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Space law challenge

Future governance special, p. 28

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The road not taken - a political and commercial crossroads

So often the choices of today - whether relating to general politics or space policy - affect the future of tomorrow. All decisions have repercussions and if ever there was a moment in time when this was so, it is now.

In 2016, the electorates of the United States and the United Kingdom both made choices that are charting new pathways into unknown territory for their respective countries.

Whilst the national space policies of the Trump administration are being defined in detail commercial space presses ahead regardless. And for the UK - Europe's third biggest space player - the future has suddenly become harder to predict.

In his opinion piece 'Could Brexit blow a hole in UK's space ambitions?' (p. 98), Dr Mike Leggett suggests Britain leaving the EU might have unanticipated effects on the long-established cooperation of the UK and Europe in space.

The long lead times associated with developing space missions and technology often puts them at odds with the short-terminism of politics. And yet today we are witnessing a rapid expansion of technology and ambitions.

Regardless of the political landscape, the cosmic tide is being turned by a new wave of commercialism driven by the NewSpace generation of space companies and entrepreneurs.

Swift progress towards deployment of large satellite constellations ('Mega challenges for mega constellations' by Holger Krag, p. 16 and 'Urgent action needed to keep satellites safe in orbit' by Mark A. Skinner, p. 22) point to serious issues in the space environment - not just for the future but for now.

As Dylan Taylor writes in 'Space economics - industry trends and space investing' (p. 75), new business models and capital sources are also changing the fundamental economics of space.

We are, indeed, at a crossroads and 'The Road Not Taken', a poem by US writer Robert Frost, serves as an apt reminder. It ends with the words, 'Two roads diverged in a wood, and I took the one less travelled by, and that has made all the difference'.

Other articles in this issue also reflect this. In 'Spaceplane rationale - a new way of thinking' (p. 60) David Ashford argues that a choice made by NASA four decades ago probably led to a very different future for the global launcher industry.

As the world moves toward a new reality, we urgently need to establish viable and effective laws capable of addressing new and very different kinds of space applications and use.

ROOM is delighted to be at the vanguard of this movement, highlighting some of the many questions that the evolving political and space landscape is throwing to the fore.

Not the least of these is the search for a new system of space governance - a globally agreed system of laws and codes of conduct for the benefit of all humanity, not just those with the power and might to muscle their way to the front.

On the face of it the subject is dry and meticulous but outdated legal regimes can no longer be ignored. Nowhere is change and adaptation needed more than in the realm of space law and governance.

The articles in our special Space Security report (p. 28) are all based on a new study contributed to by more than 80 lawyers and space professionals from around the world.

Important choices and decisions lie ahead, not only for our national and global politicians but also for those at the heart of the international space community.

In the words of Frost, we once again approach a crossroads of choices. Does humanity take the well-trodden path of least resistance or do we head intelligently and wisely into a brave new world of cooperation and togetherness - and go daringly and boldly into the future?

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

Does humanity take the well-trodden path or do we head intelligently and wisely into a brave new world of cooperation and togetherness?

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GLOBAL SPACE GOVERNANCE & SUSTAINABLE DEVELOPMENT GOALS

The 2017 Manfred Lachs Conference (MLC17) will be hosted by McGill University's Institute of Air and Space Law (IASL) in Montreal, Quebec, Canada, from 4-6 May 2017.

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Cloudless Europe in hi-definition

This spectacular Sentinel-2 cloudless layer image of Europe combines over eight trillion pixels collected during differing weather conditions between May and September 2016, merging them into a sunny homogeneous mosaic, free from atmospheric impacts.

To create the image EOX IT Services GmbH - an open source software oriented company based in Austria, Vienna, that works mainly on ESA and EU projects in the Earth observation (EO) field - crunched almost 30 terabytes of Sentinel-2 data using its own software developed by EOX IT specialist Joachim Ungar and co-founder Stephan Meißl.

Sentinel-2 is an EO mission developed by ESA as part of the EU's Copernicus programme to perform terrestrial observations in support of services such as forest monitoring, detecting land cover changes and natural disaster management.

The second of two identical satellites, Sentinel-2B, was launched on 7 March 2017 by a Vega rocket, following Sentinel-2A which was launched in June 2015.

The satellites work in complementary orbits, each carrying a single multi-spectral instrument (MSI) with 13 spectral channels in the visible/near infrared (VNIR) and short wave infrared (SWIR) spectral ranges.

"Extracting cloudless pixels from the Sentinel-2 archive and rendering natural looking colours is just an example of many possible use cases," says Joachim Ungar.

"The main area of EOX activities concerns the development and advancement of e-Environment and geo-spatial information infrastructures with special emphasis on satellite EO systems and next generation applications."

Sky-fi dawn of the space Internet era

In the near future billions of people across the globe could benefit from broadband internet access in remote areas provided by balloons, drones and satellites. After investigating the possibilities, risks and opportunities of these technologies members of the Space Generation Advisory Council (SGAC), a group of students and young professionals in the space sector, have made four recommendations to help spread the 'sky-fi' concept.

László Bacsárdi
Head of Institute of Informatics and Economics, University of Sopron, Hungary

The internet plays an essential role in everyday life - from communication, broadcasting and navigation to real-time information about any topic and, of course, virtually all business and government operations now depend on it. In the developed world, people can hardly imagine a daily routine without the Internet but, despite the benefits it delivers to 21st century life, only 39% of the world's population has internet access - meaning some four billion people continue to live their lives without it.

Internet access could greatly improve the lives of these four billion people, so many companies are now seeking to provide internet services to the developing world.

Today, the primary technology for providing internet access is based on fibre optical communication. Physical cables are laid worldwide to connect continents and to provide broadband access. The three main exceptions are local Wi-Fi networks, mobile broadband and satellite communications.

In all three cases, internet connections are supplied over a small region by a local broadcasting router, gateway or antenna, which is eventually connected to the global network via fibre optic cables.

However, such architecture is not feasible in many developing countries, where the requirement of building new infrastructure is a significant barrier to internet access. Often this is compounded by the sheer expense of connecting populations distributed over large areas where the adjacent infrastructure - such as electricity - might also be absent or of insufficient reliability.

The idea of providing global internet coverage to disconnected populations has been widely discussed by both academia and commercial companies. In 2013, a student team at the International Space University (ISU) suggested providing sustainable and affordable internet access for the Brazilian Amazon region using microsatellites.

More recently, several companies have begun to experiment with their own ideas on how to introduce global internet coverage, including the balloons of Google's Project Loon, the drones of Facebook, and the satellites of SpaceX and OneWeb.

The most popular technology for space communication is radio frequency (RF) communication, used by Project Loon, SpaceX and OneWeb. A new, emerging technology is laser communication, used by Facebook's drones.

These new approaches to providing internet connections from the sky or space - dubbed 'sky-fi' - bring with them both technical and political challenges, the latter including adapting laws and regulations among countries. Right now, very little regulation exists to govern this new approach.

Up in the air

Google's Project Loon is designed to provide worldwide internet coverage using a fleet of stratospheric balloons. Each balloon will float in the stratosphere and provide internet access to the population in a large area below it. The balloons are mobile, and will drift with the stratospheric winds across the globe. Stratospheric winds, their velocities and directions, which alter with altitude, are well-studied and well-known. It is possible to control the balloon's location simply by varying its altitude. A control centre would monitor balloon locations, ensuring that damaged balloons are replaced, and that no area is left without coverage.

In June 2013, the first balloon tests took place in New Zealand. Thirty balloons were launched to provide internet access to a test group. Currently, tests are conducted in open areas, with the aim of providing uninterrupted connectivity for distinct regions, before operating on a global scale. According to current plans, an operational system could begin later in 2017.

From the sky

Facebook's proposed drones would be powered electrically, using solar panels to remain aloft for long periods of time. This concept removes the need for landing, refuelling or the logistics needed to provide fuel to all the aircraft, at least during the proposed 90-day flight time. Drones can fly close enough to the ground to maximize signal strength but high enough so that wind and physical obstacles will not compromise mission endurance. Drones can be precisely controlled and, unlike satellites, are reusable in the sense that they can land to be upgraded or fixed if needed.

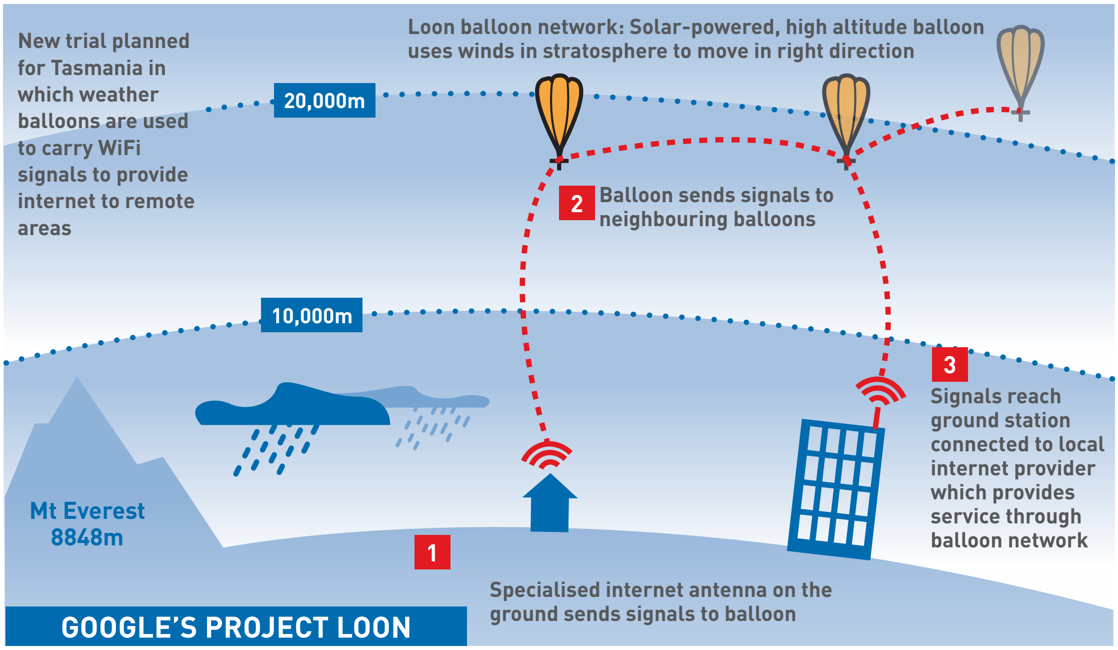
The first test flight of Facebook's unmanned drone named Aquila was completed on 28 June

Only 39% of the world's population has Internet access - meaning four billion people live their lives without it

Google

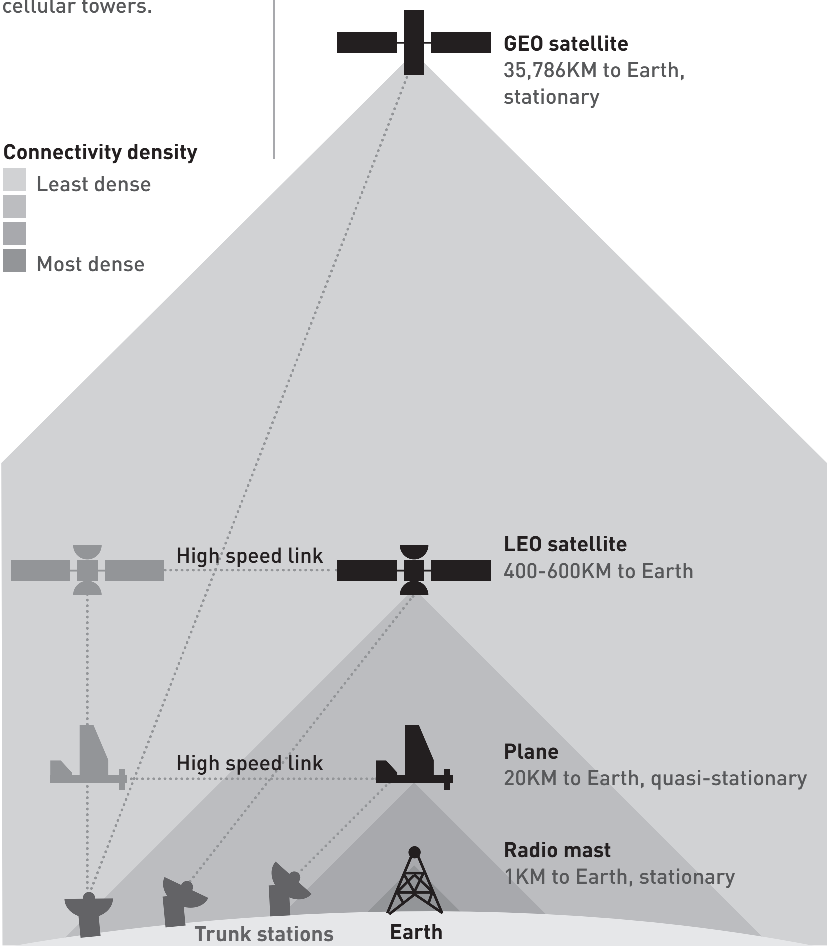
◄ Photo from the Google Project Loon launch event in Christchurch, New Zealand, in 2016.

▶ How Google's Project Loon will work.



Several companies have begun to experiment with their own ideas on how to introduce global internet coverage

▼ A combination of platforms at different altitudes using GEO and LEO satellites, planes and cellular towers.



2016. However, an unspecified 'structural failure' occurred at the end of the 96 minute flight. This spring the case was still under investigation by the US National Transportation Safety Board.

The use of drones may work well for densely populated areas but would become expensive for more sparse regions. A drone has a small footprint, so many drones would be needed to cover large areas and, without enough customers to underwrite the machines, it would become prohibitively expensive to provide the service.

As a complementary solution to this problem, Facebook proposes using satellites to cover low density areas. The satellites would naturally have lower signal strength and smaller bandwidth but still provide the requisite coverage. To complement the hardware, Facebook launched internet.org - an initiative to create an internet portal that will be more efficient and require less data, allowing connectivity even under narrow bandwidth conditions.

Recently, Facebook also partnered with Paris-based Eutelsat to lease the Ka transponder on the AMOS-6 satellite to link disconnected African regions to the internet but unfortunately, AMOS-6 was destroyed on the launch pad when its launch vehicle, the SpaceX Falcon 9, exploded on 1 September 2016.

Orbiting Earth

Both SpaceX and Washington DC-based OneWeb are working towards satellite-based solutions, though with some difference in the detailed approach.

Using geostationary satellites to provide truly global internet access is problematic due to both technical and physical challenges. Latency is significant and there would be no coverage in polar regions. At 36,000 km altitude, it takes the information about 200 milliseconds to be transmitted from the user to the server, which can accumulate to almost 500 milliseconds of delay between the request and the response.

This issue is a physical limitation and cannot be solved technologically and so both companies have decided to use low Earth orbit (LEO) satellites, which offer much lower latency and stronger signals.

However, they move fast with respect to the ground and one specific satellite is only be visible to an observer for a limited time before it sets over the horizon. To provide continuous coverage, a constellation of satellites is needed, the number varying depending on the system design.

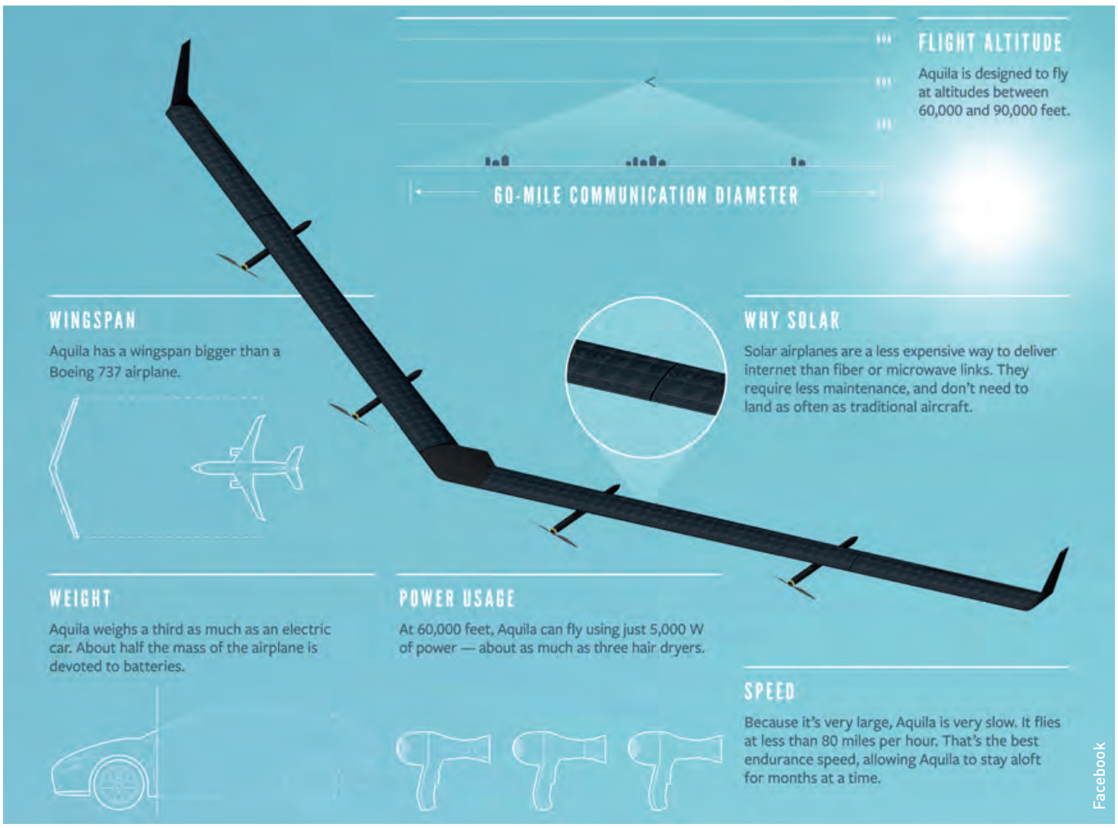
Launching such a large constellation is expensive and raises additional issues such as interference, controlling the constellation, avoiding debris and avoiding becoming debris, as well as maintaining the constellation and replacing or replenishing satellites.

In November 2016, SpaceX requested approval from the US government for a constellation of 4425 satellites to orbit in LEO between 1,150 and 1,325 km. OneWeb plans to use a constellation of 648 LEO satellites, of which the first 10 are planned for launch in late 2017.

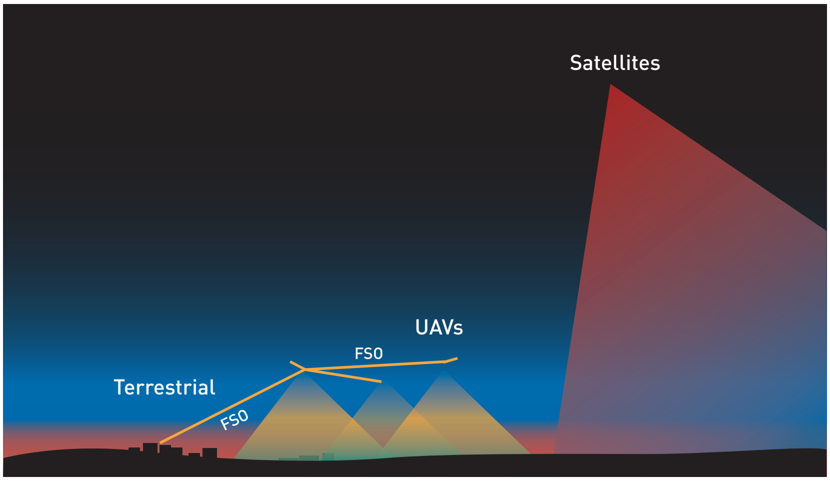
Technique comparison

Balloons are an affordable option. They can cover a wide area at a lower cost than drones and be made available with a shorter lead-time than satellites. Balloons can be deployed in a variety of locations, although they do require fortuitous wind conditions to fly over a desired area. Less infrastructure would be required than for drones, without the need for airports and maintenance facilities. Wind can be a limiting factor in the way that balloons fly at certain latitudes. Google is forging ahead with its own balloon concept called Project Loon, which would use fleet control algorithms to fly across some countries and latitudes.

Drones have high bandwidth capacity, are also highly maintainable and offer the possibility for upgrade. Perhaps one of the greatest potential uses of drone technology is for post-disaster internet, where they can be launched quickly and then directed to fly over affected areas at short notice. The biggest drawback is the low altitude giving restricted coverage area, and it is the most



◀ Facebook's Aquila solar powered aircraft.



▲ Platforms at different altitudes.

expensive option by unit coverage because of ongoing operational costs. Operational efficiencies that might be gained with the use of artificial intelligence are still in the future.

LEO satellite constellations are the truly global option. Depending on the type of constellation in place, they can cover the whole of planet Earth continuously. Satellites offer the added benefit of shorter delay times (as the satellite-to-satellite and satellite-to-ground data transfer paths are straight and have few nodes). Flight paths are also topologically distinguishable, making it easier to predict locations and then calculate efficient data paths. However, bandwidths would be smaller,

Without understanding the market need, there is a high risk of failure

due to the distance of the spacecraft from the user and the capital costs of this system would be the highest of the options, due to spacecraft manufacturing and launch costs.

Voice of youth

During the annual Space Generation Congress (SGC) in Israel in 2015 - organised by the UN-established SGAC every year for students and young professionals between age of 18 and 35 - students and young professionals representing 14 countries participated in the Space Internet Working Group which investigated the possibilities, risks and opportunities of using satellites, drones and high-altitude balloons to provide widespread internet access.

The Working Group, supported by NASA Space Communication and Navigation Office, focused on one of the barriers for worldwide connectivity - possible solutions to the lack of economic viability of providing internet access using land infrastructure. As a result, the working group participants proposed several recommendations, which take into account the numerous challenges - ranging from acquiring regulatory approval to technical and practical limitations, such as the potential for damage to property and issues related to orbital debris - that come with developing air and space-based internet access.

The key recommendations are:

Conduct market studies to illustrate demand

- A number of companies are trying to push forward with their plans for wider and cheaper internet coverage in the disconnected parts of the world but one significant issue identified was whether or not these remote or disconnected regions can even afford internet.

- There are often more pressing humanitarian issues such as lack of clean water and electricity, and malnutrition. The question here is how such a system can cater for these markets when more basic needs are not being met. The first step towards understanding this problem would be to carry out market studies to identify what the potential take-

◀ OneWeb satellites will be mass produced using fewer components and lighter weight, making them easier to manufacture and cheaper to launch. They will include state-of-the-art onboard GPS sensors and on-board propulsion systems to help avoid orbital debris and for end of life disposal.

up rate and willingness to pay would be, were such systems to be in place. Without understanding the market need there is a high risk of failure for such endeavours.

Institute a phased approach

- Instead of building a full system with all development carried out in one chunk, it is recommended that any proposed system be scaled up slowly, with consideration for both the changing market conditions and any issues relating to the system in question, such as regulatory filing and property damages.
- Scaling up helps reduce the impact of failure by ensuring the system is delivered in incremental steps where each step has taken into account lessons learned from previous versions - similar to the iterative design process of programming. For example, the system could focus on one specific region before expanding to cover other areas.

Let governments serve as anchor tenants and expedite regulatory processes

- This will help ensure resolution of any legal hurdles while governments assist in the development of systems, especially in rural areas where distribution partners are hard to come by. Having local and regional governments assist and be part of the process can ensure smoother transition to commercial operations. Risks surrounding regulatory filings, market access and other fundamental barriers to entry can be mitigated with the support and assistance of the target markets' governments.

Provide future connectivity to Internet Service Providers to ensure commercial sustainability

- Once government service has been established and the reliability of the system has been confirmed, the service can be deployed to commercial internet service providers to diversify and improve revenue streams while catering for a wider population through increased service subscriptions. ■

About the author

Laszlo Bacsardi received his PhD in 2012 at the Budapest University of Technology and Economics, Hungary. He is Associate Professor and the Head of the Institute of Informatics and Economics at the University of Sopron, Hungary. He is Secretary General of the Hungarian Astronautical Society and joined SGAC in 2012. His research interests are in quantum computing, quantum communications and space communications.

Having local and regional governments assist and be part of the process can ensure smoother transition to commercial operations.

Space Generation Advisory Council

The Space Generation Advisory Council (SGAC) is an international non-profit, non-governmental organisation for students and young professionals between the ages of 18-35 with interest in the space sector. Its roots stem from UNI-SPACE III, where the international space community, in its Vienna Declaration, recognised the need to engage with the next generation of space leaders and provide the younger generation's input to space policy.

Since then, SGAC has grown to support students and young professionals, not only providing a medium for them to share their insights on space policy, but also enabling their professional development through volunteer opportunities, as well as scholarships which provide them an opportunity to meet global space leaders at different events.

Outputs are regularly presented at the United Nations Committee on the Peaceful Uses of Outer Space and shared with national space agencies and space industry leaders. Aside from organising global, regional and local space events, SGAC is pleased to work with *ROOM* which offers our members another forum in which to provide their insight and inputs on various space topics, from technical projects to regional perspectives.

Stephanie Wan & Ali Nasseri
SGAC Co-Chairs

▼ OneWeb says its system could provide access to health centres, schools, libraries and homes through a low cost user terminal, ensuring relief to communities in need, tools to drive education, access to knowledge, and opportunities for local businesses.

▲ An artistic interpretation of orbital tracks for satellites in a mega constellation by artist Zoe Squires (see p108).

Mega challenges for mega-constellations

Concerns about preserving the space environment, particularly in low Earth orbit have intensified with the growing interest in new satellite mega-constellations initiatives. Mega-constellations are one of the biggest challenges faced by the satellite communications industry today, calling for changes in manufacturing processes, assembly and testing methods, and a need to implement technologies to minimise the potential impact on the space environment. But there are concerns that these technologies may not be enough to alleviate a cascade of increased collisions and debris.

Holger Krag
ESA's Space Debris Office, ESA/ESOC, Darmstadt, Germany

For many today access to a fast, reliable internet service is an expected and perhaps essential part of everyday life. However, access to internet services is not as widespread as it might seem at first glance. About half of the world population, mostly in underdeveloped, remote or sparsely populated regions, have no access at all. In these regions, information and knowledge shared by web communication could greatly influence their development.

Constellation	OneWeb	Boeing	SpaceX	Samsung
Satellites	720	2960	4000+	4600
Altitude	1200 km	1200 km	1100 km	1400 km
Sat. Mass	150kg	> 100kg	390kg	< 200kg

◀ Current mega-constellation concepts for global web-access.

Providing global internet access from space appears to be a logical alternative to costly infrastructure on the ground. Today, internet broadband services are rendered through telecommunication providers using satellites in geostationary orbit but their significant data latency (the amount of time it takes to send information from one point to the next), limited bandwidth and channels and their requirement for significant transmission power make them unsuitable to serve a broader private community.

Several information technology and electronics companies have announced plans to provide such service via large constellations in low Earth orbit (LEO) by 2018-2020. The proposed concepts foresee spanning a global, leak-proof network of inter-linked small satellites, accessible at any time from a set of deployed ground terminals.

It is expected that this tailored solution for wide-spread low-latency (less than 50 milliseconds) broadband (10 terabytes per second) excess will challenge the classical space-based and ground-based communication market. The proposed concepts differ in their maturity levels and constellation concepts and the companies behind them are in some cases new players to spaceflight and space-based communication.

Space traffic debris

A significant disadvantage of the proposed concepts is the high numbers of active satellites required to operate within the constellation in order to provide seamless coverage from low altitudes. Concepts range from a few dozen satellites to several thousand in the size class around 100kg dry mass.

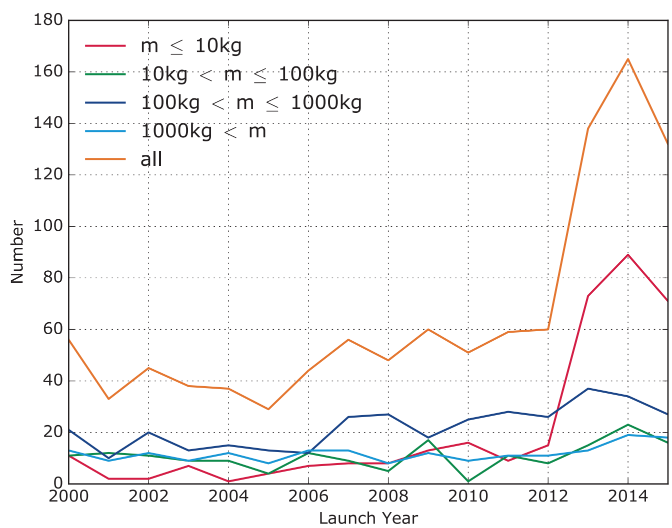
The sheer number of satellites revolutionises the way spaceflight is performed. On average, just one such constellation will have more operational satellites in space than all other spacefarers together (currently around 1100). With the operational lifetime of the satellites being limited to a few years, the constellation will have to be replenished regularly. This means that within a few decades the number of constellations satellites launched will be greater than the number of satellites ever launched by other spacefarers in the history of spaceflight (approximately 7,400).

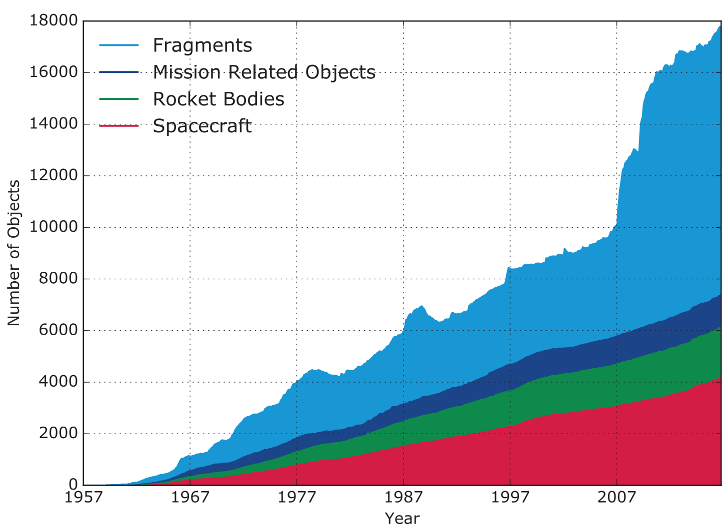
Satellites will have to be manufactured using mass production techniques common in the automotive industry to achieve unit prices of well

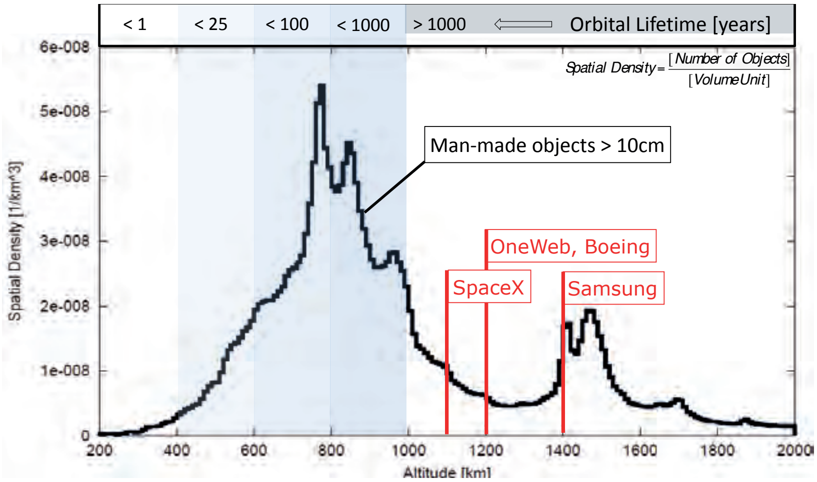
Within a few decades the number of constellation satellites launched will be greater than the number of satellites ever launched

▼ Left: Spacecraft numbers launched into LEO since 2000 per satellite mass class (ESA DISCOS database, re-entry vehicles excluded).

▼ Below: Evolution of the number of objects catalogued by the US Space Surveillance Network.







▲ Current altitude distribution of man-made objects greater than 10 cm (according to ESA's MASTER-2009 model), average orbital lifetime of an average satellite and operating altitudes of selected mega-constellation concepts.

below one million US dollars. The initialisation and replenishment will roughly double the number of launch events, which are currently around 70 per year. This is in addition to the general increase in space traffic in LEO mainly fuelled by small satellites and cubesats as well as nanosats, which grant cheaper access to space.

Even before these recent trends, space debris had already emerged as one of the major sources of risk for spaceflight. Since the first orbital launch

Proposed concepts foresee a global, leak-proof network of inter-linked small satellites, accessible at any time from deployed ground terminals

in 1957, the number of artificial objects in Earth orbit has been growing. The number of on-orbit objects tracked by the US Strategic Command (operators of the US Space Surveillance Network) shows faster growth compared to the number of operational satellites on-orbit.

This has led to a corresponding increase in the threat to active satellites from hypervelocity collisions, putting in jeopardy crucial services that benefit human society. Some future scenarios produced by computer models suggest that the space debris population has reached a tipping point such that collisions will increase in frequency even in the absence of new space traffic. Whilst such an outcome is not certain, there is growing pressure on space users to implement mitigation measures aimed at

▶ Current distribution of man-made objects tracked by the USSTRATCOM in LEO. In this artist impression the size of the objects is exaggerated as compared to Earth.

preventing the proliferation of space debris and enabling the sustainable use of space.

Space debris mitigation

In 2002 the Inter-Agency Space Debris Coordination Committee (IADC) drafted a set of guidelines for international space debris mitigation, aimed at limiting the generation of debris in the environment in the short-term, through measures typically related to spacecraft design and operation, and the growth of the debris population over the longer-term, by limiting time spent in the LEO region after the end of mission to 25 years.

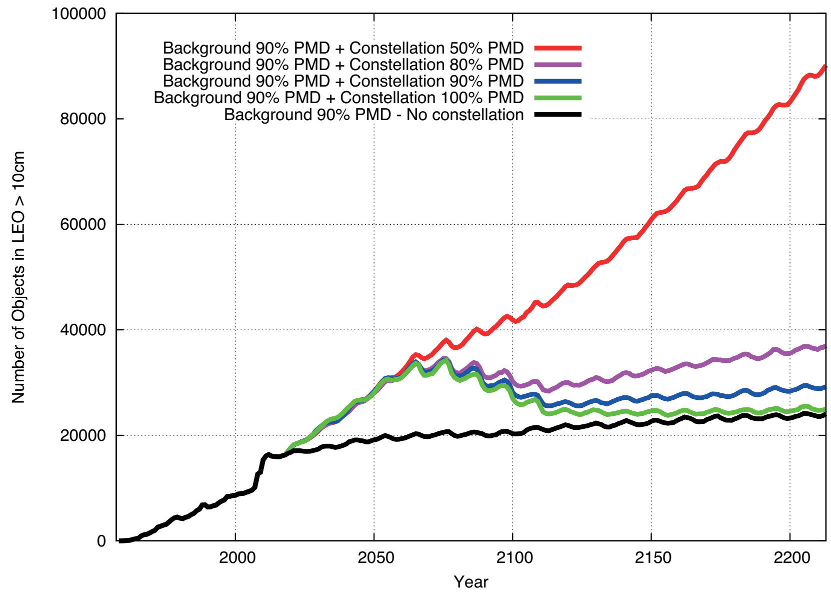
In view of the long-term mitigation guidelines, the orbital altitude selected by most of the constellations is a concern. While the remnant atmosphere in near Earth space automatically limits the orbital lifetime through the decelerating forces of atmospheric drag, this effect diminishes with increasing altitude.

Spacecraft above 600 km typically cannot rely on natural decay but have to actively reduce their orbital lifetime by manoeuvring to lower altitudes after the end of mission. Failing to do this has led to the current deteriorated environment in the 800-1000 km zone. The peak spatial density of man-made objects in this region is a result of the absence of the atmospheric cleansing effects in combination with frequent use.

The operating altitudes now selected by most of the mega-constellations correspond to quasi-eternal orbital lifetimes. They are not fail-safe in the sense that satellites have to rely on a technical function that actively lowers the orbital altitude by several hundreds of kilometres after the end of mission – and the success of this procedure cannot be guaranteed.

Analysing environmental effects

European Space Agency experts together with space debris specialists from UK, France, Germany and Italy, analysed the response of the orbital population to the introduction of a hypothetical large constellation. The constellation comprised 1080 satellites, each weighing 200 kg with a cross-section of one square metre and a five-year design life, distributed in 20 orbital planes at an altitude of 1100 km and an inclination of 85 degrees. It was assumed to be complete and operational for 50 years from 2021 to 2071. This constellation was taken to be indicative, but not an exact representation of envisaged systems, so that it would remain valid in view of changing designs and would avoid a focus on particular constellation proposals.



▲ Simulation results for the evolution of the population of objects greater than 10 cm with the background space traffic implementing mitigation measures (with 90 percent success) and the effect of a mega-constellation implementing mitigation measures at various success rates.

For the purposes of the simulations, the background (non-constellation) population consisted of all objects larger or equal to 10 cm in size, wholly residing in or crossing the LEO region on 1 January 2013, and derived from the ESA Meteoroid and Space Debris Terrestrial Environment (MASTER) model.

To study the effect of existing guidelines in view of the constellation satellite traffic and behaviour in isolation, in a first step, all other simulated objects were assumed to have a high post-mission disposal (PMD) success rate. A Monte Carlo (MC) approach (using repeated random sampling) was used to simulate the evolution of the object population over a period of 200 years from 1 January 2013 and under different post-mission disposal requirements.

Some future scenarios suggest the space debris population has reached a tipping point such that collisions will increase in frequency even in the absence of new space traffic

The results revealed that the current mitigation measures are suited to level-off the growth in the number of objects greater than 10 centimetres in the background space-traffic. Adding the constellation scenario to this, various phases could be distinguished. The first phase was a steep population increase, which extended from the launch of the first satellites of the constellation until these satellites started to re-enter due to post-mission disposal manoeuvres

The operating altitudes now selected by most of the mega-constellations correspond to quasi-eternal orbital lifetimes

(30 years after their launch in this scenario). In the short second phase, from 2051 to 2071, the satellite replacement rate and the re-entry rate were almost the same (differing only because 10 percent of the constellation satellites failed to meet the disposal requirement).

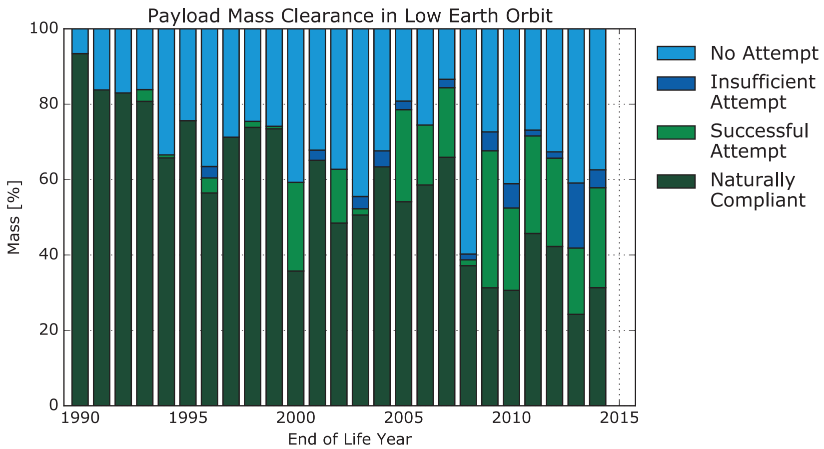
The third phase showed a steep population decrease, which started at the end of the constellation mission and ended when the last de-orbited satellite re-entered 25 years later and the final post-constellation phase showed a gradual population growth that depended only on the behaviour of the background population and on the effects caused by the constellation satellites that did not meet the disposal requirement.

