière in front of a positive pressure glovebox, containing lunar rock samples at the Johnson Space Center's Lunar Curation Laboratory. The glovebox is filled with nitrogen to minimise the samples' alteration.

▼ Bottom: Overview of Johnson Space Center's Lunar Curation Laboratory, equipped with gloveboxes dedicated to Apollo sample return missions. Note the windows at the end of the room, separating the high cleanliness part of the facility from a monitor room.

against a range of contaminants which may affect the scientific analysis to be conducted. For restricted mission samples, in addition, containment is required to prevent the release of any biohazards in the environment until they can either be proven to be devoid of any life-forms or be effectively sterilised to destroy any life-forms [3, 4]. The co-requirements for a combined high containment and ultraclean facility are unique and will lead to the development of a highly specialised and unique facility that will require the development of novel scientific and engineering techniques.

The objective of the EURO-CARES (European Curation of Astromaterials Returned from Exploration of Space) - a three-year project funded by the European Commission's Horizon 2020 research programme from January 2015 to December 2017 - was to create a roadmap for the implementation of a European Extra-terrestrial Sample Curation Facility (ESCF) to involve Europe more in sample return missions.

The EURO-CARES consortium is composed of planetary science researchers and curators, biosafety specialists, and engineers, from all parts of Europe (www.euro-cares.eu).

There have been a few previous studies on curation facilities, which have typically been either country-specific or mission/target specific [5]. EURO-CARES proposes to move onwards from these specific studies to look at what would need to be done to create a European facility that would be suitable for the curation of samples from all possible return missions likely over the next few decades to the Moon, asteroids and Mars.

The project considers all different aspects, starting with the landing of the Earth Return Capsule (ERC). A team is focused on how to bring the ERC to the curation facility, then the process of receiving and opening the different layers to access the samples. All activities related to curation are roadmapped in the framework of EURO-CARES.

Curation or science?

The term 'curation' covers all activities related to organising and maintaining a collection of artifacts, art pieces or scientific samples. Although a number of curatorial centres and institutions may have dedicated scientific laboratories, one of the main purposes of curation is to make precious samples available to science for several generations.

In the case of a curation facility for mission returned samples, the frontier between what is pure curation and what is science can sometimes be blurred. The EURO-CARES team defined that the ESCF has two main goals: first, conducting basic analyses to characterise the samples and associated hardware, then curating *sensu stricto*, i.e., storing, handling and managing the samples as a valuable scientific resource for generations of researchers to study.

The first step is the phase of Sample Early Characterisation (SEC), which aims at characterising the samples with non-destructive methods, to set the basics for high-quality research to be conducted afterwards (i.e., outside of the facility, in state-of-the-art, dedicated laboratories). The next step is the Preliminary Examination (PE) phase, in which further analyses are conducted on the samples. Depending on the nature of the samples, this phase can be done inside or outside of the ESCF.

It is planned to keep the curation facility as light as possible in term of instrumentation, and to disseminate unrestricted samples to external laboratories (and even restricted samples in specific specific sealed containers with semi-transparent windows allowing different analyses to be conducted). However, it is clear that in the case of restricted samples, it will be necessary to keep the research under containment. Some part of the sample will need to be devoted to Life Detection (LD) and Biohazard Assessment Protocols (BAP) [4], with analyses from non-destructive, to destructive, to microbiology cultures and to potentially animal tissue testing.

Flexible facility

Flexibility is seen as one of the most important concepts to be considered for such a project to allow for future developments of scientific analytical capabilities and this was developed at several scales in the framework of EURO-CARES, with the requirement of future extensions and potential growth.

Through a collaboration with the Vienna University of Technology (2016) [6], and with the Canadian branch of Merrick and Company (2017) [7], functional layouts and global designs were produced. The flexibility requirement was developed at three scales, from the room scale (some rooms should allow for restructuring or a change of the activity to be conducted inside), to the laboratory scale (a curation laboratory might be expanded for new missions, or an office building might accommodate more staff), to the ESCF scale (it is very unlikely that all different parts of the ESCF will be built at the same time from the beginning).

On top of the flexibility, architectural layouts were taken into account along with other important aspects, such as opportunities to encourage meetings and communication between personnel to increase working efficiency and cooperation, and favour the health and well-being of staff by providing a pleasant work environment.

The EURO-CARES team presented the case for an ESCF at a workshop in Florence, Italy, in July 2017. The last steps of the project will then be to wrap feedback from all different communities (architects, geologists, microbiologists, engineers, etc.) knowing that to be truly successful in such a project all different expertises and opinions should come together. ■

▲ NASA's Stardust was the first spacecraft to return cometary samples. In 2004, the Stardust spacecraft made a close flyby of comet Wild-2, collecting comet and interstellar dust, returning samples to Earth in a capsule two years later.

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About the authors

Aurore Hutzler, a geologist with a focus on geochemistry, has a doctorate in Planetary Science. Her research on cosmochemistry of meteorites led her to work on more pristine extra-terrestrial samples from sample return missions. She is currently a full-time post-doctoral researcher for the EURO-CARES project at the Natural History Museum Vienna, Austria.

Ludovic Ferrière, a doctor in geology, is chief curator of rock collections and co-curator of the meteorite collection at the Natural History Museum Vienna. He is also a researcher and has confirmed, together with different colleagues, three of the currently 189 recognised meteorite impact craters on Earth.

Flexibility is seen as one of the most important concepts to be considered for such a project

Poster from 1953 film version of H G Wells' novel, 'War of the Worlds' (1898). Wells' invading Martians were possessed of intellects "vast, and cool, and unsympathetic".

Science searches for cosmic company

The search for life on other worlds drives much of our exploration of space

Seth Shostak
SETI Institute, Mountain View, California, USA

The popular belief that we share the universe with other forms of life might once have been ascribed to the influence of fiction. Today, most of us are now aware of the torrent of exoplanet discoveries that for the last two decades have been the celebrity achievements of astronomical research. The Universe is replete with territory that might both spawn and support life. If our planet is the only one in the Universe with lifeforms able to understand science and develop technology, then Earth truly is a miracle. But if there are others then the flush of recent planetary discoveries and advances in technology make a discovery in the near future more likely than ever before.

Aliens have been a common fixture in science fiction since the Second World War when the development of modern rocketry encouraged the idea that we might eventually send humans to other worlds.

Films and television were quick to depict a universe stuffed with clever and sophisticated, although frequently unattractive, creatures. After all, if we could manage space travel, why wouldn't highly advanced extraterrestrials, light-years away, be doing the same?

Although cinematic sentiments are often disappointingly hostile - aliens usually coming to Earth with no more cogent intent than to level our cities - there seems to be a widespread presumption that many of the trillion or so planets that populate the Milky Way are carpeted with life. And surveys routinely show that the majority of the public believes that we share the cosmos with other life – even intelligent life.

Looking for life

Today, the search for life on other worlds drives much of our exploration of space. Among the several worlds of the inner solar system, Mars receives the bulk of our interest and hardware. A lot of the red planet's attraction is due to the fact that it has (and perhaps more importantly, had in the past) environments that could nourish biology. Planned missions to the outer solar system moons Europa and Enceladus are also motivated by the hope of finding life beyond Earth.

But while we might discover living things in our own backyard, they would almost certainly be simple and small. Bacteria could conceivably find adequate sustenance in the relentless darkness of a subsurface ocean, but it's hard to imagine that complex life could. Intelligence on a par with Homo sapiens, which requires an elaborate nervous system or its functional equivalent, is unlikely to arise on any of the places we can reach with our rockets. Rather, if we wish to find clever aliens, we must turn to worlds orbiting other stars.

Investigations using NASA's Kepler space telescope suggest that perhaps as many as one in five stars host a planet that could support some sort of biology. This is still a tentative result and the fraction of stars with a planet or moon that could evolve intelligent life is surely less. But even if that fraction is but one in a thousand, the number of worlds suitable for creatures as mentally agile as ourselves would still tally in the hundreds of millions And, this is only looking at real estate in our own galaxy.

Tuning-in to the cosmos

Such arguments fuel the interest in SETI (Search for Extraterrestrial Intelligence). It doesn't look for life directly but for signals that would indicate life possessing a degree of technical sophistication at least as great as our own. Most of the SETI experiments of the last five decades have tried to tune in radio signals that are either deliberately or inadvertently beamed our way.

This search, like the public's interest in aliens, grew out of technical developments during the Second World War. When the high-power microwave transmitters that are essential to radar became commonplace, scientists made a simple calculation that surprised them: such signals could be easily received at distances comparable to the typical separation of stars.

Unlike some Victorian physicists who thought that gas lamps and mirrors might be useful for sending messages to the putative inhabitants of Mars, the post-war world finally had a technology that would be adequate for communicating across astronomical distances. Perhaps the skies were filled with signals from aliens, merely awaiting efforts to detect them.

That doesn't seem to be the case. Despite more than 50 years of experiments, no confirmed, artificially produced signal from the cosmos has ever been found.

While that is an obvious disappointment to those who would like to believe in the Hollywood portrayal of a cosmos littered with clever inhabitants, it is certainly premature to conclude that we're alone. For one thing, the SETI effort has been poorly funded. This might be ascribed to the fact that its hypothesis – namely that there is intelligence elsewhere – is impossible to falsify. This circumstance separates it from much conventional research. Second, success cannot be guaranteed no matter how much time or money is expended.

In addition, SETI must deal with a perception that looking for our extraterrestrial doppelgangers is somehow a silly enterprise. Space aliens, to many, are like ghosts. Sure, ghosts are fun, but for a variety of reasons, they aren't plausible. But given the staggering plentitude of planets, one can hardly say the same for aliens.

The largest SETI effort to date began in the 1970s by NASA. The plan was to build specialised radio receivers - spectrometers with resolutions

SETI must deal with a bothersome perception that looking for our extraterrestrial doppelgangers is somehow a silly enterprise

▼ The Tatel Telescope was the first major radio telescope at the National Radio Astronomy Observatory in Green Bank, West Virginia, USA. The 85-foot antenna was used by Frank Drake in 1960 for the first modern SETI experiment.

◄ The Arecibo Observatory radio telescope in Puerto Rico has been used for SETI work many times.

as fine as 1 Hz - and hunt for signals using these instruments on existing radio telescopes. The search strategy was two-pronged: to scan the entire visible sky at relatively low sensitivity, and to zero in for a more intensive examination of approximately 1,000 nearby star systems. Although the programme cost less than 0.1 percent of the NASA budget, this effort was killed by the US Congress a year after observations began, ostensibly for reasons of economy.

Since then, experiments have continued primarily at the SETI Institute in the Silicon Valley and at the University of California Berkeley. Funding has been via private donations, and the combined annual effort runs at approximately three percent of the cost of a single Ariane 5 launch. It is also worth noting that, at present, only the United States has any dedicated SETI programmes. Despite the seductive excitement of proving that there are other beings in the cosmos, the actual effort to do so has been disappointingly limited. That, however, may change.

New approaches

Today, there is increased enthusiasm for SETI. While this is partially due to the surge in planetary discovery, there are also improvements in technology that can broaden the search and increase its speed.

Larger radio telescopes, including the new FAST 500 m radio telescope in China and the Square Kilometre Array being built in South Africa and Australia, will increase our sensitivity to signals.

In addition, the unremitting march of digital technology has allowed more of the radio spectrum to be sampled in a given amount of time. For radio telescope arrays, additional computational power can be used to 'look' at several patches of sky simultaneously. And the emergence of machine learning is offering the opportunity to hunt for an unlimited number of signal types. Past experiments could recognise only a few.

The rapid improvement in computer speed means it should be possible to examine around a million star systems for artificial signals in the next two decades

These improvements are seldom appreciated by the general public, which imagines SETI as it is portrayed in the movies. In the Hollywood version, a lone researcher with headphones strains to hear anything vaguely odd. That depiction was never 'true'; computers long ago took over the 'listening'. And computers are much better listeners – they can find weaker signals and check out more of the radio spectrum. Indeed, because of the rapid improvement in the speed of computers, it should be possible to examine approximately a million star systems for artificial signals in the next two decades. That's two to three orders of magnitude more than were targeted during the first half-century of SETI.

California's SETI Institute is getting a head start on these far larger cosmic surveys by conducting a programme using its own instrument, the Allen Telescope Array. The array will observe 20,000 red dwarf star system over a small number of selected frequency ranges in the next two years.

Red dwarfs – stars that are both smaller and dimmer than the Sun – were traditionally of little interest to SETI researchers. They aren't like the Sun, the only star known to harbour a world with intelligence. But recent exoplanet studies have shown that a considerable fraction of these bantam suns have planets in the so-called 'habitable zone' – an orbital distance at which temperatures could be suitable for liquid-water oceans. Red dwarfs also have the advantage of enjoying extremely long lifetimes – 10 times that of a Sun-like star. So, on average, they are several billions of years older. That is an obvious plus point when looking for intelligent life, which on Earth

▼ The Allen Telescope Array (ATA) is a 'Large Number of Small Dishes' (LNSD) array designed to be highly effective for simultaneous surveys undertaken for SETI projects at centimetre wavelengths.

◀ NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA) recently confirmed that the Epsilon Eridani system (10.5 light years away) has an architecture remarkably similar to that of our Solar System, although Epsilon Eridani is much younger than our Sun.

required four billion years of evolution before arriving on-stage.

Yet another thumbs-up for red dwarfs is their ubiquity. Three-quarters of all stars are red dwarfs. That means that in a sample of the nearest ones, they will typically be only half as distant as a similar-sized sample of Sun-like stars. Any signals will be stronger.

In addition to technical improvements for radio SETI, there are renewed efforts to invigorate what is termed optical SETI – a search for laser flashes from the sky. A simple calculation shows that a powerful laser, when paired with a relatively straightforward optical system, could produce a short flash easily detectable from 100 light-years away using instrumentation that is simple to build.

Unfortunately, typical optical SETI systems rely on photomultiplier detectors which, while very sensitive, limit the searches to one star system at a time. Consequently, the SETI Institute is building a set of relatively low cost devices that can simultaneously search the entire night sky in a hunt for laser pulses.

While the sensitivity for this all-sky, all-the-time, system is less than for photomultiplier instruments, being able to look everywhere would at least open our investigations to intermittent 'pings'. Such signals might be sent by extraterrestrials wishing to learn if anything of interest has developed on Earth. After all, the aliens could know that our planet has a rich oxygen atmosphere, and might be trying to elicit a response from anyone knowledgeable enough to build a radio transmitter or laser.

Cosmic company

No one can be certain whether SETI will ever succeed. However, some practitioners are optimistic that a discovery might occur in the next two decades, spurred by the exponential improvement in search speed.

If so, what would we learn? The receivers used for radio SETI are designed to find signals, but not any modulation or messages. The latter would require far larger systems, although if a detection was made, it is easy to imagine that money would be made available to fund such equipment. We would want to know what 'they' were saying.

But aside from possible messages, what would be the reaction of the public to learning that there is other intelligence in the universe? Although many imagine that the news would be disruptive, possibly to the extent of threatening civil order and provoking a crisis for organised religion, there is little reason to think this is true.

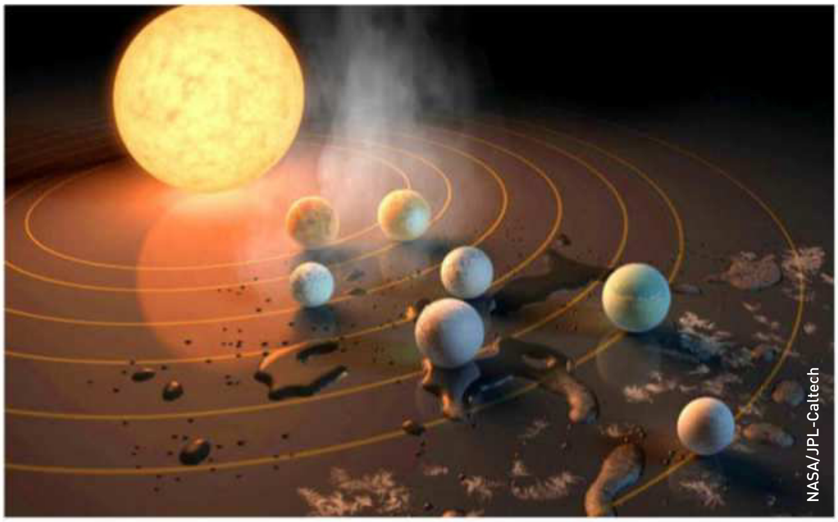
In 1996, there were claims that evidence of ancient life, in the form of microfossils, had been found in a meteorite known to have come from Mars. The story was considered interesting, but in no way disturbing. The public had been conditioned by endless science-fiction stories to expect that the red planet may once have hosted life. This was merely confirmation of a widespread belief.

