Australian Government
Department of Defence
Science and Technology

EDTAS
EMERGING DISRUPTIVE TECHNOLOGY
ASSESSMENT SYMPOSIUM

SPACE TECHNOLOGIES

INSIGHTS PAPER

Noetic GROUP

The author of this paper is Dr Darren Moore. Darren is Noetic's General Management Government. Noetic would like to acknowledge the insights that underpinned the development of this paper, which were provided during stakeholder interviews by a range of subject matter experts drawn from academia, industry and Defence. Noetic also wishes to acknowledge the review and arising comments on the draft paper undertaken by Noetic's Defence Science and Technology and academic partners (Curtin Universtiy, Edith Cowan University, Murdoch University and the University of Western Australia). Insights Paper was designed by Noetic's creative design team.

CONTACT AND FURTHER INFORMATION

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Contents

Acronyms and Abbreviations

1RSU	1 Remote Sensor Unit (RAAF)
3U	3 unit CubeSat (10 x 10 x 10 cm per unit)
ACMA	Australian Communications and Media Authority
ACT	Australian Capital Territory
ADR	Active Debris Removal
ADS	Autonomous Drilling System
AHS	Autonomous Haulage System
AI	Artificial Intelligence
ALASA	Airborne Launch Assist Space Access
ANU	Australian National University
ARDU	Aircraft Research and Development Unit (RAAF)
ARTEMIS	Advanced Responsive Tactically Effective Military Imaging Spectrometer
ATC	Air Traffic Control
BFR	Big Falcon Rocket
BLOS	Beyond-line-of-sight
COTS	Commercial-off-the-shelf
DARPA	Defense Advanced Research Projects Agency (US)
DST	Defence Science and Technology
EDRS	European Data Relay System
EDTAS	Emerging Disruptive Technology Assessment Symposium
EM	Electromagnetic
EnMAP	Environmental Mapping and Analysis Program
EO-1	Earth Observing-1 (satellite)
ESA	European Space Agency
FAA	Federal Aviation Administration
FCC	Federal Communications Commission (US)
GEO	Geostationary Earth Orbit

GLOSNASS	Global Navigation Satellite System (Russia)
GPS	Global Positioning System (US)
HAPS	High Altitude Pseudo-satellite
IOT	Internet of Things
ISRO	Indian Space Research Organisation
ISS	International Space Station
ITU	International Telecommunications Union (UN)
LCT	Laser Communication Terminal
LEO	Low Earth Orbit
LEONIDAS	Low Earth Orbiting Nanosatellite Integrated Defense Autonomous System
LiDAR	Light Detection and Ranging
MEO	Medium Earth Orbit
Mpbs	Megabits per second
MWA	Murchison Widefield Array
NASA	National Aeronautics and Space Administration
ORS	Operationally Responsive Space
PC	Personal Computer
PNT	Positioning, Navigation and Timing
PSLV	Polar Satellite Launch Vehicle
QKD	Quantum Key Distribution
RDE	Rotating Detonation Engine
RF	Radio Frequency
SBSS	Space Based Surveillance Block
SKA	Square Kilometre Array
SPARK	Spaceborne Payload Assist Rocket - Kauai
SSA	Space Situational Awareness
SSN	Space Surveillance Network (US)
SWaP	Size, Weight and Power
SWIR	Shortwave Infrared
UAV	Unmanned Aerial Vehicle
VHF	Very High Frequency
VSS	Virgin Space Ship

INTRODUCTION

Background

As the agency responsible for leading the development of Defence technological capabilities, Defence Science and Technology (DST) is seeking to better understand the opportunities, threats and challenges space technology presents for Defence. The themes for the Emerging Disruptive Technology Assessment Symposium (EDTAS) are drawn from the Next Generation Technology Fund. With an investment of $730 million over the decade to 2026, the Next Generation Technology Fund is a forward-looking program focussed on research in emerging and future technologies for the 'future Defence Force after next'.[1] Innovative technologies and concepts researched under the Next Generation Technology Fund could be further developed and realised into capability through the Defence Innovation Fund.

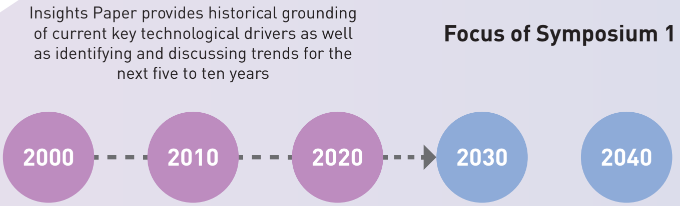
To do this, DST, in partnership with the Noetic Group and a consortium of WA universities (TeamW A), will hold an EDTAS to explore potential space advances in the 20+ year timeframe (that is, out to 2040). The EDTAS will consider space in two symposia: one at the unclassified level for a broad audience of academia, government, Defence and industry; and a second classified event for a predominantly Defence audience. Each symposium will feature a diverse range of expert presentations and facilitated immersive workshops to draw key insights on the subject areas. DST will capture the output from these collective engagements in a Big Picture Analysis Report that will help identify key research themes for future study.

1. The Next Generation Technology Fund focuses on nine areas that have been identified as priority areas for Defence. These areas are integrated intelligence, surveillance and reconnaissance; space capabilities; enhanced human performance; medical countermeasure products; multi-disciplinary material sciences; quantum technology; trusted autonomous systems; cyber; and advanced sensors, hypersonics and directed energy capabilities. The majority of these priority areas have specific application to space technology.

Aim

The aim of the Insights Paper is to present key themes relating to recent and projected developments in both space technologies and the space environment in order to provide a base level of common knowledge to inform EDTAS participants and help engender debate during the symposia. To achieve this aim, the Insights Paper provides an historical grounding of the current key technological drivers for space as well as identifying and discussing trends in space technology for the next five to ten years, thereby building a foundation for discussions in Symposium 1 to be focussed on the period 2030–2040.

Figure 1. Relationship between the Insights Paper and Symposium 1



Source: Noetic Group 2019.

Scope

This paper does not intend to be definitive. Rather, the technology drivers and broader themes discussed in this paper will form the primary focus of EDTAS Space. As well as the initial impacts, part of the foresighting process means examining potential second- and third-order effects. Symposium 1 will allow DST to do this in an immersive environment.

Given the broad nature of space technology and related regulatory, legal and military implications, the below topics were agreed to be **out-of-scope** for EDTAS Space at the joint (Noetic/DST) scoping workshop:

Space law

Excluded as the general themes of EDTAS Space should be more on the technology rather than the regulation of access to space.

Space warfare

Excluded as the offensive aspects of space warfare, such as kinetic energy weapons, should be out-of-scope for Symposium 1, noting that there is potential for similar technologies to be used for the management of space debris. There might also be some value in consideration of defensive measures, such as redundancy in satellite systems and the ability for short-notice launch, for Symposium 2.

Humans in space

Given that it is highly unlikely that Australia will have a manned space capability within the timeframe considered (2030–2040), this topic was considered out-of-scope.

Inter-planetary

It was agreed at the EDTAS Space scoping workshop that the focus should be 'looking down' rather than 'looking out', except for the orbital monitoring of satellites in higher orbit (e.g. Low Earth Orbit (LEO) satellites monitoring and receiving data from Geostationary Earth Orbit (GEO) satellites).

EM spectrum congestion

It was noted at the scoping workshop that there is currently significant congestion in some bandwidths of the EM spectrum. There is also the issue of national/international regulation of the EM spectrum and government and commercial ownership/use, with spectrum management taking on increased importance to relieve this congestion. However, while these topics are likely to be of interest/concern to industry/academia, from a Defence perspective this risk is managed by the Defence Spectrum Office and therefore was considered out-of-scope for this specific EDTAS (though is noted in the main body of this paper for the sake of completeness).

Focus

The planned focus of EDTAS Space is those technologies that ultimately improve or enhance the down-stream (terrestrial) benefits of the use of space. This enhancement could come through greater availability or reliability of an existing capability, or the development of new capabilities to create new terrestrial benefits. This is a crucial point; many of the technologies discussed in this paper (such as reusable launch vehicles, satellite miniaturisation, more efficient fuels etc.) should be considered as enablers for a terrestrial benefit, not as a technological solution in their own right.

Approach

SMEs in academia, industry and Defence were identified at the scoping workshop and then approached to participate in an explorative, structured interview. The list of SMEs interviewed is provided as Appendix 1. A detailed record of interview was produced for each interview, which was provided to the interviewee to undertake a content review. The insights arising from the SME interviews provided the foundation for the development of the Insights Paper. Material provided via the SME interviews was supplemented by extensive desktop research.

Space in 2040

Given the rate of technological change, most stakeholders interviewed were reluctant to predict what the space environment would look like in five to ten years, let alone twenty. It is perhaps worth looking back twenty years and then posing the question whether we think the rate of technological change is increasing or decreasing and considering what the implications of this factor might be.

Table 1. Comparison between space activity in 2000 and 2018

2000

- 85 operational launches of which 81 were successful.
- Countries launching spacecraft were the United States, Russia, the EU, China and Japan (noting that the only Japanese launch of that year lost control during the first stage burn).[2]
- It was the first flight of the Atlas IIIA and Minotaur rockets (US).
- 5 Space Shuttle missions were conducted.

2018

- 114 orbital launches of which 111 were successful.[3]
- Countries launching spacecraft were the United States, Russia, the EU, China, Japan, India and New Zealand (first commercial launch of Rocket Lab at Mahia Peninsula site on 11 November 2018).[4]
- First flight of the Falcon Heavy (SpaceX rocket – which launched Elon Musk's Tesla Roadster into a heliocentric orbit that crosses the orbit of Mars).
- On 5 April 2018 Virgin Space Ship (VSS) Unity performed its first powered test flight and in July 2018 reached the Mesosphere for the first time.
- New Zealand, Costa Rica, Kenya, Bhutan and Bangladesh all deployed their first satellite.[5]
- On 3 December a Falcon 9 Block 5 rocket containing 64 satellites was launched into LEO[6]. Another significant first for this launch was that this was the first time SpaceX's first stage boosters had successfully flown three times.