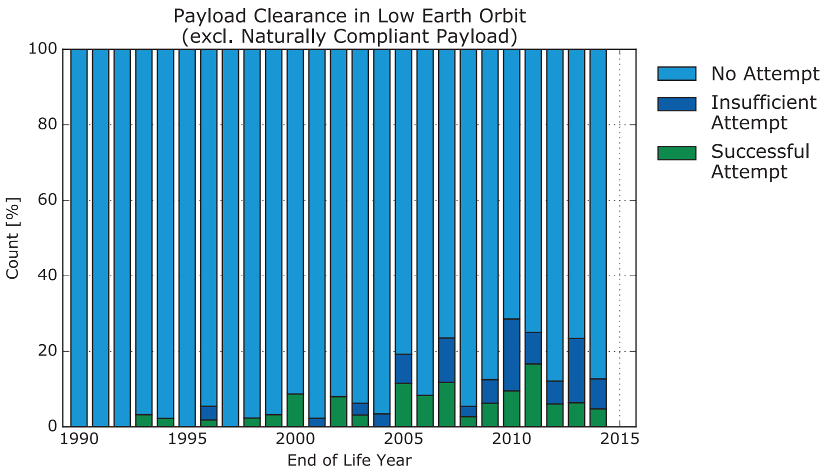
To analyse the effect on the distinct phases identified above and arising from different implementation levels by the constellation satellites of a 25-year PMD requirement, we compared the trends for PMD implementation levels of 50 percent, 80 percent, 90 percent and 100 percent. It was very apparent that the long-term evolution of the LEO population beyond this phase was greatly influenced by the extent of successful implementation of the PMD guidelines among the constellation satellites.

The lower the success rate, the higher the number of constellation satellites that were left in orbit. This accumulation of satellites, and their interaction with the background population, resulted in a detrimental evolution of the population e.g. a doubling of the population by 2071 and a five-fold increase by the end of the projection period for the 50 percent PMD implementation level.

The successful implementation of post-mission disposal by an average of more than 90 percent of the constellation was required for an invariant population in the long-term. If such invariant behaviour was to be guaranteed even for a scenario with more than one constellation, a success rate of 100 percent was needed.

▼ Currently observed practice in implementing post mission disposal for spacecraft in LEO (less than 2000 km) and historical trends (top: all spacecraft, bottom: spacecraft that require active disposal manoeuvres).





Post mission disposal

The analysis above raises the question of the success levels that can actually be expected to come with the mega-constellation - which is a difficult one to answer. A first indication could, however, be obtained from a review of the success rates observed in the recent past.

ESA experts regularly report on the global achievements in post mission disposal. This information is gathered from the automated analysis of surveillance data on LEO and geostationary (GEO) objects. About 114 satellites in LEO reach end of life per year. Since the beginning of the analysis efforts in 1990 the annual PMD success rate has wavered around a level of about 60 percent, which means that roughly 46 satellites get 'stranded' in space each year.

A closer look at the successful cases reveals that the clear majority never had to implement any post mission disposal, but the original mission orbit was low enough to ensure natural re-entry.

Of those satellites on higher orbit only a small fraction performed a de-orbiting attempt and only half of the attempts actually lowered the altitude sufficiently. In recent years there has been a weak trend towards implementing post mission disposal attempts that reached a success rate of only 20 percent.

Breaking down this analysis for satellites per mass class reveals that satellites of less than 10 kilograms (typically cubesats) obviously benefit from the low mass-to-area ratios and large satellites (greater than one tonne) benefit from the capability to perform manoeuvres and the fact that most of these missions occur in low altitude orbits (e.g. Cosmos-type Earth observation satellites).

However, small satellites of between 100 kg and 1000 kg, which are often equipped with propulsion systems, had a success rate of less than five percent for actively clearing higher orbits. It is a concern that the number of objects in this size class is expected to rise in view of the announced constellations.

A post mission disposal success rate of such low order is also observed in currently operated large constellations in higher LEO orbits, such as those of Iridium and Globalstar. As previously shown, low success rates have dramatic effects on the environment and success rates of 20 percent or lower even caused difficulties to the simulation models due to the intensified onset of collisional cascading leading to unmanageable fragment numbers.

A quantum leap in the reliability of the employed post mission disposal technology and operations paradigms is required in order to raise the current level of less than 20 percent to almost 100 percent.

Background traffic influence

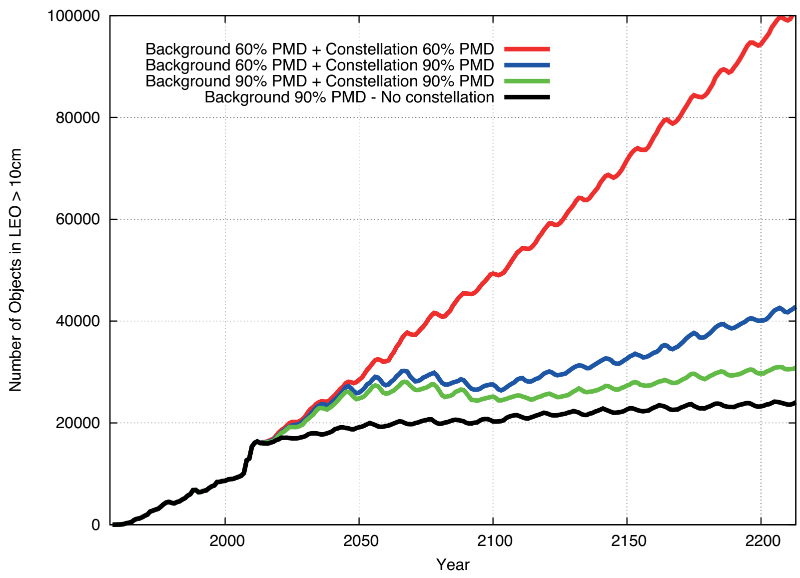
Simulations shown so far assumed that all other spacefarers (the background traffic) adhered to post mission disposal guidelines with a success rate of 90 percent. Examining recent performance records, however, revealed that the currently achieved rate is actually around 60 percent.

The simulation was therefore repeated using the more realistic assumption of 60 percent PMD success rate for the background space traffic. When combined with a mega-constellation adhering to the guidelines with 90 percent success (i.e. the inverted scenario), the simulation showed that the background traffic played a notable role in the future trend. However, with the background achieving 90 percent and the constellation 60 percent, the influence of the mega-constellation on the environmental trends was much stronger than the influence of the remaining spaceflight activities.

In other words, there is a considerable and unprecedented responsibility for a single operator to implement the technologies and operations paradigm to preserve the environment for all spacefarers.

Break-ups

In addition to PMD the technology and reliability to be developed for the constellations will have to address the prevention of break-ups. Even modern spacecraft can break up e.g. in the case of total failure preventing passivation (removal of any internal energy). Large series of spacecraft bear the additional risk that faulty parts will be present in several spacecraft. Such parts can often reveal their detrimental behaviour long after the mission, after the last of the spacecraft series has been launched.



▲ Simulation results for the evolution of the population of objects greater than 10cm with both the background space traffic and a mega-constellation implementing mitigation measures at various success rates.

Such a chain of events was observed with the NOAA Defense Meteorological Satellite Program 5D series, which were all found to be equipped with a battery charger that made batteries susceptible to explosive rupture.

Such a design flaw in a large series of mega constellation satellites that are quickly launched one after another would have disastrous effects for the space environment in LEO.

Finally, it should not be forgotten that even apparently high PMD success rates of 95 percent still mean a five percent failure rate, often leading to the loss of a non-passivated spacecraft. For a mega constellation this could mean dozens of break-ups per year with severe effects for the constellation itself, but also every other spacefarer in LEO.

We may conclude that international space debris mitigation guidelines are adequate to manage the space environment but in the presence of one or more mega constellations they only generate the desired effect when they are perfectly adhered to. Today's practice is far away from the required success rates. Failing to meet them will have detrimental consequences for all future spacefarers. ■

Some 46 satellites get 'stranded' in space each year

About the author

Dr Holger Krag is head of ESA's Space Debris Office at ESA/ESOC in Darmstadt, Germany, and he represents ESA in the IADC. The Space Debris Office plays a leading role in the research and development of space surveillance technology in Europe and since 2015 it has been studying environmental issues in relation to upcoming mega-constellations jointly with European expert groups.

Urgent action needed to keep satellites safe in orbit

The geostationary orbit (GEO) satellite belt is a unique location above Earth affording a continuous line-of-sight to satellite uplink and downlink stations. The volume defined by this belt - the altitude at which the orbital period exactly matches the rotation of Earth - is large but available slots are limited. Increasingly over the last 50 years, it has become more crowded as humankind has launched more and more satellites. Uncontrolled, incapacitated satellites and an ever growing amount of space debris pose significant hazards - and the only way for satellite operators to avoid collisions with space objects is to manoeuvre them out of harm's way. Knowing when and where to manoeuvre requires space situational awareness (SSA) - just one aspect needed to maintain safety of flight in this highly valuable orbital regime.

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From the point of view of an SSA practitioner, what are the key issues and dangers surrounding the current situation in the GEO belt? And what is the best possible set of near-term actions involving international cooperation through bodies such as the United Nations Committee On the Peaceful Uses of Outer Space (UN COPUOS), data sharing between actors in the space arena, public and private sector SSA efforts, and nascent research efforts into active space debris removal? Where should limited available resources be applied to effect the best possible outcome?

Key issues and dangers

Satellites in GEO operate in a harsh environment (including being in a vacuum and having to deal with natural and artificial hazards such as increased radiation and charged particles, orbital debris, space

CHARACTERISTIC	75° EAST WELL	105° WEST WELL	TRAPPED IN BOTH WELLS
Payload: Radugas (29), Gorizonts (9), Ekrans (8), etc	83	39	15
Rocket Body: Largely Proton-K fourth stages	17	0	3
Debris: 2006 Feng Yun and 1978 Ekran 2	2	0	0
Total	102	39	18

◀ The oblateness of Earth causes the existence of two stable gravitation wells [6] which 'trap' non-station-kept objects in the geostationary ring. The trapped objects are mostly old payloads [7].

weathering, etc.) at long distances that generally preclude making repairs to orbiting systems. But a slot at GEO is a valued, finite resource, and there is competition between countries and companies to use it. What are the major issues and hazards that are part of operating in the GEO orbit?

The year 1963 saw the dawn of the commercial satellite era with the launch of the first GEO satellite, Syncom 2. Geosynchronous satellite communications have since brought many benefits to mankind. But as a result of past activities in space, a massive amount of space debris - non-functional and uncontrolled objects - has been left in Earth orbit which poses a serious challenge to the sustainability of outer space [1].

One source of larger debris in the GEO ring is the population of non-functioning payloads and upper stages that couldn't be moved to higher orbits, as is current practice, at their end of life [2]. These objects are trapped in one or both of the two gravitational wells, or 'pinch points', caused by the gravitational anomalies (more specifically, perturbations related to the tesseral components of the spherical harmonic expansion of the Earth gravitational model) of the Earth at the Equator [3].

Objects trapped in the wells oscillate back and forth, passing through the wells, the period and amplitude of the oscillations being dependent on the specific orbital geometry. The objects thus trapped are primarily defunct payloads, including the first commercial GEO communications satellite, Intelsat-1 F1 ('Early Bird') [4].

A slot at GEO is a valued, finite resource and there is competition between countries and companies

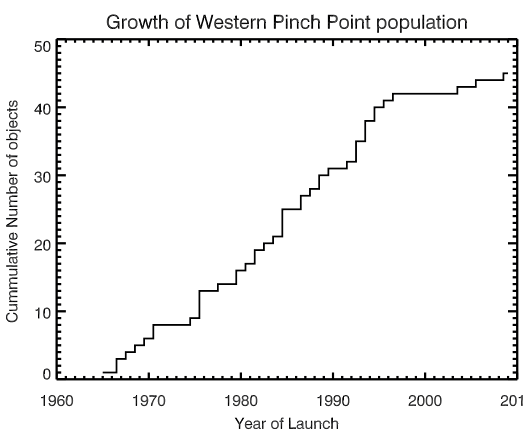
The trapped objects represent a variety of ages (~45 years) and sizes (up to a factor of 30 in size difference), as well as a number of manufacturers and launching states. The trend has been for fewer objects to become trapped over the years, as operators follow improved best practices [8]. However, the trapped objects will remain in GEO, and constitute a continuing threat to operational spacecraft.

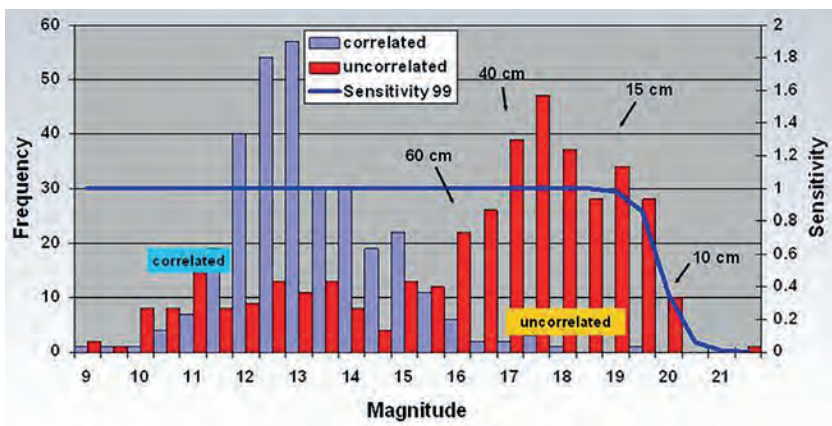
Besides the larger (greater than a few square metres in cross sectional area) tracked objects found in the public domain catalogue [9], observational campaigns estimate around 500 unknown, un-catalogued debris objects brighter than 18.5 visual magnitudes, or about 29 cm in size assuming an albedo of 8%, in the geostationary ring [10]. This figure does not include high area-to-mass (HAMR) objects drifting through the GEO ring, nor does it include large station-kept satellites not included in the public catalogue.

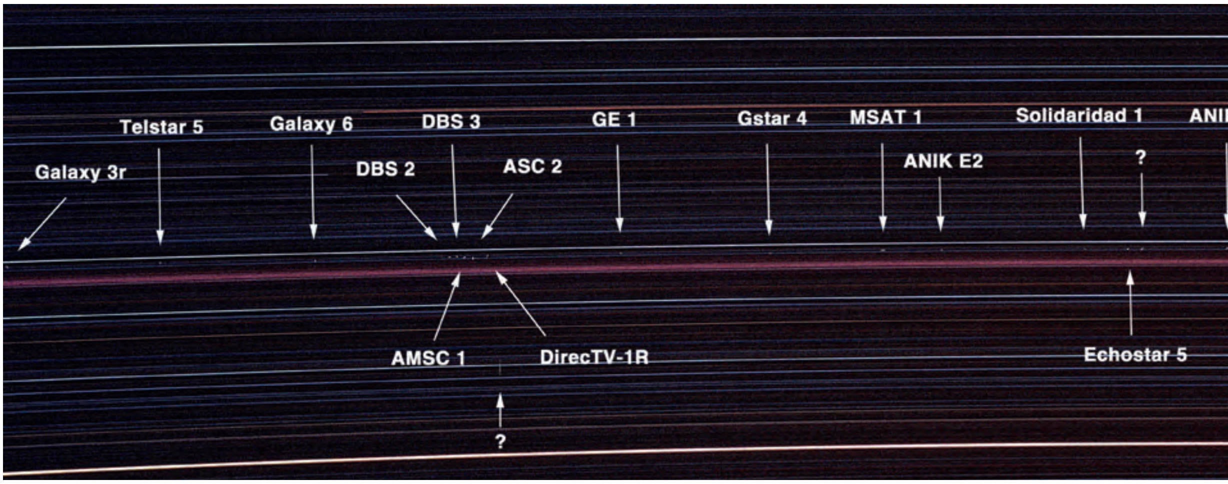
In addition, there is another class of objects that is also of concern. These objects have high area-to-mass ratios and their orbital elements can change on time-scales of weeks to months

▼ Below left: The cumulative growth of the number of defunct satellites that orbit about the western pinch point (the geo-potential well at 105 W).

▼ Below: The distribution of objects that can be correlated (in blue) with the public catalogue, as well as a new population of faint objects that are not found in the catalogue (in red). The right-hand distribution of uncorrelated objects contains the high area-to-mass (HAMR) objects [15].







▶ Geostationary satellites - photograph taken by Bill Livingston of the National Solar Observatory on Kitt Peak in Arizona (lat. 31.95, long. 248.5). Camera setting was f/6.3; focal length80 mm; film: Ektachrome 100 G.

by solar radiation pressure, which causes them to periodically pass through the GEO belt [11, 12, 13, 14].

Space weathering and satellite aging

A modern communications satellite is a complex system involving numerous subsystems that have finite lifetimes due to mechanical wearing (e.g. Sun-tracking solar panel bearings, momentum wheels, etc.), limited propulsion resources (gas jets or similar), and carefully engineered thermal surfaces which can be subject to degradation due to space 'weathering' [17] or collisions with small debris.

Aging can be viewed as a continuous slight degradation of the performance of some surfaces, such as weathering of thermal surfaces, or it can be a discrete event punctuated by 'anomalies', such as failure of a critical component.

Even though satellite subsystems are instrumented with sensors that provide health and status, or 'housekeeping', data, not everything can be sensed, and sometimes the housekeeping data stream is unavailable.

It is important that GEO satellites remain functional until the end of their useful lives when they can be re-orbited into the GEO disposal, or 'graveyard' orbit [18], deplete their stored energy sources and be decommissioned. A satellite that is not properly disposed of only becomes a new element of the debris picture, although it has been speculated that even satellites in the graveyard orbit may possibly shed debris that could drift into the protected GEO zone, or lower [19].

Trapped objects will remain in GEO, and constitute a continuing threat to operational spacecraft

Limited resources

Given the various near-term actions that might enhance the safety of flights for satellites in GEO, where should the next dollar be spent and what could have the biggest impact in the short term?

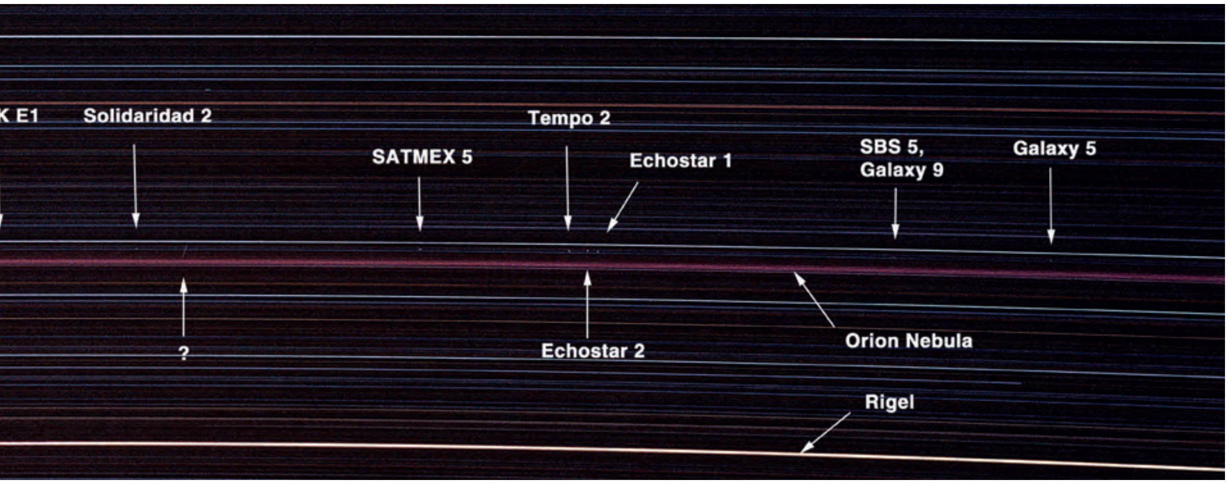
International cooperation, in this regard, means multilateral discussions, conferences and workshops (e.g. UN COPUOS meetings). Certainly a large COPUOS-style meeting might cost about US$4 million for a 10-day meeting (estimated by labour, travel, lodging and per diem costs), which is much less expensive than the US$50 million projected price for a Falcon 9 launch (excluding the cost of the payload) [21].

Talk is often described as 'cheap' but, as the ranks of actors in the space area continues to grow, these efforts are certainly needed to keep the existing problem from getting worse. Given the deliberative nature of such bodies, however, and the need for consensus, nothing happens very quickly.

If the UN COPUOS were to increase its meeting schedule by a factor of two, could it increase its output by a similar factor, or decrease the time needed to get 'results' (treaties, guidelines, reports on best practices, etc.)? Probably not, as time between meetings is used by delegations to confer with their Capitals, to read, discuss, and form positions on issues.

Data sharing is also relatively inexpensive and can allow information to flow from the 'best' sources to those who need it. All operators would benefit from exchanging information on their satellites with the owners and operators of other satellites, along the lines of the Space Data Association (SDA), and it is important to have contact information readily available for emergency situations.

Yet the likelihood of two operational satellites colliding with each other continues to be low. Of greater concern are the defunct satellites and populations of space debris, for which there are no



A satellite that is not properly disposed of only becomes a new element of the debris picture

operators providing information. Something that could be useful immediately would be a centre for the exchange of data collected on debris.

A model for such could be the Minor Planet Center (MPC), which acts in a similar function for near-Earth objects and employs a staff of only six full-time employees [22]. Such a centre would fill a need, as currently there is no existing data centre to exchange comprehensive orbital information on space debris (many debris objects do not appear in the SpaceTrack.org catalog). A global SSA data centre, while worthy of discussion in an international context, is no doubt something that would be further removed in the future, given the timescales on which international discussions take place, but could happen much sooner if interested participants join together and make it happen.

While a space debris data centre would be a convenient and useful tool to allow the exchange of information, we still need to develop additional sources for the information that is to be exchanged.

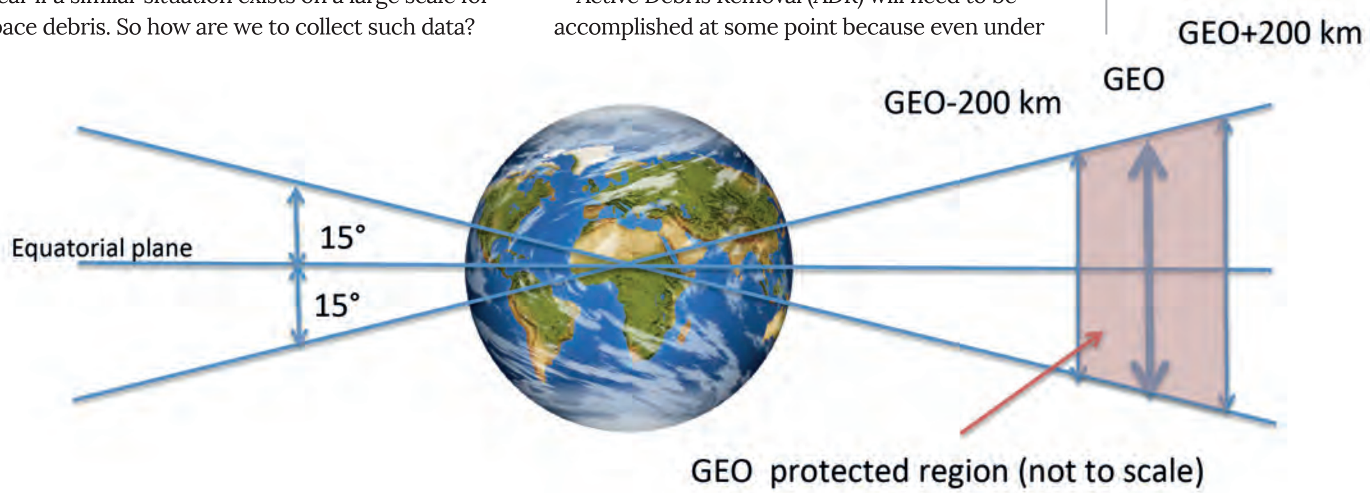
While there may exist a market for commercial SSA services for GEO satellite operators [23], it is not clear if a similar situation exists on a large scale for space debris. So how are we to collect such data?

Happily, ground-based optical telescopes provide a good, proven and inexpensive solution to this problem. As the astronomical community advanced the state-of-the-art observatory from 1-2 m diameter telescopes to 4 m, and then to 8-10 m, and soon to 30 m or larger, there exist a number of functioning, or recently mothballed, smaller observatories that could be used if funding were available to operate and maintain them.

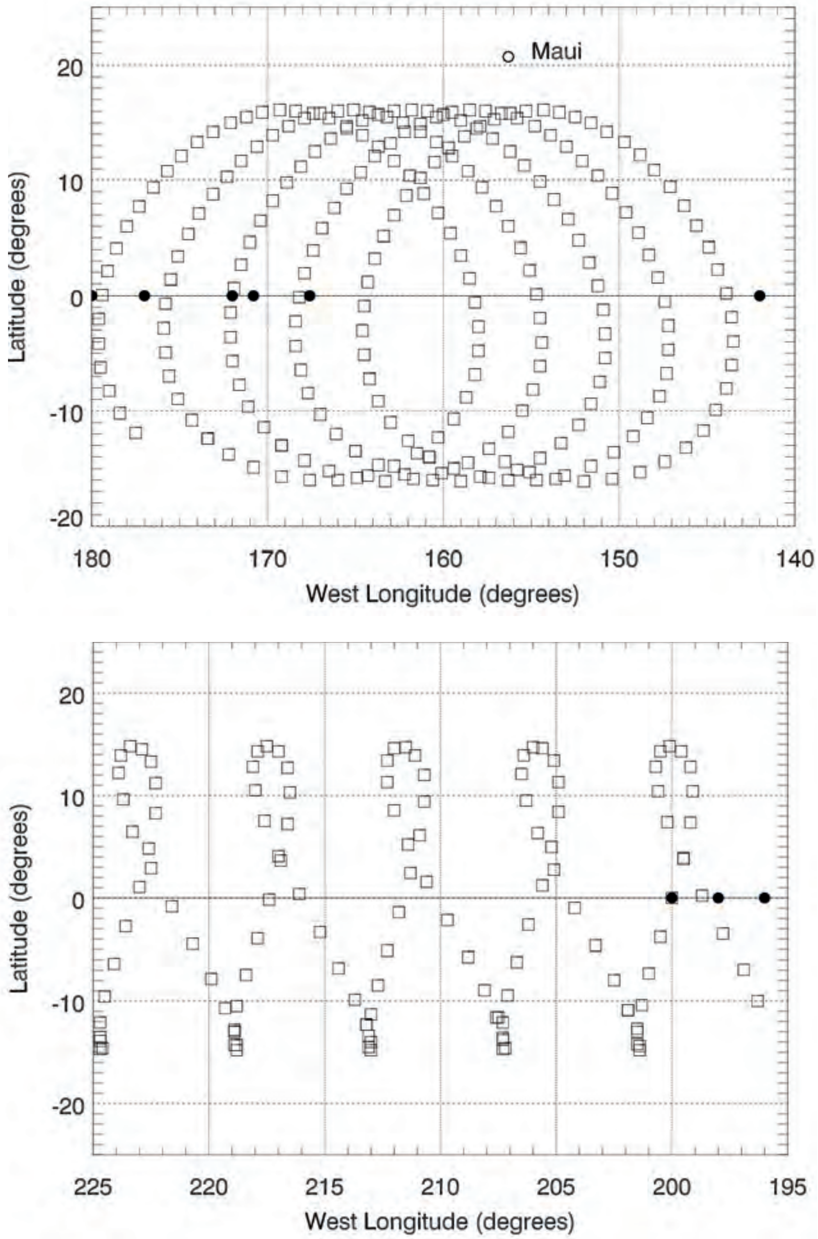
This seems another best use of the 'next' dollar: funding additional sources of high-quality observations of space debris. National space agencies or science foundations might set up a series of operations and maintenance service contracts with colleges and universities that have such underused assets, and perhaps even with motivated teams of experienced amateur astronomers. Industrial groups might also be willing to participate, perhaps motivated by profit or for reasons of outreach to enhance STEM (science, technology, engineering and maths) participation by students or the public [24].

Active Debris Removal (ADR) will need to be accomplished at some point because even under

▼ Definition of the GEO protected region as per IADC guideline 3.3.2 [2]. This defines a toroid-like band that encircles Earth.



▼ The calculated sub-latitude and sub-longitude (ground tracks) for two HAMR objects observed from Maui, spanning five days. The filled circles at zero degrees latitude represent the locations of a subset of the geostationary satellite [16].



best-case scenarios we cannot expect 100% compliance with any set of disposal guidelines. With more objects being launched to GEO, there will always be a certain fraction of items that are not de-orbited prior to their end-of-life. Additionally, there exists the ever-present danger of debris-on-debris collisions for objects trapped in the GEO belt.

ADR will be expensive; it will require multiple launches of many satellites that carry sufficient fuel to impart the necessary 'delta-V' to the spinning, tumbling debris objects that need to be removed from the GEO belt. It will also necessitate the resolution of some thorny legal issues in an international setting. Thus, ADR is a high-cost, long lead-time activity. But are there any aspects of it that might be done cheaper and/or on shorter timescales?

Certainly characterisation of space objects (an SSA task) is key to ADR. Before one might attempt to do anything with a candidate object, one would want to know as much as possible about that object. How big is it? At what rate and about what set of axes does it rotate? What is the area-to-mass ratio? What surface and thermal properties can be determined for the object]? These are all questions that can be answered by ground-based optical observations using existing technology.

Are there other schemes that might serve as well as full-blown removal, or act as stopgaps until ADR is achievable? One idea is 'just in time' debris trajectory adjustment [25]: this scheme involves expelling compressed cold gas into the orbit of a debris object to change its course a short time before it is predicted to collide with another object.

This might be achievable with a few satellites stationed near the two GEO 'pinch points', that would be called upon as needed. It does not solve the long-term problem because it does not actually remove debris but it solves the immediate problem of preventing collisions. It gets around the 'probability' problem by only interacting with objects that are actually a threat, and it greatly reduces the energy needed, compared to actually de-orbiting the object.

Another possible first-step could be to attach small beacons on debris and defunct satellites to aid in their tracking. It might have similar legal and political problems to actual ADR but it could greatly aid in tracking and identifying such objects and it would be technically much easier.

Therefore, given that ADR will require international cooperation, technology development and multiple launches, it is neither cheap, quick or easy. Yet, if we want to maintain a sustainable use of the GEO belt, it is something that will need to be done in the long-term. Thus, we should continue to investigate ADR, its derivatives and similar alternatives, though it is probably unfeasible to begin constructing any deployable systems for the near future.

What can be done now?

The GEO belt is a shared resource for use by the human race but continued safe access to this resource is not assured, chiefly for reasons of our own making.

Existing and future space debris threatens safe operations of satellites in this orbital regime. The space-faring nations whose actions contributed to the current situation will need to show leadership regarding actions needed to ameliorate the problem.

The GEO belt is a shared resource for use by the human race but continued safe access to this resource is not assured chiefly for reasons of our own making

Happily, there are a number of near-term steps that can be taken that do not entail the expenditure of vast resources. The space community should continue to enumerate, agree-upon and promulgate space safety of flight 'rules of the road' for GEO and other orbits.

We must also continue to detect, track and characterise resident space objects just like rocks and shoals in shipping lanes, as this information is fundamental. Unlike rocks and shoals, however, the space objects are in constant motion and must be frequently monitored.

In addition, space actors should perform additional measurements of resident space objects to enhance the accuracy and precision of our knowledge of these objects. Then, this orbital data should be shared as widely as possible among actors in the space arena, while incorporating operator knowledge (e.g. past and future trajectory changes) into the data on active space objects. Finally, the community as a whole should conduct system architecture and legal studies to better understand the issues surrounding active debris removal and its alternatives.

These activities are moderately priced compared to developing and launching space systems, and can have beneficial impacts on immediate and short-term timescales. They are all key components needed to ensure the long-term sustainable use of this vitally important shared resource. ■

About the author

Dr Mark Skinner joined Boeing in 1999 as a senior scientist and technical manager with the Science & Analysis (S&A) team on Maui, Hawaii, where Boeing operates the Maui Space Surveillance System for the Air Force Research Laboratory (AFRL), conducting research into observational and analysis techniques to advance space surveillance. He joined Boeing Research & Technology in New Mexico in 2015.

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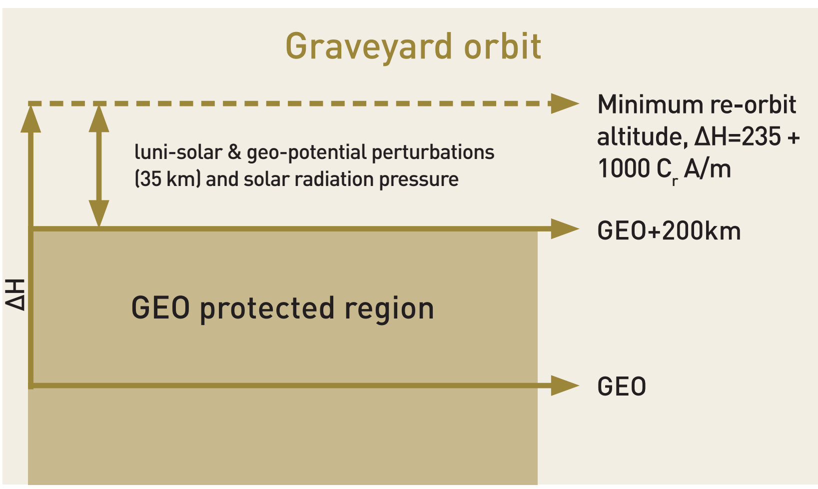
▼ The geometry for the post-mission disposal region for geosynchronous satellites, a minimum height above the GEO altitude, which depends on the satellite's area-to-mass ratio.



World needs strong space governance system

For over two, years some 80 space scientists, engineers, entrepreneurs, regulators and space lawyers from around the world have been engaged in an 'International Study on Global Space Governance'. In advance of its publication later this year, the articles in this special section of *ROOM* highlights key aspects of the study and assess some of the many challenges to establishing a viable and effective rule of law governing activities in outer space.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The global security landscape darkened in 2016 as the international community failed to effectively come to grips with some of humanity's most pressing existential threats, namely nuclear weapons and climate change.

As a result, on 26 January 2017 the Bulletin of the Atomic Scientists - which informs the public of threats to the survival and development of humanity from nuclear weapons, nuclear energy, climate change and biosecurity - moved the hands on its infamous Doomsday Clock 30 seconds closer to midnight. It believes humanity is now just 'two minutes and 30 seconds' away from annihilation.

The only other time it has been closer to midnight was in 1953, when it was set at just two minutes from 'Doomsday', as the Soviet Union and the United States tested new hydrogen weapons. In July 2014, commenting on the state of the world, the former US Secretary of State Madame Madeleine Albright acknowledged, "To put it mildly, the world is a mess." Shortly before, at the 2nd Manfred Lachs Conference on Global Space Governance at McGill University in Montreal, Canada, Prof Barry Kellman had observed, "Space is a mess. It is a physical mess [and]… is also a legal mess."

What is increasingly lacking is a prudent, efficient and strong global governance - including a robust space governance system

Technology, be it nuclear, space systems or anything else, is important for the well-being of humanity. However, it is law and order that will help not only in making economic and social benefits of technology expand in an equitable manner, but also in ensuring the very survival of the human race.

The world is fast becoming a 'failed State' and we believe the main reason for such a looming catastrophe - the muddled state of the world and disorder in outer space - is the current global geopolitical environment, which is resulting from narrow unilateralism and ultra-nationalism mainly by major powers in the wake of increasing globalisation in every sphere of human activity.

The nations, which initiated and aggressively pushed for globalisation in the 1970s and '80s, seem to feel that they are losing their power and hegemony and, thus, are reverting to nationalistic policies and are opposing globalised decision-making and international lawmaking processes.

There is also no effective regulatory means in place to control the exponential increase in space debris and no regulatory effort is underway to facilitate debris removal

In other words, what is increasingly lacking is a prudent, efficient and strong global governance - including a robust space governance system. By global space governance we mean a collection of space-related international binding agreements and non-binding guidelines (and codes of conduct) as well as the concerned international institutions. National legislation and institutions concerned with space and related matters play a crucial role in this governance process.

What we are witnessing is not only retraction from the further development of highly needed international rules to facilitate and regulate space activities, but also the weakening or abandoning of the international institutions that remained, until the mid-1970s, the global centre for space diplomacy.

For space-related affairs, the most important of such institutions is the UN (United Nations), particularly its Committee on the Peaceful Uses of Outer Space (UNCOPUOS).

When the Space Age began in 1957 at the height of the Cold War, both the Soviet Union and the US strived to have détente in the new environment. They agreed to dedicate outer space for peaceful purposes and for the benefit of the whole of humanity, a gesture welcomed by the international community.

The UN General Assembly, in its first resolution on outer space, adopted on 13 December 1958, expressed the common aim to use outer space only for peaceful purposes, to avoid the extension of present national rivalries into this new field, and to promote energetically the fullest exploration and exploitation of outer space for the benefit of humankind.

These principles were elaborated in succeeding resolutions that became the bases of the five UN core space treaties and several resolutions. Collectively, they form the framework and the primary system of global space governance. The foundational agreement of the system is the 1967 Outer Space Treaty, which is the most adhered to space treaty. More importantly, it contains several principles that have become a part of customary international law, thus apply to all nations, whether or not they are parties to the Treaty.

The global space economy is currently valued at US$320 billion annually and continues to expand from traditional applications - communications, broadcasting, weather forecasting, navigation, medicine, security and remote sensing - to embrace space tourism, space mining, space-based solar power, and the future settlement on the Moon and Mars.

Along with this, the number of space players is fast increasing, traditional space agencies and large corporations being boosted by a growing number of entrepreneurial private space companies. In stark contrast, the development of a global space governance system is at a standstill and existing measures are rapidly becoming inefficient and unable to cope.

This is compounded by a newly emerging inward-looking geopolitical situation, of which the directions being taken in the US by President Trump and by the United Kingdom over Brexit might be cited as prime examples.

Consequently, significant areas of space activity - space traffic management, orbital

PRINCIPLES AND RULES OBSERVED IN THE CURRENT GLOBAL SPACE GOVERNANCE SYSTEM

States are obliged to explore and use outer space and celestial bodies for the benefit and in the interests of all states, irrespective of their economic and scientific development

States are free to explore and use outer space and celestial bodies on the basis of equality

States and their private entities are prohibited to appropriate, by any means, outer space and celestial bodies

States are internationally responsible and could be held liable for their national, public or private space activities

States are prohibited from establishing military bases, testing any type of weapons, and conducting military manoeuvres on the Moon and celestial bodies

States are forbidden from placing in orbit around the Earth nuclear weapons or any other kind of weapons of mass destruction

States are to be guided by the principle of cooperation and mutual assistance, and must conduct all their space activities with due regard for the corresponding interests of other States

States are entitled to exercise their inherent right of self-defence in case of an armed attack.
More importantly, the existing global space governance system has aimed to strike a fair balance between the interests of all nations.

debris, unilateral exploitation of natural space resources, growing military and strategic uses of space, and the contamination of both Earth and space environments - remain without specific regulatory control and guidance.