Similarly, the public has long been exposed to the idea of intelligent aliens inhabiting other star systems. To find that they exist would be to confirm our expectations, and therefore might not be terribly disruptive. Nonetheless, knowing that we have company is a different matter than speculating on its presence. The future course of humanity might not be immediately and drastically changed - but the long arc of history would certainly be bent. ■

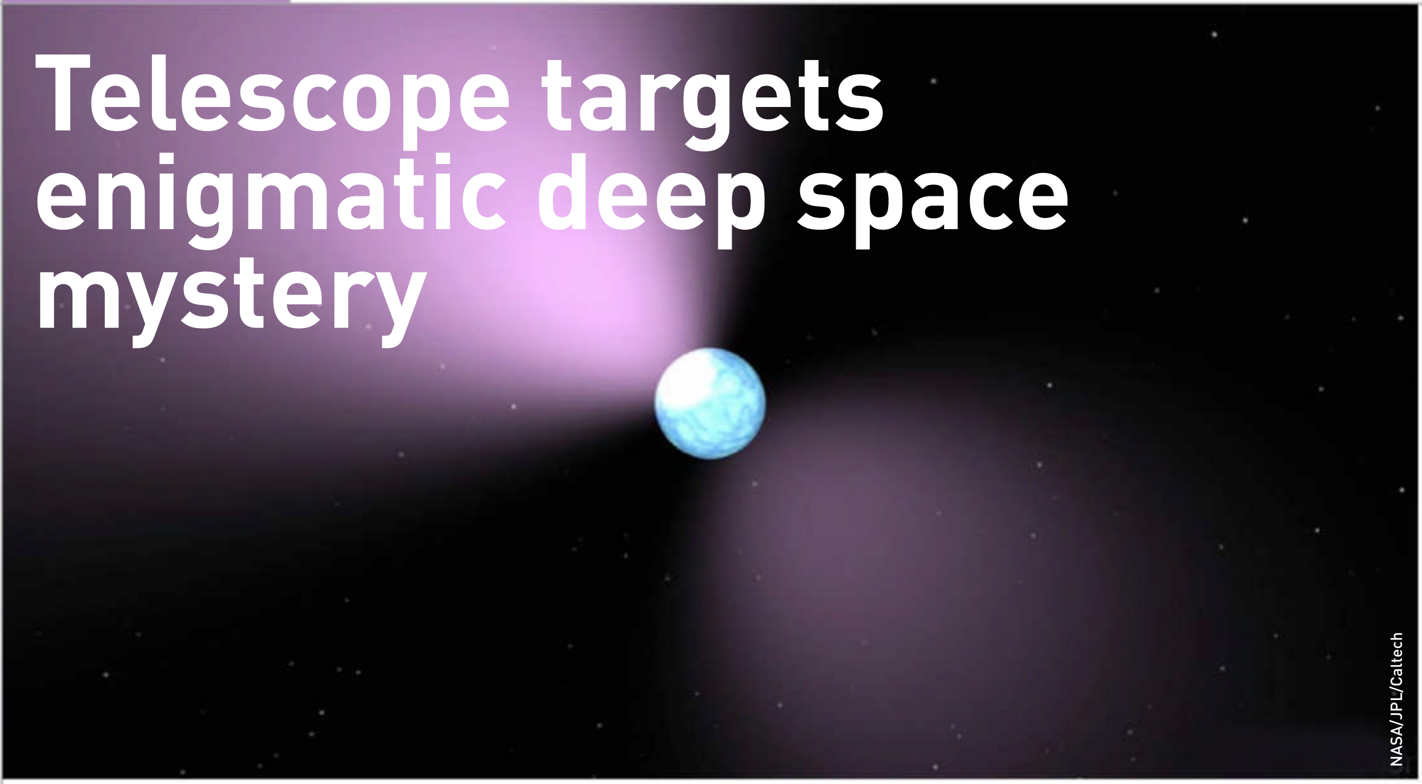
About the author

Dr Seth Shostak is Senior Astronomer at the SETI Institute in Mountain View, California. He is also the host of 'Big Picture Science', the SETI Institute's weekly radio show, and is committed to getting the public, especially young people, excited about astrobiology and science in general.

▼ Seven Earth-sized planets have been observed by NASA's Spitzer Space Telescope around a tiny ultra-cool dwarf star called TRAPPIST-1. Three of these planets lie in the habitable zone. This artist's concept appeared on the cover of the journal *Nature* in February 2017.



Telescope targets enigmatic deep space mystery



▲ Artist's concept of pulsar, which is like a lighthouse as its light appears in regular pulses as it rotates. Pulsars are dense remnants of exploded stars and are part of a class of objects called neutron stars.

For nearly a decade, astronomers have been puzzling over the origin of a signal that is very bright but lasts only for a millisecond. Dubbed the 'Lorimer burst' this type of fast radio burst (FRB) has been linked to everything from signs pointing to an extra-terrestrial civilisation to the collision of two of the densest objects in the Universe. Now, with an upgrade to the largest radio telescope in the Southern hemisphere, scientists working on a project known as UTMOST are hoping to solve the mystery once and for all.

Manisha Caleb
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In astronomy, there's nothing more tantalising than an unexplained signal. Throughout astronomical history whenever something has gone bump in the night, it has hinted towards a new phenomenon, be it pulsars or gamma-ray bursts.

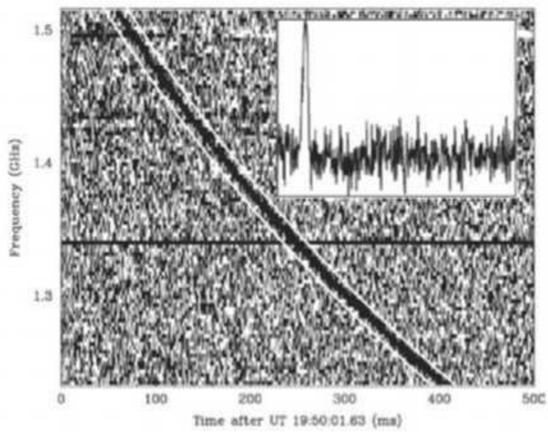
One such 'bump' came to light in 2007, when astronomer Duncan Lorimer and his team from West Virginia University, USA, announced the discovery of a never seen before, extremely bright, coherent, millisecond duration radio pulse. This pulse was found in archival data of the Small Magellanic Clouds taken in 2001 with the Parkes radio telescope in New South Wales, Australia. The pulse, dubbed the 'Lorimer burst', exhibited a 'dispersion' sweep characteristic of all pulsars.

Pulsars are ultra dense, rotating neutron star remnants of a supernova explosion in our Galaxy, which emit jets of radiation along their poles. As the pulsar spins, these jets of radiation cross our line-of-sight emitting a 'blip' similar to the workings of a lighthouse. As the radio signal travels from the source to the observer on Earth, the higher frequencies arrive at the telescope a fraction of a second earlier than the lower frequencies.

This is representative of the total number of electrons the signal has traversed in the diffuse plasma that fills interstellar and intergalactic space, called the dispersion measure. This smearing of the radio signal due to electrons in the cosmic medium is analogous to white light being dispersed by a prism into the colours of the rainbow. Naively, the dispersion measure can be thought of as a proxy for distance such that the larger the dispersion measure, the more electrons the signal has interacted with and the further away the source producing the FRB appears to be.

The electron density in our Galaxy has been well modeled using pulsars. The dispersion measure of the Lorimer burst was found to be eight times the expected Galactic contribution for the given line-of-sight from the model, placing it well outside the local Group of galaxies.

Also, unlike pulsars, the Lorimer burst was not seen to repeat despite hours spent re-observing the same patch of sky. There were found to be no known



Dispersion sweep of the 'Lorimer Burst'. The total delay across the entire frequency band is about half a second. The higher frequencies arrive earlier in time compared to the lower frequencies resulting in the sweep. The dark line across the plot is a malfunctioning frequency channel. The white lines on either side of the sweep are drawn to guide the eye. The sweep of the pulse appears broader at lower frequencies similar to what is seen in pulsars. The inset shows the integrated sweep and the pulse is clearly visible above the noise level.

astrophysical objects at the position in the sky and no other known sources or emission mechanisms at that point in time were capable of producing such extragalactic energetic bursts. Hence it appeared to represent an entirely new class of radio source.

Primer on FRBs

For years the Lorimer burst was in a class of its own. It was even suggested that the Lorimer burst was a freak event possibly due to malfunctioning electronics at the Parkes telescope or from man-made interference in the surrounding local environment. It wasn't until 2013 that four more similar bursts were discovered in the archival data of the High Time Resolution Universe survey at the Parkes radio telescope and the class 'Fast Radio Bursts' (FRBs) emerged. Fast - because they only lasted a few milliseconds, radio - because they had only been seen at this wavelength so far, and burst - because they appeared and disappeared in a flash.

These new FRBs appeared to be fainter and much farther away than the Lorimer burst which made them much more intriguing as, the further away a source is, the greater its potential of being a cosmological probe. It then became clear that whatever these FRBs were, they really were happening and quite often too.

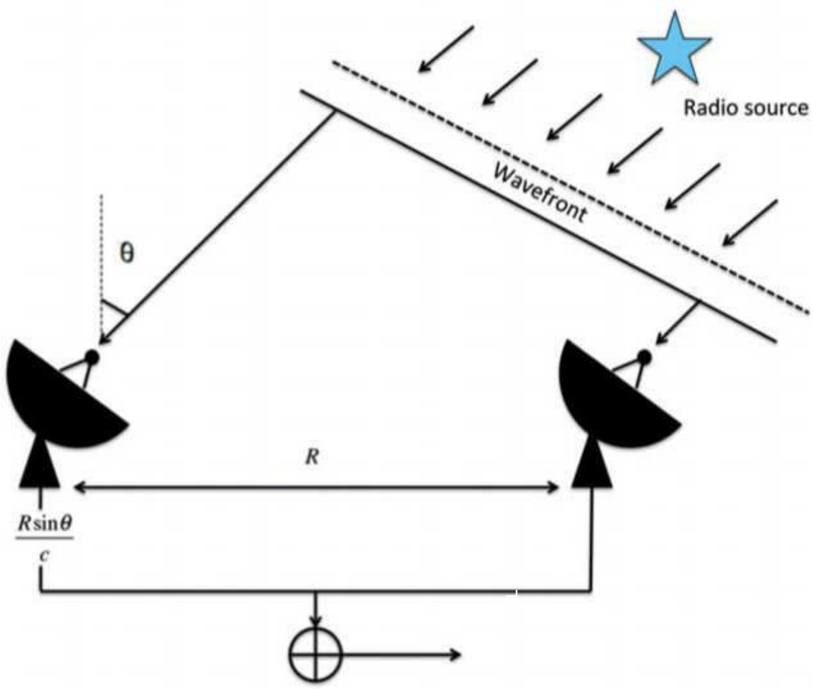
Early rate estimates suggested that there could be as many as seven FRBs per minute each coming from a few billion light-years away and releasing as much energy as the entire Sun would in a month to a year, but in just a few milliseconds of radio energy. Following the discoveries in 2013, rapid advancements minimised the time lag between the occurrence of the burst and the time of detection. Astronomers had now entered the era of real time detections with the time lag being of order seconds. These real time detections were a milestone in FRB astronomy and hoped to provide answers to some of the burning questions.

What was producing these energetic bursts? Did they occur in galaxies? Did they emit at other wavelengths? What could they tell us about the Universe? The questions and theories outnumbered the actual detections and thus began the worldwide race to demystify these FRBs.

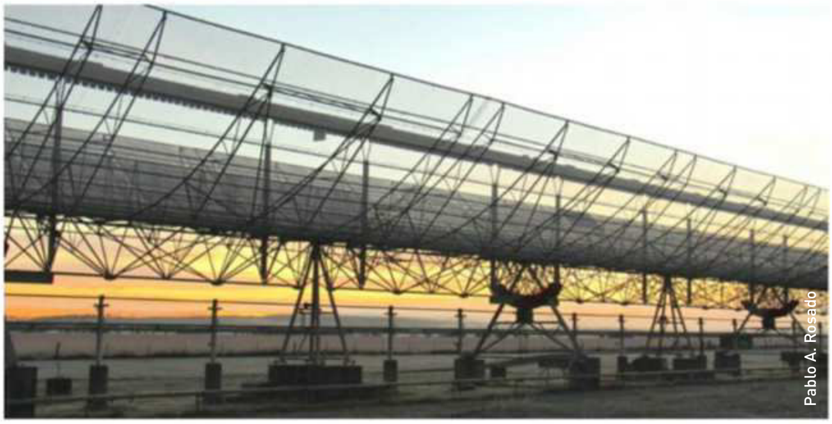
The questions and theories outnumbered the actual detections and thus began the worldwide race, to demystify these FRBs

Why do we care?

They may seem a relatively trivial phenomenon but understanding FRBs could help researchers learn a lot about the wider Universe around us. For one thing, scientists have a problem with matter; it is known that 95 percent of the



Schematic of a simple two element interferometer. Geometric and instrumental delays due to different path lengths and cable lengths respectively, are applied to the input signals of each antenna which are then coherently summed to yield an improved spatial resolution on the sky in a tied-array beam. Multiple tied-array beams are formed by replicating the input signals from the various antennas and summing them with the application of different phase offsets, each with high directivity in a particular direction inside the large field-of-view. Each beam can now be regarded as an incoming signal from a single antenna and can be imparted to the back end for transient searches.



▲ The Molonglo radio telescope near Canberra in Australia is a Mills cross design interferometer and a potential gold mine for FRB discoveries.

Universe is composed of dark energy and dark matter and only around five percent is 'baryonic matter' or normal matter, since its constituents are atoms.

Baryons make up objects of everyday life, however only 50 percent are accounted for and astrophysicists suspect that the remaining 50 percent is in the form of diffuse hot plasma between galaxies. Studying these missing baryons observationally has remained a challenge for many years. But this is where FRBs could help out.

The FRB pulse carries a fingerprint of the intervening medium it travels through and this can be exploited as a cosmological probe of the Universe. The dispersion measure of the FRB along with a measurement of redshift of the galaxy (an indication of how far away the galaxy is) can provide a direct measurement of these 'missing baryons' and consequently enable researchers to 'weigh' the Universe, as it were. Therefore, along with information gleaned from the FRB data, scientists should, in time, be able to solve the missing matter problem.

Secondly, magnetic fields play very critical roles in almost every aspect of astrophysics, ranging from star formation to large-scale galactic and intergalactic dynamics. They also have a significant contribution to the hydrostatic balance in the interstellar medium. Unfortunately, much remains unknown about how these fields are generated or how they are evolving. Polarization studies are precisely what are required to answer these questions of 'Magnetogenesis'.

Radio emission from astronomical sources is often linearly polarised with the electric field vector and a magnetic field vector perpendicular to one another, and to the direction of propagation. As the radio wave propagates from source to observer, the plan of polarization of the electric field vector rotates under the influence of a magnetic field.

This effect is called 'Faraday Rotation' and helps astronomers quantify the strength of the magnetic field of the medium, along the line-of-sight. The magnetic field of the Milky Way has been mapped extensively using this method with pulsars. FRBs could help us understand and measure for the very first time, the magnetic fields associated with the intergalactic medium.

Last but not least, FRBs can be used as cosmic rulers. A comparison of their observed dispersion measure to their measured redshift, when coupled with a model for the average electron density as a function of redshift, enables one to measure the time of flight of the photon, and hence the path length. In this sense, FRBs represent cosmic rulers.

The success of Molonglo radio telescope's observations has helped confirm the extragalactic nature of one-off FRB events

Mysteries surrounding FRBs

The FRB pulses themselves have so far only been observed in the radio portion of the electromagnetic spectrum and their high rate is a major constraint on their theories of origin. Despite the plethora of suggested progenitors, the most plausible theories can be grouped into two categories: FRBs are either caused by relatively rare explosive collisions between old neutron stars or white dwarfs, or they are more common, periodic outbursts or flares from younger, rapidly spinning pulsars.

The two categories have very different implications. The collision-based models suggest that FRBs are extremely energetic one-off events that occur billions of light years away. The outburst model on the other hand suggests that FRBs are much less energetic, repeatable and would only be a few million light years away, so in astronomical terms - much closer. However, despite all the theories, astronomers have no conclusive proof yet as to what they might be.