2. Other countries that had previously demonstrated an independent satellite launch capability are France (1965), United Kingdom (1971), India (1980), Israel (1998) and Ukraine (1992).
3. The record number of launches for a single year is 121 (114 successful) in 1990.
4. Other countries that have demonstrated an independent satellite launch capability since 2000 are Iran (2009), North Korea (2012), and South Korea (2013).
5. As of December 2018, 87 countries have had a satellite launched.
6. This is the second most satellites ever taken on a single launch after India launched 104 satellites on 15 February 2017 onboard a Polar Satellite Launch Vehicle (PSLV), with the previous record being 37 satellites launched by Russia in 2014.

Structure of the paper

The remainder of the paper will detail trends, emerging technologies, challenges and opportunities for Australia around the following four themes:

- **advanced space launch technologies;**
- **space sensors and communications technologies;**
- **comprehensive space domain awareness; and**
- **technologies supporting space capabilities.**

Icons

The following icons are used to indicate topics throughout the remainder of the paper.

Trend 

Emerging technology 

Challenge 

Opportunity for Australia 

ADVANCED SPACE LAUNCH TECHNOLOGIES

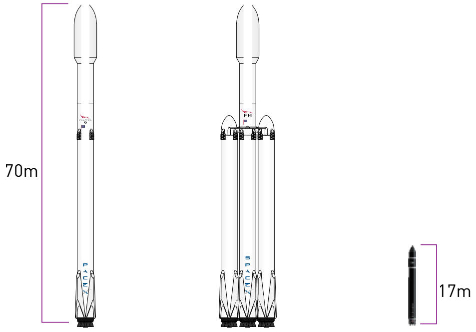
Trends

Growth in private launch providers provides greater flexibility for launches

Until the recent past, satellite operators were mostly limited to large launch vehicles that had primary and secondary (rideshare) payloads. The orbital plane, as well as the date of launch, were dictated by the primary payload (normally an 'exquisite' large (greater than 1 tonne) and expensive satellite). Recent developments have seen the diversification of the launch market to include smaller launch vehicles, usually limited to carrying a few hundred kilograms of payload into LEO. This provides additional flexibility to microsatellites (between 10 and 100 kg) operators in relation to orbital plane and launch window. Additional flexibility in relation to orbital planes are provided by satellite deployers that can execute multiple burns to place satellites into different orbits. The market viability of smaller launch vehicles is largely untested[7] and may see a consolidation of proposed providers, depending on demand stabilisation.

7. For example, in 2018, the cost for Rocket Lab to launch a 3U CubeSat (measures 10 cm x 10 cm x 30 cm and weighs no more than 4kg) – the most popular design of a CubeSat - was around $240,000 (i.e. $60,000 a kilo). The Economist, 'Is New Zealand the world's best rocket-launching site, dated 5 April 2018, viewed 5 December 2018, https://www.economist.com/science-and-technology/2018/04/05/is-new-zealand-the-worlds-best-rocket-launching-site.

Figure 2. Relative launch costs (2018) and payload capacity



	SpaceX Falcon 9	SpaceX Falcon Heavy	Rocket Lab Electron
Price per launch (2018 - USD)	**$62M**	**$90M**	**$5.7M**
LEO	22,800 kg	63,800 kg	225 kg
GEO	8,300 kg	26,700 kg	

Source: Noetic Group 2019.[8]

Economies of scale and innovative design and manufacturing techniques drive down payload cost

Economies of scale are being achieved through the use of commercial heavy rockets. For example, using the figures provided in the previous figure, the cost per payload kilo for a Falcon 9 for a LEO launch is an average of $2700 per kilo, while for a Falcon Heavy it has dropped to $1410 per kilo.

8. Information in figure drawn from SpaceX, 'Capabilities and Services', undated, viewed 5 December 2018, https://www.spacex.com/about/capabilities. Rocket Lab, Dedicated [launch], viewed 5 December 2018, https://www.rocketlabusa.com/launch/dedicated/. Guy Gugliotta, Air and Space Magazine, 'Small Rockets Aim for Big Market', April 2018, viewed 5 December 2018, https://www.airspacemag.com/as-next/milestone-180968351/.

A key enabler for providing low-cost access to space are reusable rocket components. This technology was pioneered on the Space Shuttle solid rocket boosters, which were retrieved and refurbished after launch.[9] In recent years, SpaceX has pioneered complete reuse of first stage liquid rockets by maintaining a fuel reserve in its rocket booster (which does result in a payload reduction). This fuel reserve can be reignited a few times to slow the rocket down and allows the booster to be safety returned to the ground after launch.

Innovative engineering upgrades to the SpaceX rockets to facilitate reuse include grid fins (steering the first stage as it plummets from the edge of space through Earth's atmosphere), cold-gas thrusters (flips the rocket around as it begins its journey back to Earth), and landing legs (deploy as the rocket approaches touchdown).[10] To put this cost saving from reusable components into perspective, SpaceX has calculated that the fuel for each Falcon 9 flight is less than 0.5 per cent of the total cost of the launch. The majority of the launch cost therefore comes from building the rocket, which in the past usually flew only once.

Innovative construction techniques can also reduce the cost of rocket production. For example, the Rutherford (First and Second stages) and Curie (Third Stage) engines used in Rocket Labs' Electron launch vehicle are 3D-printed from sintered metallic power, rather than being cast and machined in a conventional way. A new engine can therefore be produced from scratch in 24 hours. Additionally, the rocket is made of a carbon-composite fibre that is much lighter than the usual

9. Although the Space Shuttle was technically reusable, its giant fuel tank was discarded after each launch with only its side boosters being parachuted into corrosive salt water, beginning a long and involved process of retrieval and reprocessing.
10. On 22 December 2015, SpaceX achieved the first-ever orbital class rocket landing. In March 2017, SpaceX achieved the first reflight of an orbital class rocket (the first stage for the mission having flown on a previous mission in April 2016). Following stage separation, the first stage successfully returned to Earth for a second time, landing on SpaceX's autonomous drone ship stationed in the Atlantic Ocean. SpaceX, 'Reusability: The Key to Making Human Life Multi-Planetary', undated, viewed 5 December 2018, https://www.spacex.com/news/2013/03/31/reusability-key-making-human-life-multi-planetary.

metal employed for rocket bodies and uses a high-performance electric propellant pump that reduces the amount of plumbing required. These engineering solutions all reduce the launch mass, thereby saving fuel.

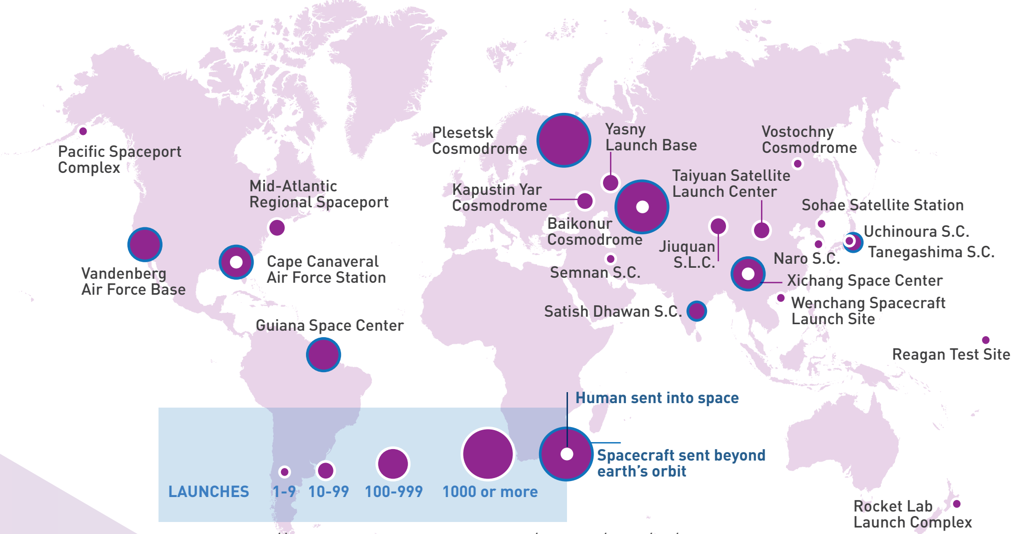
Fuel savings may also be achieved via the use of a rotating detonation engine (RDE). A RDE is a proposed engine using a form of pressure gain combustion, whereby one or more detonations continuously travel around an annular channel. Theoretically, detonative combustion (i.e. that which happens at speeds above the speed of sound through the use of shockwaves), is more efficient than the conventional deflagrative combustion. If this theoretical gain in efficiency (projected to be as high as 25 per cent) can be realized, there would be a major fuel savings benefit. Because the combustion is supersonic, and compression is via internal detonation wave, it can also more efficiently provide thrust at speeds above the speed of sound. A RDE may be capable of taking a rocket up to orbit in one stage (as opposed to the more common three stages currently in use) as it has no moving parts, is relatively simple in design and is able to operate in atmosphere as well as out of atmosphere in a 'rocket' mode.

Another aspect that will potentially drive down costs is the vertical integration of launch providers, whereby they launch from privately-owned spaceports rather than leased orbital launch sites developed and owned by the space agencies of nation states. Rocket Lab launches from its Launch Complex 1 on the Mahia Peninsula in New Zealand (the world's first private orbital spaceport). SpaceX is currently constructing a spaceport near Brownsville Texas[11] that will be used exclusively for the launch of the Big Falcon Rocket (BFR) (with a projected payload of 100,000 kg to LEO).

11. Blue Origin also has a sub-orbital launch pad near Van Horn West Texas and is building an orbital launch site at Cape Canaveral, Florida.

Since the launch of Sputnik 1 from the Baikonur Cosmodrome (now in Kazakhstan) in 1957, 30 spaceports around the world have been used to launch satellites to orbit, of which 22 are still active.[12] In addition to these spaceports, there are an increasing number of speculative spaceports proposed or being developed. For example, by August 2018 the Federal Aviation Administration (FAA) has issued 11 launch site operator licences[13] but of these, only three (Cape Canaveral Air Force Station, Florida; Vandenberg Air Force Base, California and the Mid-Atlantic Regional Spaceport – Wallops Island, Virginia) launched orbital vehicles in 2018.