The 2015 'Space Resource Exploration and Utilization Act' of the US initiated an international controversy, since it unilaterally allowed national private property rights over natural resources from asteroids and the Moon, an action considered contrary to the well established international prohibition of property rights in space.

Shortly afterwards, Luxembourg and the United Arab Emirates indicated they would also draft legislation regarding space mining activities and the former has already adopted a draft law to this effect. It is likely that more States will follow these examples, setting in motion the development of a very different set of space governance principles.

Currently, there is also no effective regulatory means in place to control the exponential increase in space debris and no regulatory effort is underway to facilitate debris removal - at least the big pieces - which in themselves will generate more debris as they collide in space.

Over the past six months, international news media have carried regular stories on space security and the prospect of war in space which could affect operating satellites. For the world at large, even a day without satellite systems could be devastating and bring about the possibility of serious disruption and damage of unimaginable extent, scope and nature. One US Air Force General is reported to have stated that after a war in space, "You go back to World War II... you go back to the Industrial Age".

Most of the above issues can only be resolved through better international cooperation and understanding, which should in turn lead to the expansion and strengthening of a global space governance system built on solid legal principles.

The following sections of this feature expand on the need for mechanisms of governance covering specific areas of space activities, as well as looking at issues that have to be resolved in the longer term. The subject is complex and these summary articles can only provide limited information about global space governance as an access point to the wider debate.

Rule of law is very important here on Earth and, as we expand ever further outwards, this is increasingly so in outer space as well. Space matters for everyone and it is our combined responsibility to ensure that the sustainable use of outer space is assured for the benefit and perhaps even ultimate survival of all humankind. ■

About the authors

Prof Dr Ram S. Jakhu is the Director of the Institute of Air and Space Law and the Centre for Research in Air and Space Law of McGill University, Montreal, Canada. He possesses professional experience of over 30 years in the field of international and national space law and policy.

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Space matters for everyone and it is our combined responsibility to ensure that the sustainable use of outer space is assured for the benefit of all humankind

▼ The Bulletin of the Atomic Scientists moved the hands on its infamous 'Doomsday Clock' 30 seconds closer to midnight in January 2017.

Scott Madry
Executive Director, the Global Space Institute, North Carolina, USA

Creating the future for space applications and their regulatory needs

Over the past six decades the world has moved through a number of very different eras and now anticipates a fascinating, yet uncertain, future in space. Our ability to make use of the immediate vicinity of our planet has multiplied from the first lone Sputnik satellite to more than a thousand satellites today. What are the primary satellite applications and what are their evolving regulatory needs? How will we meet these new requirements, and who will take responsibility for these, so that our satellites can continue to provide their vital services? In short how do we create the future?

We use the term satellites every day, but what does this word really mean? The first use of the term satellites goes back to the discovery of the telescope and Galileo's discovery of the moons of Jupiter. He needed a name to describe these small objects, rapidly rotating about the giant planet, which was named after the powerful king of the gods, master of the sky and thunder of the ancient Romans.

In Latin, a satelles (or plural satellitis) was an attendant or servant of a powerful person, often a slave, scurrying about doing the bidding of its master. This seemed an appropriate name for these newly discovered objects, and so they became known as satellites.

Satellites, invisibly embedded in many aspects of our modern lives, are our servants in space

◀ An incvreasing number of satellite constellations in coming years will need focused and specific global traffic magagement rules.

Once Sputnik was launched, for several years, objects launched into orbit were termed artificial satellites, but today we simply know them as satellites. And it is an appropriate term. They are our servants, the servants of humanity, scurrying about our planet, doing our bidding and serving our needs, providing a wide range of very practical and useful services.

There are three, primary satellite applications today. Satellite telecommunications, remote sensing and Precision Navigation and Timing (PNT). The global space industry today is a commercial market of over US$322 billion per year [Satellite Industry Association '2016 State of the Satellite Industry Report', prepared by the Tauri Group].

The satellite segment is $230 billion in annual global revenue and continues to grow. Over half of this ($123 billion) is made up of satellite services, with ground equipment some $60 billion (including GPS receivers), satellite manufacturing some $15 billion, and the launch industry some $6 billion. Most of this represents the commercial satellite telecommunications industry.

Today the number of operational satellites in Earth orbits exceeds 1300. These orbits range from the geostationary arc (35,786 km) down to very low Earth orbits (~200 to 2000 km). About half of these are telecommunications satellites, 25% are civil and military remote sensing and weather satellites, and 8% are for navigation. The rest are research and scientific platforms. Some 57 nation states operate at least one satellite, but the vast majority of satellites are operated by the major, spacefaring nations.

Satellite telecommunications is by far the largest and most important of the three main applications, and the largest commercial market. It was Arthur C. Clarke who, back in 1945, published his idea of three, equally spaced 'radio beacons' in a stable, geostationary orbit, thus providing near global and instant radio coverage. Today we have hundreds of large and powerful telecom satellites out in the 'Clarke' orbital plane, broadcasting a never-ending stream of data, broadcast, radio and TV. New constellations of hundreds of small satellites in low Earth orbit are being proposed as well. Our digital world is connected by these orbital broadcasting systems.

Remote sensing satellites provide us with a view back on our home planet, and are used for a variety of purposes. Weather satellites, far out in the Clarke geostationary arc, provide near instantaneous warning of severe storms and weather patterns. In lower, polar Sun-synchronous orbits of some 500-800 km we have hundreds of moderate and high resolution satellites constantly mapping our planet, providing data on our changing environment and applications as varied as disaster response, urban planning, agriculture and water resources.

Both passive and active radar satellites provide us with the ability to map our world and our impact upon it. Remote sensing also has vital defence and military applications, and these inherent dual use implications complicate the international cooperation and regulatory aspects of this vital capability.

Global Navigation Satellite Systems (GNSS) are a more recent technology but have quickly

The landmark space treaties of 50 years ago are now relics of a past world

▲ European Galileo satellites in low Earth orbit.

become a vital utility for our interconnected, digital world. Starting with the US GPS system in the late 1970s, we also now have positioning and timing satellite systems operated by Russia, China, India, and Europe.

These constellations of 20-30 satellites in a medium orbit of ~20,000 km (and some in GEO), constantly broadcast a stream of signals that allow us to accurately locate ourselves, navigate around our planet, and know our time to a fraction of a second. Satellite navigation systems have quickly become a vital aspect of our interconnected digital world, and represent a hidden component of many of our daily life activities, including timing for our power grids, the Internet and vehicle navigation, just to name a few.

We are now moving into a far more integrated satellite applications future, where telecoms, remote sensing and navigation are being integrated with Geographic Information Systems (GIS), and are available on smart phones and apps for new uses like Location Based Services, crowd sourcing and big data analytics. The internet of things is quickly becoming the internet of places as well.

New, innovative, and disruptive technologies such as cubesats, satellite constellations, and rapid advances in computing and networking are altering the space domain and putting tremendous pressure on the existing order.

There are many very difficult issues facing the satellite applications community. These are related to complex and difficult issues of spectrum needs, orbital crowding, space traffic management, liability and orbital debris.

International policy and regulatory issues must find new outlets for constructive and practical decision-making and conflict resolution

The near-Earth orbital domain is severely polluted with debris. We are quickly running out of electromagnetic spectrum, which is a finite and limited resource that we must learn to manage better in the face of tremendous pressure to allocate existing space spectrum to new, commercial terrestrial uses.

Orbital crowding, space debris and the resulting need for space traffic management, are quickly becoming major priorities - but who will develop the technologies and who will manage (and pay for) these resources?

The proposal to launch a number of new low Earth orbit constellations with hundreds and even thousands of satellites each makes addressing the orbital debris issue even more urgent. Will we pollute space as we have done with Earth?

International policy and regulatory issues, complicated by dual use, national security and disruptive commercial developments, must find new outlets for constructive and practical decision-making and conflict resolution.

The landmark space treaties of 50 years ago are now relics of a past world. How can we not only update them to meet the needs of today but also create the international policy framework for a tomorrow we can only dimly see?

Existing space legal structures, including liability, must be reconsidered to catch up with the quickly evolving reality. Innovative new commercial entrants, funded by venture capital and armed with disruptive technologies and perspectives, along with many traditionally non spacefaring nations, are now competing for increasingly limited orbital slots, spectrum, and their own place in space.

Satellites, invisibly embedded in many aspects of our modern lives, are our servants in space. This will only increase in the future and so we must find a path forward into a very different world, a path that will allow us to continue to grow and manage our use of near Earth space. We need new ideas, new technologies, new markets, new legal and policy structures, and new ways of cooperating.

The future will be exciting if we can make a success of managing these vital issues. Failure is not an option. It is up to every one of us to create our future in space. Let's get to work and solve these urgent space policy and regulatory issues. ■

About the author

Dr Scott Madry is the Executive Director of the Global Space Institute, research associate professor of archaeology at the University of North Carolina at Chapel Hill, USA, and is the President of Informatics International, Inc.

Will international space law struggle to remain relevant?

Steven Freeland
Professor of International Law, Western Sydney University, Australia

If there is one stand-out feature that encapsulates humankind's adventures in space over the past 60 years, it is the exponential growth and development of space-related technology, which has given rise to possibilities that would have been beyond contemplation even a few years earlier. This trend looks set to gather pace over the coming years and decades. Here, Steven Freeland argues that there is an urgent need for a more comprehensive and 'holistic' system of global space governance if international space law is not to become irrelevant.

◀ LeoLabs, a commercial provider of data to track debris and prevent collisions in low Earth orbit (LEO), completed a new addition to its network of phased-array radars this spring. The Midland Space Radar (MSR), located in Texas, USA, is now operational and providing high resolution orbital data on LEO-based satellites and debris.

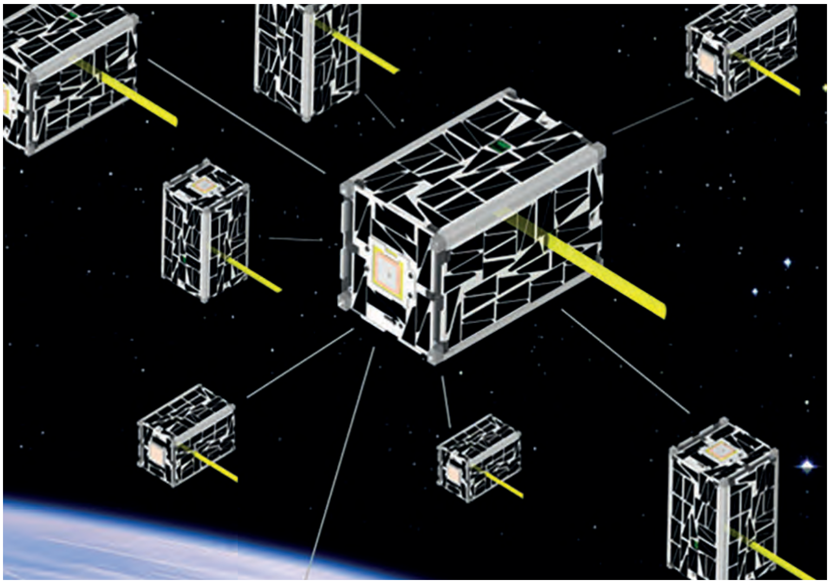
The prospects for the future use of outer space offer both tremendous opportunities and challenges

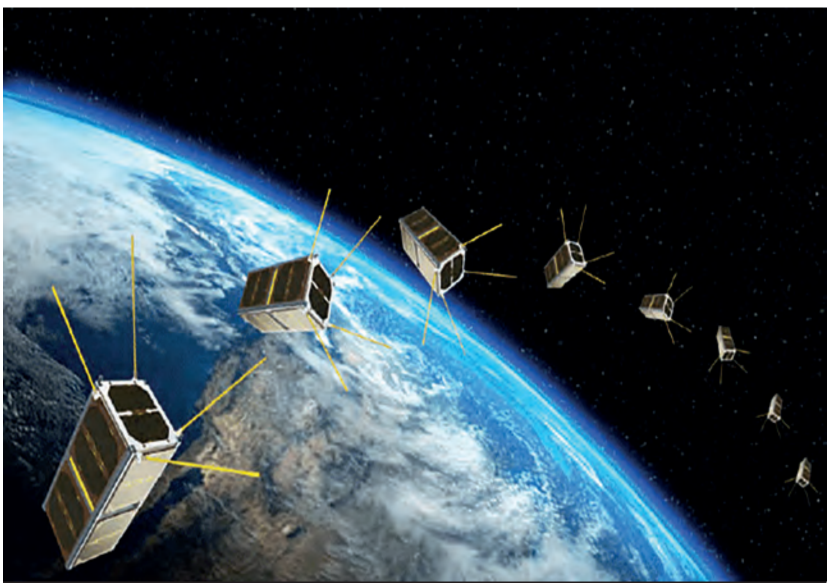
One of the characteristics associated with the rapid development of space technology is that comprehensive standards of regulation cannot easily be specified in advance. Simply put, if we do not fully understand the technology - and the risks and consequences associated with its use - then further uncertainties and potential risks often result from attempting to regulate for the 'unknown'.

It is clear that the prospects for the future use of outer space offer both tremendous opportunities and challenges, whilst international law will struggle to remain relevant and adequately address all aspects of this seemingly irreversible dynamic.

Adding further complexity to the regulatory framework necessary to address expanding space technologies, the fundamental rules that do exist arose at a time when the development of

It is too easy for States not to abide by the terms of voluntary non-binding instruments





▼ Existing international legal regimes are not designed to cope with a rising number of cubesats flying in loose formation some 500 km above Earth - a more institutional form of space traffic management might now be required.

space-related technology was principally directed towards military objectives.

The relationship between space activities and military conduct had always existed in practical terms, irrespective of the rules that had been developed. It became self-evident to military commanders that space technology could be utilised to create an 'integrated battle platform' to aid in the implementation of military strategy.

This embeddedness of space technology and warfare has ratcheted up considerably since those early days. It was during the Gulf War in 1990 that the military value of space assets for the conduct of warfare was first used to a significant degree. 'Operation Desert Storm' is now often referred to as the 'first space war'.

The militarisation of space is therefore a given, notwithstanding that many regard this as flying in the face of the Outer Space Treaty. The 'non-military versus non-aggressive' debate regarding the 'peaceful purposes' doctrine in its Article IV is a long-redundant argument in practical terms, and the role that international law can play now centres on the risks and uncertainties associated with the trending 'weaponisation' of space.

Following the terrorists' attacks of 11 September 2001 in New York, the US government embarked on a policy designed to enhance its domination of the space dimension of military operations. This necessitated having the ability to protect critical infrastructure and assets in outer space.

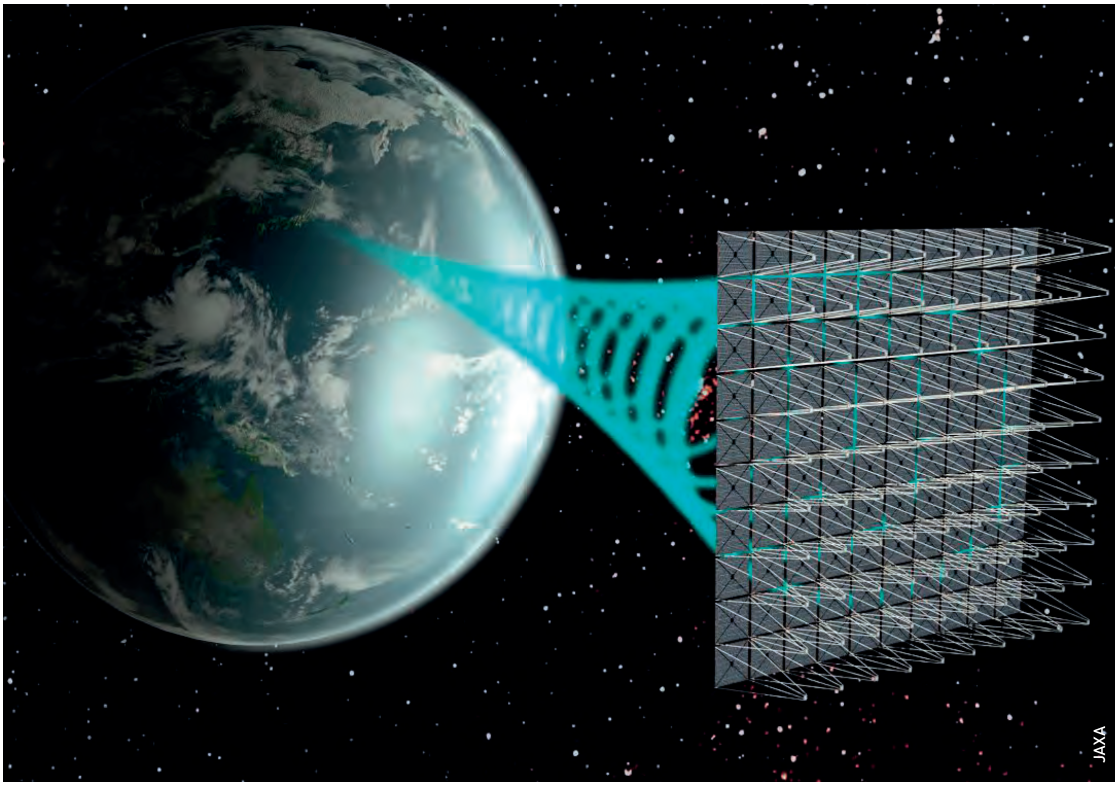
Subsequently, although the Obama administration emphasised co-operation in space to a far greater degree, hawkish sentiments still appeared to guide US space policy. It is so far unclear how the Trump administration will direct military policy in this regard but initial rhetoric suggests an even greater engagement with military activities involving space.

Other space powers are engaged in similar activities directed towards maximising the strategic (and potential military) advantages to be gained through space-related technology and we appear to be locked into a true 'space arms race'. It is within the realms of reality that outer space may itself become an emerging theatre of warfare.

The situation is complicated further by the increasing prevalence of 'dual-use' satellites and a growing reliance by States on continuous and reliable access to privately operated commercial satellites for the protection of their national security interests.

This means any attempt to apply the *jus in bello* principles to a 'space war' is fraught with complexity, challenging the overly simplistic assumptions that are often made by commentators when seeking to apply 'terrestrial' international law principles to an outer space paradigm.

A carefully thought-out *sui generis* system of global space governance is required to meet modern-day challenges. The deliberate destruction by both China (2007) and the US (2008) of their own satellites highlighted the dangers posed and the fact that neither country felt constrained by existing space law, or by other principles of international law, further emphasises the need to develop more rigorous international rules to protect the space environment.



◀ Computer graphic depicting a future solar power system in orbit around Earth, beaming energy to receiving antennas on the ground. As well as technology hurdles, such systems will also need to be subject to specific space governance issues.

In the case of the Chinese action, while much international reaction centred (quite understandably) on the military consequences, the additional pieces of space debris caused by the destruction of the Fengyun FY-1C polar orbit satellite at such a strategically important altitude raised significant concerns.

These uncertainties coalesce with other risks and all point to the need for an institutional form of space traffic management because the existing international legal regime does not address such concerns in anything approaching a comprehensive manner. Whilst spacefaring States (and others) are aware of the heightened risk of space warfare with its adverse consequences for the already hazardous state of the space environment, there has not been a corresponding willingness to either take 'ownership' of the problem or agree to strict, comprehensive and binding international space rules.

It might be argued that the prevailing 'soft law' and TCBM ('transparency and confidence-building measures') approach to space regulation may take on an increasing relevance by providing appropriate international benchmarks, at least for currently foreseen risks and uncertainties. However, it is too easy for States not to abide by the terms of voluntary non-binding instruments.

Not only is the issue of space debris a major environmental concern, but it also clearly impacts upon human safety. For example, on 12 March 2009, the astronauts on board the International Space Station (ISS) were forced to evacuate the main station and remain in the escape vehicle for nine minutes, while a piece of debris passed by.

At around the same time, an operational American commercial satellite (Iridium 33) and an inactive Russian communications satellite (Kosmos 2251) collided approximately 790 km above the Earth, resulting in their total destruction. The collision resulted in approximately 700 additional pieces of hazardous debris, each with the potential to cause further decades-long pollution in space.

At a time when it is envisaged that, in the relatively short term, many more humans will have the opportunity to go into space through the development of a commercial space 'tourism' industry, these risks translate

They are not strange bedfellows after all because everything that we do in space is interrelated with everything else

not only to the problems associated with the destruction of important infrastructure upon which many societies depend, but also direct loss of human life, due to a lack of adequate space situational awareness, and the absence of an institutionalised system of space traffic management (STM).

Putting aside the obvious inconsistencies of attempting to develop a comprehensive STM system within a context of warfare involving space - it would be impossible to maintain any semblance of a centralised and orderly regime for spaceflight in circumstances where belligerents were using space assets to engage in direct conflict - many other challenges arise before such a system could be designed and implemented.

The risks need to be assessed and understood; not an easy task by any means but a necessary one and this poses a series of questions. Would any existing international organisation be in a position to administer such a system? Should a new governing body be created and, if so, what would be its mandate? What specific laws would apply, particularly given the advent of sub-orbital technology? Indeed, would it be necessary to 'create' a new form of legal regime - 'aerospace law' - to more appropriately govern such activities? And, if so, how would this coalesce with those laws that would apply to more traditional forms of spaceflight?

Of course, it is always easy to ask questions and much more difficult to provide answers. However, what is clear is that it is no longer appropriate to think of the challenges associated with our activities in space as somehow quarantined into separate 'pigeon-holes'.

Each type of space activity - be it military, or civil, or commercial, or scientific, or 'dual/multi use' - has an impact on other space activities. They are not strange bedfellows after all because everything that we do in space is interrelated with everything else. There is therefore an urgent need for a more comprehensive and 'holistic' system of global space governance going forward. Moving away from our existing silo approach is an important first step. ■

About the author

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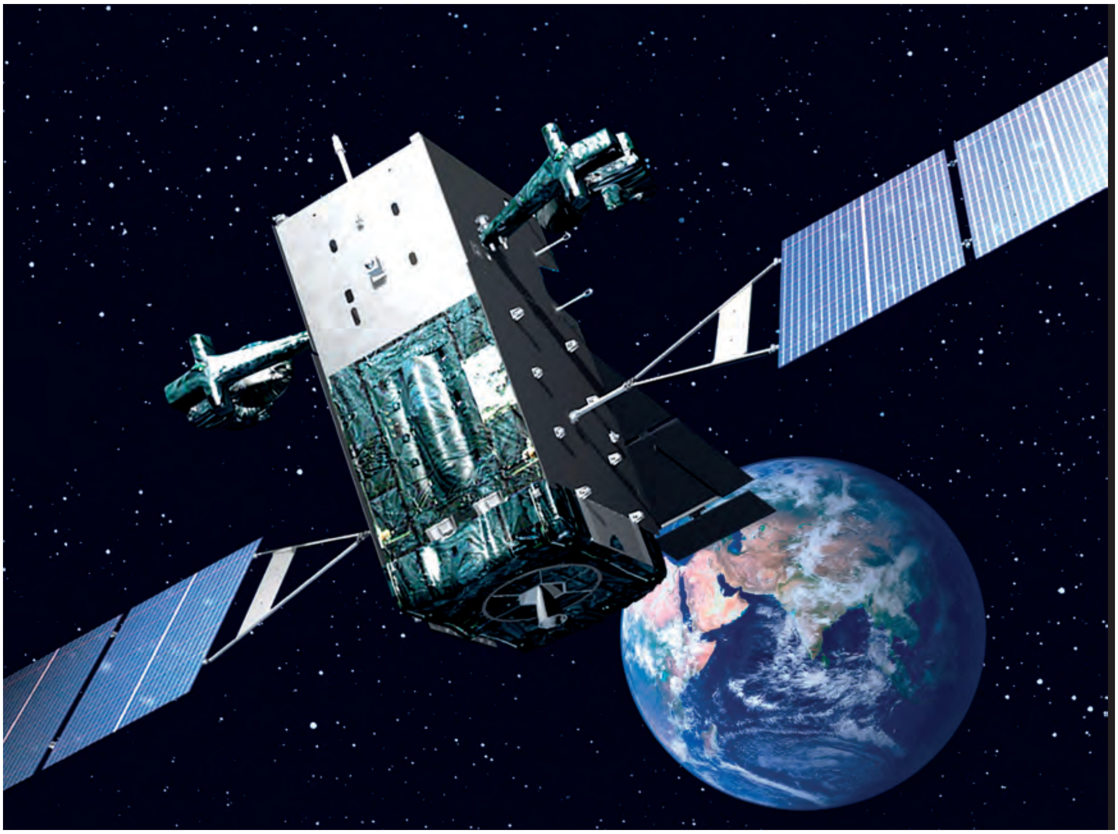


▶ United States' military Space Based Infrared System (SBIRS) spacecraft in support of missile early warning, missile defence, battlespace awareness, and technical intelligence mission areas.

Humanity is moving towards a new reality

If life as we know it a century hence has not ended in a nuclear holocaust, a viral pandemic, or perhaps run-away climate change with catastrophic storms ravaging Earth, our world could still be quite different. There could be a much different and broader range of space activities than now is the case and along with them will be a need for a new range of space regulations, confidence building measures, and 'rules of the road' in space.

Joseph N. Pelton
Executive Board Member of the International Association for the Advancement of Space Safety (IAASS)

The future world of space will not be like it has been up to now. Activities will include a much wider range of operations, many different types of space applications, and the regulatory and 'policing' mechanisms will be considerably different. The problem is how does regulatory regime keep up? How does global space governance keep up with space technology invention and the disruptive activities of NewSpace companies and constant entrepreneurial innovation?

There was a time in human existence when change took millions of years. Then it took thousands of years, followed by hundreds of years, then decades, years, and now it seems as if our world changes in only hours or minutes.

In another century it seems likely that we may see the operation of space-based solar power systems, as well as businesses engaging in new types of mining. A hundred years hence, we may also well see the creation of permanent space bases and perhaps even true space colonisation.

In this future time the importance of understanding and coping with cosmic hazards will be much better understood. We will be actively engaged in defending against asteroids, comets, solar flares, coronal ejections, changes to Earth's magnetosphere, and orbital space debris.

The world is moving towards a new reality where humanity will depend increasingly on a new space economy and it will be recognised that space hazards can threaten global prosperity

There will indeed be a need for a regulatory framework under which totally new types of activities can be carried out peacefully and in a business-like manner

Even today, the world is moving towards a new reality where humanity will depend increasingly on a new space economy and it will be recognised that space hazards can threaten global prosperity.

A study by Lloyd's of London, for example, has suggested that a massive coronal mass ejection (CME) from the Sun could result in a two trillion dollar hit to the North American electrical power grid. The US National Intelligence Council found that a major CME to be one of seven major 'black swan' events that the world should prepare for.

This may have been one of the reasons that President Obama in early October 2016 signed an Executive Order that assigned specific authority to NASA, the Department of Defense, the National Science Foundation and the Department of Homeland Security to cope with a major CME event. The recent determination about the shift in Earth's magnetic poles by ESA's Swarm and NASA's MMS satellites raises this concern even higher since it is the magnetic poles that shape the Van Allen Belts and protect us from CME blasts.

Although the UN General Assembly recently endorsed the new International Asteroid Warning Network (IAWN) and the Space Mission Planning Advisory Group (SMPAG) to help coordinate a better defence against asteroids, we are a long way from a global space governance system for planetary defence.

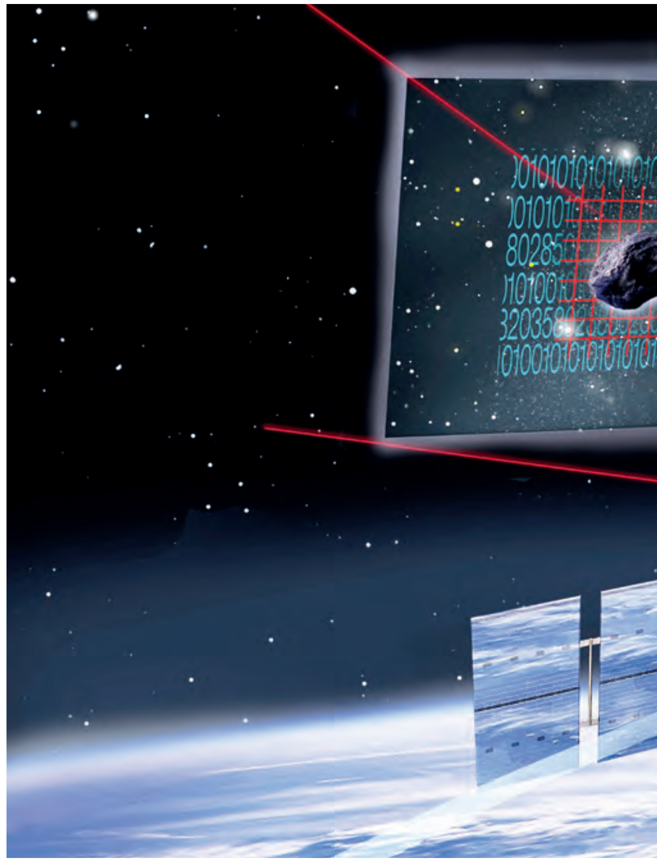
In fact, as UNISPACE+50 prepares to convene in 2018 what is striking is that the world is really not prepared for the emerging new global space economy and the new longer term uses of deeper space.

There are widening gaps in space governance regardless of whether it is for new types of space business, space exploration and research, environmental concerns, space defence and security, space traffic management, space debris, frequency management, liability, or ownership and use of space natural resources.

A new space activity that has recently excited attention is that of space mining. Four US companies - Deep Space Industries, Planetary Resources, Moon Express and Shackleton Resources - have already declared their intention to engage in natural resource extraction.

Indeed, a new US law enacted in December 2015 seems to give the right for companies, nationally licensed to do so, to reclaim and own extracted resources 'consistent with international law' obligations of the US.

Already some have claimed that authorising such space mining activity is tantamount to a claim of sovereignty over the celestial body where the extraction would take place. Those proposing to undertake this type of extraction says this is not the



case and that extraction is just the same as fishing in the open seas of international waters.

This type of uncertainty in the world of global space governance - such as who can undertake space mining and under what terms - is but one example of why international agreement is needed. Governments and space-related businesses both need to know what the way forward will be for the longer term.

There will indeed be a need for a regulatory framework under which totally new types of activities can be carried out peacefully and in a business-like manner. There will need to be some form of rules that stops space businesses - or countries - fighting over why, when and how these activities will be accomplished. These will involve sorting out issues such as safety, liability, environmental concerns, ownership - or sharing of resources of the 'common heritage of humankind' - and so.

These 'rules of the road' will cover activities like those associated with solar power satellites and ground based 'rectennas', asteroid and celestial body mining, material processing in space, and even the establishing and operation of space bases and colonies. There will be a number of thorny issues that will create the most difficulty and angst.

The main issues today seem to be those related to global sharing and the so-called 'common

◀ Hunting and mapping asteroids by US-based artist James Vaughan.

heritage' of humankind and concerns related to the exploitation of celestial bodies, plus environmental hazards, safety, liabilities related to all types of space activities and, of course, concerns about the deployment and use of space weapons.

Of these unresolved issues, the deployment and use of weapons in space is perhaps the most important and dangerous threats we face.

One of the big problems is that the Outer Space Treaty of 1967 and the other agreements that followed in the 1970s relating to the safety of astronauts, registration of space objects, liability provisions, and the Moon and other celestial bodies are now several decades out of date.

These agreements did not anticipate significant commercial activities in space, the potential of our cluttering up Earth orbit with space junk, or the advent of cubesats, megasatellite constellations, hypersonic transport, stratospheric and celestial body pollution or robotic freighters - and many other issues stimulated by emerging technology.

Today no one seems to believe seriously that any new and sweeping space treaties are possible to negotiate and agree. Baby steps seem to be the way forward. Thus, instead of space treaties we seem to try to cope with things such as 'codes of conduct', transparency and confidence-building measures, model space national laws, and international voluntary guidelines such as those associated with orbital space debris.

Until it becomes clear as to who can do what, under what terms and conditions, under what types of possible liabilities, and with what opportunity for personal or shared profit, this will be a deterrent to new types of space business.

Some activities now underway - such as the UNCOPUOS Working Group on the Long-Term Sustainability of Outer Space Activities as well as the InterAgency Space Debris Coordination Committee (IADC) and the creation of the IAWN and the SMPAG committees to cope with asteroid threats. These, and other international efforts, all seem to indicate possible pathways through this minefield.

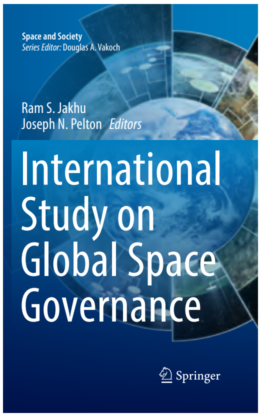
But the future is not what it used to be and more needs to be done. Much will depend on new way of thinking towards enlightened global space governance both now and in the coming decades. ■

About the author

Joseph N. Pelton, Former Dean International Space University. Author of The New Gold Rush: The Riches of Space Beckons (Copernicus Press, 2017) and co-editor with Professor Ram Jakhu of the *International Study on Global Space Governance* (Springer Press, 2017).

Today no one seems to believe seriously that any new widely agreed and sweeping space treaties are possible to negotiate and agree

International Study on Global Space Governance



In advance of the publication later this year of the International Study on Global Space Governance, the editors Ram Jakhu and Joseph Pelton summarise the study process and its findings, along with its recommendations on how to move forward to create a NewSpace economy and new regulatory gestalt for space activities - including economic, social and cultural activities; research, technology, science and education; and human existence off our planet.

Some space lawyers and nations consider what we have examined in our two-year international study on 'global space governance' as being a very restricted subject indeed. They would argue that global space governance should only address and consider a very limited amount of 'established space law', essentially meaning the 1967 Outer Space Treaty, its supplementary international agreements and perhaps a few international law precedents created over a significant period of time.

This global study has involved over 80 space scientists and engineers, space business people, regulators, space lawyers and policy experts from over 25 countries around the world.

It addresses international, regional and national space laws and policies around the world, technology trends and future space activities that are anticipated, along with regulatory mechanisms that might help the future development and use of outer space. It has considered emerging technical trends and NewSpace entrepreneurial business.

This study has examined new and expanding uses above commercial air space, increased use of various types of Earth orbits, along with expanding frequency needs and new commercial ventures planning to use deep space to extract natural resources and solar energy to return goods and services to Earth, space colonisation and the equitable sharing of space benefits.

This international and interdisciplinary study, which was commissioned to fill the gaps and holes in the fabric of global space governance, was launched as a result of the so-called Montreal Declaration of May 2014 at the 2nd Manfred Lachs Conference.

It has, in essence, broken most of the rules in terms of what strict space law experts consider the well defined realm normally designated space law. Whereas space lawyers usually drill deep into a particular facet of space law, this study was broad and interdisciplinary. Whereas space lawyers examine past precedent in great detail, this study examined future trends and emerging regulatory and policy questions.

In seeking to carry out a broad brush look at all aspects of global space governance, we have thus considered codes of conduct, national space laws, safety and technical standards, transparency of operations and confidence building measures, especially with regard to space security and space traffic management concerns.

We have endeavoured to identify institutional reforms that might meet emerging space business concerns and help smooth out disputed areas of interpretation of international regulatory actions.

This intensive international study reached a wide range of conclusions. We see the need for some urgency to address the why, when and how of space traffic management and orbital and frequency allotments in the context of mounting levels of commercial activities in Earth orbit, orbital space debris, the planning for large-scale constellations of satellites in low Earth orbit and unregulated space mining.

Other drivers of concern to create improved global space governance include the rapid expansion of NewSpace entrepreneurial activities that involve new types and lower cost launch vehicles, commercial space stations, hypersonic transportation flights and commercial space tourism flights.

There are also concerns about the possible weaponisation of space and conflicts in space, environmental concerns related to more intensive launch schedules for private, civil government and military space systems, as well as a realisation that space systems are critical to weather monitoring, disaster recovery, and monitoring and control of climate change.

There are multiple purposes for which this study was conducted, although prime among them was to assist UNCOPUOS in planning for the UNISPACE +50 Conference in 2018. The table below lists just some of the topics of concern where improved global space governance might help in the future. These initiatives seek to assist the future development and implementation of space science, space exploration, space applications, and safer and more effective commercial utilisation of outer space. Progress in many areas of global space governance will be required as we move forward to embrace a global space economy in the decades ahead. ■

Ram S. Jakhu & Joseph N. Pelton

Co-editors, *International Study on Global Space Governance*

AREAS OF CONCERN	POSSIBLE PATHWAYS FORWARD
Common heritage of humankind issues	Recognise the limits but significance of the 'Moon Agreement' in seeking a way forward towards an organised governance system for space mining. This involves trying to identify a new and viable structure to capitalise and develop technology to allow resource extraction from space, such as the Intelsat international public-private organisation offered at the start of satellite communications
	Explore possible precedents from 'Law of the Sea' or other sources of law for further development of the regulatory regime for space mining
Cosmic hazards and planetary defence	Creation of an inter-agency committee of civil space agencies to better understand cosmic threats and potential of new ideas like 'solar space shields' to cope with coronal mass injections and climate change, the dangers of Earth's changing magnetosphere, and reduced protective shielding of the Van Allen Belts
	Expand scope of IAWN (International Asteroid Warning Network) and SMPAG (Space Mission Planning Advisory Group) to explore new technologies and concepts to cope with asteroids hitting Earth
Environmental concerns	Develop better understanding of environmental risks associated with expanded launch of rockets, spaceplanes and hypersonic craft, and of systems that pollute the stratosphere the least
	Improved space-based environmental monitoring systems
	Globally agreed guidelines for deep space exploration and activities to prevent global viral pandemics from space
Frequency and orbital allocations	Improved rules and enforcement powers for the ITU (International Telecommunication Union) to reduce jamming, ensure equitable sharing of radio frequencies, require greater technical efficiency in frequency reuse and efficiency in new satellite systems and more ably control orbital assignments to prevent runaway use of large-scale satellite constellations
	New national laws to enforce frequency efficiency (terrestrially and in space) and limit runaway authorisations of satellite networking systems
Orbital space debris	Improved and mandatory system to restrict the generation of space debris
	Regulatory guidelines (including proper liability provision) to encourage active space debris removal
	Process to ensure debris removal efforts do not constitute space weapons and most dangerous debris removed first
	National space laws to enforce removal guidelines
Private NewSpace initiatives standing under international law	Place international responsibility and international liability more directly on owners of privately-held spacecraft or launch systems
	Create national regulatory systems to implement such responsibility and liability
Fragility of space security	Address concern that more and more space-based capabilities and vehicles designed to operate in so-called Protozone areas could lead to hostilities in space. Systems to deal with cosmic hazards, systems that might deployed in the Protozone, robotic systems, high altitude platform systems, etc. further increase these risks. Development of space weapons and preparations for use of force threaten the use of space for peaceful purposes. Efforts to create space and Protozone traffic management need to include military forces and seek controls to eliminate space warfare
Space & Protozone traffic management	UN Mandate to UNCOPUOS and the International Civil Aviation Organization to develop new regulatory framework, together with national agencies charged with aviation safety regulation, as well as space to create a new international traffic control and management systems. This would oversee and coordinate safety for aircraft flights, spaceplane flights, spacecraft launches and international hypersonic craft flights into the Protozone, as well as other international deployments of balloons, dark sky stations or robotic flights into the stratospheric regions outside of prescribed national aerospace controls
Global Space Organisation	UNCOPOUS should start considering the creation of a global space organisation, which would be indispensable for achieving the goal of sustainable use of outer space for peaceful purposes and for the benefit of all states. This is becoming increasingly important since numerous issues related to space (like space mining, cosmic hazards and planetary defence, orbital debris removal, space security, space and Protozone traffic management, etc.) are becoming intertwined in terms of technology and policy. Such issues and concerns need to be addressed in an international forum with permanent administrative and expert staff, and with active participation by States, the private sector and civil society

Surviving radiation for space colonisation

▲ Multi-dome lunar base being constructed, based on the 3D printing concept. Once assembled, the inflated domes are covered with a layer of 3D-printed lunar regolith by robots to help protect the occupants against space radiation and micrometeoroids.