Nonetheless, in 2016 an FRB discovered at the Arecibo telescope in Puerto Rico, has been found to repeat and has been localised to a dwarf galaxy three billion light years away, opening up possibilities for new theories and models. Astronomers have spent several hundreds of hours re-observing the known sky positions of various other FRBs but this is the only FRB known to repeat thus far. Each of the 26 FRBs detected is unique in its own way but common characteristics amongst these 26 pulses are that they last only a few milliseconds and have dispersion measures well in excess of the Milky Way's contribution. The key to progressing in the field of FRBs lies in localising them the instant they happen which in turn requires an 'interferometric detection' in the radio.

First interferometric detections

Until 2016, each one-off FRB event was discovered using a single dish telescope, such as the Parkes radio telescope in Australia. This generally results in a detection with relatively poor angular resolution, meaning researchers are unable to indisputably rule out a near-field or atmospheric origin. In astronomy, the larger the telescope the more signal it can collect. Consequently, this means that it has a small field-of-view, while the inverse is true for a smaller dish - it collects a weaker signal but has a larger field-of-view. An interferometer is a special type of radio telescope formed by linking many small telescopes together electronically to form one large telescope. This way, it retains a large collecting area, as well as a large field-of-view, which is excellent for blind searches as in the case of FRB searches.

The Molonglo radio telescope near Canberra in Australia is a Mills cross-design interferometer and a potential gold mine for FRB discoveries. This 50-year-old telescope has been refitted and refurbished with a new digital back end system to be transformed and reborn into an FRB hunting machine.

The telescope's unique architecture can place a minimum distance to the FRB bursts due to its large focal length unlike single dish telescopes. Molonglo made the first interferometric detections of FRBs in 2016, ruling out local sources of interference as a possible origin and confirming their extragalactic nature.

Molonglo consists of two arms, each 1.6 km long and intersecting one another in the form of a cross. Presently only the East-West arm of the telescope is fully functional, which can be thought of as 352 little telescopes all looking at the same patch of sky. Each of these 352 telescopes produces signals, which are digitised and combined to create a more sensitive and cleaner signal.

Like most astronomical observations, FRB detections require high frequency and time resolution, and a supercomputer to process the resulting data. With the aid of graphic processing units (GPUs) - 54 to be exact - originally designed for the video games industry, the Molongo inteferometer receives one petabyte (PB) of data a day (the equivalent of 200,000 DVDs a day where each DVD is 5 GB), that is processed on its mini-supercomputer, helping to munch through the data faster than real time.

Future of FRB research

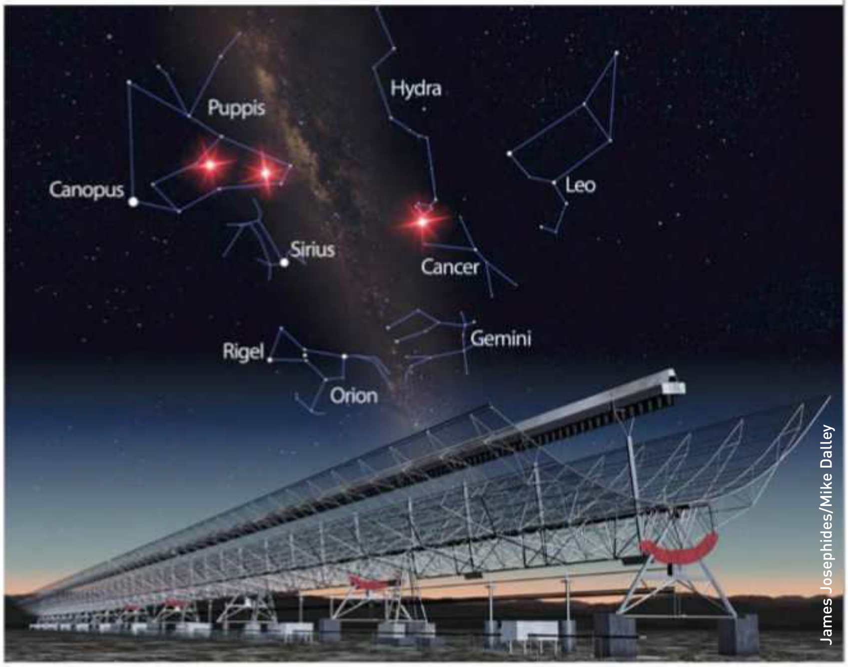
The success of the Molonglo radio telescope observations has helped confirm the extragalactic nature of one-off FRB events, though the exact localisation of the FRB position on the sky, still remains ambiguous. The signal can be limited to within a long line on the sky but to truly pinpoint the FRB event, further resolving power is required.

Luckily then, in the next couple of years the North-South arm of the Molongo inteferometer will come online as part of the UTMOST-2D project. Once operational with both arms up and running, UTMOST will be able to localise an FRB burst within a few arcsecond radius (an arcsecond is about the width of a human hair seen ten metres away). X it would seem, will figuratively mark the spot. Once the burst location is determined scientists will have all the information needed to identify its host without having to look for repeat pulses. Without a doubt, the key to understanding these enigmatic bursts lies in localisation, and observations at additional wavelengths would not go amiss either. Once we understand the FRB population, given the large discovery rates expected from future and present telescopes, we can expect the next decade to answer some if not all the open questions in FRB astronomy.

About the author

Manisha Caleb is a postdoctoral researcher at the University of Manchester, UK, in the area of radio and multi-wavelength astronomy. Her research is related to the attempts to search the radio sky for pulsars and fast transients and to rapidly and accurately locate them and understand their origin and characteristics.

Early rate estimates suggested that there could be as many as seven FRBs per minute



James Josephides/Mike Dalley

▶ Depiction of the strange object of AR Scorpii. In this unique double star, a rapidly spinning white dwarf star (right) powers electrons up to almost the speed of light. These high energy particles release blasts of radiation that impact the companion red dwarf star (left) and cause the entire system to pulse every 1.97 minutes with radiation ranging from the ultraviolet to radio.

Binary stars and their extraordinary lives

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There is a population of stars that, despite their impact in the field, have remained under the radar for too long: binary stars. Perhaps not favoured as much as other astronomical head-line grabbing phenomenon, these double-star systems have a lot to offer. Whatever their size, binary stars of all kinds play an important role in the circle of galactic life, proving that without their existence, stellar life could otherwise be a bit dull in the Universe.

Stars light the Universe and provide the chemical elements which are the keys to all life as we know it. Stars also link apparently disparate branches of physics, from the microscopic quantum world to cosmological general relativity. Binary stars are particularly crucial to our understanding of the Universe on all these scales. They are an indispensable tool for measuring the masses of stars, as discovered by Kepler and Newton in the 17th century. Their orbital properties, such as period and eccentricity (the shape of its orbit), derive directly from fundamental physical properties of matter, i.e. its mass and angular momentum - which is a measure of spin.

▲ White dwarf Sirius B is dwarfed by its brilliant blue-white binary companion Sirius, the Dog Star.

Eclipsing binaries tell us stellar masses and radii to an accuracy of a few percent, thus they are vital to understanding the inner workings and evolution of all stars. In the 21st century, binary stars continue to drive the cutting edge of astrophysical discovery, for example white dwarfs in binary stars explode as type Ia supernovae and confirm that the Universe is accelerating its expansion.

Not only that, but the latest surveys of very massive stars tell us that most of them are binaries and half of them interact severely during their lifetimes. We have seen binary stars and binary black holes merge in real time. With upcoming bigger and better surveys of the sky, binary stars remain a vital pillar of modern astrophysics and a laboratory for testing extreme physics which remains inaccessible on Earth.

Stellar birth

Structure in our Universe forms when matter collapses under its own gravity. Stars form, for example, when giant clouds of gas collapse, compress and hydrogen is eventually fused in their cores. The energy released by this nuclear fusion energy halts the collapse and is radiated at the stellar surface, to give the distinct, bright, point-like source we identify with far-off stars. Often, however, if a gas cloud has sufficient mass and spins rapidly enough, or if it becomes involved in gravitational interactions with other young stars in the gas cloud, some stars are gravitationally bound to a companion star when they are born. These are the binary star systems. In any binary system, we label the more massive star the primary and the less massive the secondary star.

Typically, we can identify secondary stars with around 10 percent or more of the mass of the primary. Very low mass secondary stars are simply invisible against the light of the usually much brighter primary. Sometimes, because stars in binaries can interact by exchanging mass, the secondary is brighter. The Algol system located in the constellation of Perseus is a good example of such a star system. Its variability in brightness, which eventually led to the discovery that it was

Binary stars are particularly crucial to our understanding of the Universe

Understanding binaries is critical to understanding stars and the physics that drives them

an eclipsing binary system, was first noticed as far back as 1667. Successive observations have revealed that Algol A, while more massive than its companion Algol B, is less evolved. This would occur if Algol A transferred much of its mass to Algol B as they evolved; a process that would be impossible if the stars formed on their own.

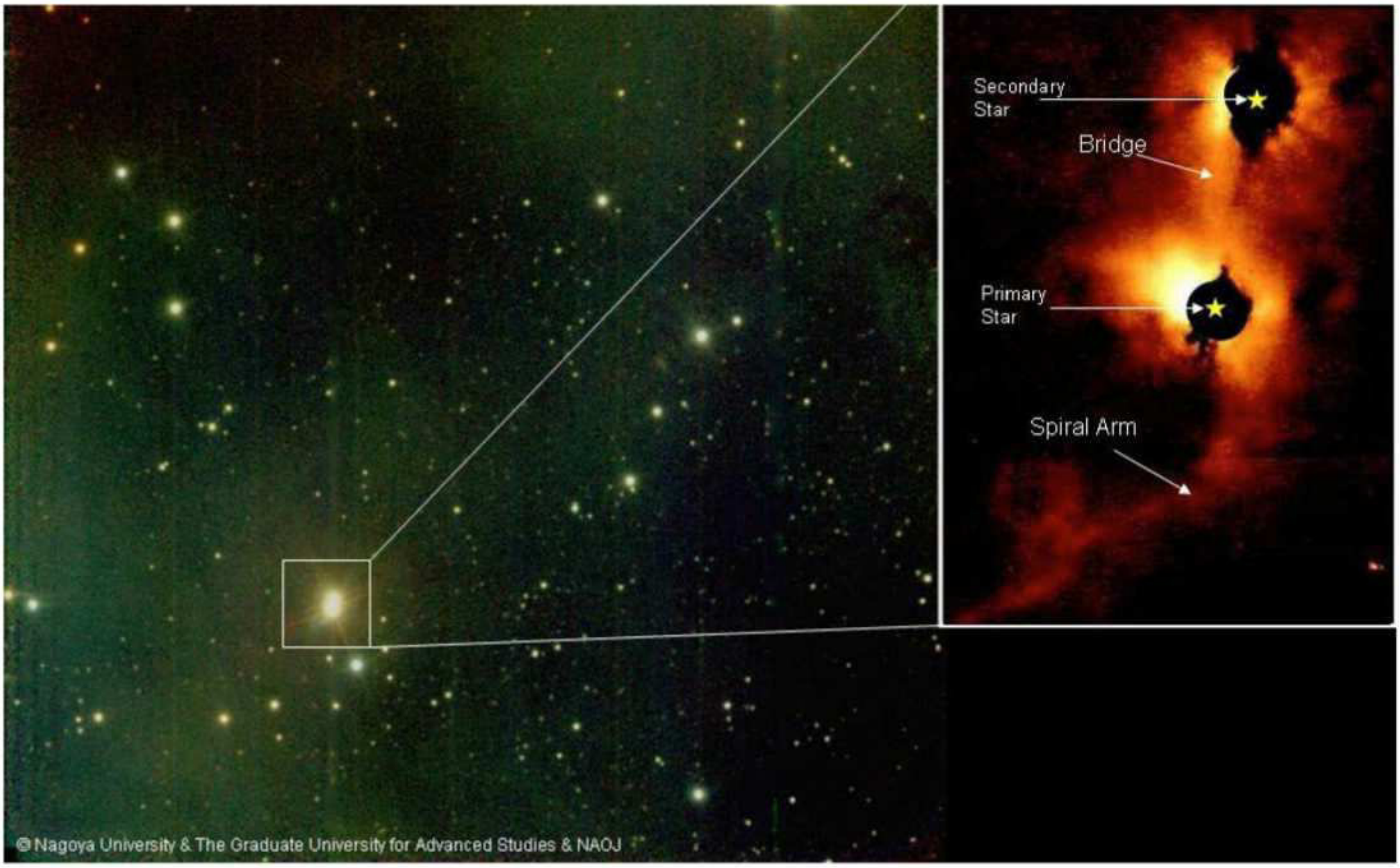
The likelihood of a star having a companion depends on its mass. Stars like our Sun have a 40 percent chance of being in a binary while among lower-mass red dwarfs, with masses one tenth of our Sun, the chance is below 20 percent. At the other end of the scale, the most massive and brightest stars with masses in excess of ten times the Sun, at least 70 percent have a companion star. Recent work shows that of these, many are so close that the stars interact by mass exchange during their lifetimes, significantly altering their stellar evolution. This can occur when mixing, induced by the proximity of the secondary star, transforms one of them into a chemically peculiar star. Not only that, if the stars are close enough, the binary system can merge to form a new single star. This has been proposed as an evolutionary route to making double black hole binaries, which can later merge into one with the emission of detectable gravitational waves. Indeed, if we look only at very massive, single stars in the sky, half of them used to be binaries and have now merged. Understanding binaries is thus critical to understanding stars and the physics that drives them.

Extreme physics

Mass transfer in a binary system is the key process in changing a star's evolutionary sequence and it is linked to an imaginary surface that lies between the two stars. Known as the Roche surface, it is shaped as a figure of eight with a star in each lobe and is the critical location at which gas is equally bound to both stars. If the star's surface crosses the Roche surface, mass is exchanged and can alter the evolution of both stars forever.

Processes that can cause a star to cross the Roche surface include a shortening of the orbital separation of the binary, or the expansion of one of the stars. When two bodies are sufficiently close to one another, their mutual gravitational pull induces a tide. Just like the gravity of the Moon makes tidal bulges in Earth's oceans, two orbiting stars cause tidal bulges on each other. These bulges result in the transfer of angular momentum (a measure of rotation) from the

▼ Binary star system SR24 in the constellation of Ophiuchus as observed with the Subaru Telescope.



orbit to the stars, and vice versa. If orbital angular momentum is transferred to the star, the orbit shrinks, while the stars spin faster. If their separation shortens sufficiently, mass transfers from the largest of the two stars onto its companion.

Alternatively, mass transfer can be caused by the natural process of stellar evolution. Stars expand as they age and most become a red giant, many hundreds of times the size of the Sun. If a star has a close companion, as in many binary systems, this expansion causes mass from one star to spill onto the other. This transfer of gas makes the mass-gaining star spin faster and contributes to a range of diverse stellar phenomena. If the rate of mass gain is fast enough, the companion star is unable to accommodate the newly acquired mass and it also expands and eventually fills its own Roche lobe. The two stars enter a common envelope in which they orbit inside a shared gaseous cocoon. Sometimes, the stars merge; other times the gaseous envelope can be ejected to form a nebula around what is left of the two stars in the binary.

Oddballs and observing

Is it possible to see objects that are exchanging mass? Put simply, yes and no. Modern astronomy, with its ever more powerful telescopes that can monitor large swaths of sky for anything that changes in brightness, can detect binary interactions directly. However, these interactions are fleeting and so hence are rarely observed. We do, however, often see the stars which are products of binary interaction because these can survive sometimes for billions of years.

One example is the peculiar set of stars called blue stragglers. These stars were first identified in globular clusters where all stars have the same age and, correspondingly, a maximum possible mass. More massive stars in the cluster should no longer have a nuclear-burning core, and should instead be dim white dwarfs.

Yet, many clusters have been discovered to house stars which are too massive to still be alive according to current stellar evolutionary theories - fortunately, the binary evolution channel naturally explains their continued existence. At some point in their past, these stars must have acquired some mass, possibly by merging with another star, to give them a new lease on life.

Other notable oddballs are those that are known as chemically-peculiar stars. These stars are at a stage in their life when they are not expected to have certain chemical elements, such as

> Notable oddballs are those that are known as chemically-peculiar stars

carbon and barium, at their surfaces. The only explanation, again, is that they have 'inherited' the peculiar chemical gas from a companion star that made these chemical elements in the past. Today that companion is likely too faint to be observed directly, but lurks undiscovered near our chemically peculiar star.

Mass gain is not the only peculiar binary phenomenon. The star that has its mass removed is often stripped of its surface layers. In very massive stars, this process makes unusual objects called Wolf-Rayet stars. These are often rich in helium, carbon and oxygen but because of a binary interaction. The outer layers have been stripped from the star and these gases are now detected at the surface, when ordinarily they shouldn't be. When these type of stars run out of nuclear fuel, they explode as the peculiar, hydrogen-free type Ib and Ic supernovae, and may cause long gamma-ray bursts.