Figure 3. Active spaceports of the world



Source: https://www.nationalgeographic.com/science/2018/10/news-spaceports-cosmodromes-maps-world-space-week/

12. Centre for Strategic and International Studies, 'Aerospace Security', undated viewed 5 December 2018, https://aerospace.csis.org/data/spaceports-of-the-world/.
13. The 11 FAA launch site operator licences are for California Spaceport (Vandenberg Air Force Base), Mid-Atlantic Regional Spaceport (Wallops Island Virginia), Pacific Southport Complex (Arkansas), Florida Spaceport (Cape Canaveral Air Force Station/John F. Kennedy Space Centre), Mojave Air and Spaceport (California), Oklahoma Air and Spaceport, Spaceport America (New Mexico), Cecil Field Spaceport (Florida), Midland International Air and Space Port (Texas), Houston Spaceport (Texas) and Spaceport Colorado. Federal Aviation Administration, 'Fact Sheet – commercial Space Transportation Activities', dated 17 August 2018, viewed 5 December 2018, https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=19074.

"If one can figure out how to effectively reuse rockets just like airplanes, the cost of access to space will be reduced by as much as a factor of a hundred. A fully reusable vehicle has never been done before. That really is the fundamental breakthrough needed to revolutionize access to space"

Elon Musk

Emerging Technologies

Responsive space launch capability

Responsive space launch aims to provide assured space access to enable the rapid proliferation, disaggregation and replacement of satellite systems to meet real-time operational needs in response to adversarial action. Key enablers for a responsive space launch capability are:

- enough low-cost launch vehicles built in advance of need and stored for future use (or able to be manufactured at short notice through techniques such as 3D printing);
- a rapid launch capability after arrival of the payload at launch site or payload stored at or near the launch site;
- low number of launch personnel; and
- ability to launch from multiple sites, with minimal infrastructure required at each site.

In effect, responsive space seeks to enable a level of flexibility and resilience for orbital launch that is similar to airline operations, with frequent launches from myriad locations worldwide.

In addition to a short-notice launch capability, the other key requirements for a responsive space launch capability are ready-to-go satellites payloads and the ability to rapidly integrate the payloads into the launch vehicle, likely through a satellite dispenser/satellite bus. Depending on the required capability (e.g. surveillance, communications), a number of satellites would likely need to be built and 'kept in the shed'. Upon direction to deploy a particular mission, the appropriate payload would be selected, integrated with the launch vehicle and then launched.

Potentially a key limiting factor for responsive launch is the time required to build and test a mission-specific satellite. For example, Australia's only accredited testing facility for space objects is located at Mount Stromlo in the ACT and is operated by the Australian National University (ANU). This testing facility incorporates several physical tests. These tests include placing an object into a thermal vacuum as well as a vibration stress test to ensure the object can withstand the rigours of the space environment and is able to function in this environment without causing damage to other orbital objects (i.e. an unstable satellite will shed parts thereby adding to the amount of space debris). Currently, ANU tests approximately one satellite a month and undertakes the testing in accordance with a set of detailed testing parameters specified by the launch provider (e.g. SpaceX). If the satellite passes these tests it is provided with a certification. All satellites need to obtain this certification to be launched. That requirement for satellite certification potentially constitutes a 'choke point' in relation to plans to launch many satellites via a domestic launch capability (noting certification may also be provided via overseas testing facilities).

A responsive space launch capability may provide an option to satisfy a potential Defence operational need but will likely be only part of the solution. Defence's future satellite fleet is likely to comprise a number of high (exquisite) and low (CubeSat) capabilities. A responsive launch may enable the rapid replacement of low capability satellites in LEO via small launch vehicles. However, it is unlikely from both an economical and developmental perspective to be a viable option for the rapid replacement of large, expensive satellites in GEO (or other orbits for that matter). For these exquisite satellites, preservation and redundancy measures (such as spare or reassignable assets in orbit) become very important.

A range of technological solutions have been proposed to enable the minimal infrastructure required for rapid launch, including the move away from the use of cryogenic liquid fuels that require highly specialised structures for storage and fuelling of the launch vehicle. Solid fuels have provided this capability for decades and have been employed extensively for air-to-air and air-to-ground missiles due to their ability to remain in storage for long periods and then be reliably launched on short notice. However, the chief drawbacks of solid fuels are that once ignited they cannot be shut off because all the ingredients necessary for combustion are contained within the engine chamber, and they provide lower performance when compared to liquid fuels.

The development of hybrid engines containing a mixture of liquid and solid fuels seek to address some of the limitations of solid fuels. Key capabilities of hybrid engines are that they are mechanically simpler than liquid engines (less plumbing and fewer valves), and when compared to solid fuel engines they have less explosive hazard and are therefore easier to store, as well as the ability to be shut-down and restarted and for the thrust to be throttled. The use of non-cryogenic liquids that can be stored at room temperature enable the liquid fuel to be pre-loaded into the launch vehicle. The specific impulse (a measure of how effectively a rocket uses propellant) for hybrids is generally higher than solid fuel engines but lower than liquid ones and refuelling a partially or totally depleted hybrid rocket would present significant technical challenges. Therefore, these rockets are invariably single-use and thus not reusable.

Air launch

The key advantages of an air launch are that:

- it provides greater flexibility for launches (plane could take off from any major airport);
- not as weather dependent for launch windows as planes used for air launchers can fly above most weather;
- allows an increase of approximately 5 per cent in payload weight due to less fuel being needed to be carried as the rocket is launched in the higher atmosphere and therefore encounters less drag and thus requires less fuel to achieve orbit;

- reduces insurance costs as launches are conducted well away from land;
- does not require extensive fixed infrastructure, such as a launch pad and fuelling tower; and
- provides the ability to fly to a preferred launch site to achieve the desired angle of orbital inclination, noting that satellite operators are generally reluctant to change the angle of inclination once in orbit due to the amount of fuel such a manoeuvre would expend.

The key disadvantages of air launches are:

- the current requirement for a specialised aircraft to carry the launch rocket;
- airplanes generate large lateral forces that could damage payloads;
- the size of the rocket and resulting payload that can be carried is limited by aircraft size; and
- need to convert horizontal velocity to vertical velocity requires specialised structures (such as a delta wing) when compared to a traditional launch vehicle, which can reduce the payload increase achieved from needing to carry less fuel.

Pegasus Air Launch Rocket

Northrop Grumman have successfully conducted air launches using the Pegasus XL rocket, which was launched from underneath the Stargazer L-011 aircraft at approximately 40,000 feet over the open ocean (rocket is released and then free-falls for five seconds before igniting its first-stage rocket motor). Pegasus has successfully conducted 43 missions and launched 94 satellites (up to 1000 pounds into LEO), with the last mission being conducted in December 2016.

Pegasus XL rocket being carried under a Stargazer Aircraft

Source: http://www.northropgrumman.com/Capabilities/Pegasus/Pages/default.aspx

Reference:

Northrop Grumman, 'Pegasus', undated, viewed 9 December 2018, http://www.northropgrumman.com/Capabilities/Pegasus/Pages/default.aspx.

Traditional air launches have the rocket carried under a wing and then placed into a free-fall drop before its internal engine ignites. New techniques being trialled include a higher incline for launch, therefore further deceasing the fuel required to achieve orbit as the rocket when dropped from the plane is already pointing in the right direction to achieve orbit.

The US Defense Advanced Research Projects Agency (DARPA) had a cancelled program called Airborne Launch Assist Space Access (ALASA) with an aim of producing a rocket capable of launching a 100-pound satellite into LEO for less than $1 million. The ALASA program's objective was to use an unmodified aircraft platform to place a 100-pound satellite into orbit that requires only 24 hours' notice to integrate and launch the payload, with the ability to re-plan the launch in flight and relocate the aircraft to any civilian airport or military airfield in a crisis. This launch solution would thereby provide a very agile system for satellite launches (noting previous air launches had occurred from a heavily modified Lockheed airliner). DARPA terminated the program in late 2015, due to safety concerns with the unique monopropellant, NA-7 (kerosene based), which exploded in two ground tests.

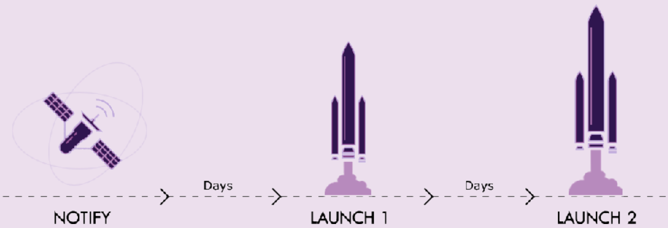
In 1985 the US Air Force successfully launched a rocket that was slung underneath a F-15 (payload less than 50 kgs) to conduct an anti-satellite test.[14] The RAAF's Aircraft Research and Development Unit (ARDU) was exploring conducting air launches using a F-18 Super Hornet but there were structural and aerodynamic issues from under-slinging a rocket on the aircraft's centre line. Additionally, under-slinging on a wing also proved problematic due to the weight unbalancing the aircraft when the rocket was launched. It was also determined that the loaded aircraft could not gain the appropriate altitude for an air launch to occur. The combination of these factors resulted in the cancelling of the project.

14. The missile used was the ASM-135 ASAT and was launched on 13 September 1985 destroying the Solwind P78-1 satellite at a height of 555 km. The satellite broke-up in LEO and as of January 1998, 8 of 285 trackable pieces remained in orbit. In December 1985 the US Congress banned testing the ASM-135 on targets in space.