The long-held dream of humankind to explore and colonise space is closer than it has ever been. As the budding commercial space mining, tourism and transportation sectors along with national space agencies extend their reach further into space, concepts are now being developed with the ultimate goal of establishing human outposts and colonies on the Moon and Mars. Here, in the first of two articles, Joseph Parker considers the dangers that different types of radiation will pose to crews travelling and living beyond Earth. His second article, to be published in *ROOM* later this year, will suggest how these extreme radiation risks might be managed and mitigated.

L. Joseph Parker
MD, Arkansas, USA

Building a space colony that will protect and sustain a population of hundreds or even thousands of colonists in an environment that is hostile to human life presents huge technological and economic challenges. One of the greatest challenges for the first humans living away from Earth will be that of excessive radiation exposure which can lead to the early onset of cancers and affect reproduction.

Threats posed by radiation exposure will always be particularly high for the first colonists tasked with the job of building habitats and preparing the infrastructure of a new colony. To understand and evaluate the threat, scientists have to analyse what expected radiation exposure levels are, how well humans can tolerate these levels and what can be done to mediate the risks.

Understanding radiation

Radiation is energy emitted as electromagnetic waves or high-speed atomic or subatomic particles. Radiation waves are generally ‘invisible’, have no mass and no positive or negative charge. Some radiation waves, such as light or heat, can be seen and felt, while others like X-rays can only be detected by instrumentation. Radioactive particles are also invisible but they have ‘weight’ and may have a positive or negative charge.

Ionizing radiation converts atoms or molecules into ions by stripping one or more electrons from them, breaking molecular bonds and damaging cells. Examples of ionizing radiation include X-rays and gamma rays.

Non-ionizing radiation is relatively low-energy radiation that doesn’t carry enough energy to ionize atoms or molecules. Radio waves, microwaves and low energy visible light are generally included in this category. Ionizing radiation can be categorized as photonic or particulate.

Photons

Photons have no rest mass and their impact is determined by their energy levels. Radio waves have the lowest energy level of all photonic radiation. Microwaves have more energy and can cause hydrogen atoms to speed up, increasing temperature. Infrared light has more energy than microwaves and it transmits heat in general, and then the energy of visible light increases from red through to violet.

When photons have enough energy to be ultraviolet they become ionizing and can cause damage. Ultraviolet rays cannot penetrate very far but they are of concern as they cause plastics and other materials to break down more quickly, and on human skin extended exposure strips electrons off the DNA molecules in the nucleus of skin cells, causing mutations that can result in cancer. The Sun emits a lot of ultraviolet light but we are protected from most of it by Earth's ozone layer.

X-rays are higher frequency photons which are useful for medical imaging because of their ability to penetrate the human body but, for the same reason, they can cause damage if we are exposed to too many. Earth's atmosphere absorbs most X-rays from space but a small proportion get through and people who live at higher elevations or fly often tend to receive a higher exposure than those who stay near sea level.

The most energetic (highest frequency) photons are gamma rays and these can penetrate from several centimetres to several metres of lead, depending on their energy. Almost all gamma rays are absorbed by the atmosphere of Earth.

Our Sun produces every level of photonic radiation - from ultra-long wavelength radio waves to gamma rays, although the latter are converted to lower-energy photons before they are emitted into space.

Particulate

Particulate radiation is produced when an atomic or subatomic particle with rest mass is accelerated to very high speeds, usually near the speed of light. These particles are like tiny bullets and all are ionizing.

The lightest particles are electrons, also known as beta radiation. These have a negative charge and, although very light, can penetrate several centimetres of wood and cause damage to living things.

High speed protons are about 2000 times as heavy as electrons and are positively charged particles found within atomic nuclei. They are produced in huge amounts by the Sun and are a major component of solar radiation and solar wind.

A proton is simply a hydrogen nucleus. Hydrogen can have other isotopes that have a proton and a neutron, called deuterium, or two neutrons and a proton, called tritium. These are much less common but have, respectively, twice and three times the mass of a simple hydrogen nucleus so they transfer more energy if travelling at the same speeds.

High speed helium, or alpha particles, have two protons and one or two neutrons. Helium-3 is not readily found on Earth but is emitted by the sun and is present on the Moon in the regolith.

The Sun generates a lot of this type of particle from its fusion reactions and there is quite a bit in the solar wind. The nuclei are all ions, their electrons stripped away as they are accelerated, and they have a charge.

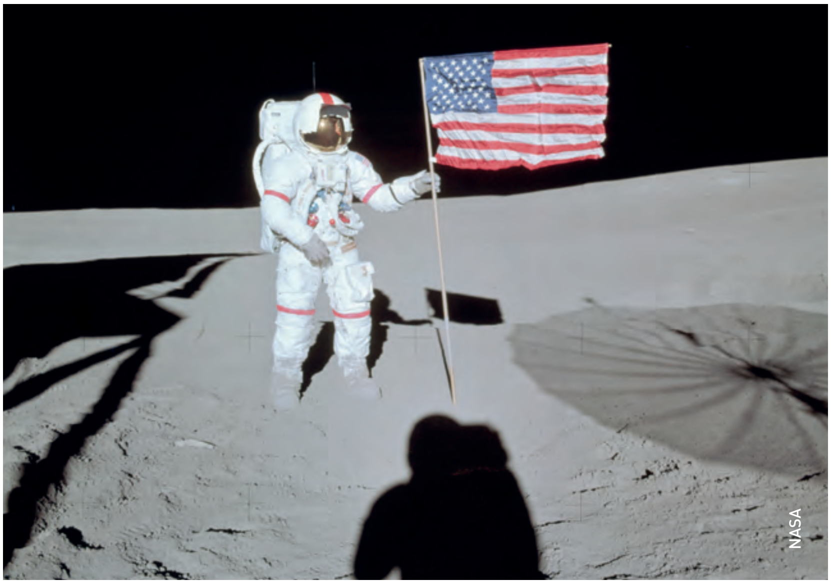
The last level of particulate radiation to consider is created in supernovae and other energetic cosmic events that produce fast moving particles much heavier than hydrogen or helium. Atoms as large as iron atoms - the heaviest element a star can normally make - can slam into objects in space, transferring a huge amount of energy in the collision. The particles interact with the electric fields of the matter they hit and slow down, transferring energy to whatever they hit.

This energy causes a cascade of high energy photons, free electrons and sometimes neutrons to be generated. These particles go on to produce damage themselves in a process known as secondary radiation. Particulate radiation that comes from outside the Solar System rather than the Sun is called galactic radiation.

Earth's magnetic field has a strong effect on all these ions because they have an electric charge. The field redirects them around Earth where they orbit and lose energy until they enter the atmosphere at the poles and in the process create the Northern and Southern Lights. Almost all of the particles that get through are absorbed by Earth's atmosphere before they reach the ground.

One of the greatest threats to future humans living away from Earth is that of excessive radiation exposure

▼ The Apollo lunar landing craft were part-shielded to afford some crew protection from radiation. Apollo 14 astronauts Alan Shepard (pictured) and Ed Mitchell, who spent 33½ hours on the Moon in 1971, received the highest exposure of any of the crews due to active solar storms.



▲ The Mars One habitat plan includes using landing capsules as living space and inflating large greenhouses and other structures. The inflatable structures would then be buried under soil to provide radiation protection, a task requiring a considerable number of unshielded hours to accomplish.

Moving off Earth

Protection provided by Earth's magnetic field and atmosphere means that in general people living on the surface are not exposed to the damaging effects of radiation exposure.

Today, however, as future plans are being developed for people to move and live away from Earth in orbiting colonies or on the Moon or Mars, exposure to space radiation will be a serious hazard.

Scientists and engineers will have to find creative ways to deal with this danger. One of the greatest concerns when planning a permanent settlement, for example, must ultimately be that of successful reproduction. If humans cannot conceive and produce healthy children away from Earth it will become impossible for a colony to expand and grow naturally.

The first question to answer is how much radiation someone will be exposed to as they travel through space from Earth orbit to their destination on the Moon, Mars or elsewhere.

On Earth we are protected from radiation by the mass of the Earth itself, then by the magnetic field and finally the atmosphere. Low Earth orbit (LEO), where the International Space Station is located, is protected by Earth's magnetic field but not its atmosphere.

Mars on the other hand has no strong magnetic field to shield us from ions, no ozone layer to stop ultraviolet rays and only a thin atmosphere to absorb radiation. On the Moon there is no magnetic field, insignificant atmosphere and only the Moon's rocky mass to block some radiation.

Once the first crews leave Earth orbit they will be hit from all sides - by solar radiation from the direction of the Sun and by galactic radiation.

Measuring radiation

Radiation doses can be measured in Sieverts (Sv), which is a measure of radiation absorption by the human body equal to 10 ergs of energy of gamma radiation delivered to one gram of living tissue. It is adjusted to take into account the relative biological effectiveness of ionizing radiation of all types - therefore, one Sievert of X-ray radiation would have the same danger to a living thing as one Sievert of gamma radiation.

A worldwide average of radiation exposure on Earth is about 3 millisieverts (1 Sv=1000 mSv).

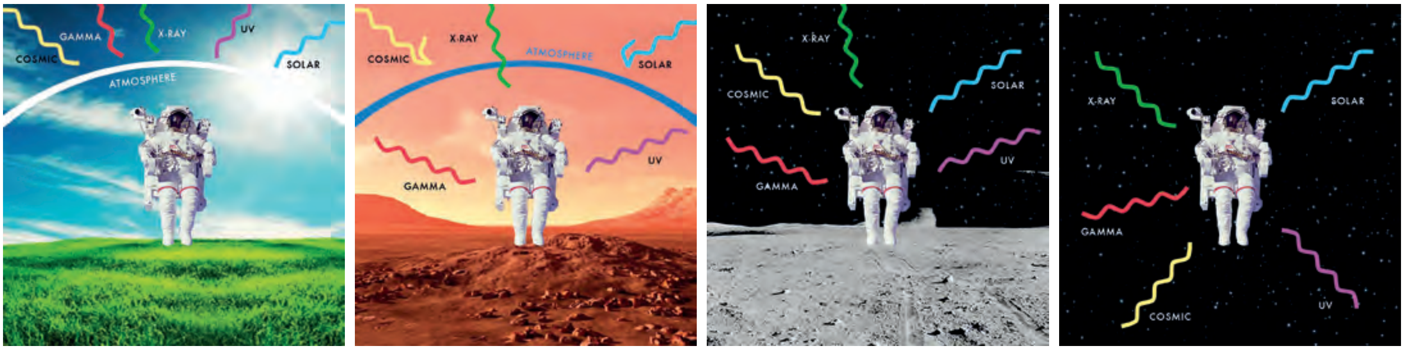
Table 1 shows that the average annual radiation exposure in open space is 219 times more than on Earth while that on the Moon is 146 times more. The surface of Mars would be a little more than 81 times the average annual exposure rate of Earth

The Apollo astronauts, the only humans so far to travel outside of LEO, received from about 1.6 mSv to 5.8 mSv - with Apollo 14 receiving 11.4 mSv from solar storms which occur when the Sun releases a huge burst of plasma that travels at high speed out into space. The astronauts' lunar

Table 1: Annual ambient radiation levels for the Earth, Mars, the Moon and space.

	EARTH	MARS	MOON	SPACE
Annual Total	3 mSv	245 mSv	438 mSv	657 mSv
Daily Average	0.0082 mSv	0.67 mSv	1.2 mSv	1.8 mSv

▼ The different categories of radiation experienced on Earth, Mars, on the Moon and in open space



landing craft were part-shielded to afford some protection to the crew.

The dosage of radiation a human being can tolerate depends on how quickly it is delivered. One Sv over a short period of time will cause acute radiation sickness and 10 Sv is often fatal. Emergency workers at Japan's Fukashima nuclear plant disaster in 2011 received up to 678 mSv, yet none of them suffered acute radiation sickness. The effects of radiation are somewhat cumulative, however, and long periods of continued exposure to higher than normal levels of radiation cause increased likelihood of cancer.

Studies of radiation exposure in large populations like Hiroshima, Nagasaki, Chernobyl and Fukashima have allowed projections to be made about relatively safe levels of radiation. NASA considers an increase in lifetime cancer risk of three percent to be reasonable.

Evidence from these events has also shown that the younger the person is at the age of exposure the greater the risk over the lifetime of the person, and that women suffer greater effects from radiation than men. As a result, NASA has created a graduated standard for maximum radiation exposure for astronauts, dependant on age and sex for one year and lifetime limits.

The European Union (EU) and Russia have set a more conservative standard based on their own research, a 1000 mSv career limit across all ages and sexes.

NASA career radiation exposure limits.

AGE	MALE	FEMALE
25	1500 mSv	1000 mSv
35	2500 mSv	1750 mSv
45	3250 mSv	2500 mSv
55	4000 mSv	3000 mSv

The first colonists tasked with building habitats on the Moon or Mars will need to survive on the surface with little protection, at least until the first shielded structures have been completed. These structures will likely have to be buried under about 800 cm of regolith to offer sufficient long-term protection. How long this will take without heavy equipment has not yet been accurately determined though we can still broadly estimate the 'safe' time builders can spend working on such a project.

A seven-day journey to the Moon would give a dose of about 11 mSv. Yearly exposure without shielding should average 438 mSv. This would give the Russian and European astronauts 2.58 years to work on the surface in inflatable or thin metal habitats before they reach their career limits, which would seem to be a reasonable amount of time to accomplish habitat construction.

Conversely, a six-month journey to Mars will give a dose of about 324 mSv and, assuming an equal dose on the way home, would leave only 352 mSv of unshielded surface work before the 1000 mSv limit was reached. This would translate to about 1.44 years at 245 mSv per year exposure. Again this seems like a reasonable amount of time to get the job done, depending on the size and sophistication of the habitats.

NASA limits are more generous and would allow a minimum of 1.44 years for a 25-year-old female to a maximum of 13.68 years for a 55-year-old male. It seems clear that, even using a shovel and the most stringent standards, it should be possible to build sufficiently shielded habitats on the Moon or Mars without the builders exceeding their nation's career limits for radiation exposure.

Of course, not every one of the same age and sex has the same risk. Some people are genetically more resistant while others are more vulnerable. So age, sex, medical history and individual susceptibility to radiation will also have to be taken into account when selecting the first colonists.

Depending on the speed of travel, the Moon has the advantage of being only a few days from Earth. This allows for an easy return for someone who has reached their exposure limit or some other emergency. Mars is much farther away and, while some colonists will choose to return, those travelling there to establish the colony should be willing to stay and make their lives there. The question of who to send as the first colonists to Mars or the Moon is therefore very important to the success of these endeavours. ■

About the author

L. Joseph Parker has a doctorate of medicine from the Mayo Clinic with honours in Neuroscience, and a Master's of Science in Space Studies from the American Public University. He was a Captain in the US Air Force, serving first as a Minuteman II ICBM Deputy Commander at Malmstrom AFB in Montana, and also with the US Strategic Air Command and later with US Space Command. He went to medical school becoming an Air Force doctor and now practices emergency medicine and has a private clinic.

The first colonists tasked with building the habitats on the Moon or Mars will need to survive on the surface with little protection

▼ Orion is NASA's first spacecraft for long-duration deep space exploration. It will transport humans to and from interplanetary destinations such as asteroids, the Moon and eventually Mars.

Lockheed Martin

Margarita A.Levinskikh, Laboratory of Biological Life Support Systems, Russian Academy of Science Institute of Biomedical Problems, Moscow

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Growing plants without gravity

Whilst today's space missions in near-Earth orbit use partial water regeneration and oxygen is replenished by water electrolysis systems, crews remain reliant on supply ships for timely delivery of food supplies. In the future, on long-term flights to the Moon or Mars, they will carry plants and crew members will need 'green fingers' to cultivate, tend and harvest crops that will supplement food stocks. Learning how to grow plants in space now will also contribute to the development of advanced life-support systems of the future, from gas exchange and food production to potable water reclamation.

The idea of using plants to maintain life support systems in space is not a new one. Russian scientist Konstantin Tsiolkovsky first suggested it over one hundred years ago in his 1911 work, *Exploration of Outer Space by Rocket Devices*. "Just as the Earth's atmosphere is cleaned by plants with the help of the Sun," he wrote, "so our artificial atmosphere can be renewed... the plants we take along with us during the journey can work uninterruptedly for us."

Tsiolkovsky understood not only the main principle of using regenerative systems for deep space flight but, in his 1926 works Outside the Earth and Plan for Conquering Interplanetary Space, he also suggested the construction of a cylindrical space greenhouse in order to obtain oxygen, food and clean the air in the capsule. "Man then achieves greater independence from Earth, as he is able to procure necessary life support elements on his own," he wrote.

Tsiolkovsky had no doubt that if an appropriately developed plant cultivation method was used, many varieties of fruit and vegetables would grow and bear fruit in weightlessness. His greenhouse project was technologically very advanced and has lost none of its potential even today.

First attempts

By the time the spaceflight era really got under way there was already a clear understanding of the potential role of plants in space exploration. But unlike Tsiolkovsky, modern scientists had doubts that plants would be able to successfully grow and reproduce in a zero gravity because their dependence on gravity was considered too great.

Early experiments also suggested it was unlikely that plants would thrive in space. From 1971 to 1990 plants in space were cultivated in small greenhouses, fitted with low-power lights and, for the most part, without regulatory control systems. Because of the imperfect horticultural equipment used many of these experiments failed.

The best result of that period was the successful growth of arabidopsis (a member of the mustard family) seeds on the Saylut-7 orbital station in a Phiton-3 apparatus in 1982. But many later attempts to repeat this experiment failed.

The Svet greenhouse, a joint project by Russia and Bulgaria, was the first automated greenhouse in orbit. It had a larger planting area than previous devices, a higher vegetation chamber, a much brighter light system and automatic controls - and it was also able to process and send to Earth collected data on the plants' environment and the conditions of the greenhouse modules.

In 1990, the first experiment in cultivating pak choi cabbage and radishes was conducted in the Svet greenhouse on board the International Space Station (ISS). The productivity and speed of ontogenetic plant development (from the earliest stage to maturity) in this experiment was lower than in the Earth control group, which again confirmed the position of those scientists who believed that weightlessness had a negative impact on plants.

Later, specialists at the Institute of Medical and Biological Problems (IMBP) at the Russian Academy of Sciences and the Space Dynamics Laboratory at Utah State University equipped the Svet greenhouse with the Gas Exchange Measurement System (GEMS), which measured hydrocontent dynamics in the vegetation chamber and plant gas exchange, as well as controlling the conditions of plant cultivations.

After in-flight experiments were completed, control experiments were run on Earth in special climate-controlled chambers with simulated dynamics of the main parameters of plant cultivation, as recorded during the spaceflight. To provide normal growth and development of plants in weightlessness, both the correct methodology and the right equipment to regulate the water and air settings of the root environment were needed.

FEEL-GOOD FACTOR

The 1997 Brassica rapa L. experiment was noteworthy not only because of interesting biological results but also because of the intricate work performed by astronaut Michael Foale on the manual cross pollination of the tiny Brassica flowers, all achieved despite the dramatic events of 25 June 1997 when Mir was depressurised after a collision with a Progress transport ship during a docking test, which almost cost the crewmembers their lives.

In an interview about his in-flight experiment Michael Foale spoke of the wider benefits he experienced of the presence of green plants.

"The greenhouse experiment provided me with peace of mind," he said. "It's a special sort of task – to be a gardener, to live together with your plants, to fully grasp their situation and have a sort of connection with them; it impresses on you visually and allows you to do the sort of work that's very different from the extremely technological environment of spaceflight that lacks so many things.

"It's a connection with Earth that you take with you and that gives you comfort. I took great pleasure in checking up on the greenhouse every morning. It was supposed to take twenty minutes a day, but I spent a lot of time in the greenhouse and valued that time very much. And I think that during lengthy flights or at any space station, experiments where something is grown [such as plants] can find a wide range of uses not only in scientific research but also for psychological support."

Observations like these - on the psycho-emotional condition of space crews - have been expressed by almost all astronauts that have participated in plant experiments.

The thermo-impulse method of monitoring the root moisture levels in weightlessness was suggested and subsequently used, and data obtained on root moisture levels during these space experiments provided the necessary information to allow astronauts to control moisture for the first time in human spaceflight history.

If at first you don't succeed...

In 1995 a joint team of Russian and American researchers attempted to grow super-dwarf wheat in space for one ontogenesis cycle – 'from seed to seed' – in the Svet greenhouse on the Russian Mir space station. This first attempt was not fully successful; lamp sets failed and the plants did not form a head, remaining at the vegetative stage of development. In

◀ Pea flowers in the 'Lada' greenhouse.

▼ Michael Foale and Alexander Kaleri beside the pea plants growing in the Lada-4 greenhouse experiment.

the Earth control group, with similar low light, the plants still formed heads, albeit sterile ones without seeds. This led to the conclusion that some negative factor had affected the wheat in flight, a theory that was confirmed by the next experiment in 1996.

This time, the wheat grew and formed heads but it was obvious from photographs and videos that something strange was going on with the plants. When the materials were delivered to the Russo-American team back on Earth we were all shocked to discover that in almost 300 fully formed wheat plants there wasn't a single seed!

The plants also showed significant morphological changes. Compared to Earth-control plants the microgravity plants had almost three times as many heads, while the culm (stem) was half the length, the head mass half the weight, the flower head length was shorter, and there were less spikelets in a head though the average number of flowers in the spikelets was higher.

Microscopic cytoembryological analysis of the biological materials showed that the lack of seeds in the heads was due to utterly sterile pollen.

Morphological and cytoembryological changes in the plants that had grown in space were in many ways similar to the results described in literature on ectogenous use of ethylene and ethylene-containing products, which are strong phytohormones, and this led to the assumption that one of the most important factors that influenced the growth and development of plants in the Svet greenhouse was high levels of ethylene.

The first measurements of ethylene in the Mir atmosphere showed an average concentration of 1.1 mg/m³, a perfectly safe concentration for humans. Higher levels of ethylene in the atmosphere in Earth control conditions also led to increased tillering (shooting from the root or bottom of the original stalk) without changing the plant mass, a shorter culm and no viable seeds.

The next Russo-American experiment in the summer of 1997 planned to grow a model short-cycle plant, Brassica rapa L. in two generations. And for the first time in history it was a success! Brassica turned out to be more tolerant to higher ethylene concentrations in the station's atmosphere and it produced viable seeds both in the first space generation and in re-seeding of those seeds in the space greenhouse.

Ethylene did, however, cause serious changes in the plants – all morphometric characteristics, such as plant height, number of pods and seed mass, turned out to be half of their Earthly counterparts.

In 1998-1999 we repeated the experiment on growing two-generation plants on Mir but this time with wheat – a more interesting plant in terms of future life support systems. The USU-Apogee type of wheat was selected for better tolerance to ethylene and the variety chosen was created by researchers at Utah State University under the leadership of Bruce Bugbee, especially for greenhouses of various bioregenerative life support systems, including those in space.

Both experiments on Mir resulted in viable wheat seeds, and the space plants did not differ in their morphology from the Earth plants.

During lengthy flights an experiment where something is grown can find a wide range of uses not only in scientific research but also for psychological support

DEVELOPING TASTE

For the final experiment in the Svet greenhouse on Mir in 2000, the flavour of leafy vegetables grown in weightlessness was evaluated by the cosmonauts. Tasting the greens, cosmonauts Aleksandr Kaleri and Sergey Zaletin remarked that adding fresh greens to a crews' diet would be very desirable, particularly if they were spicy rather than bland.

Later on, cosmonaut Maksim Surayev wrote about the lack of flavour: "Roma (Roman Romanenko) was growing some sort of salad on the space station. And the salad was so green, Roma obviously wanted to eat it. I too really wanted to eat it! But back on Earth they wouldn't allow it. They said – you have to freeze it and send it back to Earth for science!

"Imagine this green salad, and two young healthy cosmonauts staring at it, unable to try it! We decided nothing awful would happen if we just tried a tiny piece. So we chewed some. Such a disappointment - because the greens had absolutely no taste!

"When I was planting my own salad, I found some wheat seeds that had been left behind by another expedition and I sneaked them in and planted them too. But then the scientists from Earth told me to get rid of the wheat.

"I'm sorry, dear scientists, I couldn't do it – it was growing so beautifully! Just look at the heads on this wheat! And I really do hope that they turn out tastier than Roma's salad!"

▼ Cosmonaut Sergey Volkov, the seed-to-seed cycle of the super-dwarf wheat growing experiment in the 'Lada' greenhouse on the International Space Station in 2011.

Building on success

The first plant experiments conducted in the Svet greenhouse onboard Mir showed that spaceflight does not seriously impact fundamental biological processes such as growth, development, seeding, photosynthesis and metabolic activity. The results of research on higher plants in weightlessness made it possible to integrate greenhouses in spacecraft with the use of technology for cultivating higher plants in zero-gravity environments, as part of the spacecraft life support systems.

Overall, this series of experiments was very successful but a lot remained unknown, such as how plants would behave during long-term cultivation in space and if their genetic make-up would subsequently change.

In order to continue our plant experiments on the ISS, our Russo-American team built a new greenhouse called 'Lada'. Many thought the name was chosen after, Lada, the Slavic goddess of marriage, love, home and harvest but the truth was much more down-to-earth.

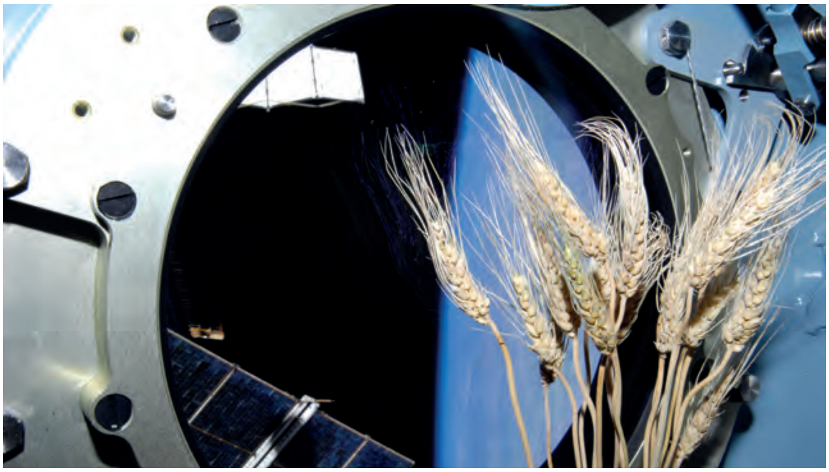
Work on the future space greenhouse began in the spring of 1999 with very little financing, very little time, very limited space on the ISS and an energy allowance of only 60 watts for all lights and supporting mechanisms. So, rather than opt for a complex and sophisticated 'Rolls Royce' greenhouse, we decided to build a simple, yet reliable one – like the Russian 'Lada' car!

Thanks to our invaluable experience with Svet, we were able to build and get certification for Lada very quickly and in October 2002, the first experiment in cultivating mizuna (a type of mustard greens) began.

Between October 2002 and November 2011, 17 experiments were conducted in the Lada greenhouse aboard the ISS, including experiments with mizuna, radishes, two genetically marked types of dwarf peas, two types of barley and super-dwarf wheat and there were some interesting results.

In each of these experiments the plants grown in space showed the same characteristics and speed of development as those in the control group on Earth. The pea plants retained their reproductive function and formed viable seeds during four full consecutive in-flight 'seed to seed' cycles. Genetic analysis gave serious weight to the hypothesis that the plants' genetic makeup does not change over a few generations growth on the ISS.

Microbiological research on the mizuna plants showed a lack of disease-causing microorganisms on mizuna leaves in spaceflight and analysis of the dietary characteristics showed that space-grown mizuna biomass conforms to food safety and nutritional content standards.



▲ Top: Roman Romanenko with some of his mizuna plants.

▲ Above: Super-dwarf wheat grown by Maksim Surayev.

Increases in the T-value, an index of overall air impurity on the ISS, did not affect the productivity of the mizuna plant. The average amount of aerophilous microorganisms corresponded to the normal amounts recommended for nutrition with crews that remain on the ISS for up to 360 days.

A super-dwarf wheat growing experiment for the full vegetation cycle in the two chambers of the Lada greenhouse showed that the plants developed normal sprouts, heads and seeds.

With these results we now know that it is possible to grow leafy green vegetables and biologically viable and normal wheat seeds in a greenhouse on board the ISS that do not significantly differ from their Earth-grown counterparts. This data will be of great interest for projects dealing with the creation of working greenhouses that can become part of life support systems for future space crews. ■

The authors would like to extend their thanks to Gail E. Bingham and their other American colleagues for all the years of our successful cooperation, and would also like to thank Russian cosmonauts and astronauts for their wonderful camera work while recording the in-flight experiments on Mir and the ISS.

It's a special sort of task – to be a gardener, to live together with your plants

▶ The HI-SEAS habitat on Hawaii.

Recipe for success on flights to Mars

Astronauts and cosmonauts working for six months or more on the International Space Station have already proved that eating and sharing meals together is a vital part of any successful long-term space mission - food is not just fuel for the body but also a conduit for culture, comfort and camaraderie. And nowhere will this be more so than on the first human flights to Mars when mission durations will be measured in years.

Dr Martha Lenio
Mars Green Consulting, Ontario, Canada

Sophie Milam
SVL Analytical Inc, Idaho, USA

Zak Wilson
Chief Engineer, HI-SEAS Mission III

Space food might conjure thoughts of the fruit-flavoured Tang drink, astronaut ice cream or space food sticks, but none of these products have the strong connection to space that one might imagine. Tang wasn't developed for space, merely used during some early flights. Astronaut ice cream, the staple of air and space museums worldwide, was actually developed for spaceflight but hasn't ever flown to space. And space food sticks were mostly a commercial product attempting to cash in on the excitement around spaceflight in the early 1960s, though they did fly aboard Skylab III.

Today's space food eaten aboard the International Space Station (ISS) shares more similarities with military Meals Ready to Eat (MREs), vacuum sealed plastic pouches that must be rehydrated or reheated. Ideally, space food should be lightweight, compact in volume, nutritious, easy to prepare, eat and clean up (microgravity complicates all of these requirements), long lasting and delicious.

For a mission to Mars, food will need to last many years. Food for Mars-bound astronauts would be nearly two-and-half-years old by the time the astronauts returned to Earth, and supplies pre-positioned on Mars, sent during the launch window

prior to a manned mission, would be three-and-a-half-years old by the time a crew arrived on Mars.

From a logistics view, the ideal food is a nutrient- and calorie-dense brick that would last for many years; the modern equivalent of hardtack and salt pork, though with better nutritional value. But such food 'bricks' are less than ideal from a crew perspective.

We were three of the six members of HI-SEAS Mission III, which gave us an insight into some of the issues that will be faced by future crews journeying to Mars.

HI-SEAS (Hawai'i Space Exploration Analog & Simulation) is a series of simulated Mars missions funded by NASA and run by Dr Kim Binsted of the University of Hawaii. The study's overall goal is to investigate crew selection, performance and cohesion; and how to apply those lessons to a crewed mission to Mars.

Our mission, ran for eight months up to June 2015. During this time, we lived in a dome on the side of the Mauna Loa volcano in Hawaii, in the middle of a desolate lava field. We didn't see people beyond the members of our crew and communication with the outside world was limited to methods with an imposed 20-minute delay to simulate the time it takes for a signal to travel between Earth and Mars.

Water was only periodically trucked in, thus limiting crew members to eight minutes of showering a week. Power was supplied by an off-grid energy system. And to venture outside we had to don simulated space suits. And for meals, we could only eat food cooked from shelf-stable ingredients - i.e. food that would last a three-year mission to Mars without spoiling.

Most of our meat, vegetables, fruit and dairy came in either dried or freeze-dried form. Removing the water delays spoilage and reduces weight and freeze-dried foods tend to have a Styrofoam-like texture before they've been rehydrated, while dried foods are much denser.

There was also a large stock of grains, legumes, flours, spices, seasonings and a variety of snacks. Generally, canned items were avoided because of their relatively heavy weight. Our pantry was

▲ Top: Expedition 20 crew members Timothy Kopra, Frank De Winne, Roman Romanenko and Michael Barrett share a meal in the Unity node of the International Space Station. Above: Martha collects rocks.

Life in the HI-SEAS dome could become a little stale

> **Space food might conjure thoughts of Tang, astronaut ice cream or Space Food Sticks, but none of these products have the strong connection to space that one might imagine**

a 20-foot shipping container mostly full of food - but even that wasn't large enough to keep six people fed for the eight months. We needed three re-supplies as well.

Initially, we ate some of the pre-made freeze-dried meals similar to the kind used for camping, but they were disliked by most of the crew. A favourite low power meal was Build-Your-Own-Ramen - put all your favourite freeze dried veggies, meats, soup base and noodles in a big bowl and just add boiling water. On sunny days, when power wasn't a concern, we were able to be more creative.

Social structure

As a crew, we decided how we wanted to organise our meals. For breakfast and lunch, people mostly cooked for themselves whereas dinner was prepared by a team of two and eaten all together. We set a rotating cooking schedule, which was occasionally interrupted by days of leftovers, low-power days or special celebration meals. Each day there was a chef in charge of making dinner with an assistant sous chef. There was also a clean-up crew of two for the day. After each chef and sous-chef had cooked, the sous chef would shift, so eventually every crew member worked with every other person in both a leading and following role. This was one of our few areas of social structure over the course of the mission and was devised by the crew. Other crews have organised their time and duties differently.

Our kitchen was small but well-equipped. We had induction cooktops, a small oven, microwave, toaster, kettle, rice cooker and yogurt maker. We also had a small garden which was Martha's personal research project. It wasn't large enough to make a significant contribution to our calories but the rare, small portions of fresh salad we got from it and the slightly more plentiful herbs were always a welcome addition. It was also a connection to 'Earth' and our only source of green.

Life in the HI-SEAS dome could become a little stale. The scenery through the one window never changed, the work was repetitive and the EVAs never took us more than a mile or two away.

The greatest source of variety day-to-day was our food though crew members quickly found out that cooking with the shelf-stable ingredients could be difficult and sometimes frustrating.

Challenges in the kitchen had to be overcome with willpower, creativity and necessity. Something that would take a few seconds on Earth, like adding cheese to a meal, might take a full hour on our simulated Mars because rehydrating the freeze-dried shredded cheese could only be done slowly and incrementally by adding cold water and keeping the container in the refrigerator.

The pre-made meal most commonly eaten in the dome was macaroni and cheese. Its popularity was more dependent on it being a staple comfort

Zak Wilson

Jocelyn Dunn

▼ Below: Selection of shelf-stable food.
Below right: Home grown salad and homemade herbed cheese.

food; something that kept us all connected to our childhood, our days as college students and our 'cheat days' from whatever diet we were trying. Again, it tied us back to Earth.

Cooking for others was one of the ways that enabled us to come together as a crew. We celebrated the successes and laughed off the failures, and bonded much faster and deeper than in a traditional friendship.

Of all the challenges we faced as a crew, the daily meal we shared together consistently brought us closer together and kept us connected. It served as a gauge of morale; when a crewmate didn't attend dinner, it was a signal to the rest of the crew that there was something wrong. Whether it was bad news from home, depression, isolation or just being in a good flow with your personal research, it gave the rest of the crew an indication to check in and keep better tabs on someone. If the social structure inside the dome became stressed, it was always most apparent during mealtimes when the normally jovial atmosphere became tense and quiet.

Expression of culture

Apart from nutrition, food affects us on so many levels; it's hard to understate its importance on a mission. Not having enough food can cause low levels of blood sugar, make people irritable, resulting in low energy and lethargy. Not getting the right foods can affect mood, the body's ability to function and repair itself, and to fend off illness.

Food is also an expression of culture and can connect you to a feeling of normalcy. Weekly debriefs were made pleasant by having our discussions over a batch of fresh scones and a pot of coffee. It's also a creative endeavour and, by spending time creating something delicious for your crewmates, it becomes an expression of caring for them and fulfils the urge to do something nice for the people around you.

Living in the confinements of the Dome, each day can seem very like the one before - you begin to lose a sense of time and the exact chronology of events becomes lost. But particularly good meals from the Dome still shine brightly in our memories. Stand-outs that we still talk about were special BBQ night, burger and multiple sushi and pizza nights. These meals were made even more special by witnessing the amount of time and effort each person put into making things as perfect as possible for the crew. Sophie recalls how proud she felt after spending an afternoon cooking and being able to present the crew with a splendid and delicious dinner.

Zak Wilson

▲ Interior of the dome.

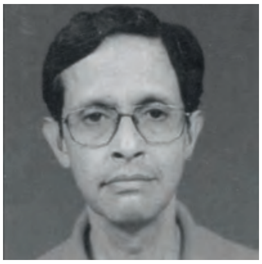
Occasionally, the reality of space makes some of these activities and foods difficult. We didn't have to deal with zero gravity, or even try to simulate that part of a mission to Mars. Living off-grid on renewable energy, however, we did have to deal with power shortages when the solar panels weren't generating enough electricity to allow for cooking. We used to joke that when it's cold and dark out, we can't have heat or light - or a proper dinner.

One of the hardest parts of getting through dust storms, or patches of bad weather, was the inability to cook a regular meal. We had poor weather at Christmas, but decided to splurge on running the generator. We all felt it was important to have a festive holiday dinner with roast turkey, vegetables, stuffing and potatoes at a time when everyone on the crew would be missing their family and friends back home.

At a later point in the mission, we had a whole week of poor weather and lacked sufficient fuel for our back-up generators. That was a very cold, dark week where we had to get by on dried fruit and nuts, cereal and cereal bars, and other foods that didn't require cooking. If we did heat water, we would coordinate with others so that we only had to run the kettle once or twice. Instant foods tend to be high in sodium, have a lot of wheat filler, and are generally not as tasty as what we could prepare ourselves. We were very happy when the sun started shining on us again and we could return to cooking.

Eating a freshly prepared, home-cooked meal every night and only cooking once a week was a luxurious arrangement. We ate well in the dome, and our best memories from those eight months involve special food that we made, though that doesn't mean we weren't excited when we got out and were able to eat all the things we'd been missing. ■

We ate well in the dome, and our best memories from those eight months involve special food that we made, but that doesn't mean we weren't excited when we got out and were able to eat all the things we'd been missing



Srinivas Laxman
Space author & journalist, Mumbai, India

India confirms commercial launch intent

In one sense we have just witnessed science fiction turning into reality. That is what it felt like on the morning of Wednesday, 15 February 2017, when I watched India's nearly 50-year-old space programme rocketing into spaceflight history as the country's space agency ISRO (Indian Space Research Organisation) successfully deployed 104 satellites in a single mission in a span of only 30 minutes. The daring mission sent out a clear message regarding India's commercial intent to the rest of the world.