It is not just massive stars that are prone to alteration; binary interaction can also affect stars with masses more like our Sun. In single-star evolution, smaller-mass stars ignite helium deep within their hydrogen-rich envelope. If this envelope is removed by binary interactions just before helium ignites, a new type of star called a subdwarf-B star forms. What we see is the exposed, nuclear-burning core of a red giant, and we know this can only be made in binary stars.

Transients

Transient sources are bright objects in the sky which appear, then disappear or dim, quickly on astronomical timescales but fast enough to be seen by astronomers. They may last from seconds to years and they can often be seen at all wavelengths, from radio to gamma ray. Many transients are associated with binary stars and mass transfer in binaries is the cause in many of these cases. Perhaps the best-known are novae, which is Latin for 'new stars'.

In classical novae, material piles up on a white dwarf until the increasing pressure triggers a nuclear explosion on its surface. If the mass of the white dwarf increases, it may reach the Chandrasekhar mass and at this point the whole star explodes as a type Ia supernova, enriching the interstellar medium with iron in the process.

> If this envelope is removed by binary interactions just before helium ignites, a new type of star called a subdwarf-B forms

▲ Chandra X-ray Image of Mira (left pic) showing Mira A, a highly evolved red giant star, and Mira B, a white dwarf. Mira A is losing gas rapidly from its upper atmosphere via a stellar wind. Mira B exerts a gravitational tug that creates a gaseous bridge between the two stars. Gas from the wind and bridge accumulates in an accretion disk around Mira B and collisions between rapidly moving particles in the disk produce X-rays. Pic (right): artist's impression of the binary system.

A merger between two white dwarfs may also trigger the same type of supernovae. Because of their homogeneity, these explosions can be used as 'standard candles' such that we can calculate their distance accurately and use them to deduce that the expansion of the Universe is accelerating.

Transients are also associated with the mergers of stars, so not just when mass is transferred but when the two objects combine to leave behind one massive star. As this happens, the energy that was in the orbit of the two stars goes into the newly formed single object, causing it to expand and brighten dramatically. The resultant transient event is known as a red nova and an example of this was observed in 2008 when the stars in the binary system V1309 Scorpii spiralled in and crashed into each other. The star is now a single entity, surrounded by a dust cloud that was ejected during the merger.

Similarly, when two neutron-stars merge, not only does the process produce the heavy elements found in our Galaxy, such as gold, platinum and uranium, but the amalgamation produces radiation that we observe in the optical and infrared as a bright kilonova transient and a short gamma-ray burst at higher energy.

Gravitational radiation has recently been detected from merging stellar-mass black holes, validating Einstein's theory of General Relativity, although the origin of such systems remains a matter of some debate.

Models of binary stars will explain how physics works in the most extreme environments we can imagine

A binary future

Binary stars are as vital to astrophysics today as they were in the 17th century to Kepler and Newton. They can be used to measure the expansion rate of the Universe and can help us to understand the formation of the chemical elements when the Universe was young.

Astronomers have even found planets around binary stars, providing yet more intrigue as to how planets form and survive. To help us solve these challenging questions we have an exponentially increasing volume of astronomical data from surveys like ESA's Gaia.

The challenge now is to understand stars of all kinds - single, binary and multiple - to establish how they were formed, how they evolved and what brings about their end. Detailed modelling of binary stars is a major challenge which will require the best of astronomy, astrophysics, applied mathematics and computer science on many levels.

Coupled with state of the art observational surveys, our models of binary stars will explain how physics works in the most extreme environments we can imagine. Binary stars are key to pushing the boundaries of our knowledge and will remain so for a long time to come. ■

For a more detailed review of binary stars, the authors have written the 2016 Dawes Review paper 'The impact of companions on stellar evolution', available at https://arxiv.org/abs/1611.03542 and http://adsabs.harvard.edu/cgi-bin/bib_query?arXiv:1611.03542

About the authors

Dr Robert Izzard is an STFC Rutherford fellow at the Institute of Astronomy, University of Cambridge, where he works on understanding binary stellar evolution. He was previously a professor at die Rheinische Friedrich-Wilhelms-Universität Bonn, a Marie-Curie fellow at l'Université libre de Bruxelles and an NWO fellow at de Universiteit Utrecht. In September 2017 he will join the astrophysics group at the University of Surrey.

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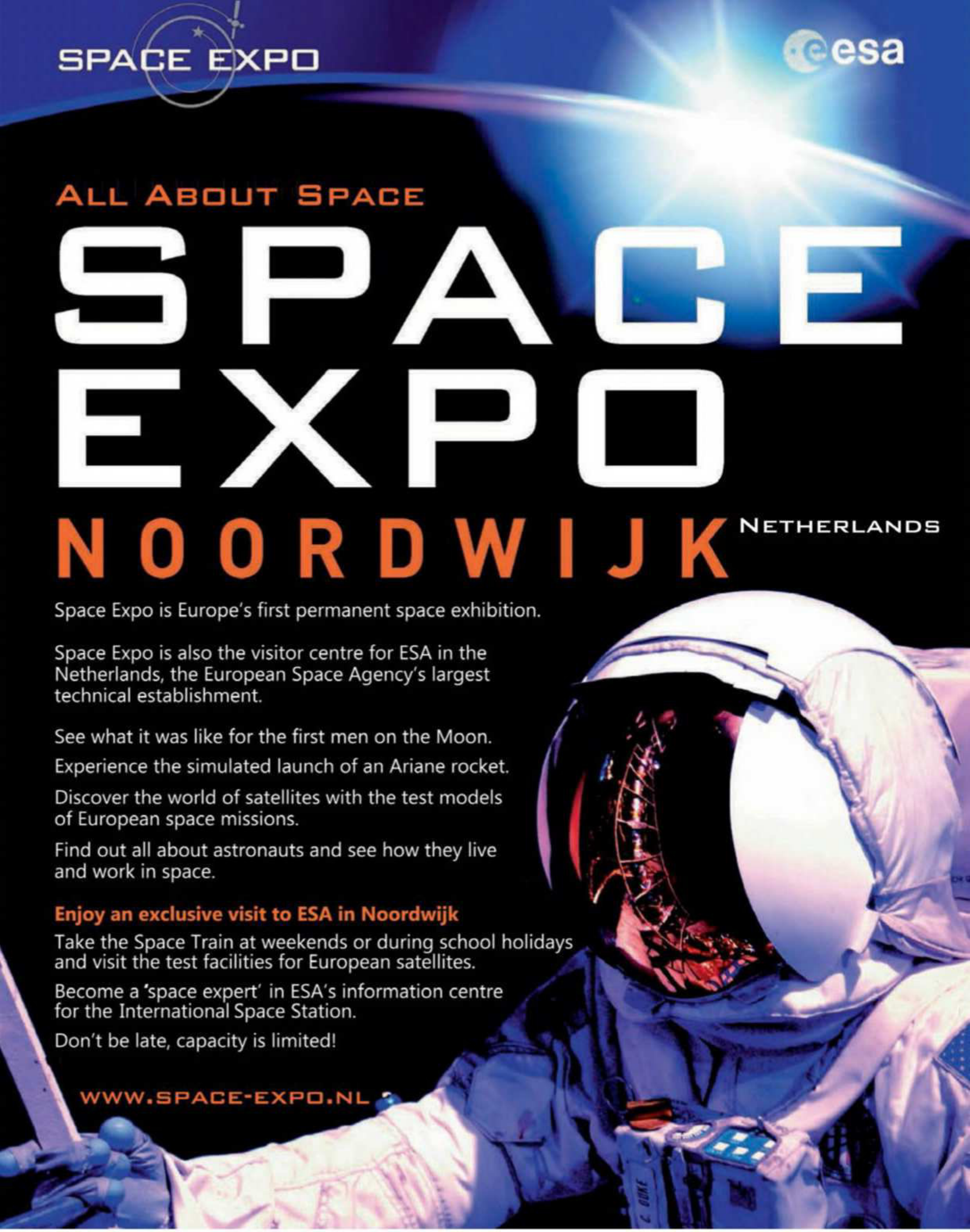

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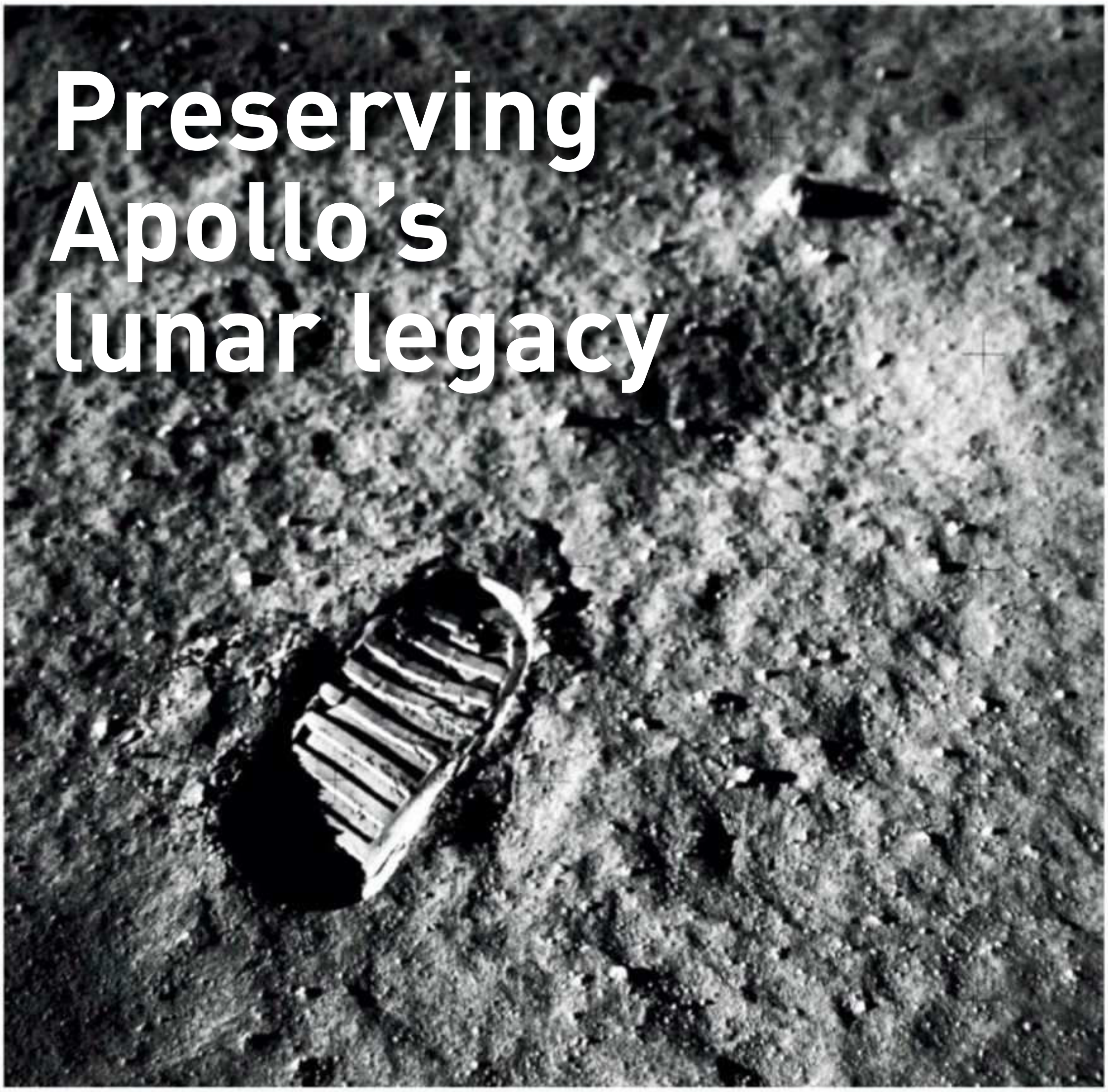
Preserving Apollo's lunar legacy



▶ A first off-world step, imprinted in the jagged lunar soil, photographed on July 20, 1969 in the region known as the Sea of Tranquility.

Imagine if these first off-world footprints, preserved until now by the vacuum of space, were erased?

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. Here, Michelle Hanlon, co-founder and Roy Balleste, member of the Advisory Council of For All Moonkind, Inc, suggest there should be a way of preserving relics left on the Moon after the Apollo missions for the benefit of future generations.

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Buzz Aldrin described the surface of Earth's Moon as "magnificent desolation". On this surface, battered by sharp and jagged lunar dust lie many oddities, including a golden olive branch, two medals and a mission patch honouring two Soviet cosmonauts and three American astronauts who advanced humankind's quest to explore space but perished before the first Moon landing was achieved.

There is also a piece of silicon. A disc, just over 30 mm in diameter filled with photos of messages from the leaders of 74 nations at the time. They are congratulatory and optimistic. Some speak with hope, some with respect of the great inventors and thinkers, like Galileo Galilei who formed the foundation upon which modern science was developed. Many speak with pride, recognising the world's first humans to step on the lunar surface - Neil Armstrong and Edwin 'Buzz' Aldrin - as true envoys of almost all humankind. And all speak fervently of peace.

On 16 July 1969 a Saturn V rocket lifted off on a historic voyage and four days later millions of people watched as the first human footprints were set on the Moon's desolate surface and a flag was planted. Though no claim of sovereignty was made, the familiar stars and stripes is prominent in many iconic photos of the first lunar landing and the five that followed.

If any fragments of the flags have survived the harsh lunar environment, they are most likely by now bleached of all colour and a ghostly reminder of an achievement that belongs to all humanity. In contrast so much else from those first landings will be very well-preserved. Without wind, water or weather to erode the soil, equipment, including cameras and even urine bags, the medals, the olive branch, the disc and footprints are likely to remain close to their original state. Imagine if these first off-world footprints, preserved until now by the vacuum of space, were erased?

Each of the six crewed lunar landings to date - all part of NASA's Apollo programme - was fraught with its own dramatic missteps and failures, each representing a litany of firsts and each reverberating with demonstrations of human perseverance, ingenuity and accomplishment.

In 1972, Apollo 17 was the final mission and remains the last time humans travelled beyond low Earth orbit (LEO). But that will soon change because it is clear that we stand on the threshold of the spacefaring age and that our Moon is about to get very crowded.

Japan, China, Russia and the United States all are weighing manned Moon missions within the next decade. Private manned missions may get there even sooner and more robots will be deployed to the Moon by nations and private interests from as early as next year.

It is not difficult to imagine the damage an autonomous vehicle or an errant astronaut - an explorer, colonist or tourist - could do to one of the Apollo lunar landing sites, whether intentionally or unintentionally.

In 2013, two well-meaning but woefully misinformed legislators from the United States sought to have the US Department of Interior administer the Apollo lunar landing sites as US National Historic Parks. The resulting Apollo Lunar Landing Legacy Act of 2013 was ill-conceived and in violation of United States Treaty obligations and this attempt to bring the landing sites under the purview of the United States was roundly, soundly and rightfully criticised.

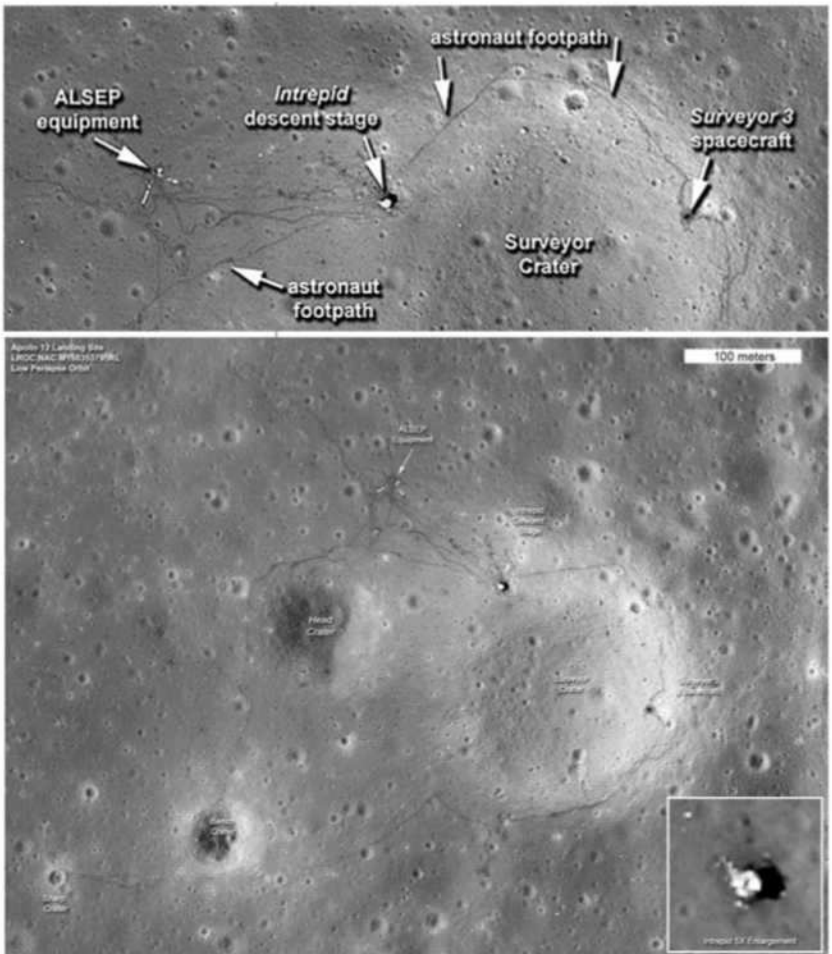
First, as George Robinson, retired Associate General Counsel for the Smithsonian Institution pointed out, the Act implied that only the United States should be recognised for the Apollo programme, and yet "many countries offered and provided critical components of the programme, from alternate emergency landing sites, to unique technology and personnel with equally as unique specialty capabilities, to tracking stations and on and on."". And second, it also implied that the United States has the ability to make sovereign proclamations in respect of the Moon which is categorically incorrect and a violation of international law and the Outer Space Treaty by which the United States is bound.