DARPA Launch Challenge

On 4 April 2018, DARPA announced the 'DARPA Launch Challenge' with the aim of demonstrating flexible and responsive launch capabilities. DARPA was seeking to leverage the expertise developed by the commercial small-launch (10 -1000 kg) industry via advances in manufacturing, micro-technologies, and autonomous launch/range infrastructure to transform space system development for the nation's defence. The challenge will be held in 2019, with a top prize of $10m (USD). Teams will receive exact details on the payload in the days before each of the two launch events, with only a few weeks' notice about the location of the first launch site. Once they successfully deliver their payload to LEO, competing teams will get details of the second launch site. Teams again will have just days to successfully deliver a second payload to LEO for a chance at a prize. DARPA was coordinating this challenge with the Federal Aviation Administration (FAA), which is responsible for granting licenses for commercial space launches. All participants are required to obtain FAA licenses for all launch activity conducted for the challenge.

Overview of the DARPA Launch Challenge



Source: https://www.darpalaunchchallenge.org/

Reference:

DARPA, 'New DARPA Challenge Seeks Flexible and Responsive Launch Solutions', 4 April 2018, viewed 8 December 2018, https://www.darpa.mil/news-events/2018-04-18.

"Current launch systems and payload development were created in an era when each space launch was a national event. We want to demonstrate the ability to launch payloads to orbit on extremely short notice, with no prior knowledge of the payload, destination orbit, or launch site. The launch environment of tomorrow will more closely resemble that of airline operations—with frequent launches from a myriad of locations worldwide."

Todd Master, DARPA Launch Challenge Program Manager

Super Strypi Railgun Failure

On 3 November 2015, Spaceborne Payload Assist Rocket – Kauai (SPARK), also known as Super Strypi, failed in mid-flight shortly after lift-off likely due to a failure with its first stage motor. SPARK was being developed under the Low Earth Orbiting Nanosatellite Integrated Defense Autonomous System (LEONIDAS) program, funded by the Operationally Responsive Space (ORS) Office of the United States Department of Defense. It utilised a derivative of the Strypi rocket, which was developed in the 1960s in support of nuclear weapons testing, to place miniaturized satellites into sun-synchronous orbits. SPARK was designed as a three-stage, all-solid carrier rocket, with a spin-stabilized first stage and an active attitude control system on the second and third stages. It was launched using a new rail-guided system, with an expected payload capacity of 250 kg to a sun-synchronous orbit at an altitude of approximately 400 km.

The Super Strypi launch vehicle at the Pacific Missile Range Facility in Hawaii

Source: https://spacenews.com/super-strypi-failure-blamed-on-first-stage-motor-malfunction/

Reference:

Jeff Foust, Space News, 'Super Strypi failure blamed on first stage motor malfunction', 8 August 2016, viewed 9 December 2018, https://spacenews.com/super-strypi-failure-blamed-on-first-stage-motor-malfunction/.

Challenges

Economics

It is anticipated that within the next 10 years Australia will have a domestic launch capability capable of sending satellites from 500 to 1000 kg into orbit. The key challenge for developing a domestic launch capability is likely more its commercial viability rather than the enabling technology. The Defence policy position in relation to a domestic launch capability is that of a buyer of services but not as a funder of development. While Defence is willing to provide some funding to grow domestic space capabilities, when it comes to launches there are a range of existing commercial options to choose from.

It was noted in stakeholder interviews that the global space economy is approximately $350b, of which the global launch bucket is approximately $6b. There is also a lot of competition for those launch dollars. It was considered that a domestic launch capability would be a 'nice to have' capability; the key question is whether you actually need it.

Australia's space capabilities largely rely on access to other nations' space infrastructure, particularly that of our allies. Australia does not have the means to replicate this space infrastructure, nor to replace it if it becomes degraded. However, Australia could achieve a degree of self-sufficiency in some respects, such as a capability to undertake a responsive launch. An enabler for responsive launchers in Australia would be a move towards more operational use of satellites by

Defence. Currently, satellite data is mainly directed towards strategic rather than operational objectives, and the growing need for operational-level space infrastructure may drive demand for a responsive launch capability. It was also noted by stakeholders that big satellites present a big target and that having a decentralised satellite capability creates redundancy.

Although less of an issue for Defence use, from a commercial perspective, a domestic launch capability reduces the regulatory burden arising from the application of export controls (noting the fundamental 'dual nature' of space technology (i.e. space launch technology can be adapted for ballistic missiles).

Opportunities For Australia

Geography

Due to the rotation of the Earth, the closer to the equator a launch is undertaken the greater the boost in speed provided by the Earth's rotation (the speed the Earth rotates at the equator is 1670 km/hr – 0.46 km/s), though to maximise this factor you need to launch east (as that is the direction the Earth spins). This can result in substantial savings in fuel to obtain the necessary velocity to stay in LEO and hence an increase in the payload that can be carried. As you move north or south of the equator the surface velocity decreases.[15] This speed advantage is most important for satellites going into GEO but less so for LEO satellites, as if launched on the equator they would circle above the equator and have limited orbital view. Most LEO satellites launched into equatorial orbits are launched slightly north or south of the equator so that they have an orbital plane inclined relative to the Earth's equatorial plane, which means each pass (approximately every 90 minutes) is over a different part of the Earth than the previous pass.

15. A launch vehicle must travel at more than 7.8 km/s (28,000 km/h) to stay in LEO. Therefore launching eastwards from the equator the velocity to stay in LEO is reduced from 28,000 km/hr to approximately 26,000 km/h.

Conversely, the further north or south the launch location the easier it is to get a sun-synchronous orbit, in which the satellite passes over any given point of the Earth's surface at the same local mean solar time (i.e. varies from local time when factors such as daylight saving are added in). These satellites are launched in a north or south direction and so cannot utilise the equatorial speed advantage.

South Australia would be a good location from which to launch (to the south) to achieve a sun-synchronous orbit as the first stage of the launch would be over the ocean (and hence the booster stage would not fall on a populated area) and this launch would have a low inclination. In relation to an equatorial orbit, the optimal launch location in Australia would likely be a coastal launch site in either the Northern Territoy or northern Queensland. Some concerns, however, were raised by the stakeholders interviewed that if launched from the Northern Territory the first stage would potentially fly over Indonesia or Papua New Guinea. Similar concerns were expressed for a northern Queensland launch in relation to the first stage flying over the environmentally-sensitive region containing the Great Barrier Reef.

From an historical perspective, on 27 November 1967, the Weapons Research Establishment Satellite (WRESAT) was launched from Woomera in South Australia. Woomera also provides a favourable location for re-entry capsules as it is easier to recover these capsules from land than fish them out of the ocean, noting that the Japanese Hayabusa spacecraft was returned to Earth at Woomera in June 2010 containing a sample of a near-Earth asteroid.

SPACE SENSORS AND COMMUNICATIONS TECHNOLOGIES

Trends

Incremental improvement rather than revolutionary changes in sensor and positioning, navigation and timing capabilities

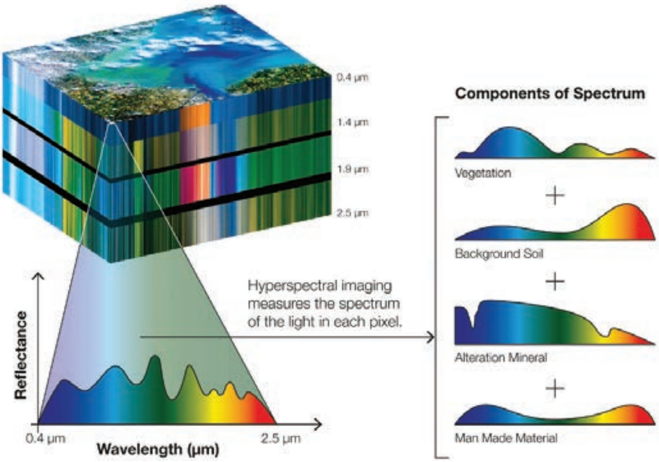
Major technological development in individual space-based sensors are not considered likely, rather there will likely continue to be evolutionary improvements in sensor capabilities. An example of this is hyperspectral imaging, which uses a satellite-based imaging spectrometer to measure contiguous spectral bands reflected or emitted from the Earth's surface and captures the information in 3-D data cubes.[16] A hyperspectral camera can acquire data well beyond the spectral range of the human eye, including a large portion of the infrared spectrum. This allows objects to be identified by their spectral signature.

A challenge for space-based surveillance is the low contrast presented by many targets with respect to the background, particularly when deliberately hidden. The goal for hyperspectral imaging is to obtain the spectrum for each pixel in the image of a scene with the purpose of finding hidden objects, identifying materials or detecting changes. A civil example would be being able to identify unhealthy crops and a military example would be identifying concealed objects. The key advantage of hyperspectral imaging is that it facilitates the detection, analysis and identification of an object with a single measurement (or hyperspectral image). Traditional sensors produce images within a narrow spectral band (e.g. ultraviolet or near infra-red) that then need to be combined to obtain the data provided by a single

16. A key difference between multispectral and hyperspectral imagery is the number of bands and how narrow the bands are. Multispectral imagery has 3 to 10 wider bands, while hyperspectral imagery has hundreds or thousands of very narrow bands.

hyperspectral image. Major downsides of hyperspectral imaging are the large amount of raw data produced and the associated difficulties of transmitting the data from airborne platforms to ground stations. Another concern is decreased radiometric quality arising from the signal-to-noise ratio and radiometric stability that currently limits the usefulness of such images for some scientific applications.