A feat of this type had so far not been achieved by any space agency or commercial company, though records for the most satellites launched in a single attempt have continued to tumble in recent years. In April 2014, Cornell University's Kickstarter project consisting of 104 one-inch square 'chip sats' (known as Sprite satellites) were carried inside a Cubesat onboard a SpaceX Falcon 9 rocket. The role of this mission was to develop technology that can be sent deep into space in swarms, with each individual satellite beaming

▼ Launch of India's PSLV-C37 carrying a record number of 104 satellites.

ISRO

back its own stream of information. The Kicksat mothership reached its orbit and transmitted beacon signals that were received by radio amateurs. However, due to a clock reset, the tiny satellites couldn't be deployed and burned up inside the KickSat on re-entry about a month later.

In June 2014 a Russian Dnepr rocket launched 37 satellites from different countries for scientific and commercial purposes in one go and prior to this, in November 2013, an American Minotaur rocket had deployed 29 satellites in a single flight.

India's 104 satellite mission surpassed all previous records, attracting interest not only within the country but overseas too, including China. After India's Mars Orbiter Mission (MOM), it was this flight which aroused more curiosity and public interest compared to some of the other Indian space science missions.

Only three of the 104 satellites launched by ISRO were Indian - the primary payload being the 713 kg Cartosat-2 satellite which will be used for cartographic and remote sensing purposes, and two ISRO nanosatellites weighing 8.4 kg and 9.7 kg respectively.

The additional 101 foreign micro and nano-satellites were from the US, Dubai, Israel, Kazakhstan, the Netherlands and Switzerland. These included 96 from the United States, of which 88 belonged to a single organisation, the San Francisco-based Planet. Known as Dove Flock 3P nano-satellites, each weigh 4.7 kg and are imaging the Earth daily.

The remaining eight US nano-satellites - called Lemur and weighing 4.6 kg each - were from Spire Global, also from San Francisco. Their role is to carry out vessel tracking and weather measurement.

▶ The fully integrated PSLV-C37 with the mobile service tower.

When it became known that ISRO was raising the number of satellites on the mission, international customers formed a queue to have their spacecraft launched

▼ Engineering students working on Nayif-1 developed by the Mohammed bin Rashid Space Centre (MBRSC) and American University of Sharjah (AUS). It started transmitting about an hour after launch.

The other foreign satellites were PEASS-1 from the Netherlands (3 kg); Dido-2 of Switzerland (4.2 kg); BGUSSat of Israel (4.3 kg); the 1.7 kg Al-Farabi from Kazakhstan and the 1.1 kg Nayif-1 from Dubai.

The satellites from the Netherlands, Israel, Kazakhstan and Dubai are technology demonstrators, and the main role of all 104 satellites is Earth imaging, which could lend itself to any interpretation! The total weight of all the satellites was 1377 kg.

Significantly, the mission saw two arch political rivals joining hands on single mission - a rare occasion when Israel and the Arab world flew together as there was an Israeli and an Arab satellite!

The rocket for this historic mission was an advanced version of the highly-proven four-stage Polar Satellite Launch Vehicle (PSLV) - the PSLV-XL. The flight was designated PSLV-C37.

The 28-hour countdown kicked off at 5.28 am on 14 February. P.Kunhi Krishnan, director of the Sriharikota Spaceport, described it as the "shortest countdown" compared to those of earlier missions.

The countdown progressed flawlessly and the much-awaited moment came at 9.28 am as the PSLV lifted off with a thunder literally shaking the ground below it. During the initial moments, it seemed a soundless lift off but within minutes the silence was rudely shattered with the awesome roar and thunder of the powerful rocket as it climbed higher and higher on a yellowish plume of smoke. It was fire and thunder. Many were gathered on the terraces of the nearby buildings of the spaceport to witness history in the making - applauding, cheering and screaming with joy and excitement.

The rocket disappeared into a dark patch of cloud and along with it the ear-deafening sound faded away.

In mission control a team of scientists - mostly from the southern Indian states of Tamilnadu and Kerala sporting a grey ash powder on their foreheads to invoke God's blessings - were glued to their computers monitoring the progress of the flight which was going on smoothly.

The first satellite to be deployed was India's Cartosat-2 followed within seconds by the indigenous nanosatellites. Then in intervals of four to 12 seconds the foreign satellites were released into orbit.

These nanosatellites were enclosed in 25 quadpacks - three to five satellites in each - which were released in a time-sequence manner. Once the quadpacks left the rocket, they opened to place the small satellites in orbit.

The foreign satellites were released into orbit at intervals of four to 12 seconds

All the 104 satellites were deployed in a 505 km polar Sun-synchronous orbit and, according to B. Jayakumar, mission director, one of the key challenges was to ensure they did not collide during separation. For this, he explained a new separation technology had been implemented which worked efficiently.

He described the mission as a "good learning experience".

Planning for this nail biting mission began six months before, when PSLV successfully launched 20 satellites on 22 June 2016, which gave ISRO the confidence to launch a larger number of satellites.

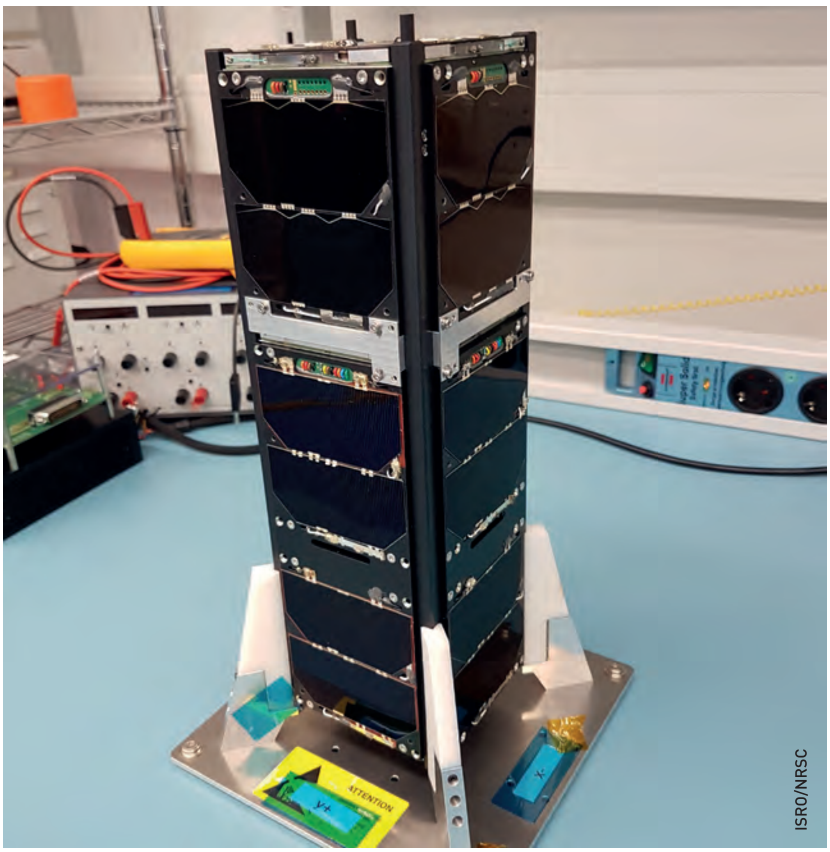
Keeping this in mind, ISRO first planned to launch 83 satellites in a single shot in October 2016. Three months later it rose to 104. And the risky and complex mission was born, which K.Sivan, director of ISRO's Vikram Sarabhai Space Centre, admitted was one of the toughest.

Dismissing oft repeated theories, ISRO chairman A.S.Kiran Kumar made it clear that the role of the mission was not to enter into a global space race or break any record, but merely to utilise the additional capacity of the PSLV. The rocket had an additional capacity of 600 kg so it was decided to accommodate the extra satellites.

In a post launch media interaction, the ISRO chief emphasised the mission was about "maximising returns and improving capacity". But there are a few sceptics who seem convinced that the mission is a signal to China. "In a way the Indian mission will trigger an Asian space race and do not be surprised if China starts planning to launch multiple satellites in one shot only to beat India," observed a space analyst.

Apparently shaken by the success of the Indian mission, China immediately began analysing the reasons why it was so successful and how it was cost-effective. Some Chinese media reports quoting its space officials even acknowledged

▼ The PEASS-1 satellite during construction in the Netherlands.



An increasing number of foreign agencies are turning towards India to launch their satellites and this is reportedly causing concern among American space officials

that India could overtake China in the commercial space launch business.

China's inability to access components and parts from the US are part of its problem. According to the Global Times, "India's achievements are largely driven by its low price advantage, a weak point for China's commercial space sector."

"Competition with India for commercial space launches may be inevitable and the most urgent action needed for China is expand its market share is to reduce the cost of putting satellites into orbit."

Reports from other world capitals, including Washington and London, responded to the ground-breaking 104 satellite mission success by suggesting India had emerged as a key player in the global space sector.

When it became known that ISRO was raising the number of satellites on the mission, international customers formed a queue to have their spacecraft launched. To date ISRO has earned more than 100 million dollars through the launch of foreign satellites and, in this latest mission, recovered half the cost by carrying 101 foreign satellites.

Certainly, this was not on account of any special loyalty they had towards India but because the overall launch as compared to other international rocket launches is cheaper.

Information obtained from various sources, show that a SpaceX Falcon 9 launch costs Rs 381 crores; other rockets-a Russian Proton Rs 455 crores; Japan's H-11A, Chinese Long March, Arianespace Ariane-5 and the American Atlas 5 each cost Rs 6,692 crores. Against these a launch by ISRO's PSLV is estimated to be around Rs 100 crores.

One of the main reasons for the comparatively lower launch price in India is largely due to the cheap labour costs. A highly qualified ISRO scientist earns much less than his counterpart in NASA.

The fact that an increasing number of foreign agencies are turning towards India to launch their satellites is reportedly causing concern among American space officials. How worried they are is amply evident from the fact that on 6 July 2016, the US Committee on Science, Space and Technology wrote a letter to former American secretary of state, John Kerry, secretary, department of commerce, Penny Pritzker, US trade representative Michael Froman and director of the office of science and technology, John Holdren, expressing concern regarding US satellites being launched in India.

They suggested that US launch services were at a disadvantage as they were being wiped out of competition for the launch of micro and nanosatellites. Similar concerns had also been expressed at a US hearing on 'The Commercial Space Launch Industry: Small Satellite Opportunities and Challenges' held in April 2016.

To date, India has carried 113 US satellites of which 96 are part of the 104 deployed on February 15. India has flown 180 foreign satellites for 23 countries, the first one being DLR Tubsat of Germany on 26 May 1999.

A spokesperson for San Francisco-based Planet which flew 88 of its satellites in ISRO's recent mission, said that the organisation will continue to collaborate with the Indian space agency whatever the policy of US President Donald Trump!

So the days ahead will see 104 and counting. ISRO is most definitely in the ascendency and promises to be true ambassador for 'brand India' in the months and years ahead. ■

▲ One of the first images from ISRO's Cartosat-2 satellite returned the day after launch and showing part of the commercial centre and Mithi River, Mumbai, India.

About the author

Srinivas Laxman, a space journalist and author, contributes regularly to the *Times of India*, India's leading national daily. He has authored four space-themed books – a biography of Abdul Kalam, rocket scientist, who became President of India, a book on India's first mission to the Moon, and two on the country's mission to Mars.

◀ Some of Planet's 88 small 'Dove' satellites flown into orbit aboard India's Polar Satellite Launch Vehicle.

Spaceplane rationale – a new way of thinking

▲ Early US Space Shuttle designs were fully reusable but after budget cuts NASA had to choose between full reusability or a smaller true spaceplane. Its decision to develop a largely expendable vehicle probably held up low-cost access to space by at least three decades.

David Ashford
Managing Director,
Bristol Spaceplanes,
United Kingdom

The very high cost of sending people and payloads into space has hardly changed in real terms over the 55 years of human spaceflight - largely due to the use of launchers that are based on ballistic missile technology and that can therefore be used only once. But back in the 1960s many aircraft companies had feasible, if challenging, designs for fully orbital spaceplanes which were never realised. What would then have been very difficult is now more easily achievable and, if consensus can be reached on how best to go about building an airliner that can fly into space, it might usher in a new affordable space age within as little as 15 years.

All orbital space launchers in service today can fly only once and this expendability is the root cause of the high cost and economic risk of spaceflight. It is unimaginable that we would scrap a car after only a few hours on the road – the average per day cost of owning and driving it would shoot up to around a thousand times more than it actually is. Much the same applies to aviation. If aeroplanes could fly only once before being taken out of service, the cost of a flight across the Atlantic would be roughly one thousand times more than it is. And likewise, reusable launchers could reduce the cost of spaceflight by about one thousand times, given high enough traffic levels for economies of scale.

Just as steam locomotives transformed land transport, so spaceplanes will transform spaceflight and thereby make a huge contribution to life on our planet. Imagine a new space age in which a fleet of 50-seat aeroplanes that can fly to space and offer routine and affordable transport to and from orbit. These spaceplanes look similar to the Anglo-French supersonic Concorde, taking off from and landing on conventional runways.

In this scenario the cost per seat to orbit is about one thousand times less than it is today (a few tens of thousands of dollars compared with a few tens of millions) so that middle-income people prepared to save can even afford to visit space hotels in orbit round Earth. Cargo versions would launch satellites and space platforms at greatly reduced costs.

The future possibilities for science, the environment, human endeavour and leisure are immeasurably vast and this new space age could be achieved at low technical risk within 15 years, given a change in our approach to space transportation.

Rocket science

In order to understand the argument, a little knowledge is required of the various types of trajectory, the need for staging, and some design logic.

Launching a spacecraft into orbit requires climbing to space altitude - about 100 km (62 miles) or higher - and then accelerating horizontally to satellite speed, which is about 7.8 km per second for low Earth orbits (LEO) of around 90 minutes. It is the acceleration to satellite speed that requires most of the energy - just climbing to space altitude requires far less. A so-called suborbital flight, up and down again with just a few minutes in space, requires a maximum speed of about 1 km per second, or about eight times less (see diagram below right).

Suborbital rockets, or 'sounding rockets', have been used for many years for various kinds of scientific research. They are far smaller and less expensive than orbital launchers, but of course only provide a few minutes in space. Two reusable suborbital aeroplanes have already flown, and new ones are being developed to provide suborbital space experience flights. These will be useful stepping-stones to orbital spaceplanes.

Staging

To achieve such a goal as soon as possible, we need to use existing technology as far as is practical and this will require the use of two stages. This is analogous to the in-flight refuelling used to extend the range of military aeroplanes. It adds complexity to a mission but enables it to be achieved with existing technology.

The amount of fuel needed for a flight to orbit using a single-stage vehicle with existing rocket engines, measured as a fraction of take-off weight, is about 87 percent. This is roughly equivalent to the amount needed to fly an aeroplane one-and-a-half times round the world non-stop. The present record, held by the Virgin Galactic Voyager, is just once.

▲ The Anglo-French supersonic Concorde of the 1970s could have been a precursor to the first spaceplanes.

To fly one-and-a-half times around the world without in-flight refuelling would need either very advanced technology or the use of two stages - a large aeroplane carrying a specialised very long-range aeroplane part of the way.

This analogy explains why flying to orbit with existing technology needs two stages. The lower stage boosts the upper stage to a speed such that it requires a practicable fuel fraction to continue on to orbit, and the two stages separate at this speed.

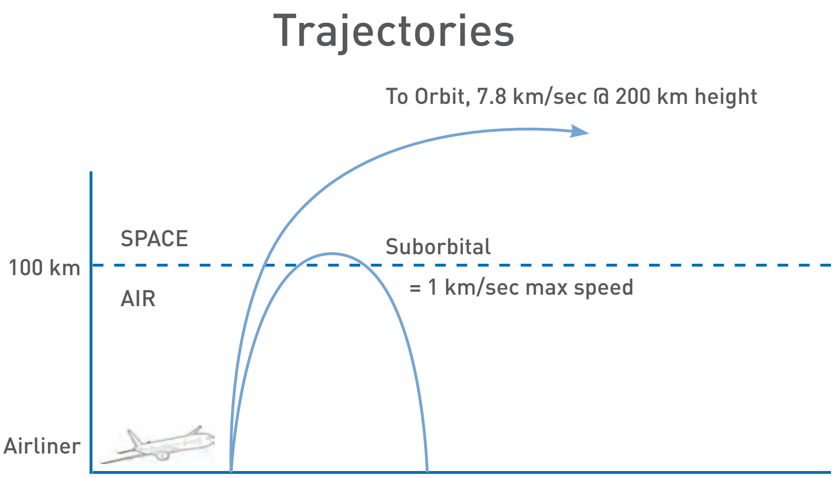
Single-stagers are clearly preferable in the long term, but these will need very advanced new engines.

Design logic

An airliner capable of flying to LEO would transform spaceflight by providing vastly lower costs and improved safety. The essential design features of the first such vehicle can be derived from straightforward design logic.

The most important design requirement is greatly improved safety. To date, human spaceflight has

▼ Orbital and suborbital launch trajectories.



To achieve the new space age sooner rather than later, we need to use existing technology as far as is practicable

achieved a safety level of about 100 launches per fatal accident. Such poor safety records are almost inevitable with throwaway launchers and the level contrasts with the more than one million flights per fatal accident achieved by scheduled airlines.

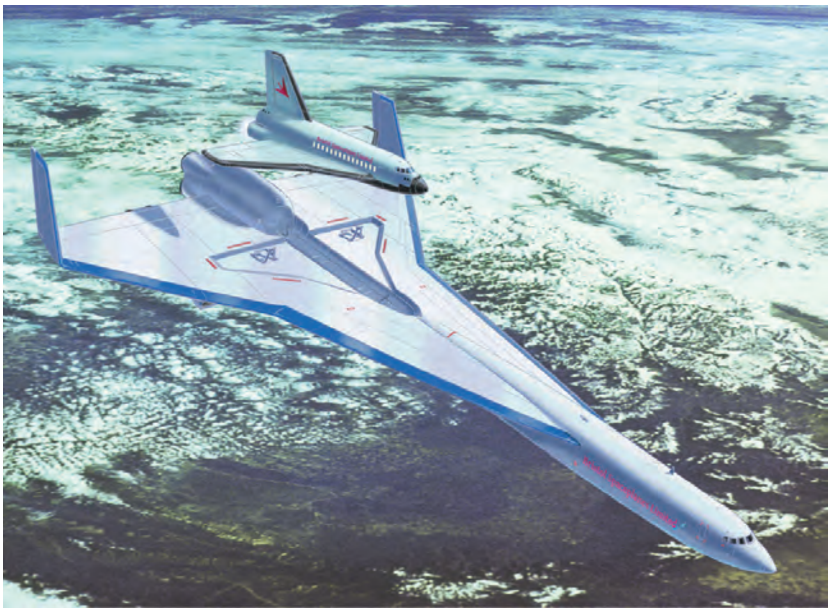
To achieve the required safety level, the first orbital airliner should be as much like today's airliners as practicable, because these are the safest flying machines yet invented. It should therefore be piloted and have wings for taking off and landing using runways. This configuration would also be more attractive to passengers than landing vertically on a pad.

The spaceplane that will usher in the new space age will have two stages and will be designed for 'safety soon'. It will be piloted and have wings for conventional take-off and landing.

Surprisingly, perhaps, the spaceplane design model that could revolutionise spaceflight and herald a new space age is similar to many of the reusable launcher designs of the 1960s. Currently there is only one such orbital airliner offering all of these features - the 'Spacebus' concept developed by my own company, Bristol Spaceplanes.

Perhaps the most remarkable aspect of Spacebus is that prototypes can be built with proven technology. All the individual technologies needed for the 1960s spaceplane designs have since flown in other projects. What would then have been a feasible but difficult project would now be reasonably straightforward for a large or medium-sized aircraft company.

Such prototypes would inevitably fall far short of airliner standards of structural life, turnaround time and maintenance cost; several years of operating service and product improvement would be needed to come close to these standards. However, early spaceplanes would still be safer and far less expensive than expendable launchers so initial models could be put into service for non-passenger missions such as launching satellites, supplying space stations and space agency human spaceflight until the operating experience required for passenger carrying is gained.



▼ The Bristol Spaceplanes Spacebus - designed to be the first orbital airliner. It has two stages, both of which are piloted, features needed to achieve a safe vehicle soon.

Spaceplane history

The extraordinary situation that space transportation has reached can be explained by looking at the history of spaceflight. The first satellites in the 1950s were launched using converted ballistic missiles, as these were the first objects able to reach space. However, ballistic missiles can fly only once, and it was soon recognised that having to use a new vehicle for each flight could never become economical.

By the 1960s, large aircraft companies in Europe and the USA such as British Aircraft Corporation, Boeing, Dassault, Hawker Siddeley, Lockheed, Martin and others, were studying orbital spaceplanes in depth. The consensus was that such a development was the obvious next step and that it was just about feasible with the technology of the day.

Spaceplanes were not developed at the time because the 'space race' to the Moon, driven by the Cold War soaked up the available funding. The aircraft company design teams were allowed to disband and the lobby for an aviation approach to space transportation was gravely weakened.

There was a second opportunity to build a true spaceplane in the mid-1970s, when the early designs of the Space Shuttle were indeed fully reusable. However, President Nixon imposed a budget cut and NASA could no longer afford their large reusable design. To stay within budget, they had a choice. They could maintain the size but give up on full reusability, or build a much smaller true spaceplane along the lines of several of the 1960s designs with a payload of one or two tonnes instead of the planned 25-30 tonnes.

By then, the habit of expendability was so strong that NASA opted to take the former course. The resulting Shuttle was mostly expendable and therefore just as expensive and risky as the throwaway vehicles that preceded it. This decision probably held up low-cost access to space by at least three decades.

Since then NASA has not entirely abandoned spaceplanes. It spent a few billion dollars on two projects, the X-30 National Aero-Space Plane (NASP) and the X-33, which were of single-stage configuration and hence so advanced for the period that they had to be abandoned. It is unlikely that

▲ The North American X-15 (above) and SpaceShipOne (SS1) - the only fully reusable spacefaring vehicles to date. There was a 36-year gap between the last flight of the X-15 and the first flight to space of SS1.

either design would have passed muster with any of the 1960s spaceplane design teams.

The history of spaceflight has created institutions and concepts that repeatedly reinforce the habit of throwing away one launcher per flight. Even today, space agencies are promoting new single-use launch vehicles.

During the heady days when orbital spaceplanes were seen as the future of spaceflight, the X-15 suborbital research aeroplane made several successful flights to space height. There was then a gap of 36 years between the last flight of the X-15 (in 1968) and the first flight into space (in 2004) of the only other suborbital spaceplane to have flown - the Scaled Composites SpaceShipOne. This hiatus is an indication of the lack of priority given to reducing the cost of access to space.

The way ahead

A spaceflight revolution has already started, although this is not yet widely appreciated. In the USA, the Federal Aviation Administration is encouraging entrepreneurial passenger suborbital spaceflights and the UK's Civil Aviation Authority recently published a ground-breaking report, 'UK Government Review of Commercial Spaceplane Certification and Operations'.

Several companies are developing suborbital vehicles for carrying passengers on brief space experience flights. The activities of Richard Branson's Virgin Galactic in particular have been influential in shifting the mind set around space tourism from dream to a realistic prospect.

However, its spaceplane - an enlarged development of SpaceShipOne - and others under construction, provide just a few minutes of zero gravity on top of a very steep flight. As such they are useful lead-ins but to launch satellites and visit space stations fully orbital spaceplanes are needed, which have to fly about eight times faster than suborbital spaceplanes and will cost roughly ten times more to develop.

It is very likely that Virgin Galactic or some competitor will eventually make a commercial success of suborbital passenger spaceflight. There have already been setbacks, and more may follow, but the technology and passenger demand are already in place and there are no likely showstoppers. The advantages of aeroplanes over missiles will then become obvious to all and space agencies will no doubt eventually embrace development of orbital spaceplanes.

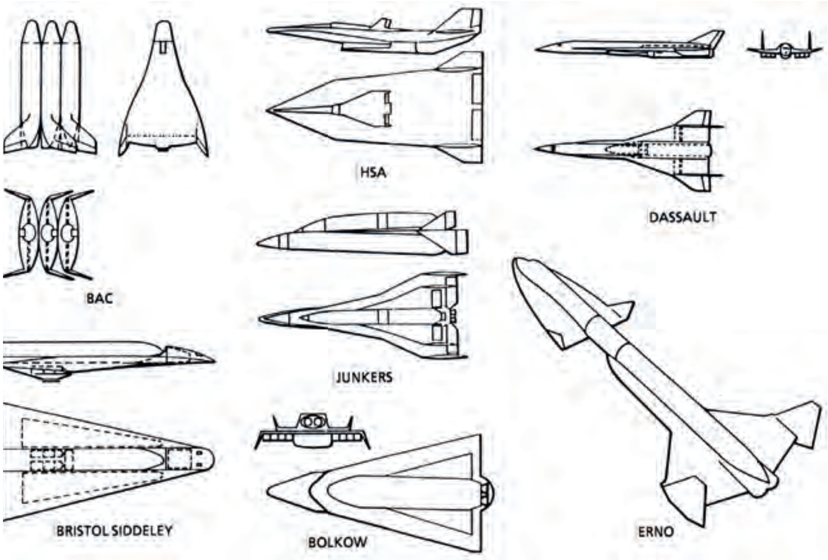
The first orbital spaceplane will be able to undercut any expendable launcher of comparable payload capacity. Lower costs and improved safety will increase traffic levels, which will in turn release funding to enlarge and mature the design. This will further reduce costs and increase traffic levels, thereby releasing even more funding for design improvement.

The result will be a virtuous downward cost spiral until Spacebus, or something like it, is built and the lower cost limit of spaceplanes based on existing technology is approached. This cost can be estimated by comparison with airliners and works out at a few tens of thousands of dollars for a few days in a space hotel.

This would be affordable for wealthy middle-income people prepared to save for the holiday of a lifetime, and market research indicates that about one million tourists per year could visit space at this cost, although such a figure cannot be precise at this stage.

Development of reusable spaceplanes is very likely to happen in the long term but the process could be speeded up considerably if major players start planning for it now. Given that advanced technology is not needed, operational prototypes of Spacebus could be flying in about seven years, which is a typical time from go-ahead to early operations for an advanced aeroplane.

The revolution in spaceflight will be one of perception as much as one of engineering



▲ European spaceplane designs from the 1960s.

▲ Above right: Virgin spaceship VSS Unity touches down after flying freely for the first time after being released from Virgin Mothership Eve (VMS Eve) on 3 December 2016 in the Mojave Desert.

It would take about eight more years for design maturity to approach that of airliners today. In particular, this requires extending the life of rocket engines and shortening turnaround time so that spaceplanes can make one or more flights per day.

Achieving this 15-year timescale will need a large investment, which probably depends on the rapid take-up and expansion of space tourism, with major players racing to be early to market and thereby providing the required funding. Trends and crazes are notoriously difficult to predict but space tourism seems to have the required ingredients.

Funding remains the key issue. The development cost of an orbital spaceplane is on the high side for private-sector investment, and government space agencies are not yet taking spaceplanes seriously.

So, with the ultimate goal of a Spacebus type vehicle the strategy should be to precede it by a less expensive suborbital spaceplane, affordable by the private sector, profitable in its own right but which has the same basic design features as the longer term objective.

On to the Moon and Mars

Low-cost access to orbit will enable the cost of travelling further afield to be greatly reduced. Large orbital space depots would become affordable, and these would be used for maintaining and re-fuelling reusable space tugs and planetary landers.

These might be similar in principle to the vehicles used for the US flights to the Moon in the late 1960s and early 1970s, except they would be fully reusable. As with transport to and from orbit, reusability and higher traffic levels would greatly reduce the cost. The cost of the first lunar base could be reduced by about 10 times using reusable vehicles, compared with present plans for using expendable ones, including the cost of developing the spaceplanes themselves [see 'The Aviation Approach to Space Transportation', David Ashford, Aeronautical Journal of the Royal, Aeronautical Society, August 2009.]

Practical travel to Mars requires shorter journey times than can be achieved with chemical rockets. The probable solution is to use nuclear rockets along the lines of those nearly ready for production in the USA in the 1970s, assisted perhaps by long electromagnetic rail guns in Earth orbit to provide an initial boost. Again, low-cost access to orbit would greatly ease the development of such new systems.

An airliner capable of flying to orbit would transform spaceflight by providing vastly lower costs and improved safety

Perception

The revolution in spaceflight will be one of perception as much as one of engineering. Spaceplanes will introduce an airline method of operating, which in turn will transform the image of spaceflight from exotic to routine.

Space will lose the 'exceptionalism' that has enabled the extraordinary practice of throwing away a vehicle after each journey to persist for so long and space operations will become subject to the same sorts of checks and balances that affect terrestrial transport.

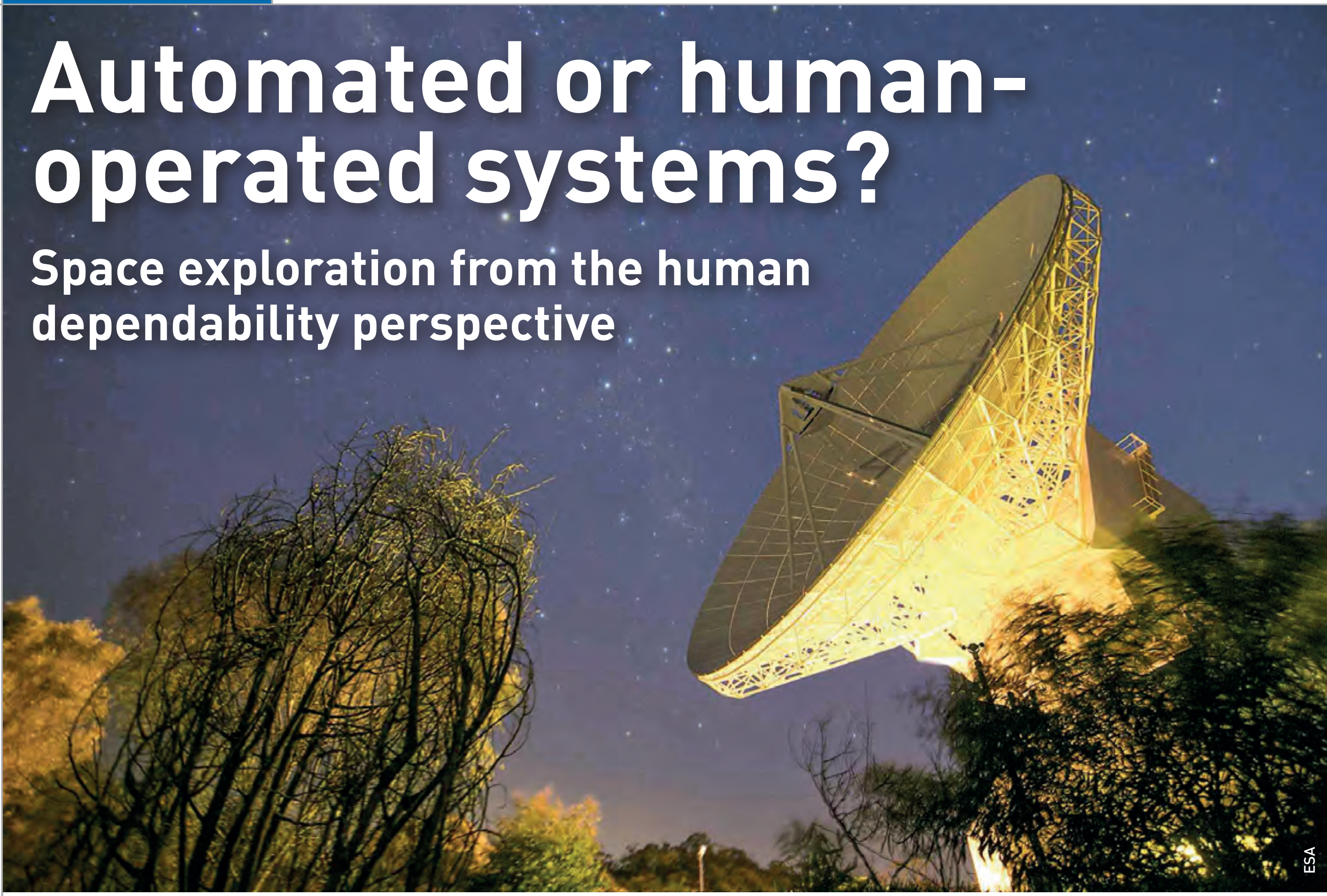
The change from expendable to reusable launchers will come to be seen as being as profound as the change from balloons to aeroplanes in the history of air transport. The perception of low-cost and safe access to space using existing technology will change from 'too good to be true' to 'why wasn't it done years ago?' ■

About the author

David Ashford is Managing Director of Bristol Spaceplanes Ltd, an innovative small company developing the Ascender spaceplane. He was involved in Concorde, the Skylark sounding rocket, and missile and electronic warfare projects at Douglas Aircraft and BAE Systems, and has published some 20 papers on space transportation and has written three books on spaceplanes and space tourism. His book, *Space Exploration: All That Matters* was published by Hodder in 2013. David is a Fellow of the Royal Aeronautical Society and is a Rolt Fellow at the Centre for the History of Technology at the University of Bath.

Automated or human-operated systems?

Space exploration from the human dependability perspective



▲ The 35 m diameter dish antenna of ESA's deep-space tracking station at New Norcia, Australia.

In both crewed and automated spaceflight, unique exploration missions and routine services, humans conceptualise, develop, design, operate, use and manage technology. Only by understanding this as a joint 'human-tech' effort can the capabilities and limitations of both elements be leveraged most effectively for reliable, robust and resilient operations, systems and infrastructure.

Alfio Mantineo
ESA/ESOC,
Darmstadt, Germany

Watching the movie The Martian recently I was captured by the creativity demonstrated by two key characters - the astronaut stranded on Mars, played by Matt Damon, and the astrodynamicist from NASA's Jet Propulsion Laboratory (JPL), played by Donald Glover.

The astronaut builds a greenhouse on the red planet using all of the available material in a totally different way from its intended use - the production of water from hydrazine (rocket fuel) or the redefinition of a communication protocol with an old probe left on Mars from a previous Pathfinder mission, for example. The JPL employee redesigns the entire mission of the Hermes spacecraft using a flyby of Earth to return to Mars in a much shorter time.

The Hollywood adaptation of Andy Weir's book of the same name celebrates the bravery, humour and ingenuity of the protagonists. It also reflects very well the experiences and challenges of real space exploration and the huge component of the unknown and unplanned that can only be overcome with flexibility and imagination.

System reliability is essential to the success of a mission but the external environment is a source of continuous discovery and surprises – otherwise why would we call it 'exploration? – and to cope with this the system requires resilience.

While we do not yet have a greenhouse on another planet, we do have a long list of creative solutions to both big and small emergencies in space, from the successful return to Earth of Apollo 13, through to the complete redesign of missions to ensure the accomplishment of the objectives for the the European Retrievable Carrier (EURECA) mission.

At the same time, when considering the reliability of the system and the probability of success it is not uncommon to hear about the risk of human error that could jeopardise the entire mission, and extensive studies have been conducted to model human behaviour and to predict the probability of people making errors as a result of internal and external factors.

'Human Factors' (HF) as a discipline has a particular focus on human performance. Traditionally, the human operator was seen as a liability within an otherwise perfectly designed, safe system, and this is still the case in many industrial contexts today.

NASA's Mercury programme, which was the United States' first man-in-space programme, had been designed for fully automatic control – a controversial engineering decision, which reduced the astronaut's role to little more than a passenger.

During the flight of Faith 7, the final spaceflight in the Mercury series, there were mission-threatening technical problems. After experiencing power failure in the capsule, pilot Gordon Cooper took manual control and successfully estimated the correct pitch for re-entry into the atmosphere using just his wrist watch and his knowledge of the star patterns outside the window. He then fired the retrorockets at the right time and splashed down close to the recovery ship.

His actions brought about a re-thinking of the design philosophy for space missions and from that point on the human component was no longer seen as a liability but as an improvement of overall reliability.

However, humans are not perfect and mistakes will inevitably be made in any system that involves people, be it in the design, development or operations phase. Many studies are currently taking place around the human 'system component', identifying ways to improve human-machine interfaces.

At the European Space Agency (ESA), interest in what is termed 'human dependability' has been boosted in recent years as the scope of ESA's space activities has expanded.

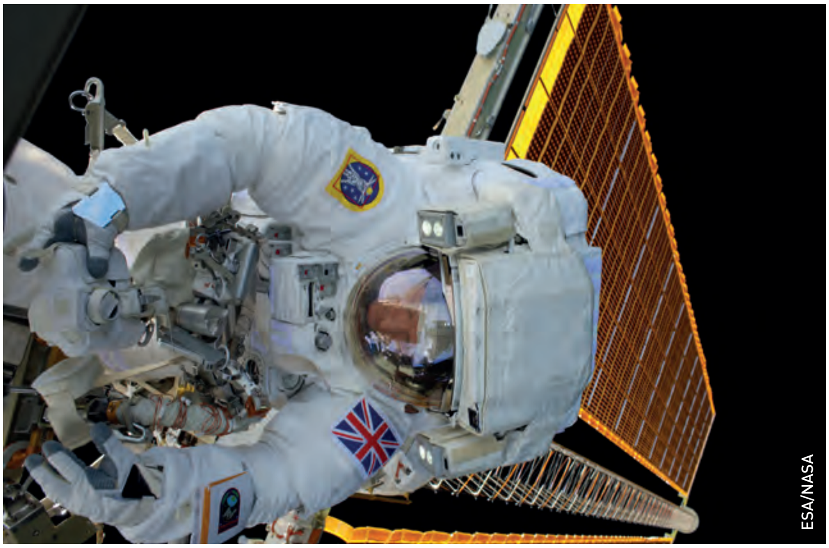
Human dependability

Human dependability is about the contribution of a crew member in a space system to safety and reliability. Machines can fail but so too can 'people-in-the-loop' of space systems, sometimes with catastrophic consequences.

ESA's Dependability and Safety Section therefore has a longstanding interest in the subject of human dependability: how the incidence of human error can be reduced and its effects minimised.

Topics relating to the human element are at the centre of discussion in the framework of Human Dependability (HUDEP) at ESA. Initiated in 2009, together with partners from the French and German space agencies (CNES and DLR), HUDEP serves as a forum to give space agencies and industry the opportunity to discuss HF topics across a project's life cycle, and it has grown into an inter-agency community of experts.

Human dependability relates directly to the fields of Human Factors, Human Systems Integration, Human-Centred Design and Human Behaviour & Performance in that it addresses the contribution of the human in a space system to safety and reliability. In the late 1980s, ESA used the term in contractor studies and policy work. At that time the focus was mainly on human error in the product assurance, safety and knowledge management context, as well as root cause analysis methodology and human-machine interaction design guidelines. More recently, it has been used to describe an extension of safety and dependability of technical systems, again in the product assurance domain.



▲ Top: ESA astronaut Thomas Pesquet installing the MARES machine in Europe's Columbus space laboratory.

▲ Above: ESA astronaut Tim Peake during his 4 hour 43 minute spacewalk to replace a failed power regulator and install cabling.

▼ Below: ESA astronaut Samantha Cristoforetti working on the TripleLux experiment, an investigation into the effects of microgravity on immune cells. A smoke detector deep in the belly of the Biolab rack on Columbus had to be replaced quickly before the cell cultures expired.

▼ Bottom: Inside the European Space Operations Centre (ESOC) engineers control spacecraft in orbit, manage the global tracking station network, and design and build the ground systems that support missions in space.