Article II of the Treaty states that "outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation or by any other means." It is a principal so embedded in the bedrock of space exploration as to be considered by many to be not just a treaty obligation but customary international law.

With this in mind, For All Moonkind, Inc - a non-profit organisation seeking to preserve the memory of all those who toiled during the intense competition of a Cold War that saw humankind leap into space - believes it is not the United States,

It is not difficult to imagine the damage an autonomous vehicle or an errant astronaut could do to one of the Apollo lunar landing sites

▼ Astronaut Harrison Schmitt, a geologist and the first person initially trained as a scientist to walk on the Moon, photographed on 13 December 1972 during the third Apollo 17 EVA at the Taurus-Littrow landing site.



▲ NASA's Lunar Reconnaissance Orbiter (LRO) took these images of the Apollo 12 landing site in 2011, note that the astronaut footpaths were still distinguishable after more than 40 years.

If we cannot achieve peace on Earth, certainly we can work together to preserve peace in the heavens

but the United Nations that should act formally to protect and preserve the Apollo landing sites.

In 1972, the General Conference of the United Nations Educational, Scientific and Cultural Organization (UNESCO) introduced a convention concerning the protection of the world cultural and natural heritage. The World Heritage Convention, now boasting 193 state parties, recognises "that deterioration or disappearance of any item of the cultural or natural heritage constitutes a harmful impoverishment of the heritage of all the nations of the world." Regardless of sovereignty, the Convention emphasises "the importance, for all the peoples of the world, of safeguarding this unique and irreplaceable property, to whatever people it may belong".

UNESCO's World Heritage Convention has been a great success, helping preserve natural and cultural landmarks around the world - from the Tsodilo in Botswana to the Taj Mahal in India But as humankind stretches its reach into space, so must the United Nations and UNESCO.

Just as we revere fossilised footprints of a long-forgotten hominin species in the Ngorongoro Conservation Area as evidence of the development of human bipedalism, we must preserve our first footprints on the Moon. Each of the Apollo lunar landing sites is evidence of humanity's first tentative steps off planet Earth and to the stars. They mark an achievement unparalleled in human history and they embrace, and poignantly echo, our continued efforts to achieve peace.

Article 1 of the World Heritage Convention defines a "site" as "works of man... and areas including archaeological sites which are of Outstanding Universal Value from the historical, aesthetic, ethnological or anthropological points of view".

In turn, paragraph 49 of the Operational Guidelines for the Implementation of the World Heritage Convention define "Outstanding Universal Value" as "cultural and/or natural significance which is so exceptional as to transcend national boundaries and to be of common importance for present and future generations of all humanity". Permanent protection of such sites is seen as "of the highest importance to the international community as a whole".

Paragraph 77 of the Guidelines requires that, in order to be considered of "Outstanding Universal Value" proposed heritage sites must meet at least one out of 10 listed selection criteria. The Apollo sites arguably meet six:

- Represent a masterpiece of human creative genius
- Exhibit an important interchange of human values, over a span of time or within a cultural area of the world, on developments in architecture or technology, monumental arts, town-planning or landscape design
- Bear a unique or at least exceptional testimony to a cultural tradition or to a civilization which is living or which has disappeared
- Are an outstanding example of a type of building, architectural or technological ensemble or landscape which illustrates a significant stage(s) in human history
- Are an outstanding example of a traditional human settlement, land-use, or sea-use which is representative of a culture (or cultures), or human interaction with the environment especially when it has become vulnerable under the impact of irreversible change
- Are directly or tangibly associated with events or living traditions, with ideas, or with beliefs, with artistic and literary works of outstanding universal significance.

Unfortunately, simply meeting the criteria is not enough. Article 11 of the Convention sets forth the process by which property may be submitted for inclusion in the World Heritage List. And it relies on the concept of sovereignty, anathema to the Outer Space Treaty. State Parties to the Convention are instructed to submit properties within their territory. But the Moon is the province of all humankind, not subject to territorial claim by one State.

The Operational Guidelines do contemplate, at Paragraphs 134 and 135, the nomination of a "transboundary" property which should be prepared and submitted by State Parties jointly. The Moon can certainly be considered a "transboundary property" that essentially has "adjacent borders" with every State on Earth. Which is to say that a nomination for inclusion of the six Apollo landing sites on the World Heritage List is unprecedented. It is also necessary.

The future of humanity in space promises infinite possibilities. More and more countries are becoming spacefaring nations and a new wave of commercial space activities has given both states and the private sector unique opportunities and challenges to make history. And just as the Apollo project was built on the foundation of centuries of science and discovery from around the world, these new endeavours are built upon the legacy and lessons of those Moon landings.

To fully understand those lessons and the sacrifices made by all the men and women who have contributed to humanity's quest to explore space, we need to preserve the history and heritage found in those first Moonsteps. Because they hold not only the crumbs of our past, but enduring expressions of hope for a peace-filled future.

Recognising that no one country can or should spearhead the process to nominate a World Heritage Site, For All Moonkind will organise the nomination documents and carry out all prepatory work with the hope and intent that all States join, as transboundary participants, in the ultimate nominating submission - a nomination that will truly transcend the bounds of nations. We must start to recognise that we are together one species, with a shared goal, too often obscured, of preservation, peace and goodwill.

If we cannot achieve peace on Earth, certainly we can work together to preserve peace in the heavens. And conserving the Apollo landing sites as human accomplishments, protected by United Nations decree, is a first step toward affirming the universality of our shared posterity under a unified regime.

Today, this may feel an overly symbolic gesture, as the days of potential monument desecration seem a distant horizon. But however symbolic it may seem, it will assure that the base of a new generation of competitive space exploration will be founded in our shared humanity.

Humankind's path to space started with a race to put a human imprint on the "magnificent desolation" of the Moon. But even in the midst of that competition it was universally acknowledged - as noted in the legislation that created the United States' National Aeronautical and Space Administration - that "activities in space should be devoted to peaceful purposes for the benefit of all mankind."

The Apollo astronauts left equipment, footprints and numerous symbolic mementos on the Moon. There is no doubt that these objects and these sites are "so exceptional as to transcend national boundaries and to be of common importance for present and future generations of all humanity". They deserve to be preserved. ■

▲ This plaque, left on the Moon at the Apollo 15 landing site in August 1971, commemorates the 14 NASA astronauts and USSR cosmonauts who perished before the mission. The tiny, man-like object in front represents the figure of a fallen astronaut/ cosmonaut.

Conserving the Apollo landing sites as human accomplish-ments is a first step toward affirming the universality of our shared posterity

About the authors

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Call for Australia to head back into space

Australia relies heavily on its relationship with the United States for access to space infrastructure and space services

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. Here, with the spotlight of the international space industry about to fall on Australia, Duncan Blake asks if the country has become 'lost in space' and suggests a new impetus might be afoot with the possibility of a national space agency even in the offing.

Duncan Blake
PhD candidate, the University of Adelaide, South Australia

Adelaide will host the International Astronautical Congress (IAC) this September - the biggest conference in the global space community's annual calendar [1]. Australia, and particularly the state of South Australia, has a long heritage in the space industry stretching back to the Woomera rocket range and long-range Weapons Research Establishment (WRE) in 1947 and the launch of WRESAT in 1967 on an American rocket from Woomera [2], which made Australia the seventh nation to launch its own satellite and only the third to do so from its own territory. Yet, this was the first and only satellite launched from Australian territory, prompting some Australian politicians in the federal parliament to initiate an inquiry in 2008 into how the country had become 'lost in space' and what to do to reinvigorate the Australian space industry [3].

On 21 March 2017, the Space Industry Association of Australia (SIAA) released a white paper 'Advancing Australia in Space', in which it asserted that the Australian space sector could, with the 'right impetus', double its current annual revenues of approximately US$2.5 billion (about 0.8 percent share of the global space economy) within five years and that four percent global market share could be a realistic goal within 20 years. The 'right impetus' would be "the establishment of an Australian Space Agency to lead a cohesive national space strategy" [4].

Civil space leadership

The SIAA white paper has been presented to the Minister for Industry, Innovation and Science for his consideration [5]. Although responsibility for specific aspects of space activities is disparate throughout Australian government, the Department of Industry, Innovation and Science is responsible for civil space issues and is the central point of contact and coordination for the government's involvement in national and international civil space activities.

That responsibility is manifested in a small number (less than 10) of dedicated staff in an office known as 'Civil Space and Cyber Security section' - a far cry from a fully-fledged space agency. The department also has responsibility for administering legislative arrangements regulating Australian civil space activities to ensure these activities do not jeopardise national interests and Australia's "international obligations" in space, as well as for policies that provide the right conditions for entrepreneurs and businesses to innovate and capitalise on their space-related activities [6].

Even before the release of the SIAA white paper, the department recognised that it reflected a theme that has been developing within Australia for more than a decade - that the legislation administered by the department, namely the Space Activities Act 1998 and its subordinate legislation, is not adapted to providing "the right conditions for entrepreneurs and businesses to innovate and capitalise on" significant and growing opportunities for Australian space industry to contribute to the global space economy.

A review of the Space Activities Act 1998 and its subordinate legislation, initiated in October 2015, has been completed and the department is now considering legislative changes with a draft bill expected in the second half of the year [7] around the time of IAC 2017.

The timing is therefore ripe for a significant evolutionary change in the Australian space industry and while IAC 2017 represents a great opportunity to announce such a change, we will just have to wait to see what the Department of Industry, Innovation and Science will decide.

SPACE SPENDING

The Australian Department of Defence does not aggregate its budget figures under the heading 'space' or similar, so it is difficult to say how much of the Department's overall budget is spent on space.

Nevertheless, some indication of the scale of defence funding on space is available through a report released in 2015 by Asia Pacific Aerospace Consultants for the Department of Industry, Innovation and Science entitled 'A Selective Review of Australian Space Capabilities: Growth Opportunities in Global Supply Chains and Space Enabled Services'.

It involved a study of 46 companies indicative of the Australian space industry as a whole, and within that selection, 72 percent had defence as a customer.

The figure represents only the money defence spends on space through commercial space activities in Australia and does not take into account commercial space services sourced from outside Australia and money spent internally within defence on space.

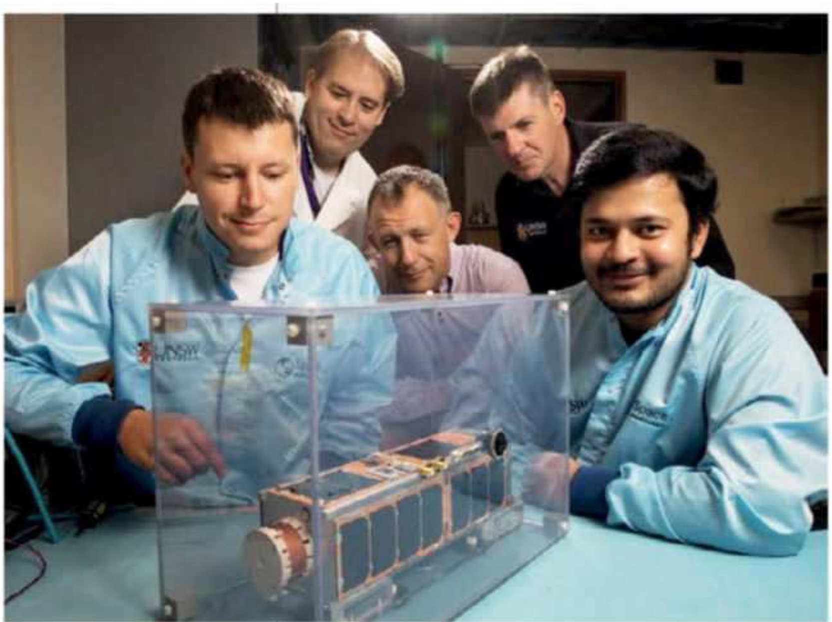
Defence space leadership

While the Department of Industry, Innovation and Science has overarching responsibility for civil space issues, by far the biggest proportion of Australian government funding for Australian space activities is through the Department of Defence.

So it follows that defence could play a larger part than any other sector in providing the 'right impetus' for a national space strategy and the growth of the Australian space industry. Such growth implies not just additional civil capability, but also access for defence purposes to a greater level of sovereign space capability than Australia has ever previously had.

Australia relies heavily on its relationship with the United States for access to space infrastructure and space services. Like other western nations, the ubiquity and increasing dependence on space-

▼ Royal Australian Air Force C-17A Globemaster with a new advanced satellite communication and imagery display system - a concentration of military forces in an area necessarily implies an extraordinary demand for satcom bandwidth, precise Position, Navigation and Timing, and remote sensing data. New capabilities, offering greater connectivity, are increasing that level of extraordinary demand.



▲ Space engineering faculty at the University of New South Wales building a satellite in their lab.

derived services is difficult to overstate and Australia provides valued trade-offs to the United States in return - like international support, participation in military coalitions, access to territory, personnel exchanges and expertise, and research and development - and, so long as those trade-offs continue to be valued, Australia does not have to pay directly for such access. There seems to be little rationale for spending public money on sovereign space capabilities when Australia already has low cost access to US space infrastructure and services.

The country's relationship with the United States, although close, does not necessarily provide everything Australia may need or want from space infrastructure - there is a 'sovereign margin'. Furthermore, the global space industry is already huge, estimated at over US$320 billion, and is set to grow substantially.

Compared to a current global inventory of almost 1,500 active satellites [8], projects underway to launch new constellations of many thousands of satellites - such as SpaceX, Google, OneWeb, Boeing and others [9] - could increase the global inventory by several orders of magnitude. The Australian economy, and, in turn, defence, could get a big boost in its efforts to capture a greater proportion of that industry without the huge public investment that space capability has previously involved.

▶ Britain's Blue Streak rocket was launched for the first time from Woomera in 1964.

Smaller, shorter endurance satellites are becoming more and more capable

Operationally responsive space

The solution is linked to a concept known as 'Operationally Responsive Space' (ORS). The new Secretary of the United States Air Force (USAF) favours the reinvigoration of the ORS Office [10]. Australia has a lot to offer.

In the past, the US and its military, like other space powers, have launched mostly large satellites weighing several tonnes, which are highly complex and highly capable, often providing services for two decades or longer. On the other hand they are expensive to launch and maintain.

Earth orbit is also increasingly contested, with several space powers developing the means to put other satellites at risk. Whilst the satellites are highly valuable, they are also vulnerable and they make highly attractive targets.

Smaller, shorter endurance satellites are becoming more and more capable and, especially with the 'production-line' approach to satellite manufacture that SpaceX, Google and others are establishing, they are becoming much cheaper and more readily available [11]. Disaggregation of space assets in this way increases the difficulty of targeting satellites and may reduce the impetus towards the use of force against such satellites in the first place [12].

n ORS concept would mean the US could launch replacements on demand, in contrast to countries like Australia, the United Kingdom, Canada and New Zealand. So far Australia has found it hard to justify public investment in space infrastructure, even where it is to replace a valuable capability.

There's more though. The ORS concept also recognises that, during a military campaign over several years or decades, demand for satellite services often outstrips supply and this problem is exacerbated by an exponential growth in networked capabilities and an insatiable demand for bandwidth by new military technologies that all promise to provide capability 'leaps' due to their connectivity.