Figure 4. Hyperspectral Imaging



Source: Boeing 2014 reproduced at https://www.spaceflightinsider.com/organizations/boeing/boeing-announces-first-customer-502-phoenix-small-satellite/

On 21 November 2000, a Hyperion imaging spectrometer (recording more than 200 wavelengths) was launched onboard NASA's Earth Observing-1 (EO-1) satellite as a technology demonstrator. This was the first operational hyperspectral imager in orbit.[17] The EO-1 satellite was decommissioned on 30 March 2017. On 19 May 2009, the US launched the TacSat-3 containing the Advanced Responsive Tactically Effective Military Imaging Spectrometer (ARTEMIS) hyperspectral imager. TacSat-3 is technology demonstrator, with the aim of providing a hyperspectral image direct to the tactical warfighter within 10 minutes of a collection opportunity. Tac-Sat3 has achieved a hyperspectral ground resolution of 4 metres, which enabled the detection and identification of tactical targets. TacSat-3 completed operations on 15 February 2012 and entered the Earth's atmosphere and burned up on 30 April 2012.[18]

The first Chinese hyperspectral imaging satellite (Gaofen-5) was launched on 9 May 2018 into LEO to monitor the Earth's atmosphere, with India launching its first hyperspectral imaging satellite on 28 November 2018. NASA is in the planning stages for a new hyperspectral satellite mission equipped with a hyperspectral infrared imager. The arising images will be used to identify the type of vegetation that is present and whether the vegetation is healthy, as well as benchmarking the world's ecosystems against which future changes can be assessed. The mission will also assess the pre-eruptive behaviour of volcanoes and the likelihood of future eruptions as well as the amount of carbon and other gases released from wildfires.[19]

17. The first satellite containing a hyperspectral imager was the Lewis (manufactured by TRW), which was successfully launched on 23 August 1997. Unfortunately, on 26 August 1997, before it became operational the satellite began spinning out-of-control because an altitude control thruster remained in the 'on' position longer than planned. The satellite was declared a loss and re-entered the Earth's atmosphere on 28 September 1997.
18. NASA, 'TacSat-3 Information', undated, viewed 8 December 2018, https://www.nasa.gov/centers/wallops/missions/tacsat3.html.
19. NASA, 'Welcome to HyspIRI Mission Study Website', undated, viewed 10 December 2018, https://hyspiri.jpl.nasa.gov/.

Germany is also in the planning stages for a hyperspectral satellite mission, titled the Environmental Mapping and Analysis Program (EnMAP), with the aim of providing data needed to address major environmental challenges related to human activity and climate change.[20]

While hyperspectral sensors will continue to be refined, the key point here is that this is now a relatively mature technology. Furthermore, it is also likely that there will continue to be evolutionary changes in other types of sensors, such as visible sensors, with higher resolution being provided via either 'staring' optical sensors placed in GEO (for example, similar to the James Webb Space Telescope[21], which will have a 6.5 m primary reflector (although designated as an infrared telescope and pointed away from the Earth)[22] or via a network of 'scanning' sensors in LEO that have higher revisit rates. Likewise, it is expected that incremental improvements will occur with infrared sensors in relation to greater resolution, increased sensitivity and a decreased noise signal.

20. EnMAP Hyperspectral Imager, 'Mission', undated viewed 10 December 2018, http://www.enmap.org/mission.html.
21. The James Webb Space Telescope will be the successor to the Hubble Space Telescope with a projected launch date of March 2021.
22. A DST study in 2009 predicted in that due to advances in technology the size of the primary mirror for a space-deployed telescope was expected to increase to around 20 m in the next 15–20 years, providing a resolution of around 1 metre at nadir and able to observe the Earth between the latitudes of +_60 degrees before the curvature of the Earth and atmospheric path degraded image quality. Len Halprin, Andrew Cruickshank, Lan Dong, Vivian Nquyen and Phil Picone, Defence Science and Technology Organisation, 'Trends in Future Space Capabilities and their Relevance to Defence', DSTO-CR-2009-0380.

Planet Earth observation satellite constellations

Planet is a US-based satellite imaging and analytics company founded by ex-NASA employees with a goal of imaging Earth's entire landmass once per day, which was achieved in November 2017.

Its operating model is based on ultra-compact, inexpensive nanosatellites[23] with a one to three-year lifespan that incorporates the latest hardware, and which are usually deployed via ridesharing.

Planet satellite constellations

Satellite constellation	Planetscope (Dove)	SkySat	RadidEye
No. of satellites	Up to 180	13	5
Orbiting altitude	400 km	450 km	650 km
Weight	4-5 kg	100 kg	150 kg
Resolution	3m	72cm	5m
Frequency	Daily (everywhere)	Twice Daily (anywhere)	Daily (anywhere)
Image collection	300 M km^2/day	185 K km^2/day	6.5 M km^2/day
Archive	2009 (includes RapidEye)	2014	2009

Source: Noetic Group 2019.[24]

23. Both the RapidEye and SkySat satellite constellations were acquired by Planet via acquisitions.
24. See list of references for callout box for sources.

Planet's satellite constellations orbit Earth in a sun-synchronous orbit, which means that due to the Earth's rotation each satellite in line will see a slightly different portion of the Earth's surface than the one before it – effectively functioning like a line scanner for the planet. Collectively, the satellites capture over 1.4 million images per day, which are stored on the satellite until it passes over a ground station.

In addition to near real-time imagery, Planet also provides extensive image archives for trend analysis. The next focus for Planet is the development of analytical features (machine learning) to undertake object recognition and associated indexing of its imagery to allow users to submit queries and build customised information feeds.

A different operating model to Planet is that of DigitalGlobe. Rather than constellation of nanosatellites, DigitalGlobe operates five high-resolution commercial earth imaging satellites in orbit from 496 km to 770 km and which provide resolutions ranging from 50 to 31 cm for panchromatic images. Collectively, the DigitalGlobe satellites have a daily image capacity of over 3 million square kilometres, with multi-spectral imaging capabilities, including shortwave infrared (SWIR), which can penetrate smoke and ash.

References:

Planet homepage, various pages, viewed 8 January 2019, https://www.planet.com/.

Michael Baylor, NASA Spaceflight.com, 'Planet Labs targets a search engine of the world', 29 January 2018, viewed 8 January 2019, https://www.nasaspaceflight.com/2018/01/planet-labs-targets-search-engine-world/.

DigitalGlobe homepage, various pages, viewed 8 January 2019, https://www.digitalglobe.com/.

25. WorldView-1, GeoEye-1, WorldView-2, WorldView-3 and WorldView-4.

Noting that individual sensor technology is now relatively mature, increased Earth observation capabilities are more likely to arise from the aggregation of inputs from individual sensors as well as innovative methods for the cueing/coordination of individual sensors. These capabilities would likely be dependent on a range of aspects including integrated and overlapping sensor networks, as well as technological developments in AI and data processing capabilities (discussed elsewhere in this paper).

Another space capability that is also likely to see incremental rather than revolutionary changes are positioning, navigation and timing (PNT) capabilities. On 23 December 2018, the US Air Force launched the first of a planned 32-satellite constellation that will form GPS III, and which will be placed in orbit over the next two decades. The satellites, designed and manufactured by Lockheed Martin, have three times better accuracy and up to eight times improved anti-jamming capabilities than the previous GPS IIF satellites, as well as an extension of operational life to 15 years, which is 25 per cent longer than the previous GPS IIF satellites.[26]

26. Lockheed Martin, 'GPS III: The Future of Global Positioning Systems', undated, viewed 30 January 2019, https://www.lockheedmartin.com/en-us/products/gps.html.

'Unhackable' secure communications enabled by a satellite network

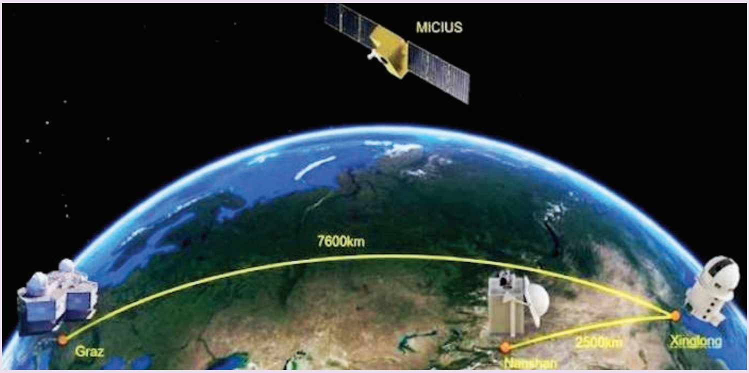
Quantum cryptography, like many other forms of cryptography, relies on a one-time pad; a key formed from a set of random numbers that can be used by the two parties to encode and decode the data. The key weakness of this system is ensuring that no eavesdropper has intercepted and copied the key during distribution. A fundamental aspect of quantum mechanics is that the act of measuring a quantum system disturbs the system.

Thus, an eavesdropper trying to intercept a quantum exchange will inevitably leave detectable traces and thus alert the users that the communication channel has been compromised. If it has, the key is abandoned, and another sent until both parties are certain they have an unobserved one-time pad. The technique is known as Quantum Key Distribution (QKD) and is used to secure communications transmitted over non-quantum channels. This means that security is underpinned by the laws of physics rather than computational complexity. However, photons can travel only a relatively short distance before light absorption from the atmosphere or inside optical fibres disrupts their use; this light absorption limits the practical distance of QKD to around a few hundred kilometres. This is where satellites come in, as once the signal is out of the atmosphere it is travelling in a vacuum where there is negligible loss and decoherence.

Chinese demonstration of quantum cryptography via satellite

The Chinese satellite Micius was launched in August 2016 and can create entangled particles[27] used to carry encryption keys. On 29 September 2017 the University of Science and Technology of China passed quantum created keys encoded in single photons via the Micius satellite to the ground stations located at Xinglong in China and Graz in Austria. The keys were then passed via ground-based optical fibres to enable a secure videoconference between the Chinese Academy of Sciences in Beijing and the Austrian Academy of Sciences in Vienna. This was the first demonstration of intercontinental quantum communication (over 7600 km).

Micius satellite enables intercontinental quantum communication



Source: University of Science and Technology China reproduced at https://newatlas.com/micius-quantum-internet-encryption/53102/.

References:

MIT Technology Review, 'First Object Teleported from Earth to Orbit', 10 July 2017, viewed 8 December 2018, https://www.technologyreview.com/s/608252/first-object-teleported-from-earth-to-orbit/.

MIT Technology Review, 'Chinese satellite uses quantum cryptography for secure videoconference between continents', 30 January 2018, viewed 8 December 2018, https://www.technologyreview.com/s/610106/chinese-satellite-uses-quantum-cryptography-for-secure-video-conference-between-continents/.