Current initiatives

The external and internal efforts conducted as part of the Human Dependability Initiative at ESA captured the emerging consensus of space agencies to systematically include Human Factors considerations in the design and operation of crewed and robotic missions.

Recent external contracts commissioned by ESA predominantly focused on raising awareness and developing methods to address human dependability, some with applied case studies:

- The Human Dependability Model (HuDeM, 2013) was a qualitative study to develop and validate a human dependability model and analysis approaches. The project primarily focused on control centre activities and looked in depth at one particular approach, the Crisis Intervention and Operability Analysis (CRIOP) method. It was validated in a case study on crew-ground interactions at the European Astronaut Centre (EAC) and at the Control Centre of International Space Station Columbus module (COL-CC).
- Human Automation Interaction (HAI, 2014) focused on the development of quantitative formal modelling and verification approaches for the design of automated systems in view of human error. Case studies were conducted on Columbus Environmental Control and Life Support System (ECLSS) operations from COL-CC, Unmanned Aerial Vehicle operations, and Control Centre of European Tracking Stations (ECC) operations.
- Integrated Failure Analysis (IFA, 2015) aimed to provide a qualitative and quantitative method to model success and failure in complex socio-technical systems with a focus on space systems design and operations, including the organisational dimension.
- Several applied design studies addressed aspects as diverse as console design and audio alarms in control rooms.

Humans should always be at the centre of any future advanced systems designed for space exploration

A two-year research project at the European Space Operation Centre (ESOC) on the 'Human Element and System Resilience', completed in 2015, focused on ESA's operations centre and the contribution of flight control teams to overall system safety. Aside from introducing the concept of 'resilience' and 'resilience engineering' to stakeholders in quality, special projects and training, this study identified work patterns in special and routine operations based on more than 300 hours of direct field observations in the operations centre, and proposed practical and policy-related recommendations based on a review of smart practice in external high-reliability organisations in seven safety-critical sectors outside the space domain.

The HUDEP community also brought together over a dozen experts to complete the revision of the Human Dependability Handbook ECSS-Q-HB-30-A with a focus on Human Error Analysis.

Accelerating pace

In today's world, automation is usually implemented to achieve lower costs and a reduction of human error. But automation may have its downsides too.

Where control centre operators are in the role of supervisor, automation will be an increasingly important factor. Systems operators and system developers will need to work together from the start, right across the life cycle of the system. This process will actually move the risk of human error from 'operation' to 'design' within the life cycle. Automated control centres will also require operators to have more training and more knowledge management.

The evolution of automation and the pace of its introduction into everyday life is astonishing. The use of an autopilot on airplanes has been the norm and not the exception for many years. Automatic rail systems are already a reality in many cities and within a decade we may not need to 'drive' a car any more, beyond indicating the destination.

In this context, the push to increase automation in space exploration is understandable but we need to understand our motivation before embarking on wholesale robotic innovation. Is replacing all human positions in systems with automated functions in order to remove the human error liability possible or desirable? And although replacing astronauts with robots might reduce the inconvenience and costs of the necessary life sustainment functions required in manned spacecraft, would that actually further the progress and quality of space exploration?

Augmenting performance

In Earth observation most processes for establishing and maintaining contact between the ground station and spacecraft e.g. to uplink commands or downlink telemetry, are now automated through schedules and configuration scripts. There are less routine activities to be performed by the ground station controllers, allowing them to concentrate on more critical activities.

Robotic automation is not just about the potential to replace human roles and functions; it also has great potential to augment human performance.

Automated functions implementation, robots, drones etc. should be seen as extensions of human capabilities allowing us to go further in exploring deep space and planets where environmental conditions are prohibitive for human life, attempting missions that could last longer than a human lifetime, gathering data well beyond human sensing capabilities, computing faster and more precisely than the brain, and ruling operations with a far greater precision.

Several high-profile space projects have made headlines in the last years. Behind the scenes, and essential to the success of any of these endeavours, is the meaningful integration of technical and non-technical aspects in design and operation.

Humans should always be at the centre of any future advanced systems designed for space exploration, managing the system and increasing its resilience, such as developing an industrial technology base for the automation and remote control of space based operations using Automated-Human-Robot-System.

Indeed, humans should always be allowed to decide and act when faced with the unplanned, the unknown, the risks and the contingencies, and to evaluate the mission results achieved. Humans should be considered the strongest link and systems should be designed around them for future scenarios.

The challenge of integrating automation and the human element is not limited to the arena of Space. Other domains - aviation, the nuclear industry and maritime search and rescue - share similar challenges and opportunities in respect of the human element; how to implement it in training initiatives, how to engineer the human element and how to regulate it in design aspects. The involvement of industry will be increasingly more important as humans learn to work in tandem with robots. ■

Author credits

Thanks for contributions on the article to R. Peldszus, formerly Internal Research Fellow at ESA-ESOC, Special Studies & Projects, L. Bianchi, Head of Dependability and Safety Assurance Section at ESA-ESTEC and M. Gabel, Training and Simluations Coordinator at ESA-ESOC.

Robotic automation is not just about the potential to replace human roles and functions - it also has great potential to augment human performance

▼ ESA's Rosetta showing the deployment of the Philae lander to comet 67P/Churyumov–Gerasimenko.

How to build a Moon base cheaply

With interests in establishing a base on the Moon on the rise again, while some look at how to get there, others look at how to stay there – for the long term. Alexander Mayboroda, an advocate for space colonisation, guides us through the technological challenges faced by those hoping to establish a base on the Moon and ways to get around the spiralling cost associated with such an endeavour.

Alexander Mayboroda
AVANTA-Consulting, Russia

Almost half a century has passed since man first visited the Moon. However, most projects for creating humanity's outpost on the Moon never made it past the drawing board due to their expensive implementation. In a 2009 study, the Center for Strategic and International Studies suggested a lunar base would cost $35 billion to construct and $7.35 billion a year to maintain. It is clear therefore that until the cost of space access is lowered the situation with building a base on the Moon is unlikely to change.

Considering the current level of rocket and other space technology development, it is more profitable to create industrial facilities on asteroids compared to the Moon. Private companies that have declared plans to mine platinoids and rare metals outside of Earth are looking at asteroids first. There is far less interest in business plans to mine resources on the Moon. At the same time, it takes a week to get to the Moon and back, whereas visiting an NEA group asteroid takes years. From an investment point of view, due to the possibility of quick equipment depreciation, mining on the Moon is potentially more lucrative than mining an asteroid.

Aside from providing a stunning backdrop to the night sky that has wowed humanity for thousands of years, the Moon has many valuable resources; just like an asteroid, it is home to metals that are rare on Earth and both uranium and platinum-based metals can be found there. It is somewhat macabre, but it can also be thought of as an asteroid cemetery of sorts, as for billions of years, asteroids that contained metals have bombarded the Moon's surface. Essentially there is no real need to chase asteroids and waste years on a lengthy trip, it's enough to simply look under the regolith surface of the Moon for metal asteroid fragments – and in order to do that a base is needed.

The true cost

If the cost of delivering cargo to the Moon becomes equal to the cost of cargo delivery to asteroids, the shorter travel distance to the Moon and, respectively, the quicker returns (100 times quicker on average), will make mining on the Moon appealing to investors. Luckily, the technology that would make this possible already exists and a method to deliver goods without rocket deceleration has already been tried successfully.

The first cargo shipment delivered to the Moon was the metal 'USSR' ball, dropped by the Luna-2 soviet spacecraft. The landing was hard but that made it energetically efficient in comparison to a soft landing that occurs through rocket engine deceleration. A hard landing occurs at a speed of around 2500-3000 m/second. In effect, it can be thought of as a crash, during which the cargo melts and partially evaporates. However, a hard landing is preferential for two simple reasons; the design allows for an increased storage capacity over soft-landing by three to five times, thus decreasing the cost of delivery by 70-80%.

Nonetheless, up until recently and perhaps to be expected, only soft landings have been considered for spacecraft despite the higher cost, as the stored rocket fuel significantly decreases the available cargo space in the rocket. In addition, the cost for the landing module needed for such a delivery system is also high. But how necessary is it to find a way for soft-landing delivery of cargo when building a base? Does all cargo that requires the use of heavy rockets need to be delivered in this expensive manner? With an outlay of $15-30 billion for the creation of one such rocket, perhaps a more cost-effective solution can be found.

From the ground up

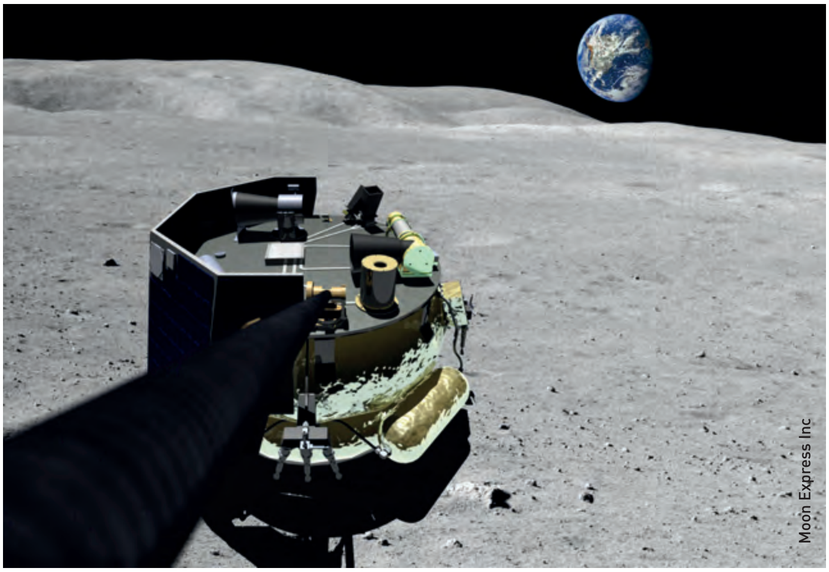
A lot has changed in the last 50 years with the appearance of additive technology i.e. the process in which digital 3D design data is used to build up a component in layers by depositing material. This negates the need, as some project developers claim, to deliver assembled equipment to space bases.

If the extraction of raw materials is streamlined, 3D printers will be able to print habitation and technological modules, rocket engines, fuel tanks and spacecraft in situ – wherever that may be in space. Thus the cost of cargo delivery will decrease. However, in order to build a base using local materials, equipment that will be able to extract metal, silicon and oxygen from the surrounding regolith, must first be delivered to the Moon.

One way to do this is to transport the necessary raw components from Earth via the hard-landing method to provide the materials to be used by 3D printers on the Moon. Once built, resources extracted from the Moon can then be used to construct everything else. In this proposal, only the parts necessary for printing base units and equipment necessary to receive and collect materials delivered from Earth would need to be sent in a controlled soft-landing scenario. Simple materials such as water and hydrocarbons, necessary as chemical reductant agents for metals and rocket fuel, as well as aluminium, titanium and other metals do not need to be delivered using this costly method and delivery via a hard landing would be sufficient.

However, implementing and controlling a hard landing is not that easy. If the cargo is made up of spheres, much like the Luna-2 sphere, after the explosion on impact the cargo would be dissipated over a large area. As a result, it would be impossible to collect most of the cargo. It is possible to prevent this explosive dissipation in a number of ways and, as long as the materials are collected and accumulated for future use, the cheaper delivery option would suffice.

One of the simplest methods used with a hard-landing involves the use of arrow or rod-shaped



▲ An artist illustration of the Moon Express MX-1 lunar lander on the surface of the Moon after a soft landing. The California-based company is one of three selected by NASA for its Lunar Cargo Transportation and Landing by Soft Touchdown (CATALYST) initiative to advance lander capabilities that will enable delivery of payloads to the lunar surface.

A hard landing occurs at a speed of around 2500-3000 m/second. In effect, it can be thought of as a crash during which the cargo melts and partially evaporates

Implementing and controlling a hard landing is not that easy

cargo portions, similar to 'Rods from God' high-precision space weaponry. Objects of this shape act like a cumulative charge spray when faced with a barrier. Upon hitting the ground, the arrow-shaped parts of the cargo, provided that the mass, form, speed and material of the cargo were chosen correctly, should enter the ground at such a depth that their partial explosive evaporation will take the form of a 'closed-cavern camouflet', without the outside dispersement of the main material mass. A camouflet, in military science, is an artificial cavern created by an explosion. If the explosion reaches the surface it is then termed a crater.

This method can be conveniently used to deliver various metals to the location of the future base construction. Other, easily sublimated materials pose a difficulty however as any gases, for example, will escape the camouflet through the entry hole.

The second method of hard-landing cargo delivery is based on the creation of hermetically sealed camouflets in the ground. This is possible if the target is hit precisely, with an error margin that does not exceed 1-2 m. In this case, a hermetic ring is built on the ground or on a side of a hill, that is embedded into the ground and has a diameter of 2-4 m. The ring covers the potential landing area for the cargo and has a closable hatch that remains open until the cargo lands in the trapping ring. After the cargo has entered the ground, the ring hatch is closed, thus hermetically sealing the entrance to the camouflet.

This method has the advantage of being able to deliver materials such as water and other easily evaporated liquids, including cryogenic ones - such as oxygen, hydrogen, chloride, fluoride and some hydrocarbons - with relative ease. In this instance, polyethylene tubes can be used as containers for such liquids.

A further option to consider when developing cargo delivery technology for hard-landings on the Moon, is the use of regolith-filled shells. The shells would also have a closable hatch, so that the entrance port is closed and the gases contained. Such 'collectors' offer added improvements including ease of material retrieval and ease of preparation of next cargo delivery, as well as the potential use of generated heat.

A lasting impact

The part of a collector that could be delivered from Earth, such as the container, can be made of highly durable materials such as aramid, instead of metal. The container would be tube-shaped, with both ends sealed off and would be mounted on a sledding mechanism or on landing wheels, or a similar mechanism with a low materials-output ratio. It would have a volume of 80 cubic meters and a total mass (when empty) of 1 tonne. Taking into account the mass of the cargo catcher and density of the regolith only the 1 tonne container has to be delivered from Earth.

Preliminary assessment shows that up to 100 kg of materials can be thrown into one such catcher trap during a single mission. The rod-shaped cargo enters the trap through one of the container sides (the rod itself contains cryogenic liquids). The rod breaks the membrane or the net

► In coming years, government-sponsored and private-sector spacecraft will land on the Moon. This image shows a resource prospector carrying a Regolith and Environment Science and Oxygen and Lunar Volatile Extraction (RESOLVE) experiment, intended to find, characterise and map ice and other substances in almost permanently shadowed areas.

at the entry side of the collector container, which serves as a temporary wall for the regolith inside the container, goes through the mass of sand and slows down deep inside the catcher environment.

The explosive evaporation of the cargo is balanced by the massive and loose regolith. After this, the quick-acting lock is activated and all the gaseous product is hermetically sealed. The gas cools and is pumped out of the container into the bases' storage containers. Then, a new membrane or net is installed instead of the pierced one (or the existing membrane is patched up), the regolith is loosened or partially replaced, the lock is opened, and the collection container is once again ready for use.

Another type of membrane container is the mobile container. Such a system can receive cargo from the space vehicle that throws the cargo out into a container area with a target error margin of tens or hundreds of metres. These rods would have lidar radar detection markings, allowing the cargo's location to be calculated as they land vertically on the Moon. The collector container will then proceed to move to the landing point for cargo interception.

This method uses small collectors with the receiving opening of about half a metre and water or high-boiling hydrocarbons are used as the braking environment. A mechanical lock and an aerodynamic porthole are used for hermetic sealing. An aerodynamic porthole or window is a gaseous curtain that prevents the buffer zone materials, such as gases, aerosols and liquids, from leaking out into the outside vacuum. At the same time, the aerodynamic window allows for raw materials in the form of threads, bands or thin gas tubes to enter the chamber. Streams of materials that enter the chamber at the speed of 1700 to 2000 m/s, interact with the buffer zone, pulverize, brake and, mixing with the chamber environment, give off heat, after which they are separated and pumped into storage tanks. The window works only when the cargo arrives in the collection chamber of the collector, when the mechanical hatch lock is open.

Cargo-carrying spacecraft that can aim the cargo with precision from orbit and into the Moon collectors will naturally be specialised based on the type of cargo they are transporting. To ensure a successful delivery, the modules have a guidance system and a rocket propulsion system to aim the cargo block at the collector prior to send off, and to turn the sending block away after the cargo has been discharged.

Upper-stage rockets of cargo-carrying spacecraft could crash on the lunar surface in order to not add to the space debris cloud that already surrounds the Earth. However, if the payload mass is chosen appropriately, the boosters retain enough fuel to make it possible to lower the speed in perigee after circling the Moon and on the approach to Earth, and to enter low Earth orbit. In this case, the low cost of cargo delivery to the Moon is complemented by the possibility to use upper-stage rockets multiple times – it's cheaper to re-fuel them in low Earth orbit than to launch new boosters from Earth. The first stages could thus provide 15-20 repeat booster trips, with the potential of increasing that number to 100-200 trips.

The method, called Moontrap Technology, uses collectors that are not only useful for transport but also for technological production. Explosive processes in regolith, when hydrogen, hydrocarbon, carbon, chloride and fluoride enter the collector, create a regenerative reaction that produces iron, titanium, nickel, other metals and silicon.

Asteroids have their uses too

The regolith on many asteroids, including the martian moons Phobos and Deimos, is rich in carbon and possibly hydrocarbon. Carbon is necessary to release metals and oxygen from regolith.

It is much easier to deliver carbon to the Moon from Phobos or Deimos or other asteroids than from the Earth. In some places where hydrocarbon will fall, gas deposits, such as CO, CO_2 and H_2O will also appear along with metals. These deposits can be used in later stages as rocket fuel components.

Accordingly, a lunar transfer point would be beneficial for not only providing resources for Earth or a base on the Moon but also for facilitating the delivery of asteroid resources. The return of derived materials to space (for example, for building space power stations and refueling stations) also becomes cheaper thanks to orbitally based collectors. Orbital collectors will thus decrease the cost of cargo delivery by 95-99% not only from the Moon but also from Earth. ■

Considering the current level of rocket and other space technology development, it is more profitable to create industrial facilities on asteroids instead of on the Moon

About the author

Alexander Mayboroda is director of AVANTA-Consulting, Russia. He is a former director of Microgravitatcia research and Technology Centre, which worked under the aegis of the USSR Space Federation and the Research and Technology Society of the USSR on non-rocket space transport systems and using microgravity for industrial purposes. He also holds a number of international patents relating to inventions in space transport.

Space economics - industry trends and space investing

The economics of the space industry are changing. Within so called 'NewSpace' not only are new entrants being created almost daily, the business models and capital sources have proven to be dramatically different from traditional models built upon large government contracts and defence related spending. If economics is to be believed, the future of the industry will be dramatically different from anything the industry has previously experienced. This will create opportunities for industry participants including agile and well-led established companies, talented and skilled professionals as well as investors.

There are hundreds of new space startups addressing a multitude of industries and disrupting the traditional space paradigm

Dylan Taylor
Founding Partner,
Space Angels, USA

What is NewSpace? It is perhaps best to describe what it is not. NewSpace companies are not multi-billion multinational companies that have other commercial interests in addition to space, nor are they smaller low growth firms focused exclusively on sovereign nations as clients via grants and SBIR (Small Business Innovation Research) awards.

They are typically either companies focused on commercial elements of space, or they are part of the supply chain for larger space companies and are disrupting that supply chain with innovation. They are characterised by a scrappiness and mentality which is distinctly associated with Silicon Valley start-ups and they see existing business models as broken, inefficient or outdated. Perhaps the most prominent example of a newspace company is SpaceX.

Notwithstanding the fact that their business is primarily, if not exclusively, driven by the US government, they have approached solving issues in space from a non-traditional Silicon Valley startup mind set.

For example, the SpaceX project management system, is based upon the agile project management model known as 'Scrum' where tasks are planned week-to-week based upon the

▶ Silicon valley, California - home for young NewSpace companies.

previous week's learnings. This couldn't be more different from the linear project management models used by its competitors which literally lay out critical paths months or years ahead of time. As well as SpaceX, however, there are literally hundreds of new space startups addressing a multitude of industries and disrupting the traditional space paradigm.

There are several subsectors with the NewSpace industry, with several attracting the bulk of the capital in 2016, including launch companies and those involved in remote sensing and communications.

New launch entrants include Vector Space, Rocket Labs, Blue Origin and Relativity Space, all of which are attempting to optimise a three variable value equation: availability, reliability and affordability.

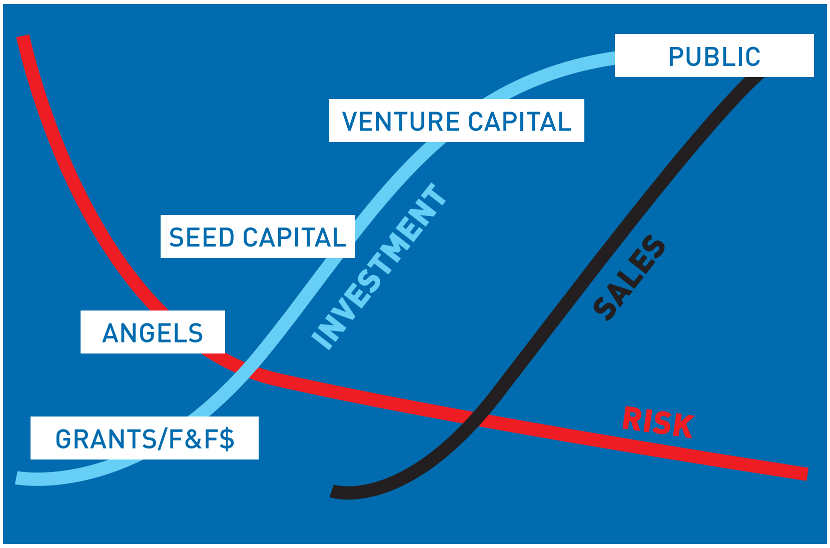
Any two of the three parameters is not enough to be successful long term, meaning, for example, having a reliable and affordable platform is not valuable if you either have no availability or can't predict availability. Similarly, being available and affordable but being seen as unreliable will not cut it either. It is for this reason that I disagree with those who predict a glut of supply for launch capacity in the near to medium term.

In remote sensing, there has been a huge explosion in company formations. Notable startups include Planet, OmniEarth, Audacy, LeoLabs, Spire, Kepler, OneWeb, Astranis and Analytical Space.

These companies are all racing to build infrastructure for what has been referred to as the 'mega-set' which will ultimately consist of a vast hyperspectral data set that is both persistent (always on) and ubiquitous (covering the whole Earth).

NewSpace companies are characterised by a scrappiness and mentality which is distinctly associated with Silicon Valley start-ups

▼ Company financing life cycle.



Primaxis Technology Ventures

Such a massive data set coupled with innovations in machine learning and artificial intelligence could literally create more value than the entire current space industry combined. Why? Because with a data set this vast the amount of products and services, especially products that are predictive in nature, are essentially unlimited. My view is that as the implications of the 'mega-set' becomes better understood, the amount of capital attracted to the space sector will dramatically increase.

Capital sources

As with all industries that have large numbers of start-ups, access to early stage capital is critical. The adjoining graph indicates that capital can be thought of in stages, starting with formation capital (typically friends and family) to so-called angel investors, private equity and venture capital and then, ultimately, public markets.

These capital sources are essentially sequential and cumulative in the sense that each stage requires successful deployment of capital at an earlier stage. For example, if sufficient capital isn't attracted at the friends and family round, the ability to create a proof of concept and/or an initial product or service that will attract angel capital could be impacted.

Without angel capital, the ability to generate client traction and revenue could be impacted which would likely prohibit the ability to raise venture capital and without successful venture capital and other sources of growth capital such

ANGEL INVESTORS
• $24.6 billion
• 71,000 deals
• 17,750 seed
• 31,950 early stage
• 19,170 expansion
• 305,000 individuals

VENTURE CAPITAL
• $59.1 billion*
• 4,380 deals
• 186 seed
• 2,219 early stage
• 1,975 later/expansion
• 718 active firms

* Sources "Angel investing Market for 2015, Centre for Venture Research/ UNH; NVCA 2016 Yearbook; PwC Money Tree

as private equity, the ability for a company to go public with an IPO (Initial Public Offering) remains nearly impossible.

Think of the life cycle of capital as a giant flywheel. It must turn in one direction from one stage to another continuously and without skipping portions of the wheel - but at each revolution (e.g. a public company exit) the next turn of the wheel becomes easier. In short, a single IPO could generate enough interest in a sector to flood it with early stage capital, which leads to more company formations, more later-stage growth companies and ultimately another two or three successful IPOs which then attracts more early stage capital.

Within all these stages, perhaps the most important is angel capital. Of 75,000 company investments in the US in 2015, more than 71,000 were funded by angel capital. Perhaps even more importantly, of the early stage investments, roughly 32,000 of the 34,000 were funded by angel investors.

Typical angel investors are high net worth individuals who have been successful in another industry and enjoy investing in starts-ups both for financial gain but also because they believe they have some other value added expertise that can be helpful to the company.

According to the Angel Capital Association, of the 8.7 US millionaires there are 265,000 active angel investors, and 15,000 belong to angel groups. Angel investing can also be potentially lucrative. Of the successful angel investment exits, the hold period was 3.4 years, the investors more than doubled their money with an average multiple of 2.6 and the internal rate of return (a measure of the investments success indexed for the time it was invested) was a whopping 27 percent.

While these returns may seem extraordinary, they presuppose that the investor is picking winners. In a portfolio of many investments, several will yield zero given the high risk of early stage investments going bankrupt. Consequently, angel investing is a craft which rewards the experienced and the knowledgeable, and certainly the fortunate.

NewSpace remains capital constrained. That is to say, the formation and growth of companies in the NewSpace sector is limited by its ability to attract new capital sources to the industry. While this constraint has been relaxed considerably in the past few years it still remains an important limiting factor to the industry's future growth.

As the implications of the 'mega-set' becomes better understood, the amount of capital attracted to the space sector will dramatically increase

▼ The fourth launch of Blue Origin's New Shepard vehicle before a successful descent and landing from a height of 101.0 km on 19 June 2016.

Blue Origin

Traditional space companies

How is the traditional space sector adjusting to the NewSpace paradigm? Clearly the larger more established space companies have competitive advantages. Such companies are typically large, well-capitalised, with large amounts of institutional knowledge, talented and experienced professionals.

However, with that institutionalism comes perhaps a risk aversion to new ideas and a classic case of innovator's dilemma. That is to say the incentives internally within traditional space companies reward status quo behaviour and typically punish disruption. As a consequence, the inertia of large organisations leads to incremental improvements in existing technologies and processes rather than radical new ways of solving problems.

Another constraint for innovation with many traditional space companies has been the cost-plus pricing model. In this model, the company charges a fee above their cost for delivering the product or service.

While this has many benefits to the company, for example consistent and predictable profits, it provides a disincentive to create new ways of delivering the product or service that might reduce its cost or efficiency, since the profits of the company would also be decreased.

Think of it as runners competing in a race. One runner is an established athlete and is guaranteed to always run a five-minute mile, rain or shine, health or illness. Another set of runners were literally pulled off the street and start out very slow, say six minutes or greater. However, there are hundreds of them and they are all competing and training every day. Eventually one of those aspiring runners will overtake the fixed speed athlete and, since the athlete has not trained or competed, their ability to then respond and become more competitive themselves has atrophied if it ever existed at all.

Impact of space policy

In addition to capital sources, space policy can have a large impact on industry dynamics and the economics of space. In recent years, the focus on using commercial elements for sovereign space programmes has created large blocks of capital that have allowed companies such as SpaceX to flourish and provided credible long term business plans that have attracted early stage capital for company formations.

In addition, early stage contract awards by organisations such as NASA, the Defense Advanced Research Projects Agency (DARPA) in the US and others have provided project based capital that has allowed many concepts to be developed from the bench or lab to proof of concept. From this stage, companies have much greater success attracting angel capital and continuing on the capital lifecycle fly wheel.

Space policy can also be helpful in terms of protecting intellectual and property rights. For example, Planetary Resources, a start-up based in Seattle which is focusing on asteroid mining was instrumental in helping to pass the US Space Act of 2015 which provided for ownership protections of certain space bodies for commercial use. Other resource oriented companies, such as Deep Space Industries, have also been involved with shaping policy regarding economic rights in space.

The other aspect of policy that drives economics is certainty. That is to say clarity around what are the priorities, the funding sources and the architectures that global sovereign space programmes are focused on. The more specific, consistent and long term these priorities are, the more comfort investors and companies have regarding their ability to align with them.

Switching from one priority to another or being vague about what the priorities are has the opposite effect. For example, it is unclear whether the new Trump administration will make the Moon a priority once again. If it does, this could be a boon to companies such as Astrobotics, Moon Express and Golden Spike.

I predict that in the future the commercial sector will take an even larger role in shaping both the priorities and the laws and policies governing space. I see this as a consequence of traditional

In addition to capital sources, space policy can have a large impact on industry dynamics and the economics of space

▼ Installation in August 2016 of the NanoRacks External Platform on the International Space Station (ISS). Houston-based NanoRacks was formed in 2009 to provide commercial hardware and services for the US laboratory on the ISS via a Space Act Agreement with NASA.

NanoRacks

space becoming less influential in that process and some of the protectionism surrounding jobs being lessened, but also because ultimately the commercial space sector will become an even more mainstream topic for citizens.

Increasingly the constituencies in countries around the world will expect more from their space programmes and become more involved with how they see human's future in space. Adroit politicians will tap into the interest and leverage it for maximum effect.

Looking forward

The economics of the space industry is evolving rapidly. New sources of capital continue to be attracted to the industry, unlocking more innovation which should ultimately lead to a handful of winners that will in turn attract new capital. This flywheel effect is just getting started in the space sector and should have a dramatic impact in reshaping the industry.

Traditional space companies must be aware of historical analogues to what is happening in space and be very careful to not fall prey to the pitfalls inherent with the innovator's dilemma and competing with companies driven by innovation and 'fail fast' business models.

I predict that in the future the commercial sector will take an even larger role in shaping both the priorities and the laws and policies governing space

The best NewSpace companies will mimic old space companies, in that their business models will be aligned broadly with industry dynamics and take their cues from space policy. They will hire experienced and seasoned talent and, notwithstanding their star-up ethos, they will still maintain a 'measure twice and cut once' mentality to insure they are seen as a safe pair of hands.

The best traditional space companies, in turn, will better mimic a successful NewSpace company. They will create skunk works or other mechanisms to insure they are innovating and disrupting their sectors even if it is to their short term detriment. They will look to other industries for both business models and talent, and they will drop any pretence of superiority for a healthy fear of the status-quo. The future of the industry is very bright for those entities self-aware enough to truly know how the industry is changing and strategic and proactive enough to shape their particular role in the industry by their actions. ■

About the author

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

▼ Changing times - SpaceX's Falcon 9 and Dragon lift off from Launch Pad 39A on 19 February 2017, the first launch from this pad since the final flight of the Space Shuttle in July 2011. The pad has since been reconfigured for use by the commercial space company.

SpaceX

European space business incubators and accelerators

Mark Boggett
CEO, Seraphim Space Fund, London

Accelerators and incubators are an important platform for advancing entrepreneurship around the globe, helping a new generation of young companies and particularly high-tech start-ups to grow, prosper and thrive. There are a rapidly growing number focused exclusively on the space industry.

This clustering of young businesses fuels the growing appetite for space technology investment from business angels and venture capital funds. Well sign-posted and highly visible, they help reduce search effort for investors by creating a pipeline of vetted technologies for the market. Likewise, larger corporates have a growing recognition that accelerators and incubators are a source for cutting-edge innovative products and services.

To have a complete picture of the different entrepreneurial space technology ecosystems around Europe and a better understanding of the different initiatives and best practices, Mark Boggett, CEO of Seraphim Space Fund, maps out accelerators and incubators serving the space industry across Europe and the UK.

The bedrock of space industry activity in this area is a network of incubators managed by the European Space Agency (ESA) operating across Eu 19 countries, with the larger countries such as France and Germany having multiple incubators. ■

		TOTAL	SPACE FOCUS	SPACE	TECH ENABLING
UK	Accelerator	68	UK wide	3	14
	Incubator	65	UK wide	9	16
EU	Accelerator	83	EU Top Cities	8	19
	Incubator	45	EU Top Cities	20	10

Incubators

Since start-up companies lack many resources, experience and networks, incubators provide services which helps them get over initial hurdles in starting up a business. These include flexible low-cost accommodation which can scale with the growing needs of the business, along with legal, accounting, computer services and other prerequisites to running the business. Business incubators differ from research and technology parks in their dedication to start-up and early-stage companies.

Accelerators

A defined programme for a cohort of companies (typically 10-20), run over a period of time (from a few weeks to a full year) which includes training, mentoring, networking, business plan and proposition development, investment readiness training and introductions to potential corporate customers through demo days and to angels and venture funds through pitch events.

EU ACCELERATORS

Space App Camp

Twice a year Space App camp assembles programmers across Europe at their one-week Accelerator in Frascati, Italy and Barcelona, Spain. The aim of the programme is to introduce attendants to the Copernicus Masters.

www.app-camp.eu

The NL Space Accelerator

The NL Space Accelerator is a 5-day accelerator supported by the European Space Solutions Agency and the Netherlands Space Office.

www.nlspace.nl

InnoSpace Masters

InnoSpace Masters Competitions leading up to the Space 4.0 conference in Berlin, Germany. Partners including Airbus Defence and ESA Incubation Centres.

http://www.innospace-masters.de

European Satellite Navigation Galileo Masters Competition

Annual competition seeking services, products, and business innovations that use satellite navigation in everyday life. Applications in June. In 2016 some 413 innovations were submitted by entrepreneurs from more than 40 countries. The prize pool is €1 million, which includes cash awards, business incubation, business coaching, patent consulting, technical support, access to testing facilities and prototype development.

www.cesah.com

Space 3ac

Space3ac is a three-month accelerator programme based in Poland, focused on the downstream sector. The programme maximum is 13 companies per cohort with applications closing March. Each accepted company receives €20,000 in seed investment with access up to €200k from later stage investors.

www.space3.ac

Copernicus Masters

The Copernicus Masters is a space technology and Earth observation competition where the winners have the opportunity to continue onto the Copernicus Accelerators. The best 40 applicants receive a customised business development scheme, an assigned mentor and acceptance onto the 6-8 month Accelerator programme.

www.copernicus-masters.com

Starburst Accelerator

Starburst is an Aerospace accelerator programme with bases in the USA, Europe and Asia. Three courses are held annually where the cohorts receive access to seed funding, mentors and business strategy planning. They also partner with the largest aerospace, defence and security groups to help land their cohorts a first US$1 million contract.

http://starburst.aero

EU INCUBATORS

SATLAS SATCOM

The SATLAS Incubator based in Luxembourg is designed to help start-ups and SME's test their business ideas over Satellites. The selected companies will be given the chance to test and demo their ideas and then present them in front Industrial Partners. The Applicants will have access to broadband platforms and terminals, hardware and software and technical assistance.

ESA Business Incubator Centres

The European Space Agency's (ESA) Business Incubations Centres work with around 130 space technology companies annually to help them commercialise their businesses. They are based at 19 sites all across Europe - Noordwijk (the Netherlands), Darmstadt (Germany), Lazio (Italy), Bavaria (Germany), Harwell (UK), Wallonie Redu (Belgium), Flanders (Belgium), Sud France, Barcelona (Spain), Portugal, Madrid (Spain), Sweden, Prague (Czech Republic), Austria, Ireland and Switzerland. All offer technical support to help transform space technology into non-space industrial products.

www.esa.int/Our_Activities/Space_Engineering_Technology/Business_Incubation/ESA_Business_Incubation_Centres12

UK ACCELERATORS

SetSquared Space Accelerator Hub

SetSquared is a three-day programme, based in Surrey, supporting space technology related businesses with their business plans, value proposition position and access to investors.

http://www.setsquared.co.uk

Satellite Application Catapult Spin-up Factory

Satellite Applications Catapult Spin-up Factory is an accelerator programme based in Oxfordshire, England, dedicated to developing companies which use satellite data. Companies can apply anytime.

https://sa.catapult.org.uk/services/business-support/spin-up-factory

UK INCUBATORS

Satellite Applications Catapult

Based in Harwell, Oxfordshire, England, the Satellite Applications Catapult is a space technology based innovation and research facility.

https://sa.catapult.org.uk

UK Space Agency (UKSA)

The UKSA has funded a number of university innovation incubators around the UK support start-ups and young companies trying to enter the space industry. Incubators are based in four centres across the UK - Durham University Business Centre; Sci-Tech Daresbury, Glyndwr; Innovation Centre, Leicester Dock; UNIP management, Loughborough University Incubator.

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

OpTIC Business Incubation Centre

The Glyndwr OpTIC Centre in Wrexham has secured grants of up to £50k to support companies trying to develop space sector innovation. Companies will receive seed investments and the ability to work in one of the UK's leading innovation centres.

www.glyndwrinnovations.co.uk

ESA Incubation Centre, Harwell

The ESA Business Incubation Centre in Harwell, Oxfordshire, accepts three sets of applications annually closing in January, April and October. It offers grants of up to £50k and support to develop business and access other ESA grant streams.

www.esa-bic.org.uk

Geovation

A 12-month programme of support including, mentor workshops, bespoke development and business support and access to software, technology and geospatial data.

https://geovation.uk

Bepi-Colombo will unveil Mercury's secrets

NASA/JPL, ESA

▲ An enhanced colour image of Mercury by MESSENGER.

With scorching temperatures of up to 400 degrees Celsius by day and a frigid -170 degrees by night, Mercury is no place for the ill-prepared! Nonetheless, this has not stopped a joint European and Japanese consortium from designing one of the most robust spacecraft ever made in order to brave these extreme conditions and get a close-up look at the 'iron planet'. Known as BepiColombo, the mission is set for launch next year and aims to spend four Mercury years unlocking the secrets of this unique planet.

Andrea Ferrero
Thales Alenia Space, Turin, Italy

Mercury, the smallest and innermost planet of the Solar System, lives the paradox of being one of the closest planets to Earth and yet one of the least known - out of the eight planets of the Solar System, only the faraway Uranus and Neptune have been less explored.

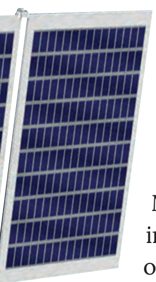
This is not due to lack of interest, as the 'iron planet' has some unique and intriguing features: it is the second-densest planet in the Solar System after Earth, and the only other inner planet besides Earth to have a significant magnetic field. This is a key parameter in allowing life to take hold on a planet, as without its shielding Earth would receive a significant amount of dangerous radiation from the Sun thus making conditions difficult for biological life to develop and persist.

Nonetheless, despite its modest gravity, Mercury also has an atmosphere, albeit very tenuous, which is constantly replenished in a way yet to be clarified, and its craters may hold more ice than the Moon.

Not surprisingly, there is a lot of scope for scientific exploration. However, many technical challenges exist in trying to get a spacecraft in orbit around Mercury. This is due to the gravitational pull of the Sun which tends to accelerate any spacecraft approaching it. Conversely, to be inserted in to an orbit a spacecraft needs to be slowed down, therefore a lot of fuel needs to be carried for the manoeuvres – in fact going to Mercury requires more fuel than going to Pluto!

Even if engineers were able to stabilise a Mercury-orbiting spacecraft, you then have to deal with the intolerable heat coming from the Sun (about 10 times the solar intensity around Earth). This naturally has implications for the temperature at the planet's surface which, in the case of Mercury, can reach 400C or more, and depending on the altitude a spacecraft is orbiting at, Mercury can reflect and emit as much heat as the Sun itself.