The US military wants to be able to launch small satellites, at relatively short notice (e.g. several months), specifically adapted to the needs of a particular campaign, to supplement and enhance existing and anticipated capabilities, and the satellites only need to endure for several years rather than a couple of decades. Ideally, the US would want to share the resource burden (and the benefits) of developing an ORS capability, as well as recognising the national security benefits of disaggregating launch facilities.

Australia's role

Australia not only has the geography, stability and knowledge to manufacture and launch small satellites from its own soil but has existing commercial and research enterprises actively involved in key areas - Equatorial Launch Australia, UNSW's Space Engineering Faculty developing small satellites, Gilmour Space developing rockets for launch of small satellites, Defence Science and Technology Group's rocket propulsion experts and the University of Queensland's rocketry research. So how does Australia offer a practical pathway for synergistic cooperation with the United States in its development of the ORS concept?

Every two years the Australian Defence Force invites the United States, 'five-eye' allies and others to participate in a large military exercise - Talisman Sabre. For several weeks, more than 30,000 military personnel from Australia and its allies amass in northern Queensland to practice how they would cooperate to initiate, prosecute and successfully end a military campaign [13].

The Department of Defence could commit to launch a small satellite, or more than one, every two years in support of Talisman Sabre and in cooperation with the US and other allies, and they could do the same in respect of major exercises in their own countries. The Department of Defence could run a competition for local industry to submit proposals on what to launch and how.

Initially, it may not be possible to do it alone, but over several iterations of the Talisman Sabre exercise, Australia could maximise local industry participation. The Department of Defence could partner with the Department of Industry, Innovation and Science to facilitate this.

For a relatively small public investment in a project in which the costs would be shared, Australia could realise significant benefits for its national security, for its allies and its alliances, whilst also providing a huge boost for the capacity of local industry and its opportunity to capture a significantly greater proportion of the global space industry. ■

▲ In June 2016 Gilmour Space successfully launched a test rocket at Westmar, about 400 km west (inland) of Brisbane in Australia - the first privately developed hybrid sounding rocket designed, built and launched by an Australian (and Singaporean) company. It was also the first successful hybrid rocket test launch using 3D printed rocket fuel. The company is developing a three-stage rocket capable of launching up to 380 kg into low Earth orbit.

About the author

Duncan Blake transferred from the permanent Air Force to the Reserves in January 2017 after 22 years as a Legal Officer in the Royal Australian Air Force. He was legal advisor to the Australian Defence Space Coordinating Office and chaired inter-departmental and international working groups in respect of strategic space law. His thesis topic for his Master of Laws degree at McGill University was on the need for a 'Manual on International Law Applicable to Military Uses of Outer Space' (MILAMOS).

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13 Department of Defence, Exercise Talisman Sabre 2017 (webpage accessed on 20 May 2017), online: < http://www.defence.gov.au/Exercises/TS17/ >.

Demand for satellite services often outstrips supply and this problem is exacerbated by an exponential growth in networked capabilities and insatiable demand for bandwidth

Australia's unique space history

▲ The Canberra Deep Space Communication Complex has played a crucial role in planetary exploration since 1965.

While Australia is not currently considered a significant spacefaring nation, it has a long history of space activities stretching back to the beginnings of the Space Age - and South Australia was the original home of those activities. For anyone planning to attend the 2017 International Astronautical Congress (IAC) in Adelaide this September and spend some extra time in the country, there are several space sites and museums that offer an insight into Australia's space history. Here's our specialist guide to help you plan and make the most of your time at the IAC in Australia and learn something of its unique space history.

Kerrie Dougherty
Independent curator and space historian, Australia

Port Adelaide

Right on the doorstep of the International Astronautical Congress, the South Australian Aviation Museum (SAAM) at Port Adelaide offers a small display of British and Australian sounding rockets launched at Woomera, together with a good collection of civil and military aircraft, many with specific South Australian connections, and aviation memorabilia. Easily reached by public transport, the SAAM is part of a heritage precinct that also includes the National Railway Museum and the South Australian Maritime Museum. www.saam.org.au/

Woomera, South Australia

Established in 1947 to test British long-range missiles and other weapons, Woomera Rocket Range was also the hub of space activities in Australia from the 1950s to 1980. Several significant programmes were carried out there, commencing with the British Skylark and Australian sounding rocket programmes in 1957.

Britain's Black Knight research missile was used 1958 - 1965 for a range of defence research projects focussed on upper atmosphere studies: additional research was carried out under Project SPARTA in 1966 - 67 using American Redstone rockets. From 1964 - 1970, ELDO, the European Launcher Development Organisation (a precursor of the European Space Agency) conducted its Europa launch vehicle programme, the largest space project undertaken at Woomera.

Although ELDO never managed to launch a satellite during this programme, Australia's first satellite WRESAT (celebrating its 50th anniversary this year) was launched from Woomera in 1967, and the last launch of Britain's Black Arrow programme, active 1969 - 1971, lofted Prospero, the second satellite to achieve orbit from Woomera.

Woomera was also the home of space tracking facilities initially established in conjunction with the International Geophysical Year (IGY). Transferred to NASA on its creation, these facilities were moved in the early 1960s to Island Lagoon, about 25 km south of Woomera, where NASA established an early deep space tracking station in 1960.

This station played an important role in the early exploration of the Moon, Mars and Venus, as well as the Apollo programme, before being closed in 1972. A spaceflight tracking station used for the Mercury, Gemini programmes and early Apollo Saturn rocket tests was also established on the Range, operating from 1960-66.

Located not far from Island Lagoon, the Joint Defence Facility Nurrungar was operated by the United States Air Force and the Australian Department of Defence from 1969 to 1999. Its role was space-based surveillance, especially the early detection of missile launches and nuclear tests using US Defence Support Program geostationary satellites.

Today, the Woomera Range Complex (as it is now known) is a busy weapons test facility with little direct involvement in space activities, although a refurbished sounding rocket launch facility is maintained and available for research use.

The Range has been designated as a National Engineering Landmark by Engineers Australia and as a Historic Aerospace Site by the American Institute of Aeronautics and Astronautics, but access to the former space facilities is extremely restricted, as is the abandoned Nurrungar complex, although its remaining radome can be seen from the highway shortly before the turnoff to Woomera itself.

The Island Lagoon tracking station site (of which, sadly, little remains apart from a few concrete footings) is also no longer accessible without prior permission from the manager of Arcoona station (ranch) on which it is situated.

However, the Woomera Village, originally built to house the staff working on the rocket range, is open to tourists and is well worth a visit for the serious space history buff. The Woomera Heritage Centre, in the heart of the village, provides an excellent exhibition that presents the history of the range from its establishment in the aftermath of World War 2 until the early 2000s.

Its collection of historic artefacts is complemented by the nearby rocket park and Woomera History Museum. The Woomera Rocket Park has a large outdoor display of original (or reconstructed-from-available-parts) missiles, weapons, rockets and aircraft used or tested at Woomera.

Space-related highlights include Black Arrow and Black Knight rockets, a Skylark sounding rocket, a variety of Australian sounding rockets and a Jabiru hypersonic research rocket. Of particular interest are the remains of the Redstone rocket used to launch the WRESAT satellite and those of the ELDO Europa F-4 vehicle. Recovered from their original desert impact locations by heritage-minded Woomera personnel in 1989 and 1994, these rocket relics are laid out on beds of desert sand inside protective cages. A recovered Rolls Royce RZ2 engine from the F-4 vehicle is also on display.

▲ Part of the Woomera rocket park, showing a Skylark rocket and the Black Arrow reconstruction in the background.

Housed in what was originally St Barbara's Anglican Church, the Woomera History Museum serves as the repository of heritage material - artefacts, photos, archives, memorabilia and other items - that could not be accommodated in the main Heritage Centre display. While the presentation is rather haphazard, if you have a strong interest in the history of Woomera you will find hours of fascination browsing through the photographic collections and the bound copies of the Gibber Gabber, the Woomera newspaper.

Located in the 'Outback' about 480 km from Adelaide, Woomera is about a six-hour drive on good sealed roads, with a car being the only convenient way to get there (although it is also possible to fly into the town of Roxby Downs, and hire a car to drive the 100 km to Woomera).

Be prepared to see kangaroos, emus and other native wildlife as you travel north from Port Augusta. Accommodation at Woomera is limited to the Woomera Travellers' Village and Caravan Park (http://www.woomera. com/p/accommodation-at-woomera.html) and the ELDO Hotel.

As its name suggests, the ELDO was originally the hostel and recreation facility established for personnel working on the ELDO project. Guests stay in refurbished and modernised accommodation blocks bearing the names of major rocket and missile programmes conducted at Woomera.

Further information and accommodation bookings are available via: www.facebook.com/eldohotel. As

While Australia is not considered a significant spacefaring nation, it has a long history of space activities stretching back to the beginnings of the Space Age

▲ A view of the Parkes Radio Telescope in 1969, during its involvement with the the Apollo 11 mission.

Woomera Rocket Range was also the hub of space activities in Australia from the 1950s to 1980

it will be school holiday time when the congress takes place, advance bookings are recommended at Woomera, as it is a popular stopover for people travelling to and from the Northern Territory.

Sydney, New South Wales

Visitors to Sydney should not miss the Space exhibition at the Powerhouse Museum, situated in the heart of the city at Darling Harbour. Australia's largest space history and technology exhibition, it places Australian space activities in their global context. Its exhibits include an Apollo 16 Moon rock and the unique Zero G Space Lab, an interactive exhibit that uses special effects to trick the mind and create the illusion of being in a microgravity environment.

The Powerhouse is also home to the Mars Lab, an innovative education programme that brings together high school education and university research around the development of robotic roving vehicles and the search for life on Mars. As part of this, students from across Australia and around the world can remotely operate research-grade robot rovers in the Mars Yard, a large, high fidelity recreation of the Martian surface.

Some Australian artefacts from the museum's space technology collection can also be seen at the Museums Discovery Centre, a display storage facility used by Sydney's major museums and situated at Castle Hill in western Sydney.

Also worth visiting for those with an interest in the history of Australian astronomy is the Sydney Observatory, the oldest surviving observatory in the country. Located right beside the Sydney Harbour Bridge, the observatory presents exhibitions about the history of astronomy in Australia and is also open for night time stargazing, using both its heritage 29 cm refractor telescope (the oldest working telescope in Australia) and a state-of-the-art 40 cm reflector.

The Powerhouse, the Museums Discovery Centre and Sydney Observatory, are all part of the Museum of Applied Arts and Sciences and further information about each venue can be found at https://maas.museum/

Parkes, New South Wales

One of the world's great radio astronomy instruments, the Parkes Radio Telescope has also played a significant role in space exploration. In addition to being the technological prototype for the 64 m dishes of NASA's Deep Space Network, Parkes has played a vital role in various NASA and ESA deep space missions and also in the Apollo lunar programme.

Australian film The Dish was based upon its role in bringing the Apollo 11 moonwalk broadcast to the world, and Parkes also played a critical role in the rescue of the Apollo 13 crew. While the radio telescope itself is not generally accessible to the public, except on special open days (check the website closer to time to see if one will be occurring during any planned visit), it operates an excellent visitors' centre with displays on astronomy and space science, a 3D theatre and an award-wining café.

Some 370 km west of Sydney, Parkes is best visited by road (about a six-hour drive from Sydney), although air/bus and train/bus travel options are possible. The lovely regional centre of Parkes, and its nearby heritage town of Forbes, are recommended as locations to spend a few extra days sightseeing.

Information on the Parkes facility's opening hours and how to get there can be found at: www.csiro.au/en/Research/Facilities/ATNF/Parkes-radio-telescope/Parkes-Observatory-Visitors-Centre/Hours-location

Canberra, Australian Capital Territory

Australia's national capital region was the home of NASA's second generation of tracking stations in

Australia, with three stations established south of the city - Tidbinbilla (for the Deep Space Network), Orroral Valley (for the Satellite Tracking and Data Acquisition Network station) and Honeysuckle Creek (for the Manned Space Flight Network).

Tidbinbilla and Honeysuckle Creek jointly participated in the Apollo programme, playing particularly critical roles in the Apollo 11 and 13 missions. Honeysuckle Creek actually brought the world the television images of Neil Armstrong stepping onto the lunar surface, before the rest of the Apollo 11 television broadcast was relayed via Parkes.

Today, as the Canberra Deep Space Communication Complex, only the Tidbinbilla station remains in operation, playing a crucial role in planetary exploration. While the tracking station itself is not open to the public, the facility has an excellent Visitors' Centre, with displays covering the history of the station in the wider context of planetary exploration.

The section on the Apollo missions includes the largest lunar sample on public display in Australia. The original antenna from the Honeysuckle Creek tracking station, which received the historic Apollo 11 broadcast, was transported to Tidbinbilla after the station closed in the early 1980s and can be seen near the tracking station entrance. Finally retired from operations in 2009, it was declared a Historic Aerospace Site in 2010 by the American Institute of Aeronautics and Astronautics.

Around Adelaide

From late August until November, host city Adelaide will be focussed on space, with special exhibitions at the State Library of South Australia and the South Australian Museum. About 10 minutes' walk from the congress venue, the State Library will be presenting 'Outback to Outer Space: Woomera and space, 1955-1980', a unique exhibition drawing on the resources of the Library and the National Archives of Australia, which will tell the story of the space-related activities at the Woomera Rocket Range, located in the northern part of South Australia. Next door, the South Australian Museum will be presenting a display about the life of South-Australian-born astronaut Dr Andrew SW Thomas, together with 'Our Place in Space', an exhibition of Hubble Space Telescope-inspired artwork from the Space Telescope Science Institute. These exhibitions all form part of the congress' education, outreach and cultural programme. Further details are available at: www.slsa.sa.gov.au/site/page.cfm and www.samuseum.sa .gov.au/

▲ The historic dish from Honeysuckle Creek tracking station that received the television signals of Armstrong's first steps on the Moon, now a heritage monument at CDSCC.

Located 35 km southwest of Canberra, the Canberra Deep Space Communication Complex is only accessible by car, a 45-minute drive through scenic forest, farmland and a nature reserve. Have lunch at the Moon Rock Café and make a day of your visit by venturing on from Tidbinbilla to the sites of the former Honeysuckle Creek and Orroral Valley stations (now both included on the Heritage Register of the Australian Capital Territory). Although little remains at these sites now but concrete footings, both have some interpretive signage outlining their NASA histories. For information on visiting Tidbinbilla go to:www.cdscc.nasa.gov

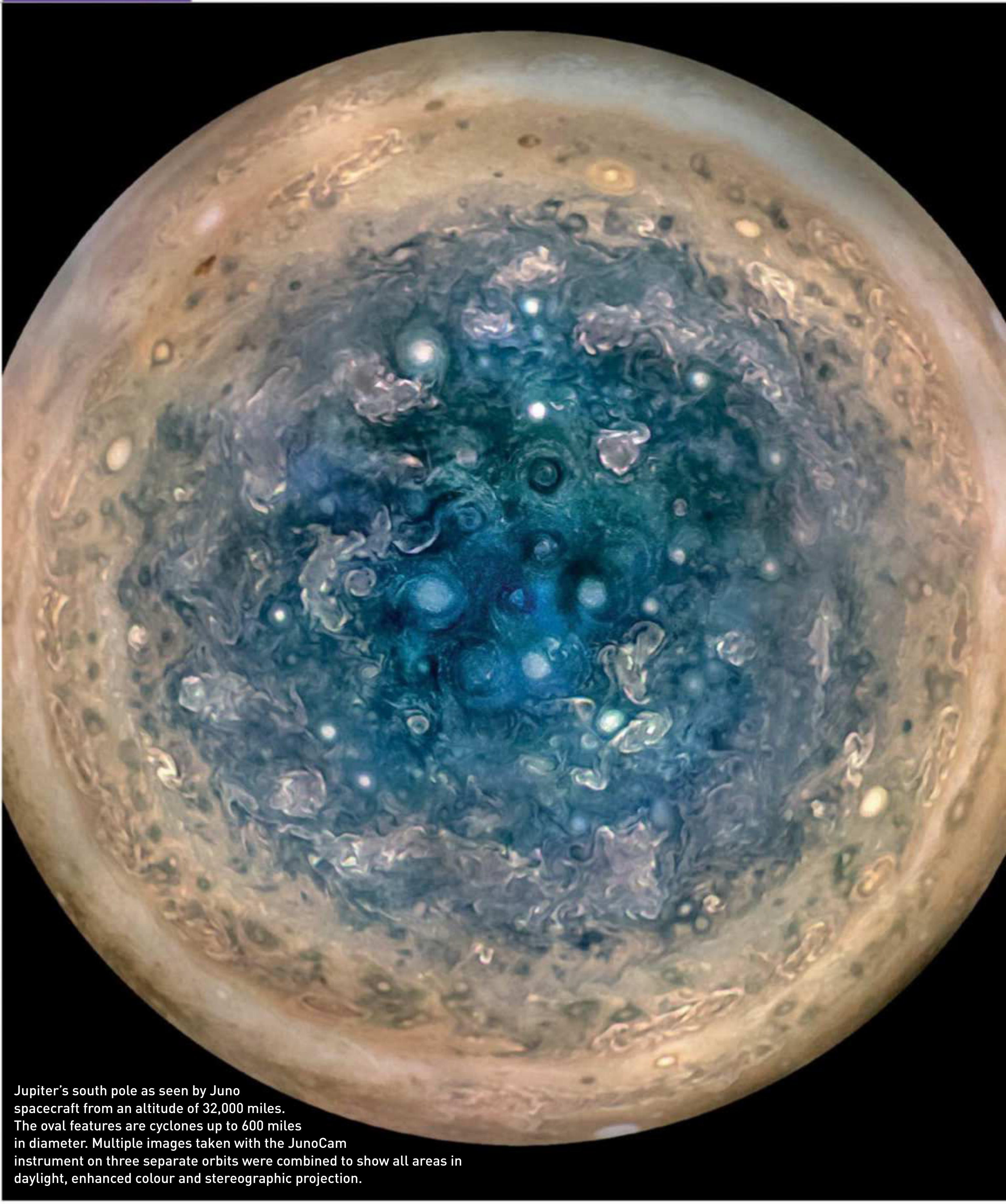
For the adventurous with plenty of time, a road trip travelling north from Perth could take in ESA's Deep Space Station at New Norcia (140 km from Perth), the Western Australia Space Centre (a commercial satellite tracking facility) and NASA's Mobile Laser Observatory, both located at Dongara, about 400 km from Perth. None of these sites, however, are open to visitors without prior arrangement.