27. Two quantum objects, such as photons (the particle form of light), that form at the same instant and point in space have observable properties that are correlated. The correlation continues after they separate, and upon measurement of one such property the other property becomes known.

A key aspect of quantum communications is that it doesn't require trusted nodes. Data can be passed from satellite to satellite without being compromised and then transmitted directly to a ground station once it reaches the desired satellite. Quantum communications will likely be a major disruptor for global communications, with satellites providing a key element of a new global communication network, that includes ground stations, airborne assets, and satellites in LEO and GEO. In essence, the GEO satellites will provide the 'backbone' of the system, noting that 6 satellites in GEO provide whole-world coverage and will always have line-of-sight to the ground stations (as well as the LEO satellite communcations nodes, which will receive the data and then retransmit to the appropriate GEO satellite).

Optical communications greatly increase data transmission rates

Earth-observing satellites in LEO orbit the Earth approximately every 90 minutes. They must wait to have line-of-sight with their respective ground station to download the data they have acquired, which means that they are limited to around a tenth of their orbit time to download data. An option to reduce this downlink delay is to transmit the data from LEO satellites to GEO satellites, which are always positioned above their ground station.

A development in communication technology is the use of lasers to transmit data via optical terminals inside satellites. Lasers are much more resistant to snooping or jamming as they provide a highly-concentrated optical stream direct to a ground station. This, however, requires pointing accuracy between the satellite and the ground station and there is not the error margin present in RF communications, which project over a wider arc. Another downside of the use of lasers is that the energy in the laser signal is dissipated when it passes through water vapour (e.g. clouds). However, redundancy can be achieved by having dispersed ground stations. Other options include sending the data by laser to UAVs that operating above cloud cover and which then transmit the data.

European Data Relay System

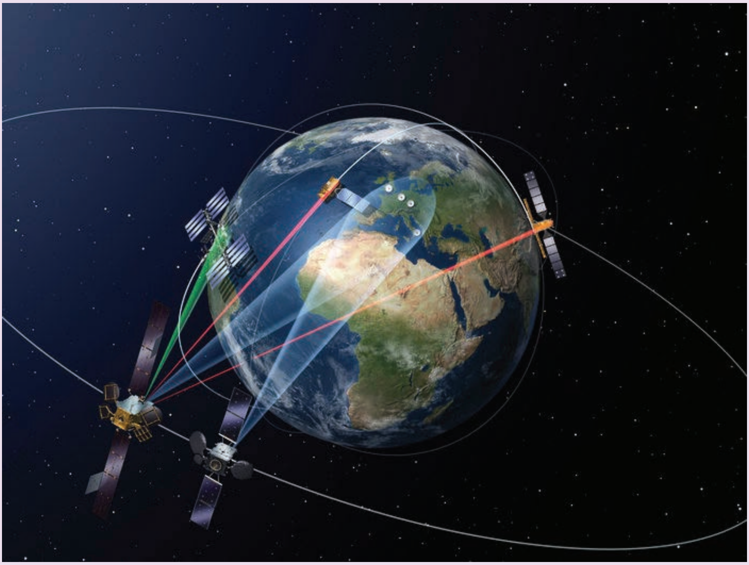
In January 2016, the first GEO satellite in the European Data Relay System (EDRS) was launched from Baikonur Cosmodrome in Kazakhstan. The second GEO satellite in the network will be launched in 2019. The EDRS (built by Airbus Defence and Space) will be the most sophisticated laser communications network yet designed. Data is sent at up to 1.8 Gbits/s between the LEO and GEO satellites using second-generation laser terminals (noting these terminals are capable of receiving and transmitting data). To put this into perspective, the laser communication terminal (LCT) on the GEO satellite locks onto its counterpart on the LEO satellite (an object moving at 7,000 km/h up to 45,000 km away) and downloads the equivalent of 2.7 million pages of text every minute.

The data is then transmitted to ground stations using a KA-band high-speed RF terminal at up to 300 Mbit/s. This is a vast improvement on current user rates and means that most information captured in LEO orbit reaches the network of ground stations (all in Europe) in near-real time. The network can transmit at least 50 TB per day.

Already the EDRS is being used to relay data from the European Commission's Sentinel-1 and Sentinel-2 Earth-monitoring satellites, which produce high-resolution images of, for example, floods, forest fires. Another key advantage of the system is that previously ground stations were typically in polar regions to take advantage of the sun-synchronous orbit (polar orbit) to maximise the amount of time the LEO satellites have line-of-sight with the ground stations.

The EDRS stations, as they are linked to GEO satellites, can be placed virtually anywhere (one is at Weilheim in Germany, another at Harwell in England and the third at Matera in southern Italy).

Overview of the European Data Relay System



Source: http://www.esa.int/spaceinimages/Images/2014/06/European_Data_Relay_System_EDRS/

Reference:

European Data Relay System, 'Overview, viewed 8 December 2018, http://www.esa.int/Our_Activities/Telecommunications_Integrated_Applications/EDRS/Overview.

In August 2018, a NASA CubeSat (Optical Communication and Sensor Demonstration) sent a laser signal from LEO to the NASA's ground facilities. This was the first occasion that a CubeSat had successfully completed space-to-ground optical communications. Data was transmitted at 100 Mbits/s, which is 50 times greater than typical communications systems for small satellites. The aim is to achieve up to 200 Mbit/s downlink speeds. The demonstration opened up the possibility of using small satellites for Earth observation that produce large volumes of data that are beyond the capability of RF downlink systems.[28]

28. NASA, 'NASA's Laser Communications Small Satellite Mission Demonstrates Technology First', 2 August 2018, viewed 8 December 2018, https://www.nasa.gov/feature/ames/nasa-s-laser-communications-small-satellite-mission-demonstrates-technology-first.

Emerging Technologies

High altitude pseudo-satellites

High altitude pseudo-satellites (HAPS) are uncrewed platforms (such as airplanes, airships and balloons) that operate for long periods, sometimes months, about 20 km above the earth (therefore above the height of commercial aircraft operation) and are relatively stationary. A key advantage of HAPS is that they provide longer duration of flight relative to UAVs as they can be electrically powered by solar panels. HAPS offer persistence and flexibility to complement satellites and drones, with key capabilities being prolonged high-resolution coverage of specific regions of Earth as well as providing emergency communications and broadband internet services. HAPS could be employed to support responses to natural disasters or to support field activities in areas lacking infrastructure, such as remote areas or the middle of the ocean. Additionally, HAPS could be useful as an intermediate relay step between a satellite and a ground station, easing the transfer of data and reducing the ground infrastructure required.

Studies have determined that HAPS don't really compete with terrestrial networks in highly developed areas or with satellite networks where the area of interest is large. HAPS, however, effectively complement the networks in between, where the target area is limited and changing, and where ground infrastructure is non-existent or unavailable. Target applications include search and rescue missions, disaster relief, environmental monitoring and agriculture.[29]

29. European Space Agency, 'Could High-Altitude Pseudo-Satellites Transform the Space Industry?', 12 November 2018, viewed 7 January 2019, https://www.esa.int/Our_Activities/Preparing_for_the_Future/Discovery_and_Preparation/Could_High-Altitude_Pseudo-Satellites_Transform_the_Space_Industry.

The key advantages of HAPS over satellites are that HAPS can be more rapidly deployed as well as being (relatively) low-cost and flexible. These platforms can be electrically powered by solar panels. The payloads for these platforms are impacted by SWaP (size, weight and power) considerations; however and tend to quite lightweight, though Thales Alenia's Space Stratobus Airship is projected to be able to carry significantly more payload (250 kg in standard configuration).

Figure 5. Thales Alenia's Space Stratobus Airship

Source: https://www.thalesgroup.com/en/worldwide/space/news/whats-stratobus

Airbus Zephyr

On 3 December 2018, Airbus Defence and Space announced the opening of the world's first HAPS flight base in Wyndham, Western Australia for the operation of its Zephyr UAV. The site was chosen due to its largely unrestricted airspace and reliable weather.

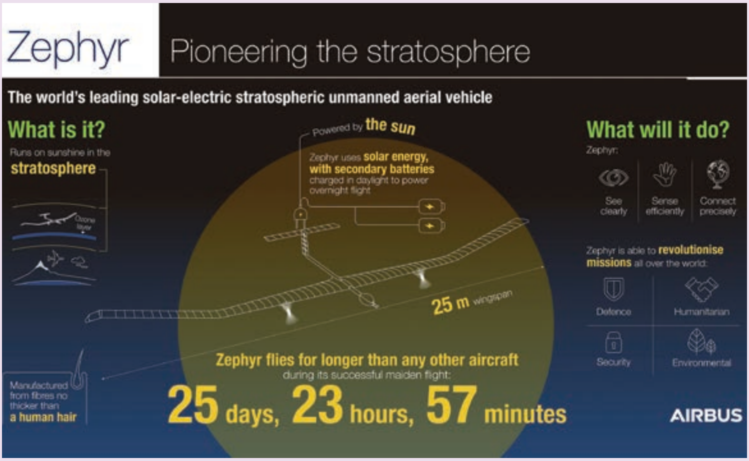
Zephyr is a reusable, carbon fibre stratospheric UAV designed to fill a capability gap complimentary to satellites, UAVs and manned aircraft to provide persistent satellite-like coverage. Zephyr operates at an average altitude of 21 kms, which places it above clouds, jet streams and regular air traffic. Persistent sunlight during the day enables it to run almost exclusively on solar power, with its secondary batteries (high-power lithium-sulphur batteries) being charged for overnight flight.

Airbus has two variants of the Zephyr. The production model Zephyr S has a wingspan of 25 m and weighs less than 75 kg (with a payload of up to 5 kg). The larger Zephyr T (wingspan of 33 m and weight of 140 kg) is currently in development.

Zephyr does not require a runway or airport to be launched. After take-off and ascent to the stratosphere the Zephyr then navigates to the desired location, which may be thousands of kilometres away. The aircraft is capable of operating autonomously from take-off to landing and can be remotely operated from its ground control station using a satellite communication system to provide beyond-line-of-sight (BLOS) operations.