Accordingly, a trip to the inner regions of the Solar System is not the place to go unless you're more than confident in the robustness of your design.



Mercury's first visitors

The first spacecraft ever to cautiously approach Mercury was the NASA probe Mariner 10 and, ironically, if the mission had gone ahead as originally planned, many features of the planet would have remained a mystery.

In the initial proposal that was presented in 1970, Mariner 10 would have flown by Mercury only once, briefly, after having passed by Venus. However, an Italian scientist named Giuseppe Colombo, who at the time was visiting NASA's Jet Propulsion Laboratory (JPL), had noticed that the period of the spacecraft's orbit around the Sun, after it flew past Mercury, would be almost exactly twice the period of the planet itself, so the spacecraft and the planet would meet again and, with a little ingenuity, a second fly-by could be arranged.

JPL looked into Colombo's idea and found that by carefully choosing the first Mercury fly-by point it was actually possible to achieve a second and even a third fly-by. In 1974-75 Mariner 10 was able to fly by Mercury three times, photograph 45 percent of its surface and detect its magnetic field, which at the time was a puzzling discovery because Mercury was thought to be too small and rotating to have one.

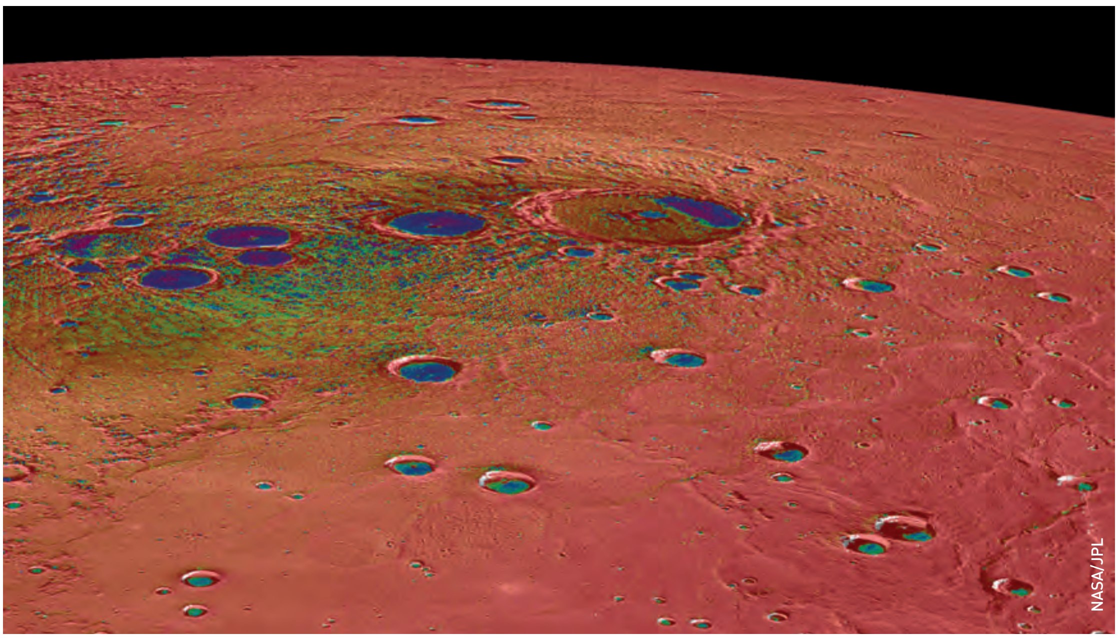
Mariner 10 remained the only spacecraft to probe Mercury until the recent MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging - a reference to the Roman mythological messenger Mercury). MESSENGER was the first spacecraft with a single aim of studying the iron planet.

Launched in August 2004, MESSENGER revealed the presence of distinct geochemical terrains and volcanic deposits estimated to be 2.5 to 3.5 km thick which covered huge basins on the planet's surface. MESSENGER also discovered a 'great valley' larger than North America's Grand Canyon in Mercury's southern hemisphere.

At more than 1000 km (620 miles) long, 400 km (250 miles) wide and 3 km (2 miles) deep, scientists suggested that the most likely explanation for this great valley is long-wavelength buckling of the planet's outermost shell in response to shrinking or global contraction – Mercury it seems is getting smaller.

MESSENGER ended its mission in 2015 by impacting onto the planet's surface, having

Not surprisingly, there is a lot of scope for scientific exploration, however many technical challenges exist in trying to get a spacecraft in orbit around Mercury



◀ Mercury's north polar region, coloured by the maximum biannual surface temperature, which ranges from >400K (red) to 50K (purple).

acquired over 250,000 images and extensive data sets and making many important discoveries. But perhaps to be expected, many questions still remain unanswered.

How 'Bepi' got its name

It is in honour of Giuseppe Colombo that the European Space Agency (ESA) decided to name its first mission to Mercury 'BepiColombo' (in northern Italy Bepi is short for Giuseppe). The mission has been developed in collaboration with the Japanese Space Agency (JAXA) and consists of two separate spacecraft, one provided by JAXA and one provided by ESA with both having their own mission agendas.

▼ Unpacking the MMO at ESTEC in The Netherlands.

ESA is also building the Mercury Transfer Module (MTM), which will carry the two orbiters from Earth to Mercury. Upon arrival, the transfer module will be jettisoned and the two orbiters will separate.

The European orbiter, called MPO (Mercury Planetary Orbiter), carries 11 scientific payloads that will investigate Mercury's gravitational field in detail, test Einstein's theory of general relativity to a greater precision than ever before, and measure the topography and surface morphology of Mercury. Instruments include the Mercury Gamma-ray and Neutron Spectrometer (MGNS), the Mercury Imaging X-ray Spectrometer (MIXS) and the Search for Exosphere Refilling and Emitted Neutral Abundances (neutral and ionised particle analyser), or SERENA for short.

ESA is also building the MMO Sunshield and Interface Structure (MOSIF), which provides thermal protection, and the mechanical and electrical interfaces for the Mercury Magnetospheric Orbiter (MMO), a spinning spacecraft provided by JAXA.

It will carry a payload of five advanced scientific experiments, including an ion spectrometer, electron energy analyser, magnetometer, cold and energetic plasma detectors, plasma wave analyser, and imager. These will help to study the structure and dynamics of Mercury's magnetic field and observe the dust which makes up the planet's atmosphere, in order to try and understand how exactly it is released.

The spacecraft will be powered by a single-sided, three-panelled solar array that uses Optical Solar Reflectors (OSRs) for temperature control and can provide up to 1000 W of electrical power during full science operation phases.

BepiColombo has been designed to complement the findings of MESSENGER, though the MPO will have a much less elliptical orbit that will allow the spacecraft to study the southern hemisphere of Mercury almost as accurately as the northern hemisphere. Having a dual spacecraft such as MPO and MMO, has the advantage of being able to study two regions of the planet at the same time.

BepiColombo will provide global spectral mapping of the surface of Mercury with a better resolution than MESSENGER and in a different wavelength range. Finally, BepiColombo will look for the crater left by MESSENGER on the surface of Mercury in 2015 and study it to understand the rate of space weathering.

Trials and tribulations

The mission will be completed by a consortium of industries, and is led by Airbus Deutschland, with the Italian branch of Thales Alenia Space in charge of the crucial thermal control subsystem.

The harsh thermal environment that BepiColombo is going to face has posed unprecedented technical challenges; not only was it necessary to develop and test new materials able to withstand the extreme environments of space, including severe temperatures, and to insulate the spacecraft with utmost efficiency, but ESA also had to extensively refurbish its test facility, the Large Space Simulator (LSS). This was a necessary part of the process in order to increase the LSS's solar simulation capability from 1300 W/m^2 (the solar flux around Earth) to more than 10,000 W/m^2, a target achieved with a set of expensive and fragile lamps of 25 kW each – power that would have any commercial electricity supplier rubbing their hands with glee if they had to supply it.

Aside from the mechanical challenges, it was necessary to coordinate teams of scientists and engineers from all over Europe to coordinate the various payloads aboard MPO and to satisfy their often conflicting technical needs.

Not only that, but new design solutions also had to be developed. For instance, a normal spacecraft has a stack of thermal blankets all around it to protect it from the environment; MPO has three carefully designed stacks on top of each other, which are partly composed of materials developed ad hoc and are able to withstand temperatures of up to 400C.

In addition, it is normal for one or two sides of a spacecraft to always be in shadow, thus allowing these sides to act as radiators, to dissipate heat coming from both the Sun and onboard electronics in the spacecraft itself, into deep space. In the case of the MPO, however, all sides of the spacecraft will receive significant amounts of heat flux from either the Sun of Mercury. It was therefore necessary to devise an intricate design of curved mirrors that will discard heat generated by the spacecraft, while simultaneously deflecting the heat coming from the planet.

Onwards and upwards

Although many issues have been successfully resolved, several unexpected problems arose when the manufacturing was already at an advanced stage. These of course have needed workaround solutions that have caused delays and put at risk the scientific significance of the mission.

Nonetheless, the team has managed to get on top of all the obstacles faced and it is with a great amount of satisfaction that we are on our way to achieve what will be an historical result for the European space industry.

The integration and testing of the various modules is being completed and the launch of BepiColombo on an Ariane 5 rocket is currently scheduled for 2018. After a six-year cruise, that will see the spacecraft fly by Venus twice and Mercury six times before it settles into the right orbit, BepiColombo will resume the exploration of Mercury, taking over where MESSENGER left off.

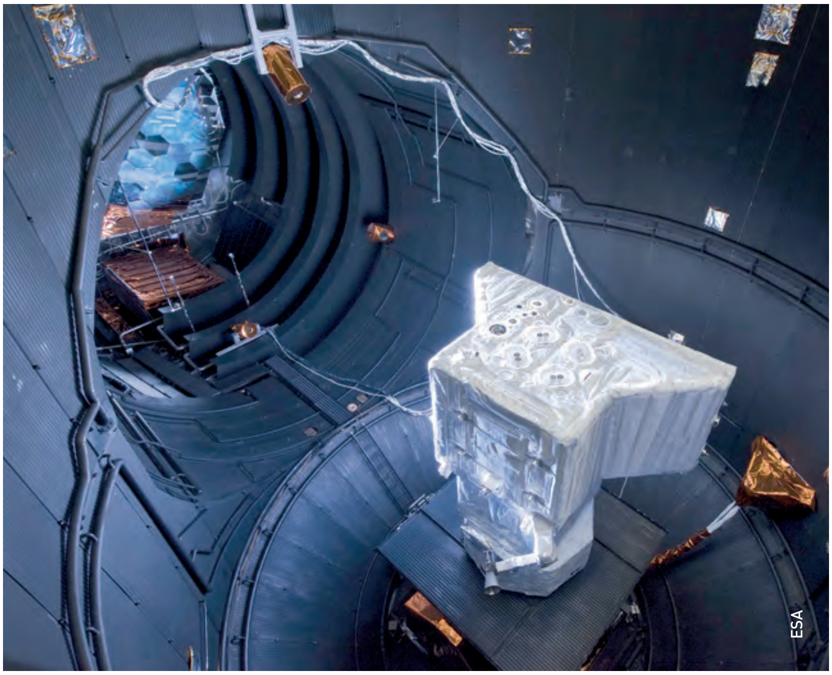
Once in orbit and using the Usuda 64 m antenna in Japan, the ISAS/JAXA Sagamihara Space Operation Centre, will take over the operation of the MMO. Similarly, the European Space Operations Centre (ESOC) in Darmstadt, Germany, will remain in charge of the MPO spacecraft.

During its one Earth year mission, which equates to four Mercury years, it is hoped that BepiColombo will answer some fundamental questions such as: is Mercury tectonically active today? Is its core liquid or solid? Why do spectroscopic observations of Mercury not reveal the presence of any iron, when this element is expected to be the planet's major constituent? These are just a few of the 12 scientific objectives that BepiColombo is hoping to answer, while helping to understand what makes Mercury so special. ■

About the author

Andrea Ferrero is a specialist in thermal verification at Thales Alenia Space Italia in Turin, Italy, where, since 1997, he has worked on modules of the International Space Station and on several Earth observation satellites. He is a thermal systems engineer for BepiColombo, and is also among the organisers of the annual International Conference on Environmental Systems.

Having a dual spacecraft such as MPO and MMO has the advantage of being able to study two regions of the planet at the same time



▼ BepiColombo's MPO antenna in the Large Space Simulator (LSS).

Hunting for neutrinos in the ice of Antarctica

Finding neutrinos is no easy task. In the past it has required huge underground liquid-filled tanks to capture the tell-tale signature of an interaction with one of the lightest known particles known to us. Now, a new project aimed at finding the most energetic of neutrinos is being constructed above ground at the Ross ice-shelf in Antarctica. Known as ARIANNA (Antarctic Ross Ice-Shelf ANtenna Neutrino Array), the project hopes to shed light on which astronomical phenomenon is responsible for creating relativistic particles that leave very little trace of where they came from.

Anna Nelles
University of California, Irvine, USA

Neutrinos are neutral subatomic particles with a mass close to zero and, experimentally, they were only discovered in the 1950s. Detecting neutrinos is a difficult challenge as being one of the lightest known particles, large quantities of matter are needed to observe them as the neutrino interaction cross-section i.e. the probability to see them interact, is very small per unit of matter.

When you think of neutrino experiments, huge tanks filled with water or other liquids spring to mind, which are not only pretty to look at but are also impressively large. However, this in itself poses a problem and when laboratory experiments could no longer be made bigger due to practicality and cost-restrictions, scientists turned to naturally occurring materials instead. Now, experiments designed to search for neutrinos can be found in locations such as the Mediterranean Sea, in lake Baikal in Russia and in the ice of Antarctica.

If you ever wondered why an increasing mass volume is so important for finding neutrinos, when they have already been detected in laboratory experiments, it is because scientists are not only

trying to count neutrinos, but they also want to study their energy.

Certain energy ranges, or in other words different ranges of speed, are occupied by neutrinos from different sources. For example, neutrinos produced in nuclear reactors have energies between three and 10 mega-electronvolts (MeV) and are usually more energetic than those from the Sun (at less than 1 MeV). Conversely, those produced in the atmosphere are more energetic (at 1 GeV - 10^5 GeV), so too are astrophysical neutrinos (10^5 - 10^6 GeV) and cosmogenic neutrinos (> 10^7 GeV). They all have their distinct place in the energy spectrum. So if one wants to study different sources, the sensitivity of the detector has to be adjusted to the desired energy range. Generally speaking, the assumption holds that the higher the energy of the neutrino, the rarer it is.

Cosmogenic neutrinos are believed to be even rarer than the already extremely rare astrophysical neutrinos detected only recently by the IceCube experiment at the South Pole. This is currently the largest neutrino detector in the world and it detects less than 10 astrophysical neutrinos per year in 1 square kilometre of ice ('IceCube').

Cosmogenic neutrinos are linked to ultra-high energy cosmic rays and these rays are the most energetically charged particles known in the Universe today. With energies that are several million times higher than what can be achieved by man-made machines, these particles are created by yet unknown astronomical objects.

There have been many theories linking them to black holes or gamma ray bursts, but no convincing evidence has yet been found to tie a type of source to the particles. The search for these elusive sources has been hindered by the fact that charged particles do not travel in straight lines. Their trajectories are bent by galactic and intergalactic magnetic fields, which makes it challenging to pin-point the objects in question. For example, a source we see towards Galactic North might actually be in the South, thus presenting an almost unsolvable problem.

Yet, there is hope. It has been postulated that a fraction of these charged cosmic rays will interact with the cosmic microwave background, the ubiquitous background residual of the Big Bang, close to the phenomenon that emitted them. In these interactions, neutrinos will be produced that carry away a lot of the original energy of the cosmic ray. As neutral particles, these cosmogenic neutrinos can then travel unhindered in straight lines before they reach Earth. Consequently, a detection of cosmogenic neutrinos would allow us to directly pin-point the source. Unfortunately, however, all current neutrino detectors are too small to find cosmogenic neutrinos.

The way forward

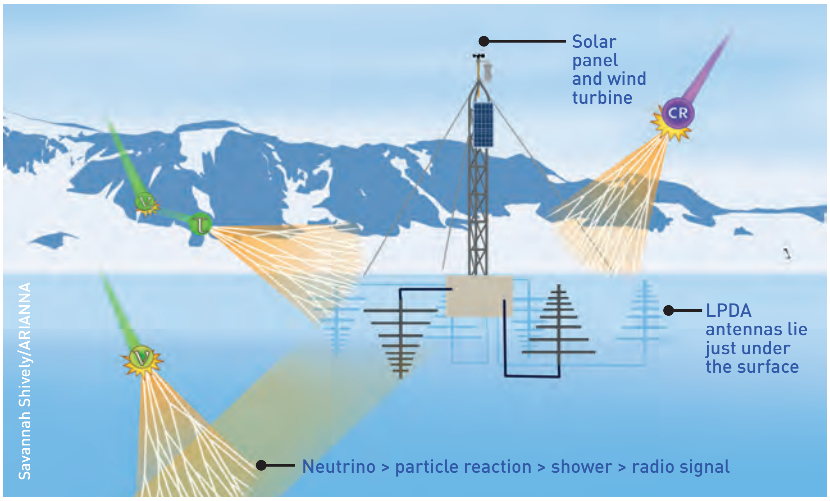
Building an even bigger detector either requires an enormous amount of funding when using the same technology or a different approach. A neutrino can only be observed indirectly by detecting its interaction products i.e. the tell-tale sign that points to its existence. A common method is to look for the Cherenkov light signal that is produced by charged particles originating from a neutrino interaction that travel faster than the speed of light in the medium.

As light 'slows-down' when it is not in a vacuum this effect happens without violating the theory of General Relativity and can be interpreted as the equivalent to a supersonic boom in air. In order to detect this Cherenkov radiation, light detectors monitor the medium at different positions and if a signal starts in the detector volume without an incoming signal, a neutrino interaction is recorded as being observed.

What drives the overall costs of a detector is, perhaps bizarrely, the space between the individual

◀ Pressure ridges near McMurdo station in Antarctica, where the ARIANNA logistics base is located. Pressure ridges occur when the annually forming sea ice pushes into the permanent ice of Antarctica.

Generally speaking, the assumption holds that the higher the energy of the neutrino, the rarer it is



▲ Diagram of one ARIANNA station and its detection capabilities. The autonomous stations are sensitive to the radio signals generated by incoming neutrinos (Greek letter 'nu', green) and cosmic rays (CR, purple). By studying the signals in different antennas, it is possible to distinguish the signals and reconstruct the arrival direction. The full array will consists of more than 1000 stations.

▼ View at camp and the transantarctic mountains. The dot in the middle is a station.

light detectors. The maximum distance is governed by ice properties such as scattering and attenuation. As these properties determine how far away a signal can be detected, they determine how far a detector grid can be spaced and therefore how big a detector can be, given a fixed budget. Even with technological progress it seems unlikely that it will become feasible to build a Cherenkov light detector that will be big enough to measure interactions that only occur about once every year in 100 km^3 of ice.

Using ice as a detector is advantageous for a number of reasons, not least because it is available in large quantities at high purity and no cost, but also because scientists can turn to other reaction products that result from a neutrino interaction: radio signals. The charged particles that are created after a neutrino interaction not only create a flash of light but also a short broadband radio pulse, mostly at MHz frequencies. This is caused by something called the charge-excess, which in basic terms relates to how the interaction of a once neutral neutrino will accumulate charge as it traverses a dense medium like our atmosphere.

Cosmogenic neutrinos are linked to ultra-high energy cosmic rays - the most energetically charged elementary particles known in the Universe today

In doing so, the neutrino initiates an electromagnetic shower as it collects electrons from the surrounding medium and leaves positively charged ions behind. In this charge separation, a changing current is created along the shower axis, which leads to an emissions of radio waves. In contrast to light, radio emission travel longer distances through ice before being attenuated which therefore allows for larger volumes of ice to act as instruments, with the same number of signal detectors, thus reducing costs.

The tricky thing about radio emission, however, is that it is not particularly unique. While it is highly unlikely for anything but an elementary particle to cause a flash of light in dark ice, every electrical machine creates radio emission. Since radio waves can travel larger distances, it is possible to confuse a neutrino signal with something man-made, like the signal from a spark plug. Thankfully, modern data-processing technology has advanced so that it has become feasible to pick-out distinct features of the radio emission that make neutrino signals unique. This technological advancement combined with a place (on Earth) associated with minimal human activity, has subsequently lead to the development of the ARIANNA project situated on the Ross ice-shelf.

ARIANNA

Currently, the ARIANNA detector is in its pilot-phase. Located in a very specific corner on the Ross ice-shelf with pure ice and shielded by

mighty trans-Antarctic mountains from the nearest research stations, nine stations are currently in operation to test the feasibility of the detection concept.

Every station is equipped with log-periodic dipole antennas. The antennas are highly sensitive and directional, meaning that they are more likely to detect a signal coming towards their front than towards their rear. These antennas are placed front first in the snow on top of the ice enabling them to monitor the ice underneath for neutrino interactions. The detection concept benefits from its location on the ice-shelf and having an ocean underneath, as the interface between ice and water acts as a mirror for radio emission. This configuration allows ARIANNA to simulate a detector with a large field of view, thus helping to overcome the problem of trying to pinpoint the location of neutrino sources in the sky.

Nine stations are certainly not enough to see cosmogenic neutrinos but they do act as pathfinders to prove that the technology will work. The stations rely only on solar and wind power and, during the endless day in the polar summer, the stations are up 24 hours a day collecting data.

Winter is another matter, however, as the operations are not quite stable and a perfect balance has to be found using cold-resistant batteries that buffer energy from wind-generated power during the windy periods. What sounds perfectly straightforward in normal conditions is not quite that straightforward in Antarctica. The wind-turbines need to be sturdy enough to survive hard Antarctic storms and sensitive enough to create sufficient power from a small breeze to allow for continuous operations. On top of that, extreme temperatures put a strain on batteries and detector moving parts, and with a site that is totally inaccessible from March through to October, it is not hard to imagine what other problems that brings.

In spite of this, once operational, the stations use very little power. With less than 5 watts, the stations are able to digitize the detected radio waves at up to 2 billion samples (Gsamples) per second and a sophisticated chip searches for coincidences between signals crossing a defined amplitude threshold in different antennas.

While it is highly unlikely for anything but an elementary particle to cause a flash of light in dark ice, every electrical machine creates radio emission

▲ Overview of the position of ARIANNA.

Currently the stations are equipped with long-range wifi and satellite communication via the Iridium network, commonly used for telephone connections in polar regions.

While the long-range wifi allows for a high through-put of data, it is more expensive, power-consuming and limited in operation during bad weather. Satellite communication is more reliable; however, it is limited to binary short-burst messages, essentially text messages, which restricts the amount of data that can be sent.

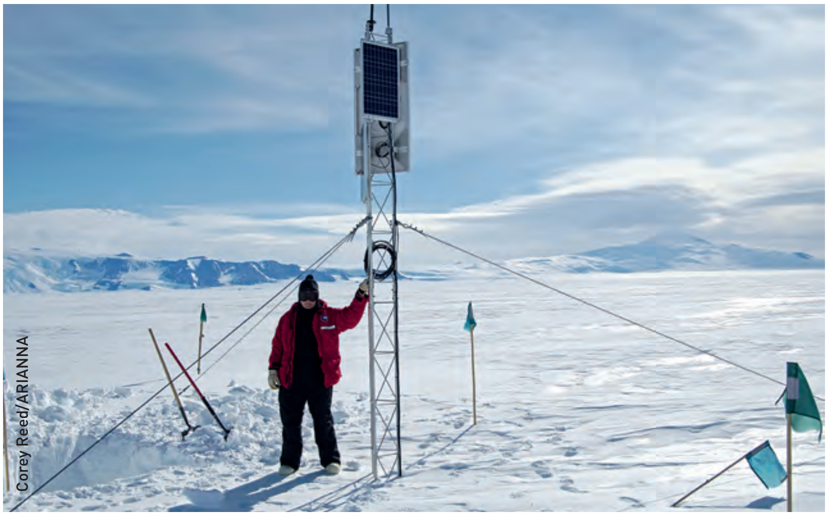
Still, the ARIANNA site has proven to be so radio-quiet that there are very few false positive triggers and the text messages have proven to be sufficient to get all data out in real-time. The stations autonomously connect to a server in the United States to check whether new instructions are available and then send their data at a given time-interval. This method ensures that there is virtually no human interaction needed - an important feature for an array that is planned to consist of more than 1000 stations and will operate for more than five years.

Deciphering the good from the bad

Since the pilot-stage array of ARIANNA is comparatively short, there are no neutrino reports

▼ Two stations in the field.

Anna Nelles/ARIANNA



▲ Anna Nelles in front of station tower with hole to access the station electronics.

yet. In fact, any supposed neutrino detection would bring the feasibility of the detector and the predictions of cosmogenic neutrinos under pressure. It would be incredibly good luck, at this stage, to detect a neutrino signal and highly suspicious if an unknown background event that mimicked neutrino signals were recorded.

Most of the currently recorded events are dominated by thermal noise, such as that heard when a radio is turned to a frequency where there is no station transmitting. In this thermal noise, coincidences between spikes in two antennas actually happen by unrelated coincidences, so some data is always recorded. Despite being called thermal noise, a part of the radio background is caused by the diffuse synchrotron emission of the Galaxy. So technically, ARIANNA is detecting a galactic signal already, though it is not caused by neutrinos. While this irreducible background limits the minimum energy a neutrino needs to have in order for it to be detectable, the fact that the Galaxy is detected without additional analysis is a sign of the wondrous harmony between an impressive detector and a perfectly chosen site.

▼ Team in Antarctica next to a station, holding an antenna for illustration purposes.

What sounds perfectly straight forward in normal conditions is not... in Antarctica

Signals more similar to neutrinos are caused by cosmic rays that interact in the atmosphere. A cosmic ray interaction in the atmosphere also causes a particle cascade, which in turn is the cause of radio emission. In air, the particle cascades are somewhat larger and affected by the magnetic field of Earth; still, their radio signals are intrinsically similar to the radio signals expected from neutrinos. The only difference is that neutrino signals will come from the ice and cosmic ray signals from above. This is where directionality of the antennas comes into play.

The full ARIANNA will have up- and downward-pointing antennas at every station, which will allow for an easy differentiation between neutrino and cosmic ray signals. While the latter are more abundant - after all cosmogenic neutrinos are caused by a fraction of cosmic rays - it is inevitable that we will detect them. In contrast, a non-detection should have us worried about detector performance and feasibility.

The future

Where is ARIANNA going from here? For now, we will improve on detecting cosmic rays, as they will act as a calibration source for ARIANNA. A pulse of a couple of nanoseconds detected in one stations is enough to reconstruct the direction of the cosmic ray and give an estimate of its energy.

Despite not knowing too much about the sources of ultra-high energy cosmic rays, their energy distribution is well-known. If ARIANNA's technique can reconstruct the same energy spectrum, we will have proof that the same will work for neutrinos and that we are ready to tackle the search for cosmogenic neutrinos.

This work will start as soon as the full suite of stations - at least 1200 of them - is deployed on the Ross ice-shelf which in itself poses a whole other logistic operation. Nonetheless, exciting times lay ahead and soon we will hopefully be reporting on a real neutrino detection thus providing a conclusive statement as to the sources of ultra-high energy cosmic rays. ■

About the author

Dr Anna Nelles is a postdoctoral researcher and DFG fellow working at the University of California Irvine. Her research interests include, radio detection of neutrinos and cosmic rays with various instruments, such as ARIANNA, LOFAR or the Pierre Auger Observatory.

▶ United Nations headquarters in Vienna, Austria, seat of UNOOSA and UNCOPUOS.

If new regulatory mechanisms, agreements or institutions are to be created, they would need to adequately tackle a new range of issues

Tomas Hrozensky
Matej Bel University, Banská Bystrica, Slovakia

Rapidly evolving space industry needs faster response from UN

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. With governing law, regulatory aspects and policy hardly keeping pace with the constant innovation and development of space science, Tomas Hrozensky urges the international space community to actively participate in the ongoing process related to UNISPACE+50.

▲ COPUOS is still the largest international forum dealing with space governance.

International mechanisms and institutions governing space activities have not been evolving and adjusting as quickly as the actors and their activities conducted in the global space sector. Although the current legal regime and related system of space governance has so far tackled issues emerging as a result of new developments sufficiently well, this may become more and more difficult in coming years.

Global space governance finds itself at a crossroads with multiple different ways to proceed. The international space community needs to adjust mechanisms and policies to more adequately reflect the rise of private space activities, ambitious visions in space exploration, current trends in space security or new types and growing numbers of actors dealing with space, both in national policies and in international arena.

Fortunately, forthcoming years are providing the international space community with symbolic anniversaries that raise both public and expert awareness of issues related to the governance of space activities and thus could create momentum for new or improved incentives for more suited ways of governing space activities.

This year marks the 50th anniversary of the Outer Space Treaty, the primary document of international space law. The Treaty itself contains mainly general provisions governing fundamental rights, responsibilities and obligations that countries have when they conduct space activities. Even though it is not an exhaustive legal text, authors of the Treaty created solid foundations for a more comprehensive mechanism establishing fair balance between freedoms and obligations, interests of stronger and weaker actors, and ideals on the one hand versus political realities on the other.

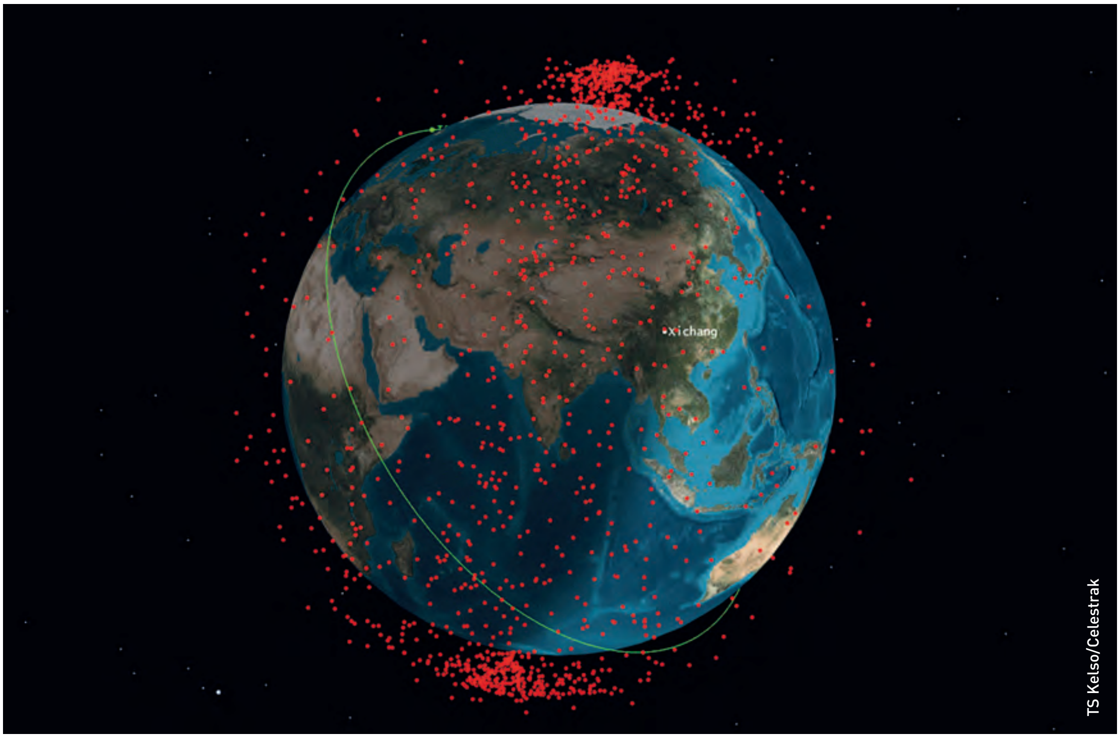
Next year will see the 50th anniversary of the first global Conference on the Exploration and Peaceful Uses of Outer Space - UNISPACE - held in Vienna, Austria, in 1968. Since then two other UNISPACE conferences have taken place in Vienna - in 1982 and 1999 - and the United Nation's Committee on Peaceful Uses of Outer Space (UN COPUOS) is now organising the fourth such conference, UNISPACE+50.

Previous UNISPACE conferences have had a significant impact on subsequent periods of time. The post-millennial agenda of UN COPUOS has been largely shaped by the results of UNISPACE III elaborated in the Vienna Declaration on Space and Human Development. As this new opportunity approaches, the international space community should take into account these results and build upon this knowledge.

Forthcoming conferences will serve as a fruitful forum with potential to create new or expand existing regulatory mechanisms, transparency and confidence building measures, policy incentives, or other relevant multilateral initiatives.

UNISPACE+50 will be held in mid-2018. The process and work plan leading to the conference includes several other events, including some high-level forums, with the most recent of them taking place in late November 2016. The Dubai Declaration, which emerged as a result of this multi-day event, outlined optimistic and hopeful visions and ambitions for upcoming months and years.

How should global governance of space activities deal with new trends and developments in national security space or space weaponisation?



▶ Distribution of Fengyun-1C debris (red), a weather satellite intentionally destroyed by China in 2007. Orbit of the International Space Station is shown in green.

However, there remain some differences related to the anniversary of the Outer Space Treaty and UNISPACE+50 compared to previous UNISPACE conferences. If new regulatory mechanisms, agreements or institutions are to be created, they would need to adequately tackle a new range of issues, such as the rising number of smaller countries taking part in the exploration and use of outer space, the continuous rise of commercial space activities and related growth of private space ventures.

How should global governance of space activities deal with new trends and developments in national security space or space weaponisation? Or, how can we effectively regulate continuing congestion of Earth orbits and radio spectrum?

The potential of the 50th anniversary conference in issues of global governance of space activities does not necessarily lie in adopting new international agreements. Opening up the existing legal regime could be a tricky decision given ongoing geopolitical realities in the world and no significant progress in the hard-law part of international space law achieved in recent years.

I believe it is in the interest of all members of the international space community to actively participate in the ongoing process between now and 2018. Often it is the journey itself that is considered to be more important than the destination - and one could certainly apply this as we approach this landmark opportunity.

The absence of significant achievements in recent history at a UN level might create an argument for questioning the importance and role of the United Nations in space affairs, especially as recent efforts to proceed with new initiatives outside of the UN have been unsuccessful. The International Code of Conduct for Space Activities, for example, led by the European Union (EU), is to all intents and purposes in 'hibernation'.

The United Nations will never be a space power and this is not the role the UN should aim to play in the global space sector. The approach taken by the UN office for Outer Space Affairs or UN COPUOS is not flawless - but on the international stage it still constitutes the best option we have to evaluate and adopt the most efficient mechanism of global governance of space activities.

One criticism often levelled at the UN COPUOS is that it does not adapt its agenda fast enough in comparison to the quick evolution and contemporary trends in the global space sector. It is therefore understandable that finding common grounds and similar mind sets between the diplomatic, political and legal

One criticism often levelled at the UN COPUOS is that it does not adapt its agenda fast enough in comparison to the quick evolution and contemporary trends in the global space sector

nature of COPUOS with economics, business and industry related ambitions of private and commercial space community is not an easy task and constitutes a significant barrier in efforts to create new, better suited mechanisms for governing space activities.

A significant part of the UN approach to outer space is related to broader UN initiatives, specifically the 2030 Sustainable Development agenda, where space is being discussed as one of the tools to achieve sustainable development goals.

When focusing more directly on space itself, the UN space agenda also remains relatively broad. Complicated diplomatic procedures and large numbers of different agenda items at the sessions of UN COPUOS and its subcommittees may appear to some external observers as a disorganised approach.

UNISPACE+50 has a significant role in defining the future role of the UN Committee for Peaceful Uses of Outer Space, which remains today the only body in the international community suitable to deal with high-level policy and regulatory issues of the exploration and use of outer space.

The future role of the UN COPUOS will be formed during the processes scheduled to play out in forthcoming months. There is the potential to create a solid foundation for multilateral discussions with inputs from the civil, commercial and military space sectors, with the participation of existing space powers as well as emerging actors from both the OECD group and developing countries, while taking into account the constantly changing nature of space activities.

But the questions that new space governance mechanisms will have to address are seemingly growing and include:

- How to adequately regulate the so-called NewSpace movement so that commercial and business rationales remain thriving in private sector?
- How to address the future of space exploration visions such as colonisation of other planets or asteroid mining should they become reality?
- What kind of regulatory model will safeguard unlimited access to and free exploration and use of space for new space actors while at the same time maintaining the long-term sustainability of space activities?

Since space science and technology are undergoing constant innovation, the governing law, regulatory aspects and policy need to maintain an equal pace.

Having an imbalanced relationship between innovation in space technology and regulatory mechanisms will inevitably cause setbacks

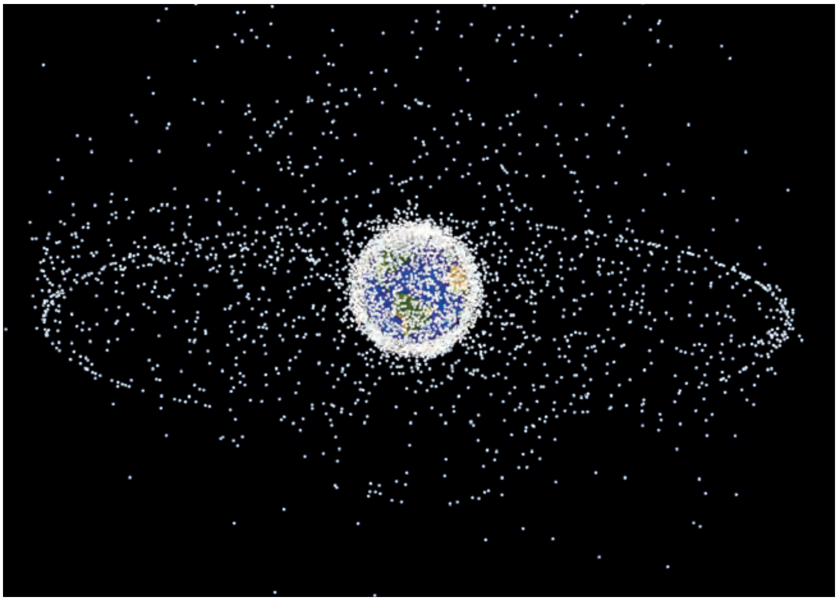
It reminds me of the lasting historical struggle between artillery on the one hand and shielding on the other. When one innovated, the other had to adjust, and vice versa. Having an imbalanced relationship between innovation in space technology and regulatory mechanisms will inevitably cause setbacks. It is good therefore that the international space community will encompass discussions dedicated to space governance over the next 15 months. Interim outcomes, such as the initially agreed first set of guidelines for long-term sustainablity of space activities, seem promising but the long-term results remain uncertain. ■

About the author

Tomas Hrozensky is a PhD student at the Matej Bel University in Banská Bystrica, Slovakia. His doctoral research at the Security Studies Department of the Faculty of Political Science and International Relations focuses on contemporary trends and dynamics in the global space sector. He is chairman of an NGO Slovak Space Policy Association, a member of the Space Generation Advisory Council representing Slovakia and regularly participates at sessions of the UN Committee for Peaceful Uses of Outer Space and its subcommittees.