Travelling even further afield, the Carnarvon Space and Technology Museum, located near the regional hub of Carnarvon, 900 km from Perth, can be found on the now-decommissioned site of Australia's first satellite Earth station (established in 1966). This privately-run museum contains a variety of artefacts from the former satellite station and the now-demolished NASA tracking station nearby. Further information on visiting this museum can be found at: www.carnarvonmuseum.org.au ■

Australia's national capital region was the home of NASA's second generation of tracking stations

About the author

Kerrie Dougherty is an independent curator and space historian with more than 30 years' experience working in museums. She is a recognised authority on Australian space history and has been involved in some capacity with almost every space site mentioned in this article.



Jupiter's south pole as seen by Juno spacecraft from an altitude of 32,000 miles. The oval features are cyclones up to 600 miles in diameter. Multiple images taken with the JunoCam instrument on three separate orbits were combined to show all areas in daylight, enhanced colour and stereographic projection.

Space for art

a universe of inspiration

ROOM's 'Space for Art' column by astronaut Nicole Stott is dedicated to the inspiration that comes from the interaction between space and art. In this issue she casts an inspirational eye over the wonderful imagery that is being returned from Jupiter by NASA's Juno probe.

Nicole Stott
Artist, Astronaut and SciArt Advocate

Wow! I don't know about you but I have to admit that "Wow" is the word that came to mind when I saw this image of Jupiter when it was released by NASA on 25 May 2017. Just, Wow!

After that came the reality check of how incredible this picture of Jupiter is on so many levels. Everything from how cool it is that we can design and build and launch a spacecraft that travelled hundreds of millions of miles for five years to arrive at a precise location in our Solar System; that this spacecraft is now in a polar orbit of Jupiter and is close enough every 53 days to collect scientific data with its eight science instruments and images with the public outreach camera called JunoCam; and that while it's still out there orbiting Jupiter we can receive all these wonderful data and images back here on Earth!

Images like the view of Jupiter's south pole. As someone that is continually amazed by the beautiful intersection between art and science, this picture presents the art of our universe in a simply stunning, mesmerizing and mind boggling way!

I think we'd all agree that pictures of Jupiter have never disappointed. I'm pretty sure we all have vivid impressions of the Great Red Spot and the ribbons of swirling colours that seem to blanket the giant planet, but this one new image has given us a whole new perspective on the planet. A translucent and almost crystalline looking view of the south pole.

This new view of a planet in our Solar System is such a wonderful example of the art of our universe - a view of nature that continues to surprise us with its beauty and complexity. This is a beauty that helps our brains wrap around and perhaps make some kind of connection with these far-off places, whilst also helping us better understand them from a scientific perspective.

The wonders and mystery of Jupiter have long inspired many to creatively and artistically express their impressions of the planet. I've had the pleasure of getting to know the space

This one new image has given us a whole new perspective on the planet

NASA/JPL-Caltech/SwRI/MSSS/Betsy Asher Hall/Gervasio Robles

▼ 'The Ancient Dance of Europa and Jupiter' (60" x 48" acrylic on canvas) by Lucy West and (right) her painting inspired by the Juno Mission - 'Intrepid Explorer: New Understandings' (10"x10" acrylic on wood panel).

▲ JPL Scientist Glenn Orton in mission control.

> We need to enthusiastically acknowledge the JunoCam camera that is providing us with these other-worldly, gorgeous views of the surface of the planet

artist members of the International Association of Astronomical Artists (IAAA), who have created some of the most beautiful art of our universe - and while some of the art might be fantastical, they all appreciate the importance of incorporating science in their art. A couple of the Jupiter paintings that have stood out to me recently are by the amazingly talented artist Lucy West (http://lucyweststudios.com).

While the primary mission of Juno is the science that will allow us to better understand the interior structure of Jupiter that we've never seen before, we need to enthusiastically acknowledge the JunoCam camera that is providing us with these other-worldly, gorgeous views of the surface of the planet. We should be thankful that as human beings we know that what we can see with our eyes and feel with our hearts will always help us better understand with our brains.

I asked JPL senior research scientist Glenn Orton if he could only share one thing about JunoCam what would it be? His response very simply was that "it is everybody's camera". While this is a simple answer, there is of course a whole lot more behind it.

Glenn told me that JunoCam was purposefully designed to allow the public to actively participate in the mission. As part of the JunoCam community, anyone can help decide what points of interest the JunoCam will photograph, engage in a discussion about these points of interest, upload your own telescopic images and data of Jupiter to help plan the mission.

Especially exciting to me and many others is that you can have access to all of the imagery collected and process these images in your own creative way. JunoCam allows you to help plan and process the imagery, and the JunoCam team is relying on your help to carry out the scientific mission and operation of the camera.

Citizen members of the JunoCam team have participated in some pretty amazing ways - beautifully blending the artistic with the scientific. Some of the most stunning images we are seeing from the Juno mission are being processed by the citizen scientists - including the inspirational south pole image for this article.

The raw images from the JunoCam are being colour enhanced and processed to showcase some of the more unusual features of Jupiter's surface; there has been collaborative scientific analysis of what's being seen and there has even been purely artistic processing of the images to generate art that's just creative and inspired by the natural beauty that is Jupiter - some of its beauty that has never been seen before.

Exploration missions like Juno are helping us become better acquainted with the planets in our solar system. As human beings though, what we learn about Jupiter and the other planets we share our solar system with ultimately comes back to a better understanding of our own place in it and how we all fit together.

We send our spacecraft ahead, travelling for many years to these distant places so we can see

▶ Citizen scientist Eric Jorgensen created this Jovian artwork with a JunoCam image taken when the spacecraft was at an altitude of 11,100 miles (17,800 km) above Jupiter's cloudtops on 11 December 2016.

and understand what's out there. We separate ourselves in a way that provides us with a closer view of these other planets but, perhaps more importantly, we are provided with another amazing vantage point for better understanding our own home planet Earth. We are all Earthlings!

In all that we see and explore in our universe we will by our nature relate it back to ourselves and Earth. To see Jupiter more closely helps us also see Earth more closely too.

Juno's flight depended on some assistance from Earth - a gravity assist from Earth to boost it with the additional velocity necessary to take it on its journey to Jupiter. During this pass of Earth, Juno also had the opportunity to test its instruments designed for close planetary encounters before travelling all the way to Jupiter to find if they would work or not. An awesome bonus from this path are pictures of Earth from a spacecraft on its way to Jupiter.

Such images from Juno remind us that we are always learning more about ourselves when we explore what surrounds us. These pictures represent both all of humanity and the farthest reaches of where human beings have actually travelled. The famous 'Earthrise' picture was the first time we saw this view of our home planet, of ourselves, from deep space. In the words of Apollo 8 astronaut Bill Anders, "We came all this way to explore the Moon, and the most important thing is that we discovered the Earth."

There is still so much more to come from Juno and I eagerly await the results of this summer's encounter when Juno will fly directly over that Great Red Spot. I can't wait to see the artistic and scientific expression that will come from that encounter! ■

◄ A colourful, graphically embellished interpretation of Jupiter's south pole by citizen scientist Michael Ranger.

JunoCam was purposefully designed to allow the public to actively participate in the mission

For more information about how to become part of the JunoCam community - www.missionjuno.swri.edu/junocam/

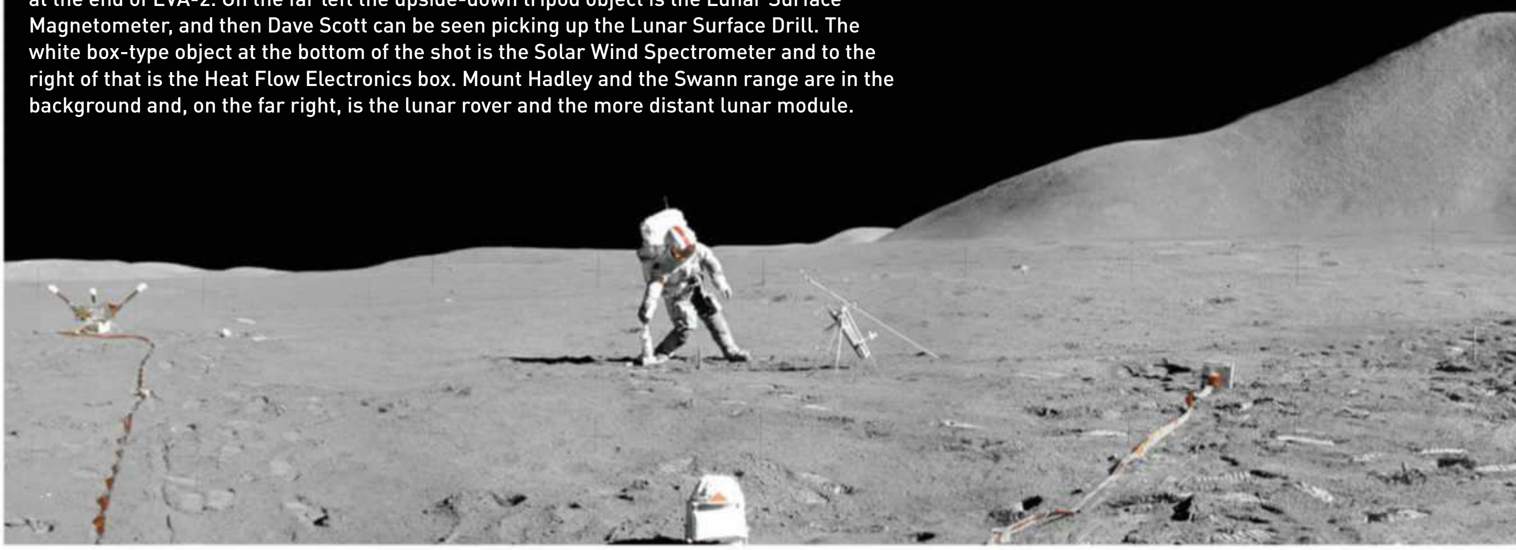
Acknowledgements

My sincere thanks to the Juno Mission team for JunoCam, for inviting our participation and for continuing to share the wonders of Jupiter and Earth and our place amongst the beautiful universal art that surrounds us. Also, special thanks to DC Agle at the Jet Propulsion Laboratory (JPL)/Caltech who, in response to my out-of-nowhere weekend request, introduced me to JPL senior research scientist Glenn Orton; and to Glenn, who I know could share all the amazing Juno scientific findings with me but who joyfully took the time to chat with me about the wonderful public outreach and engagement and excitement that's happening through JunoCam.

◄ The JunoCam caught this image of Earth during the 9 October 2013 gravity-assist flyby on its way to Jupiter.

◄ 'Earthrise' over the lunar horizon was taken by the Apollo 8 crew (December 1968), showing Earth for the first time as it appears from deep space.

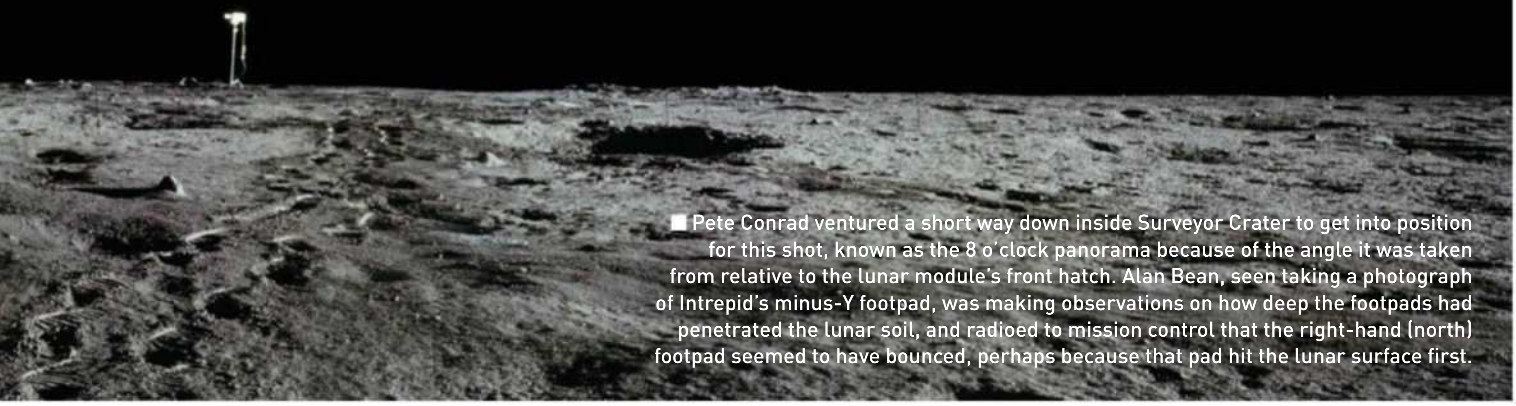
Panoramas from the



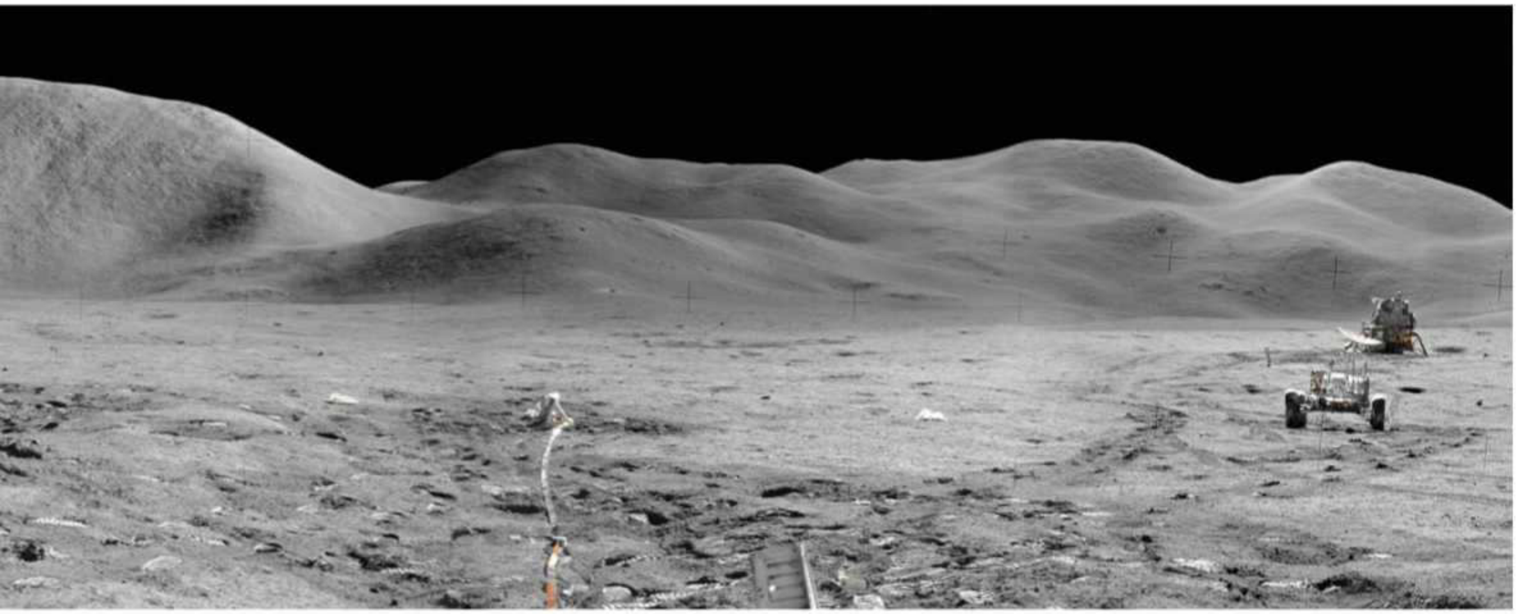
Jim Irwin, Apollo 15 lunar module pilot, captured this all encompassing panorama at the end of EVA-2. On the far left the upside-down tripod object is the Lunar Surface Magnetometer, and then Dave Scott can be seen picking up the Lunar Surface Drill. The white box-type object at the bottom of the shot is the Solar Wind Spectrometer and to the right of that is the Heat Flow Electronics box. Mount Hadley and the Swann range are in the background and, on the far right, is the lunar rover and the more distant lunar module.