It is intended for a variety of missions requiring Earth observation (such as maritime and border surveillance and also environmental monitoring) but may also serve as a platform to enable satellite-like communications. The Zephyr uses lightweight, high definition, optical/infrared cameras to produce real-time, high-resolution imagery and video of the Earth under all lighting conditions. The UAV can also access a narrowband mobile communications network to transmit information at a data rate of 100 Mbps.

Overview of the Zephyr UAV



Source: https://www.airbus.com/defence/uav/zephyr.html#medialist-image-infographic-all_ml_2-2

References:

Airbus, 'Zephyr: Pioneering the Stratosphere', undated, viewed 7 January 2019, https://www.airbus.com/defence/uav/zephyr.html.

Air Force Technology, 'Zephyr S High-Altitude Pseudo-Satellite (HAPS)', undated, viewed 7 January 2019, https://www.airforce-technology.com/projects/zephyr-s-high-altitude-pseudo-satellite-haps/.

Challenges

RF spectrum congestion

The radio frequency (RF) spectrum is vital for transmission from satellites of sensor data or satellite telemetry (data about the satellite itself) as well as transmission of commands to the satellite and to support communications to and from users on the Earth's surface. International frequency management is under the purview of the International Telecommunication Union (ITU), a UN agency headquartered in Geneva. At a domestic level, allocated frequency bands are managed by a national body – in Australia this is the Australian Communications and Media Authority (ACMA).

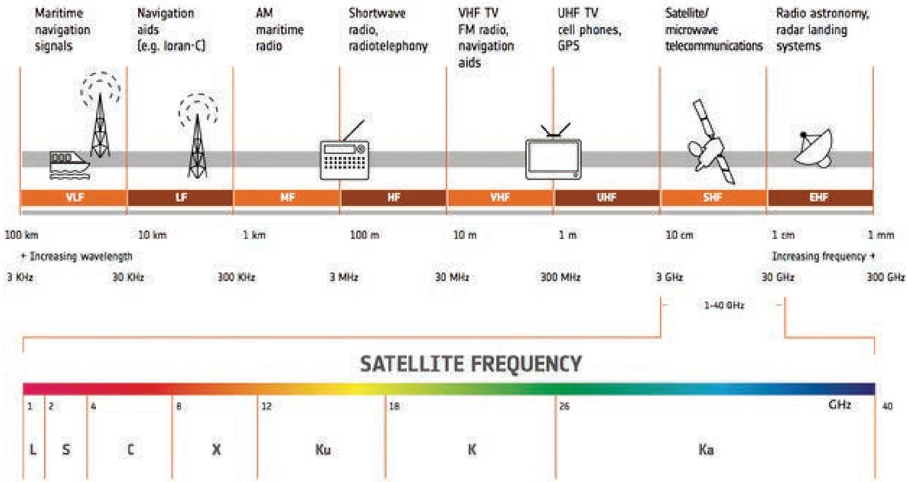
The growing number of satellites, particularly CubeSats, poses challenges for the regulation of the RF spectrum. The ITU has stated that small satellites represent a disruption from an economic and regulatory perspective, in relation to both spectrum congestion and physical congestion of the desired orbital planes. The World Radiocommunication Conference (WRC) is held every four years (organised by the ITU) to review and as necessary revise the Radio Regulations; the international treaty governing the use of the RF spectrum and geostationary-satellite and non-geostationary satellite orbits. In effect, the WRC divides up the orbital pie and provides associated RF spectrum use – this can cause issues when the allocation of certain frequencies is opposed by other parties (for example large satellite operators opposing the frequency allocation to CubeSats). A key aspect of this allocation is that some frequencies are universally allocated for specific uses – for example parts of the frequency bands typically used by CubeSats have been reallocated to 5G and Wi-Fi – and this has the potential to cause interference problems.

It is noted that the Defence Spectrum Office administers the Australian Defence Force's use of the RF spectrum and that there are military specific exemptions for the international and domestic spectrum regulatory framework. While this guarantees military access to the required segments of the RF spectrum, the Defence Spectrum Office works with ACMA to minimise the impact upon other users.

The use of the RF spectrum is a national resource and it is very expensive to obtain access to optimal parts of the spectrum – which will also become more congested with more and more parties seeking to exploit preferred frequency bands. Congestion in some bands may be approaching the Shannon limit (or Shannon capacity), which is the theoretical maximum information transfer rate of a channel with a given bandwidth and a given noise level – if you exceed the channel capacity you can expect some data loss.

An example of where there is currently significant RF congestion is in the L-band, which is used by the Global Positioning System (GPS) as well as the Galileo Navigation System (EU) and GLONASS System (Russia). L-band waves can penetrate clouds, fog, rain, storms and vegetation and so enables GPS units to receive accurate data in all weather conditions, day and night. The L-band is also used for satellite mobile phone networks, such as Iridium; Inmarsat proving communications at sea, land and air; and WorldSpace satellite radio.

Figure 6: Overview of the allocation of the radio spectrum



- L-band (1–2 GHz): GPS carriers and also satellite mobile phones, such as Iridium; Inmarsat providing communications at sea, land and air; and WorldSpace satellite radio.
- S-band (2–4 GHz): Weather radar, surface ship radar, and some communications satellites, especially those of NASA for communication with the International Space Station (ISS) and Space Shuttle.
- C-band (4–8 GHz): Primarily used for satellite communications, for full-time satellite TV networks or raw satellite feeds. Commonly used in areas that are subject to tropical rainfall, since it is less susceptible to 'rain fade' (the absorption of radio signals by atmospheric rain, snow or ice) than the Ku band.

- X-band (8–12 GHz): Primarily used by the military. Used in radar applications including continuous-wave, pulsed, single-polarisation, dual- polarisation, synthetic aperture radar and phased arrays. X-band radar frequency sub-bands are used in civil, military and government institutions for weather monitoring, air traffic control, maritime vessel traffic control, defence tracking and vehicle speed detection for law enforcement.
- Ku-band (12–18 GHz): Used for satellite communications. In Europe, Ku-band downlink is used from 10.7 GHz to 12.75 GHz for direct broadcast satellite services, such as Astra.
- K-band (12–26 GHz): Due to high atmospheric attenuation this band is useful for only short-range applications.
- Ka-band (26–40 GHz): Communications satellites, uplink in either the 27.5 GHz and 31 GHz bands, and high-resolution, close-range targeting radars on military aircraft.

Source: https://www.esa.int/Our_Activities/Telecommunications_Integrated_Applications/Satellite_frequency_bands

The higher frequency bands typically give access to wider bandwidths but are also more susceptible to signal degradation due to rain fade. Because of satellites' increased use, congestion has become a serious issue in the lower frequency bands. Consequently, technology is looking at ways of exploiting under-utilised or less-utilised spectrum bands. Protected communications (which have a higher tolerance of interference by using more power and bandwidth [more spectrum] to build up the signal to overpower background noise (which occurs naturally)) are better supported at the higher frequency bands where more bandwidth is available, noting that highly protected communications require a large amount of resources to transmit a relatively small amount of data.

Advances in the fields of optical communications provides the prospects of significantly increasing the capacity of the RF and wider EM spectrum. Cognitive radio approaches (see emerging technology element of the next section) that allow 'secondary' users (for lower costs) to access spectrum on an opportunity basis without interfering with primary users are well advanced for terrestrial communications and may offer future opportunities in satellite communications.

Opportunities For Australia

Linking the IOT through satellites

The Internet of Things (IOT) refers to the projected billions of physical objects - vehicles, machines, homes appliances - that collect data using sensors and exchange this data over the internet, usually via an application programming interface (API) utilising a wireless network. Most definitions of IOT usually exclude devices that would be expected to have an internet connection, such as a PC.

Several Australian start-ups are developing products to link IOT objects via satellite communications networks.

Myriota's key commercial offering is providing the interface platforms for IOT sensors that connect direct to the satellite, with the data being processed in the Cloud and then transmitted to the customer. This direct-to-satellite linkage negates the need for supporting ground infrastructure, such as hubs, to support deployed sensors and therefore increases the flexibility of sensor placement (essentially can be deployed anywhere on the planet). A key application is sensor placement on mobile assets such as livestock or vehicles/equipment.

Myriota's focus is on the sensor platform to provide a low-cost transmitter with extended battery life – these are provided in developer kits to fit a range of COTS sensors (temperature, location (GPS), pressure). Indeed, battery life is seen as one of the key system limitations particularly for remote assets due to the time required to travel out to the asset to replace the battery. Myriota has focused on improving the power management system of its sensor platform so that now a couple of AA batteries (the standard power source) could potentially last a few years. They are also looking at incorporating solar cells for sensors (such as livestock ear tags) or other forms of renewable energy to reduce the need for battery replacement.

Myriota currently utilises a few satellites owned by one of their investors but are moving towards deploying their own nanosatellites (CubeSats) that require low power as they transit data at a low frequency. The lower power requirements extend the operational life of the satellite.