If you would like to submit an opinion, letter or comment article for publication in ROOM please contact or send via email to: Clive Simpson, Managing Editor - clive_simpson@room.eu.com

▼ Measures, so far not yet legally binding, preventing the growth of space debris were included in the UNCOPUOS Space Debris Mitigation Guidelines back in 2007 and are currently part of discussions regarding long term sustainability guidelines.



Could Brexit blow a hole in UK's space ambitions?

▲ The UK and Europe as viewed by British astronaut Tim Peake during his ESA mission on the International Space Station.

***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, Dr Michael Leggett analyses the possible effects of Britain leaving the EU ('Brexit') on the long-established cooperation of the UK and Europe in space.**

Mike Leggett
Programme Manager & space lecturer, Milton Keynes, UK

"We are leaving the European Union not Europe", an often-repeated phrase since the UK Referendum of 23 June 2016, and one which might offer some comfort to those who are participants in organisations outside the European Union (EU), including the European Space Agency (ESA). However, the distinction between the EU and intergovernmental organisations such as ESA is not always clear cut and the way ahead might not necessarily be plain sailing.

ESA is not part of the EU; it has 22 member states, not all of which are EU members. Norway and Switzerland are members of ESA, for example, but not members of the EU. Furthermore, the EU currently has 28 members (including the UK), not all of which are members of ESA.

On the face of it, Brexit should not directly affect the UK's membership of ESA. However, there might be indirect effects as a consequence of ESA-EU programmes and depending on the final nature of Brexit.

The EU itself is a major contributor to ESA, principally for the Galileo global navigation satellite system (GNSS), which began operations in December 2016, and the Copernicus Earth observation programmes. Funded and owned by the EU, ESA acts as design and procurement agent for Galileo on behalf of the European Commission. Copernicus is also led by the EU.

The UK is a key participant in these programmes but after Brexit continued UK participation in these programmes might become problematic.

There is considerable support across the board for continued UK participation in ESA after Brexit. The UK is a significant contributor to ESA and it is recognised that membership of an organisation such as ESA allows its member

◀ Flags are raised to mark the formal opening of ESA's first UK facility - the European Centre for Satellite Applications and Telecommunications (ECSAT) - at Harwell, Oxfordshire, in July 2015.

states to do more in space than each country would be able to do by itself.

Nevertheless, there have been calls from some within the UK for a completely 'home-grown' space programme, with a suggestion that the returns could be much greater than are currently obtained through participation in ESA.

Spaceflight Bill

In February this year the British government published a draft Spaceflight Bill aimed at providing a regulatory framework for the commercial launch of satellites from UK spaceports and though receiving much media publicity this should not be seen as something that would provide anything like an alternative to ESA membership.

Plans for commercial spaceflight launches from UK spaceports might become more viable with cheaper launch systems, including some of the horizontal launch systems with which the UK space industry is involved.

However, several of the proposed spaceport locations are in Scotland, which might be affected if Scotland, which voted to remain in the EU, has a further independence referendum and decides to leave the UK in order to seek membership of the EU.

Perhaps a bigger issue in relation to any space fallout from Brexit is that of 'mission creep'. The referendum presented a simple choice, that of whether to leave the EU or remain in the EU. There were sometimes discussions of what the UK outside the EU might look like, with Norway, Switzerland, Greenland and Canada (among others) being suggested as possible models, but there was nothing really concrete about a new EU-UK relationship.

Post-referendum it looks increasingly likely that the UK will opt for a 'hard Brexit' rather than a 'soft Brexit', the principal difference between the two relating to whether or not the UK would remain a member of the Single European Market.

Central to the concept of the Single European Market, which was established in 1992, is the free movement of people, goods, services and capital - and it is perceived that many of those who voted 'leave' did so because they objected to free movement of people into the UK.

In addition to a hard Brexit outside the European Single Market, there is a suggestion that the UK could leave the Customs Union, the European Convention on Human Rights (which is under the much larger Council of Europe with 47 member states) and Euratom (which is legally distinct from the EU but is governed by it). Consequently, it is not clear where this might end, especially if those for whom the word 'Europe' is an anathema get their way.

The distinction between the EU and inter-governmental organisations such as ESA is not always clear cut and the way ahead might not necessarily be plain sailing

▲ Artistic depiction of European Galileo navigation satellites in their 23,222 km altitude orbit. Galileo is a joint EU/ ESA project.

Success story

UK space is the industry major success story and it is expected that the industry would continue to grow, though targets include business in the EU as well as globally.

The immediate concern about Brexit is probably uncertainty about the future but this might become clearer after Article 50 has been triggered and the two-year negotiations for Brexit begin in earnest. It is possible that all the talk about a hard Brexit stems from the adoption of an initial hard bargaining position; only time will tell.

Some in the industry also have a sense of optimism that the UK will be able to cope as a consequence of its leadership in some areas of technology and also an increased focus on markets outside the EU.

UK space industry has participated extensively in ESA-EU projects such as Galileo and Copernicus, and continued involvement might be at risk following Brexit, without an agreement for the UK to continue to so.

However, the participation to date might also work in the UK's favour as its absence from the project might be seen by ESA and the EU as a considerable loss for them (and not just the UK).

A further concern relates to the use of satellites such as Galileo where basic services are available to all, but use of the encrypted, robust Public Regulated Service (PRS) for government-authorised users such as fire brigades and the police may be restricted outside of the EU. If that were the case it may still be possible for the UK to negotiate continued access post-Brexit.

A soft Brexit would allow continued access to the European Single Market, so the effects on the UK space industry would probably be much less. A hard Brexit, however, would have implications for the free movement of goods, with potentially negative consequences on the export of UK-manufactured goods to mainland Europe and the import of components, with the risk of tariffs and customs-related paperwork. This would be particularly difficult for companies working in the aerospace industry that have multiple sites across Europe, many of which may be manufacturing parts for assembly elsewhere.

Higher education

A further concern for the British space industry and also higher education is the effect of Brexit on the free movement of people. The UK space industry often has multi-national teams working on space projects and there is a high proportion of people from other EU countries working in the UK space industry. Furthermore, this movement of people is not only one way. There are UK citizens working on space-related projects in ESA, in universities and the space industry across the EU. The status post-Brexit of EU citizens in the UK and UK citizens in the EU is currently uncertain.

A hard Brexit is viewed by many in academia as a major threat to higher education and research in UK universities. The world-class status of many UK universities has been achieved through growing networks of international partnerships during the decades in which the UK has been part of the EU. This has led to the most successful institutions competing across the EU and indeed globally for the best talent. As with the space industry, universities have a high proportion of staff who are EU nationals from outside the UK. However, there is concern that following the referendum vote there is a perceived anti-immigrant tone and consequently many academics from the EU are now unwilling to work at UK universities, while others are leaving.

There is also concern about potential negative impact on scientific research. From conversations during early 2016, including with scientists involved in space-related projects, it was clear that they were concerned about negative implications if 'Leave' won the referendum. UK universities are among the biggest beneficiaries from EU research funding - such as Horizon 2020 - and fear loss of research funding, while those in the EU are questioning the UK's participation in research projects and consortia.

> There is considerable support across the board for continued UK participation in ESA after Brexit

Some have suggested that there will be a benefit for higher education after Brexit, through higher tuition fees for EU students. UK higher education is a major 'invisible' export and after Brexit, EU students could be charged the same as other overseas students. However, as with EU academics, EU students may be deterred by a perceived anti-migrant hostility. A drop in applications from EU students could have a considerable effect not only on university finances, but also on the wider economy, though estimates vary on what the exact impact of this could be.

In any case, would the students from the EU be able to afford the higher fees or would they go elsewhere? If the UK universities could afford to do so, would they have to offer scholarships to attract the EU students? And if the UK universities could afford to offer scholarships to EU students, why not offer more scholarships to UK students?

Critics might suggest that the space industry and academia have become too dependent on foreign talent. However, both often cite UK skill shortages as a reason why there is so much recruitment from the EU. It has been suggested that reduction in the number of EU students studying at UK universities might further reduce the available number of engineering graduates. Consequently, there might need to be more effort to source suitable candidates from within the UK, resulting in more opportunities in the space industry and academia for suitably-qualified individuals from within the UK.

University academics and the space industry are unlikely to gain much sympathy from many of those who voted leave

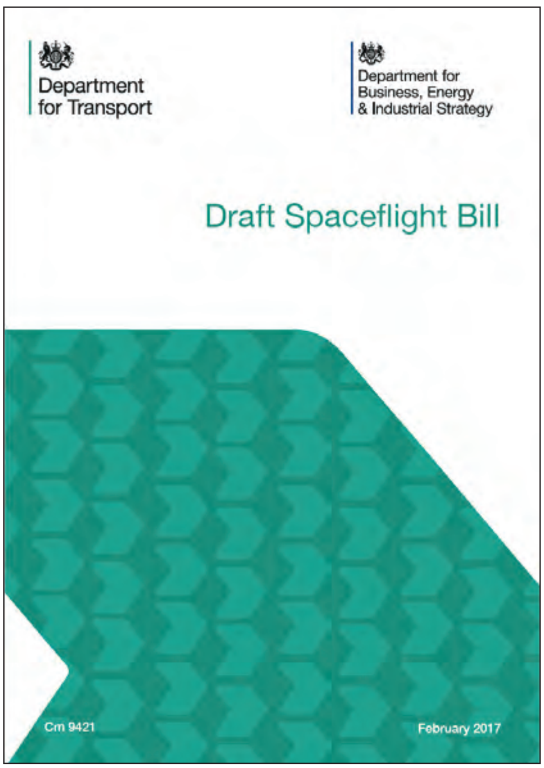
This might also depend on changed circumstances and also changed attitudes. Improved social mobility might only be achieved if there is some restoration of student grants (or industry sponsorships) and a reduction or even an end to tuition fees. Furthermore, a regrettable and unfair attitude in some Leavers and some Remainers alike has been to be critical of the lack of even basic skills and lack of work ethic in some UK citizens.

So what of the future of the UK space programme? As ESA and the EU are separate organisations, the UK will most likely continue with ESA membership as the preferred option for the foreseeable future. Although it is possible for other reasons that the UK might look for other models, including a home-grown space programme, it is highly unlikely that the UK alone could undertake the breadth of activities in space science and technology that has been possible as a member of ESA, including human spaceflight.

As an advocate for space research, exploration and development, I have always sought through my talks to astronomical and other groups to promote its importance, not just to enthusiasts but to the taxpayer and voter.

However, in my experience, problems for university academics and the space industry are unlikely to gain much sympathy from many of those who voted leave, especially among those who feel marginalised and left behind by globalisation.

Whatever one's personal views about the wisdom or otherwise of Brexit, many people in the UK see it as a positive development. One can only hope that such a level of confidence and goodwill for a high-risk project results in success. ■



◄ The British government published a draft Spaceflight Bill in February.

About the author

Dr Mike Leggett has worked on a variety of international and European projects across a wide range of industrial sectors during the past 25 years. A keen advocate for the public understanding of science and also the importance of space exploration and technology, he has presented lectures throughout the UK. A graduate in chemistry and pharmacology, Dr Leggett also holds a PhD in Chemistry and is Fellow of the Royal Astronomical Society and the British Interplanetary Society. Opinions presented in the article are the author's own and do not reflect those of any of the named organisations nor of any present or former employer.

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Science meets history and art

▲ The main SAO observatory.

Located deep in the mountains of Northern Caucasus between the Black Sea and the Caspian Sea, the Special Astrophysical Observatory (SAO) of the Russian Academy of Sciences is a unique scientific research centre, a place where history meets modern astrophysics. During 2016 the observatory opened its doors to a number of Russian and Austrian artists, giving them an exclusive opportunity to use the entire observatory territory for art installations.

Ksenia Adamovitch
Editor

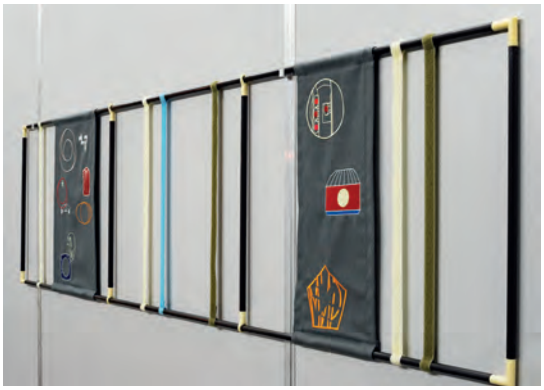
The astrophysical observatory was founded in 1966, six years after an initial move by the Soviet government to build the largest fundamental space research observatory in the country. To this day, it is the largest space observation centre in Russia.

It is home to the BTA-6 (Large Altazimuth Telescope), a 6 m aperture optical telescope. From 1975 until 1990, the BTA-6 was the largest telescope in the world, and was the first to use an altazimuth mount with a computer-controlled derotator, now standard in large telescopes. Starting in early 2017, the observatory is using the BTA-6 to observe classic luminous blue variable (LBV) stars, spectra and magnetic fields of massive stars. Only 20 km from the BTA-6 is the RATAN-600 radio telescope, the world's largest-diameter individual radio telescope.

The observatory that houses the BTA-6 is located on the Pastukhov mountain at a height of 2100 km and some 17 km from the village of Nizhny Arkhyz, the residential village built for the scientists and their families.

Setting the scene

Nizhny Arkhyz, formerly known as Bukovo, is anything but a typical village. Made up of two apartment buildings, a school, a kindergarten, laboratories and a hotel, it is home to residents who are exclusively astronomers working at the observatory and their family members. Many of the nearly 1000 inhabitants of the village are second or even third generation astronomers - descendants of those who had worked at the observatory in the 1970s. The director of the observatory, Yury Balega, has been with the observatory since 1975, when he came there shortly after graduating college.



◄ Far left: Engelbert's 'Space emblem for GB' was dedicated to the Russian space designer Galina Balashova.

◄ Curators Simon Mraz, Madina Gogova and Mariana Gogova in front of the observatory.

The observatory's working structure is composed of two divisions and a support team. The optical division is made up of 12 components, including the Laboratory of Extragalactic Astrophysics and Cosmology, the Laboratory for Stellar Magnetism Study, the Laboratory of Spectroscopy and Photometry of Extragalactic Objects, the Laboratory of Stellar Physics, the Advanced Design Laboratory, the Observations Support Laboratory, the Extragalactic Systems Investigation Group, the High-resolution Methods in Astronomy Group, the Relativistic Astrophysics Group and the BTA technical support team.

The radio astronomical division includes the Radio Astrophysics Laboratory (made up of the Group for Study of Galaxies and Cosmology and the Group of Active Galactic Nuclei Investigation), the Laboratory of Continuum Radiometers, the Group of automatic control systems, the Geodetic Measurements Group, the Group of Continuum Observations, the Group of the Sun Study, and the RATAN-600 technical support team.

The observatory also has a branch in St Petersburg and the support sections of the observatory include an educational component with a PhD in physics and astronomy. Overall, it is a self-contained scientific centre, with its employees living only a short ride away from their main place of work and for the most part rarely leaving the general vicinity.

Inspiring location

One of the most fascinating and unique aspects of the observatory and the village of Nizhny Arkhyz is the location, as they are situated in what is essentially the middle of the ancient kingdom of Alania.

Science meets history here, as only a short walk away from the village centre are the remnants of the town of Maas, a medieval Alanian town which ceased to exist sometime in the 12th century. The Northern Zelenchuk cathedral in Maas was built around the 10th century and is one of three cathedrals that are still left standing in what used to be a bustling medieval town.

The surrounding area is home to the ruins of almost a dozen smaller churches and multiple pagan sites dating as far back at the sixth century. A number of these sites are believed to be ancient astronomical observatories that pre-date the Christian era in this area, making the location's astronomical heritage well over a thousand years old.

It's hardly surprising that artists would find this enigmatic location inspirational. In the autumn of 2016, a joint project by the Special Astrophysical Observatory of the Russian Academy of Science, the Karachay-Cherkess Ministry of Culture, Austrian Cultural Forum Moscow, Gogova Foundation and Section A Wien, Vienna, with the Federal Chancellery of Austria put on a unique exhibit called 'The Observatory'.

A unique scientific research centre, a place where history meets modern astrophysics

▼ The Large Altazimuth Telescope (LAT).

▲ Homes in the city of astronomers built in a plain, modernist style.

Artistic licence

In honour of the observatory's 50th anniversary, it opened its doors and allowed artists to roam free and install art objects in places of their choosing, from the astronomers' village to the observatory itself. As succinctly put by Simon Mraz, director of the Austrian Cultural Forum Moscow: "A striking location was chosen for the observatory, simultaneously clandestine and providing the clearest, best view of the stars. And even more remarkable is the juxtaposition that has resulted - the new observatory building alongside the ruins of an ancient city.

"I think this collision of ancient history and the endlessness of space is extremely philosophical and metaphorical, and is an inexhaustible source of inspiration for artists. I'm so glad that the observatory, this centre of science, opened its doors to allow artists from Austria and Russia to grasp the vastness of the universe, and also the life and history of the observatory itself."

▼ Irina Korina's 'Svetilishcha' (svetilo, a heavenly body that radiates light, and svyatilishche, a sacred place or altar). Objects were placed on the streets of the village and resemble street shrines, mailboxes and nativity scenes.

Artists had a unique opportunity to integrate their works into the surroundings. One particularly striking art object was Alexandra Paperno's 'Abolished Constellations'. Paperno researched the constellations that did not make it into the recognised list adopted by the International Astronomical Union in 1922. Using water-based paint and small wooden panels, Paperno depicted 51 constellations that date back to the time of Ptolemy, including the famous Argo Navis constellation, named after the mythological Greek Argo ship.

The constellations, many of which can no longer be seen in the Northern hemisphere due to star shift over time, were then assembled and displayed in the medieval Northern Zelenchuk cathedral. The resulting combination of a thousand-year-old cathedral and the ancient night sky was impressive to say the least. According to the artist, the placement of the constellation maps "demonstrated the link between the scientific and artistic aspects of the evolution of human thought."

Ancient origins

Anna Titova's composition 'Why Work?' was dedicated to the local heroes of Nizhny Arkhyz - Bagrat Ioannisiani, chief constructor of the observatory, and archaeologist Sergei Varchenko. Titova's neon installation of the wind god Aeolus was located above a bench in one of the village's working technical workshops. Combining a functional workspace and break room light fixture with a mythological creature, Titova's work reflected the ancient origins of the village in a modern industrial space.

Austrian artists Eva Engelbert created installations inside the observatory itself. Engelbert's 'Space emblem for GB' was dedicated to the Russian space designer Galina Balashova, who had created the interiors of USSR spaceships, rockets and space stations, including the original design for Soyuz-19 and Mir orbital station.

In the dedication of her piece, Engelbert wrote: "You created a semblance of reality in a fabricated environment. You built a world in outer space, from the walls all the way to the emblems on the astronauts' spacesuits."

Balashova (retired since 1990) was instrumental in both the interior design of the Mir station and the first landscapes that were sent up into space in the 1960s to alleviate astronauts' psychological pressure.

One of the most unexpected artworks at the exhibit was certainly Timofey Radya's 'Brighter than Us' installation. Set up on a construction crane in the middle of the field behind the

observatory, it is better visible at night. It should, perhaps, be mentioned that there are no outside lights by the observatory, since, as one of the astronomers noted, "There's simply no need. By the time it gets dark, everyone who should be here is already here, and there's no need for anyone to go outside."

Radya, a well-known street artist from Ekaterinburg, set up the installation so that it was only visible when looking straight up at the night sky - at the right angle, it spelt out 'They're brighter than us' in letters that appear to be floating in the sky.

At the opening of this joint Austrian-Russian project, Emil Brix, the Austrian ambassador to Russia, congratulated the observatory on its 50-year anniversary, noting that the year was cause for celebration in Austria as well as 25 years ago the first and only Austrian astronaut had flown in space. "Here, in Akrhyz, in these objects, there is much historical memory that we are trying to retain in European countries as well. The project has not only cultural and scientific significance but a political one as well. The first and foremost reason we go into politics is to change our circumstances, including through the use of cultural and scientific exchange," he said. ■

▲ Alexandra Paperno's 'Abolished Constellations'.

Artists had a unique opportunity to integrate their works into the surroundings

▼ Titova's work reflected the ancient origins of the village in a modern industrial space.

▶ The 'Space for Art' exhibit in the central gallery of the Space Center Houston. It featured artwork from many employees.

Space for art

an element of surprise

Recently, I was delighted to discover the artistic talent of another well-known space figure, Robert H. Goddard, known as the 'father of rocketry'

ROOM's 'Space for Art' column is dedicated to the inspiration that comes from the interaction between space and art. One of the things I still find so interesting about this is how surprised many people are by the idea of space and art interacting at all - and most especially when they discover people working in the space industry that are also blessed with some form of artistic talent.

I am pleased to be one of those people that has always found a balance between the space, engineering and artistic aspects of my life. I have actually always found that it's not just a balance but more of a natural interaction and blend that has just occurred for me versus a deliberate distinction between them.

As a result, I have always been very interested in discovering other engineering, space, scientist and technical types that are also actively involved with artistic things in their lives.

Over the years as I have been blessed to work with our space programmes at the Kennedy Space Center (KSC) and Johnson Space Center (JSC) as an engineer and astronaut, I have quietly kept a list of these people I've met along the way and I'm very happy to have recently had the opportunity to showcase some of their wonderful artwork and the interaction that space and science and art has had on their lives.

This showcase took the form of an art exhibit called 'Space for Art' which was supported and hosted by the wonderful exhibit's team at the Space Center Houston, and it was so much fun to 'curate' the art and artists from this list I had compiled.

This show specifically focused on the Johnson Space Center (JSC) community and on display was artwork from JSC employees typically only thought of as engineers, scientists or astronauts. Their works of art included paintings, quilts, photographs, sculptural cakes, stained glass, hand-crafted wooden longboard skateboards, intricately drawn doodles and musical instruments.

Some of this collection had originally been created in space, including a portrait sketched by cosmonaut Alexei Leonov of astronaut Tom Stafford during their Apollo-Soyuz mission; a hand-sewn and stuffed toy dinosaur that astronaut Karen Nyberg created from scraps of fabric during her ISS expedition; a watercolour painted by myself during my ISS expedition; and musical instruments played in space, including Ellen Ochoa's flute she played during one of her Space Shuttle missions and the bagpipes played by Kjell Lindgren during his ISS expedition.

This exhibition was also an opportunity to display as a centrepiece the HOPE and UNITY space suits from the Space Suit Art Project - such a beautiful example of the inspiration that comes

Nicole Stott
Artist, Astronaut and SciArt Advocate

through the interaction between art and space.

To me the 'surprise factor' associated with this interaction between art and space is what stood out the most throughout the exhibit. Not only the public's surprise to discover this wonderfully creative and meaningful side of these scientist's, engineer's and astronaut's lives but more interestingly even was the surprise amongst the local JSC community itself.

Some of these folks have worked together side-by-side for over 20 years and had no idea of the shared artistic talents of their co-workers. It was so cool to see the reaction when they discovered this and to know that from that point forward they would have a totally new understanding of these people they had worked with for so many years.

For me it was especially gratifying to make this re-introduction and I'm hopeful that it will encourage more inspiration for using artistic expression to communicate the amazing things we're doing every day in space - and here on Earth - through our space programme.

The surprises through all this didn't stop there for me though. As an artist and astronaut, I knew that cosmonaut Alexei Leonov was the first to draw in space (coloured pencil drawing of an orbital sunrise); astronaut Alan Bean was the first to retire from the astronaut office to pursue life as an artist and uniquely share his spaceflight experience (I am proud to follow in his footsteps as only the second astronaut to take that path as an artist post-NASA); and I know of many other astronauts who also have artistic talent that they pursue as hobbies.

Recently, however, I was delighted to discover the artistic talent of another well-known space figure, Robert H. Goddard, the 'father of modern rocketry'. A collection of Dr Goddard's scientific papers, his diary and about a dozen paintings are held at the Robert Hutchings Goddard Library at Clark University in Worchester, Massachusetts, where he was a fellow of physics. The subject of his paintings, however, were not space but the scenery of New Mexico.

The fact that Robert Goddard, the man whose study and invention associated with rocket technology made space travel possible, also loved to paint is very reassuring to me and is another impressive example of the very positive influence that comes through the interaction between art and space in someone's life.

I hope you'll take the time to discover more about both the space technology and the artistic talents of Robert Goddard, and perhaps the artistic talent that can be found in surprising ways in the people that surround you. As you consider the work of Robert Goddard and his New Mexico landscapes, I hope you'll also continue reading and be inspired by the wonder of space that is so beautifully captured in the vibrant and unique 'Spacescape' paintings of artist Zoe Squires featured on the following pages. ■

▲ From left: the first watercolour painted in space by Nicole Stott along with artist Ron Wood's paint brush, which she used whilst in orbit; original framed pencil sketch of astronaut Tom Stafford by cosmonaut Alexey Leonov during the joint Apollo-Soyuz mission; stuffed toy dinosaur sewn by astronaut Karen Nyberg during her ISS flight.

▼ Robert H. Goddard often relaxed by painting. This picture is a view about 90 miles west of Roswell, New Mexico, where Goddard lived and worked for many years.

'Spacescapes' capture hidden qualities and nature of space

British space artist Zoe Squires talks to *ROOM* about her love of art and space - and of how the two combine in her vivid imagination to produce stunning 'spacescapes' in which she attempts to capture the hidden qualities and nature of space.

▲ Zoe Squires is a young space artist living in Hampshire, England. She graduated with an Honours degree from Anglia Ruskin University in 2005 and since then has worked primarily as researcher and producer of charity events whilst also pursuing her love of painting and exploring the world with colour.

What inspired you to become interested in space?

A research role with the Institution of Engineering and Technology introduced me to world experts in solar mass ejections and satellite communications, and I began to learn about the effects of space on our lives here on Earth - from its influence on our emotions to the clarity of our telephone calls and TV reception.

Progress across space technologies means we are all connected to space, each and every day. My paintings take this a step further, and couple art with achievements across engineering technology.

Using images taken by the Hubble Telescope as my starting point, I began by layering acrylic colours onto canvas to capture the qualities and nature of space, in a series of 'spacescapes'.

Some of my paintings are dramatic, explosive and unstable and reverberate with pulses of energy. Others are restful incantations of serenity and bliss as cloud layers undulate and cocoon around pockets of glittering stars.

What is it about space that made you want to paint it?

Space is thrilling, deep, expansive and there for the most adventurous of intellects to explore. It offers a myriad of colours that dance, sing and shimmer against expansive velvet gloom.

Inspired by comic book sci-fi illustrations, it occurred to me from a young age that space exploration is the epitome of giving permission to the human imagination. Seeing images taken by Hubble, I was struck at the rich variety of emotions and colours above our head.

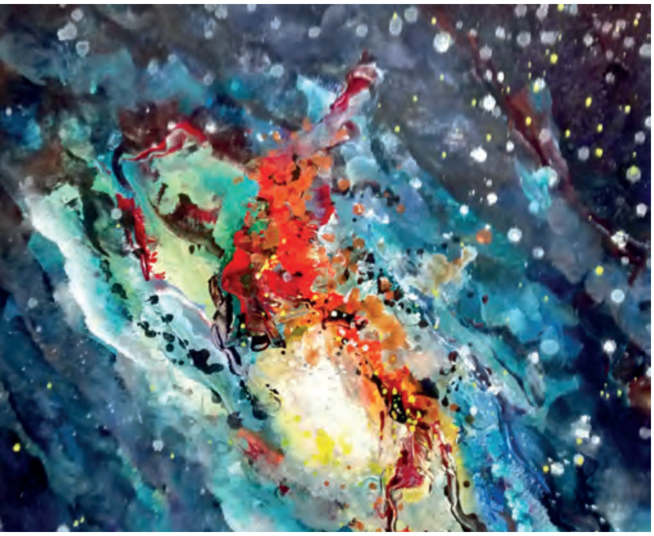
I paint with an uninhibited vigour and freedom, creating luminous images that vibrate with life, energy and colour. Whether I am depicting a riotous impression of deep space, stars and gas clouds or inviting the onlooker to enter a radiant new world of abstraction, the vibrant palette and loose formal structure make my paintings instantly recognisable and utterly irresistible!

How did you develop your style of 'spacescapes'?

Colour and vibrancy is the backbone of my work. In everything I see I study and discover richness and layers of luminosity.

My spacescapes style was invented through play - immersing myself into Hubble's imagery, I let my mind journey into the factual images. I painted what I saw, not the flat black backdrop with white stars, but layers and shades of space, floating shimmering tones and flickering clouds.

I never find painting my spacescapes daunting but rather comforting in that every



Hubble image dared me to play with colour, in quantities and combinations I would not previously have constructed.

What is your approach to painting the machinery of space?

I see the machinery of space as collecting and connecting tools. The designs for space machines is purely practical but the elegance and precision of this equipment marries well with the unstructured, dynamism of the hostile space environment.

Is it important to you to base your paintings on real galaxies, nebulae etc?

Working with images of real galaxies and nebulae relaxes my mind to be able to see and understand the many and varied movements of gases and colours in space. My imagining of space is flat and undramatic.

What do you want people to take away from your paintings?

I want people to enjoy my paintings. Each painting is unique and I do not make prints - and so to own a piece of my artwork is to own something inspired and handmade.

In my paintings of nebulae and gas clouds and the birthplace of stars, I want people to enjoy the beauty and colours space shares with us.

In my paintings of space machinery operating in deep space, I hope people appreciate the achievements of the human mind.

Space exploration is the epitome of giving permission to the human imagination

Would you describe space as a peaceful place?

I believe space is enigmatic. Space presents the opportunities for us to communicate and live in ways undreamt of just a decade ago.

Some of my paintings give an impression of light and brilliance and softness, while others offer intrigue, drama and phenomenal energy.

Have your perceptions about space been changed by your art?

Before working with space technologists, I believed space was dark and hostile. Now, I perceive space as a rich and dynamic treasure chest, which will continue to offer us beautiful, inspiring imagery and ever more reliable communications and intelligence to make the most of our planet.

Mark Williamson
Space Technology Consultant

Book reviews

ROOM reviews books of interest to the space professional. Our policy is one of impartiality and honesty, so if a book has failings we believe should be brought to the attention of potential purchasers, we will do so. On the other hand, if it is useful, informative and entertaining, we will say so. In this way, we hope to provide a useful service to our readers.

Skylab 3 – The NASA Mission Reports

Dwight Steven Boniecki,
Apogee Books, 2016, 354pp, softback
$32.95
ISBN 978-1-926592-28-2

Although many people are well aware of the International Space Station, those without a particular interest in space history may not realise that America had a large and capable space station in the 1970s. The Skylab Orbital Workshop was a converted Saturn V third stage, left over from the Apollo lunar programme, and hosted three 3-man crews in 1973 and 1974.

This book – the latest in Apogee's long-running NASA Mission Reports series – covers Skylab 3, the second of the three manned Skylab missions (Skylab 1 was the launch of the station itself and was the subject, along with Skylab 2, of a previous volume). The signature feature of the Mission Reports series is the 'bonus DVD' included with the books. In this case, the DVD includes a launch video, a 14-minute 'Skylab 3' mission documentary, a 55-minute guided tour of the station with astronaut Jack Lousma and a 'digital animation' of the station. The archive film is fairly low definition in today's terms but the animation reel provides a clear impression of the station's interior. Along with the 350-page book, the DVD makes this a good value-for-money package.

The book itself has three main sections: the Skylab 3 press kit from July 1973; the mission report (which fills some 170 pages of the volume); and a transcript of the Technical Crew Debriefing (another 150 pages). The mission report section is illustrated with black-and-white photos and facsimiles of the original line drawings, diagrams and tables; it covers everything from training and medical experiments to food and other consumables. The debriefing is akin to an extended interview and provides readers with invaluable insight not only into a Skylab mission, but to living and working in space in general. Indeed, these Skylab mission debriefs should be required reading for any budding space mission designers.

An important factor for a space station is its size and Skylab compares extremely well with the ISS considering the four decades that separate the two. Taking into account Skylab's so-called Apollo Telescope Mount (designed for solar observations), an airlock module and a docking adapter, its total volume was some 360m^3 (compared with about 930m^3 for the ISS).

America's first space station no longer exists, having long ago re-entered the atmosphere, burnt up and showered Western Australia with the remaining debris. However, this book does a great job in keeping the memory of its significant accomplishments alive.

International Space Station – Architecture Beyond Earth

David Nixon

Circa Press, 2016, 416pp, hardback
£65.00
ISBN 978-0-9930721-3-0

The main triumph of the International Space Station (ISS) project is not so much the experiments conducted on board (though of course many of them are important in the context of human space exploration) but the fact that it is a football field-sized structure built in Earth orbit. This aspect is fully recognised by the author of this book, an architect with "a particular interest in designing for space exploration" and one of "a handful of architects invited to work on the design" of the ISS.

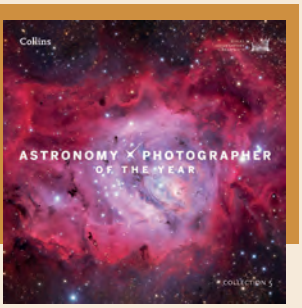
His intention, in this significant tome, is to celebrate the ISS, demystify the technical aspects (in part by eschewing acronyms and jargon) and "hold the attention of readers...without them dozing off". Always a good plan! He does this in four main sections covering specific successive periods between 1979 and 2011 and includes a decent index, a reference section and a short glossary. The book also includes a memoir from NASA astronaut (and ROOM contributor) Nicole Stott, who writes about her impressions of living on the ISS.

As one might expect from a book that concentrates on the architecture of the Station, there are numerous module diagrams of both early concepts and actual ISS assembly, and it is instructive to have both together for comparison. The historical analysis of the many precursor designs is particularly interesting. The book is illustrated with colour photography throughout and shot selection is good, though reproduction is spoiled somewhat by the matt paper; this is not a glossy coffee-table book.

However, the book is large enough to cover the main points of the Space Station's design history while still having room for issues of detail, such as windows, which have been an issue in spacecraft design since the famous argument about the Mercury capsule. The author mentions the equally famous Skylab window, which architectural consultant Raymond Loewy championed "as its recreational value alone...would justify its cost". ISS astronauts would no doubt agree, and windows - even a cupola - are now seen as de rigeur. It's unlikely that this is the only book on the ISS that space aficionados will want but it should certainly be on their list.

Astronomy Photographer of the Year (Collection 5)

Collins, 2016, 191pp, hardback
£25.00,
ISBN 978-0-00-819626-4



Astrophotography is both an art and a science and this is nowhere better illustrated than in this collection of astronomical images resulting from the 2016 Astronomy Photographer of the Year competition. The glossy, well-produced volume contains all 140 of the winning and short-listed images in 11 categories including 'skyscapes', 'our Moon', 'stars and nebulae', 'people and space' and 'best newcomer'. Each section showcases the winner, runner-up and highly commended entries followed by the images that reached the respective shortlist.

The book succeeds on several levels. For anyone interested in astronomy, it's an obvious hit because it illustrates their subject in an immediate and easily accessible way. And for those into photography, although it represents a fairly narrow and specialised field, it offers a significant technical challenge for those in search of a 'different image'.

It also works as both an artistic and educational resource. One could open it as one would a coffee table book, with expectations of a quick flick-through, but I challenge anyone not to stop and go 'wow' occasionally; or say "what on Earth is that?". Of course, the point is that many of the images are not 'on Earth' at all, effectively representing the limits of the human imagination as much as scientific research. And that is one of the beauties of astronomy: that it crosses the putative cultural divide between art and science.

What was the overall winner of the 2016 competition? A series of images from the start to the end of a solar eclipse stacked together to form an artistic composition with the dark circle of the Moon in the centre and concentric arcs on either side. The arcs show the phenomenon known as Baily's Beads which occurs when light from the sun flickers out as the eclipse begins and appears at the opposite edge of the disk as the eclipse ends. You may not always agree with the judges' decisions - but that just adds to the fun!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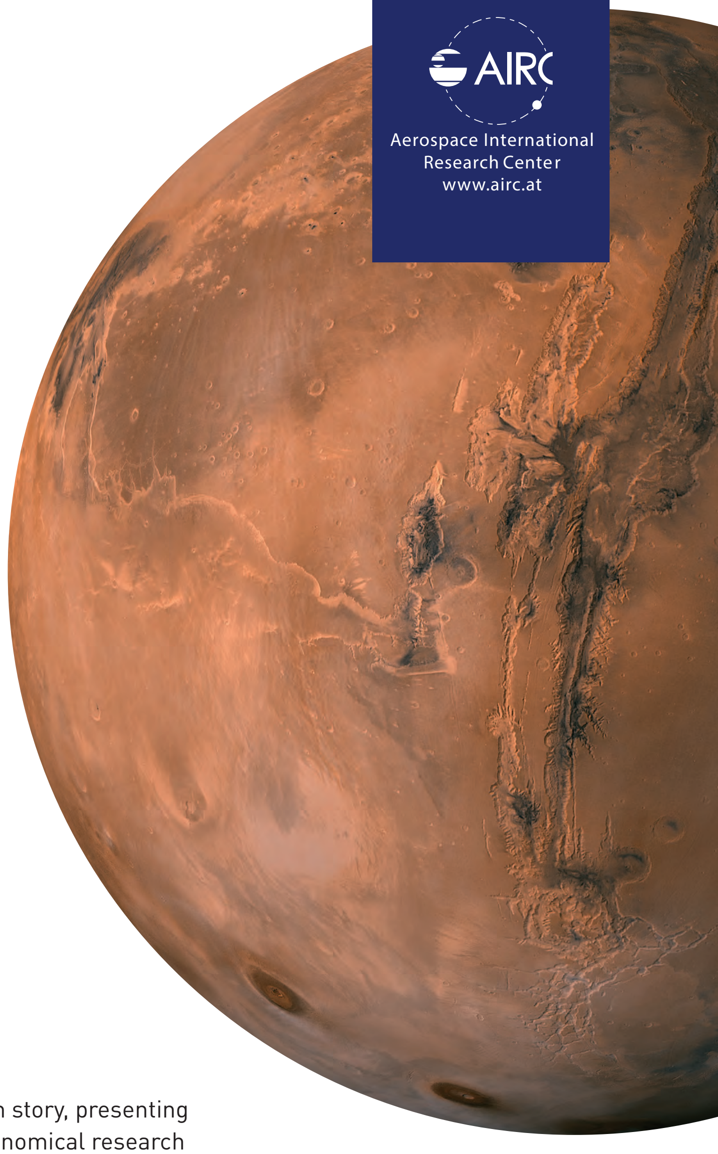
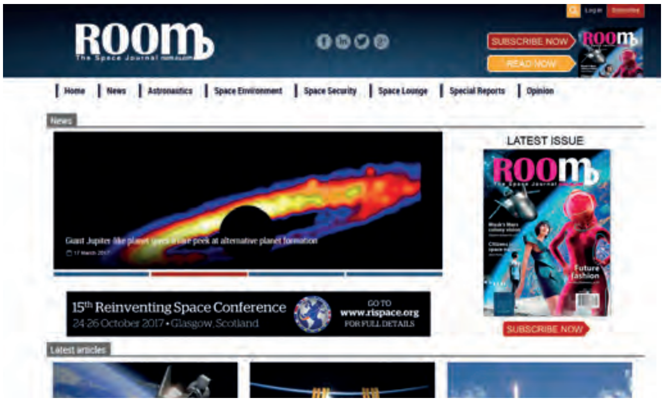


The next issue of *ROOM* will be published in the early Summer and will include a wealth of interesting, informative and challenging articles all written by leaders and experts in their field.



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