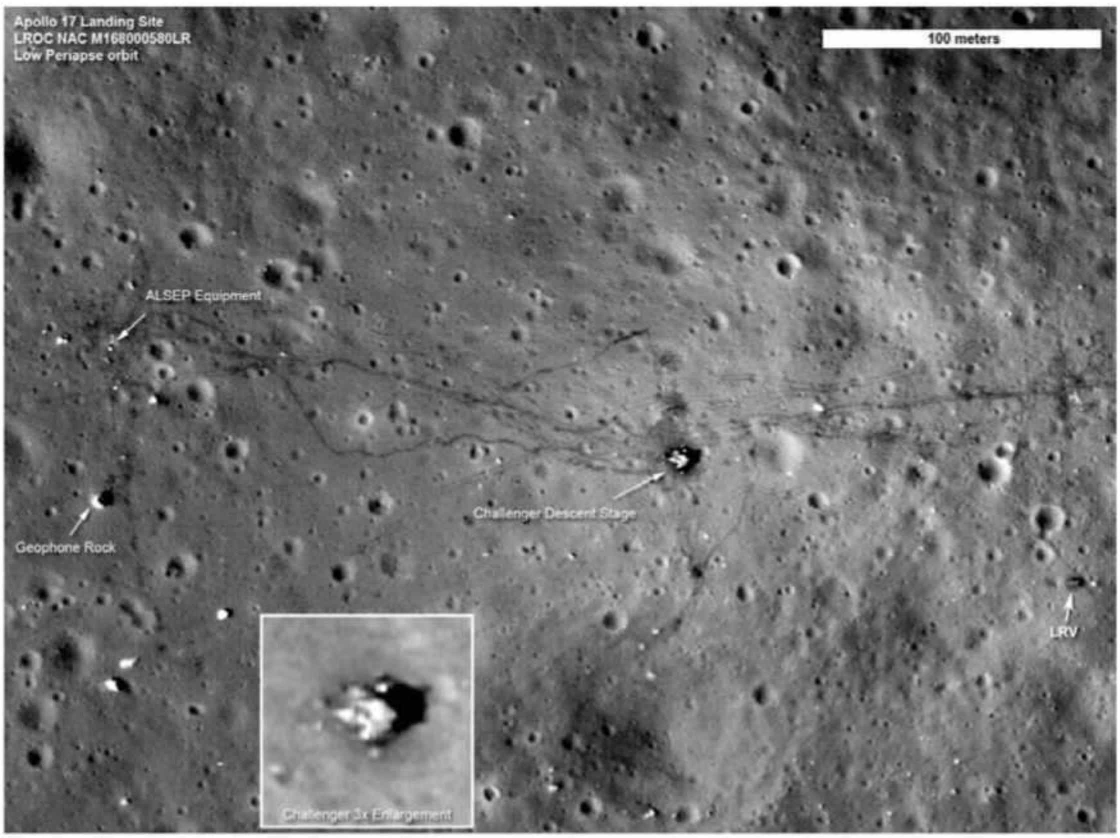
surface of the Moon

The first Apollo moonwalk in July 1969 was watched by millions of people all over the world and became a great moment in humankind's history. Five more successful landing missions followed Apollo 11 and each successive soacecraft touched down amongst more challenging terrain and for a longer duration. Thousands of high quality photographs were returned showing stunning scenery from huge craters, valleys and rilles to vast mountain ranges. Many of the photographs taken were part of panoramic sequences where the astronaut turned on the spot in a 360 degree circle whilst capturing frames. These images would later be printed out and assembled to form complete panoramic mosaics. Designer Mike Constantine has used digital technology to seamlessly blend between 15 and 25 separate frames to produce a collection of high resolution panoramas. The resulting images - just released in a new large format book and some of which are reproduced here - are beautiful, high-quality vistas that offer the viewer an astronaut's eye-view of the lunar surface.



■ Pete Conrad ventured a short way down inside Surveyor Crater to get into position for this shot, known as the 8 o'clock panorama because of the angle it was taken from relative to the lunar module's front hatch. Alan Bean, seen taking a photograph of Intrepid's minus-Y footpad, was making observations on how deep the footpads had penetrated the lunar soil, and radioed to mission control that the right-hand (north) footpad seemed to have bounced, perhaps because that pad hit the lunar surface first.





◀ Some 37 years after Apollo 17, NASA's Lunar Reconnaissance Orbiter overflew the landing site at an altitude of 50 km and captured photographs at a resolution of 50 cm per pixel. The resulting image clearly shows the LM, the rover and its tracks.

This Apollo 15 EVA-2 panorama gives a great view of the immediate landing site, with the Minus Z strut of the lunar module inside a small crater, giving a pronounced tilt and almost causing the engine bell to touch the lunar surface. Barely visible in the far distance on the right, Dave Scott is standing in front of the lunar rover adjusting the high-gain antenna to point directly at Earth.

▲ An evocative black & white panorama showing what a diverse and geologically interesting location was chosen for Apollo 15. Dave Scott can be seen on the slope of Mount Hadley measuring the size of rocks whilst the lunar rover, sitting at the bottom of the slope, has its high gain antenna pointing directly at Earth. The right side of this panorama is dominated by the breathtaking Hadley Rille, as it meanders across the Hadley Plain.

◀ The book cover of 'Apollo: The Panoramas' - www.moonpans.com

Mark Williamson
Space Technology Consultant

Book reviews

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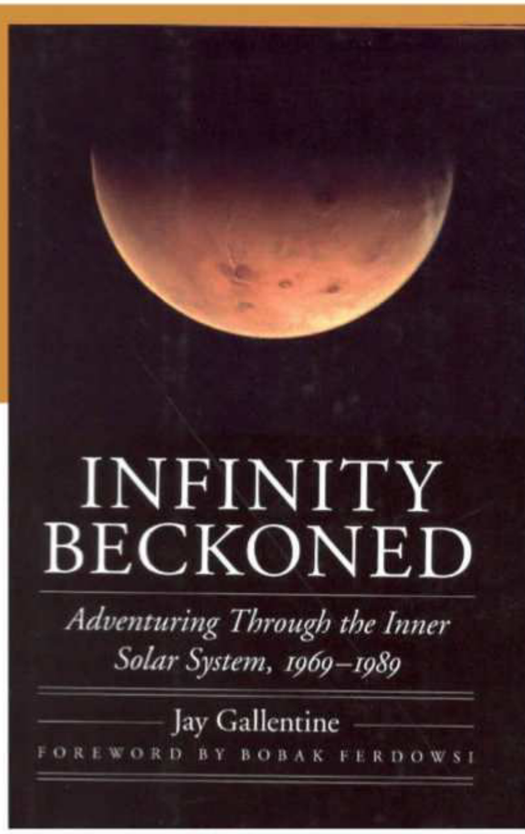
Infinity Beckoned: Adventuring Through the Inner Solar System, 1969-1989

Jay Gallentine

University of Nebraska Press, 2016, 474pp, hardback

£28.50,

ISBN 978-0-8032-3446-8



Since the beginning of the Space Age, space history books have gone through a sort of evolution: the early ones described the technology and the missions; later, more professional texts analysed political motives in a Cold War context; and then, in search of a different angle, authors began to concentrate on the personalities. This book is very much in the latter category; that's not to imply that it ignores the technology and the politics, but people are clearly identified as the driving characters in this story.

In what the fly-leaf describes as an 'irreverent and engaging style', the author tells the story of some of the Russian and American space science missions of the 1970s and 1980s through the eyes of those responsible. The book is based on dozens of interviews and other personal communications and, though somewhat sparsely illustrated with black-and-white photos, has a useful index.

The writing style is one in which American authors, in particular, seem to excel. Each chapter begins with a quote or statement that seeks to grab the audience, much as a fiction author might do. Such as: '"Get Frank Borman on the phone!" barked Chris Krafft. He didn't have time for this – another bothersome issue on his lengthy list. The order vortexed his secretary into a scramble.'

Whether or not you like this style will depend on how you take your history: strictly academic and scrupulously referenced or, like this, widely accessible and broadly entertaining.

In my opinion, there is room for both. This book will probably appeal to those who think they will find history boring, though it has to be said that the somewhat academic presentation of the volume militates against them opening it in the first place. To be clear, they should read it, because it's far from boring!

It might also appeal to those who have a fair grasp of the historical facts, as it will place those facts in a different perspective. Ultimately, with books written in this style, it requires the reader to trust the author to portray the true facts and not get carried away with the 'novelisation'. If pressed, I'd say it goes a little too far in the latter direction... but space history virgins are unlikely to agree.

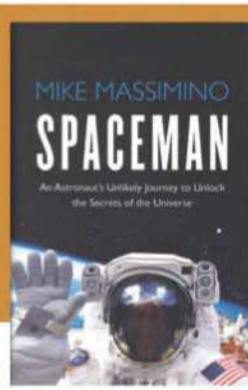
Spaceman: an astronaut's unlikely journey to unlock the secrets of the universe

Mike Massimino

Simon & Schuster, 2016, 316pp, hardback

£20.00,

ISBN 978-1-4711-4952-8



Mike Massimino is one of a few astronauts who have gravitated towards the media as part of an effort to explain space exploration and humanise space explorers in a way that almost never happened in the 20th century. He has appeared in TV documentaries, talk shows and popular science programmes in the US and UK and has even played himself in the science-based sitcom *The Big Bang Theory*. His 'day job' as a NASA astronaut lasted from 1996 to 2014 and he flew on two Shuttle missions to the Hubble Space Telescope (as reflected in the book's subtitle).

This is the latest of several books by former astronauts to bring space down to Earth and, as he is only one of 500 to have been in space, Massimino deserves a platform to explain his experiences. He takes us on a very personal journey from his impressions of the first Moon landing, through his career as an astronaut, to the time of his inevitable 'grounding'.

After his last flight, he had a chance to go back for a long-duration mission to the ISS but decided against it: "I calculated the date of my return as the week before Daniel would graduate from high school", he says. "I'd miss seeing Gabby off to college. I'd miss everything. It wasn't a hard decision to make".

Massimino's description of his emotions on his return to Earth is honest, engaging and, above all, understandable to 'mere humans'. "I was so grateful to be home alive", he admits. After seeing his family, he returned to the crew quarters and found himself alone for the first time in two weeks. "I had been around my crewmates in close quarters, staying focused on the mission, keeping my emotions in check", he says. "But there, alone in my room, I started thinking about the journey I had taken, the incredible beauty I had seen... and started to cry uncontrollably". Massimino's release of pent up emotions continued for 10 or 15 minutes as he "let it all out". "Then I pulled myself together", he says, "took a shower... put on my jeans, and re-entered the Earth". It might not be the 'right stuff' to which we've all become accustomed, but it's certainly not the wrong stuff either. Good one, Mike!

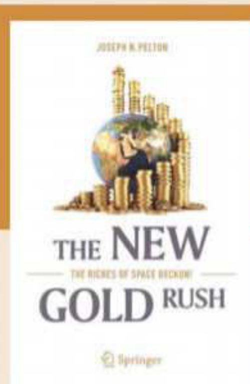
The New Gold Rush: the Riches of Space Beckon!

Joseph N Pelton

Springer, 2017, 237pp, softback

€20.79,

ISBN 978-3-319-39272-1



It has long been a mantra within the space community that there is money to be made in and from space. It has already been proved to some extent by the communications satellite revolution but writers have also predicted untold wealth generation from more ambitious applications such as solar power satellites and asteroid mining. This, effectively, is the message of this book which, according to its publicity, "captures the most exciting new advances in harnessing space as a global resource". With reference to a common legal phrase, it also "explores how all people can share in the bounties of the global commons of outer space".

The book seeks to explain why the gold rush of its title is different from what has gone before and what it might mean for "jobs, resources and more". It covers solar power and space mining – but also delves into nascent developments such as commercial space transport and in-orbit servicing.

The author also looks at space security and defence, and risk issues such as orbital debris and cosmic hazards. He then moves on to more long-term space proposals including space habitats and colonies before a concluding chapter 'Looking toward a more hopeful global society'.

The author is, by his nature, an optimist but he is realistic in warning of the problems faced in achieving the goals described. He also has his 'finger on the pulse' as far as world affairs are concerned and even steals a catchword from Donald Trump. The idea, he says, is "not to make the USA great again but to transform our global economy and its worldwide human services to make all Earthlings great". One of the key steps towards this, he adds, is ensuring "the peaceful use of outer space... for all humankind".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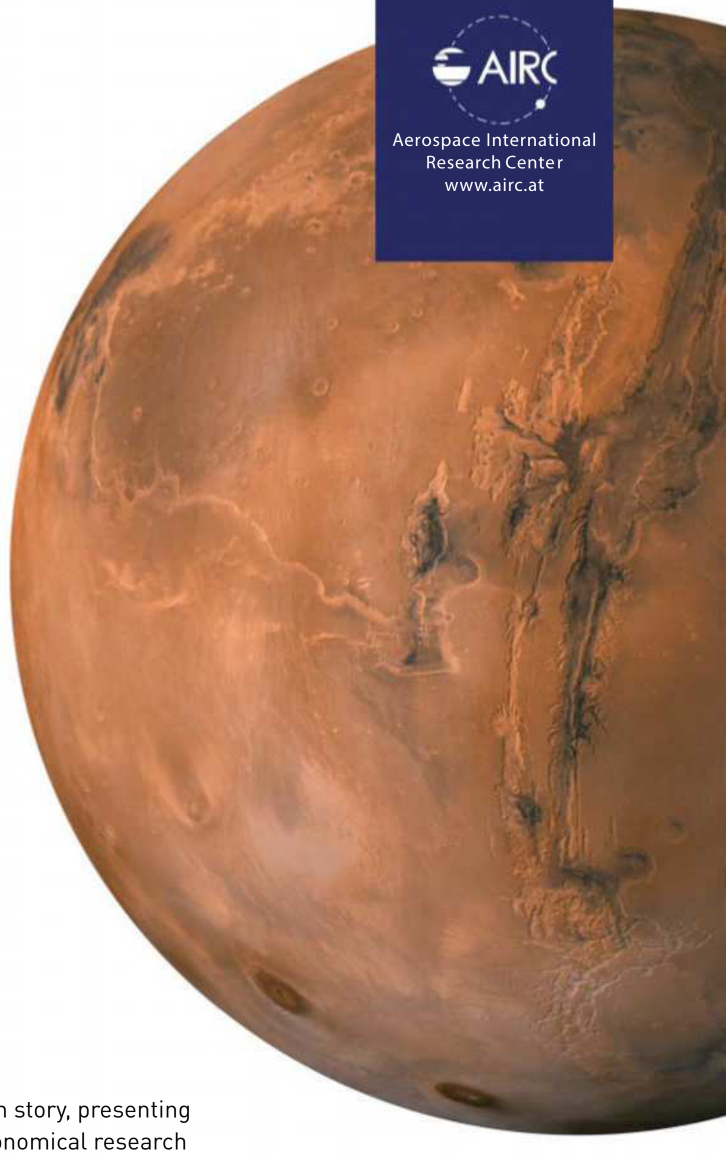

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