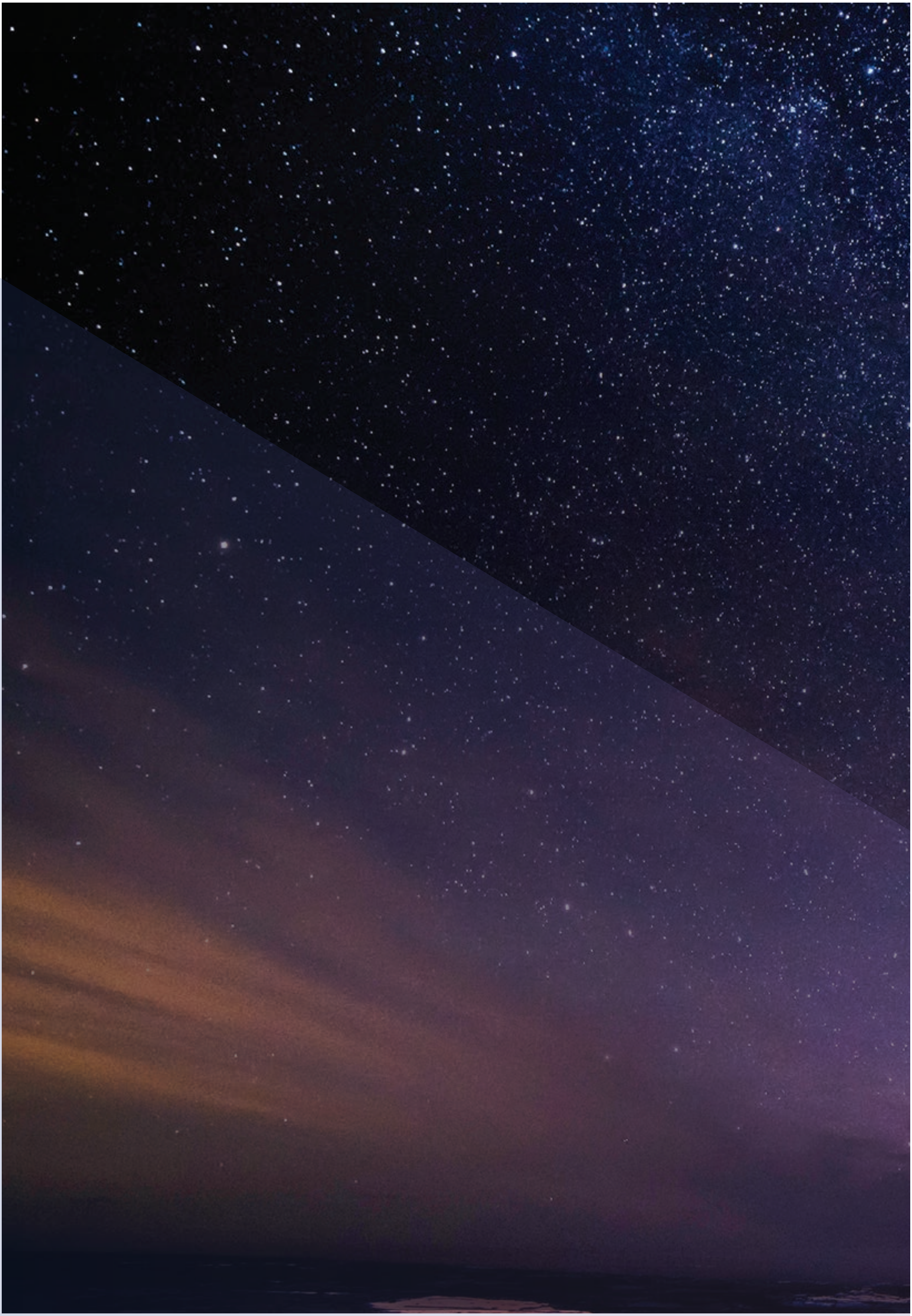
Fleet Space Technologies' main product offering at present is the Fleet Portal, which incorporates a Linux server, a LoRaWAN (low power wide area network) gateway, and a satellite modem and antenna. These portals act as a hub from which up to 1000 nodes (devices) transmit encrypted data and communicate using LoRa, a patented digital wireless data communication technology. Each node can be connected to multiple sensors (usually a physical connection). The hub aggregates the data, undertakes data processing and compresses the data for transmission to satellites at set intervals (e.g. every 15 minutes, weekly) using L Band and S Band frequencies, though in future Fleet will mainly move to the S Band. From the satellite the data is passed onto the Cloud where is it decrypted and made available to the customer. A key design factor is that only the data the client needs, not the raw data, is passed over the network once it reaches the hub (portal).

Uses of this technology include for agriculture to track animals (though if the animals are ranging over a wide area this may require multiple portals), tracking for mining equipment or even miners (incorporated into their personal equipment), or other personnel working in remote areas (such as construction workers). Fleet's technology can also be used to remotely operate equipment such as opening and closing gates or turning on/off taps. Fleet sees itself as a re-seller of nodes (e.g. designed by third parties) with its focus on developing proprietary technology for the radio link between the portal and satellite as well as the software to select, compress and send only the data the business needs.

In November 2018 Fleet's Proxima 1 and II CubeSats were launched from Rocket Lab's Launch Complex 1 on New Zealand's Mahia Peninsula.[30] This was the first satellite launch of CubeSats by the Australian private sector, with the CubeSats being designed and built within six weeks. An additional two CubeSats (Centauri 1 and 2) were launched in November/December 2018 via the Polar Satellite Launch Vehicle (PSLV) of the Indian Space Research Organisation (ISRO) and by SpaceX (US) using a Falcon 9 rocket.

The launch of its own satellites reduces Fleet's dependence on third-party satellite providers, such as Iridium. Fleet are intending to operate a constellation of 100 nanosatellites in LEO by 2022. Fleet has also established a mission control centre at its headquarters in Adelaide and a satellite ground station in the outskirts of Adelaide, both of which will operate (with a high degree of automation) 24/7 and be responsible for control of Fleet's satellite network.

30. The launch (11 November 2018) was Rocket Labs second successful orbital launch.



COMPREHENSIVE SPACE DOMAIN AWARENESS

Trends

SSA becomes more critical

Space situational awareness (SSA) is the process of identifying, tracking and cataloguing objects in space across orbital bands.

There are around 4,700 satellites orbiting the Earth, of which approximately 1,800 are active.[31] In total, there are some 29,000 objects larger than 10 cm, 750,000 objects between 1 and 10 cm, and 166 million objects smaller than 1 cm orbiting the Earth[32], the majority of which are travelling at 28,000 km/h. Even paint flecks can cause damage when travelling at this speed and a few Space Shuttle windows needed to be replaced after being struck by paint flecks.[33] The total mass of man-made objects in space is more than 7,600 tonnes and over 290 in-orbit fragmentation events have been recorded since 1961 (an average of four to five per year).[34]

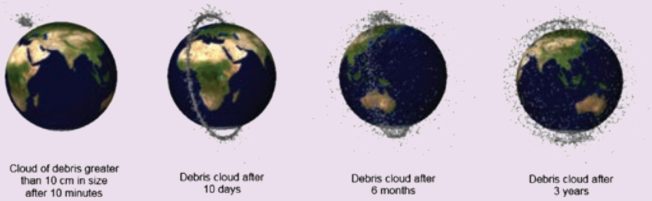
31. For example, Vanguard 1, which was the second US satellite to be launched (and the fourth satellite overall), was launched in 1958 and stopped transmitting in 1964 when it last solar cells gave out but is expected to remain in orbit until 2198.
32. Peter Teffler, Euobserver.com, 'Europe's space trash chief: situation getting worse', 31 August 2018, viewed 30 November 2018, https://euobserver.com/science/142685.
33. Mark Garcia, NASA, 'Space Debris and Human Spacecraft', last updated 7 August 2017, viewed 9 December 2018, https://www.nasa.gov/mission_pages/station/news/orbital_debris.html.
34. These in-orbital fragmentation events arise from either orbital collisions or explosions onboard satellites. To reduce the incidence of such explosions, passivation measures are encouraged. Passivation requires unused fuel to be burnt at the end of a mission, batteries to be discharged and pressure released.

Satellite debris fields

On 11 January 2007, China destroyed an inactive Chinese weather satellite with a ballistic missile ('kinetic kill') at an altitude of 865 km, which is roughly the altitude used by US and Japanese imagery intelligence satellites. As of mid-September 2010, the US military's Space Surveillance Network (SSN) had tracked 3,037 pieces of debris (larger than a golf ball) from the event, of which 97 per cent have remained in orbit. Scientists have estimated that there are more than 32,000 smaller pieces of debris that are currently untracked. As of 2010, the debris field spread from an altitude as low as 175 km to as high as 3600 km – this is the largest debris cloud generated by a single event in orbit. It was estimated that this event alone increased the total amount of orbital debris by 20-30 per cent.

Approximately 2/3 of all active satellites pass through the debris field created by the Chinese anti-satellite test. The first acknowledged manoeuvre to avoid a piece of debris occurred on 22 June 2007, when flight controllers at NASA's Goddard Space Flight Centre briefly fired their thrusters on their TERRA satellite to avoid a 7 per cent chance of a collision the following day. In 2007 it was estimated that just 6 per cent of the debris will have re-entered the Earth's atmosphere within a decade and that 79 per cent of the debris will remain in orbit a century after the event, thereby posing ongoing risks to operational satellites.

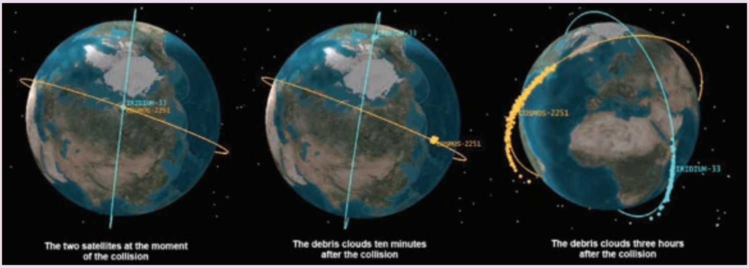
Debris field arising from the 2007 Chinese anti-satellite test



Source: https://swfound.org/media/205391/chinese_asat_fact_sheet_updated_2012.pdf

On 10 February 2009, an inactive Russian communications satellite, designated Cosmos 2251, collided with an active commercial communications satellite (Iridium 33 satellite, which provides L-band mobile telephone services). The incident occurred approximately 800 km above Siberia with a relative impact speed of 36,000 km/h. This collision produced almost 2,000 pieces of debris, measuring at least 10 cm in diameter, and many thousands of smaller pieces. Much of this debris will remain in orbit for decades or longer, posing a collision risk to other objects in LEO. The Cosmos 2251 is the second-biggest breakup recorded in orbit (after the destruction of the Chinese weather satellite - see above) and the Iridium 33 the fourth-biggest. This was the first-ever collision between two satellites in orbit.

Debris field arising from the 2009 Cosmos/Iridium satellites collision



Source: https://swfound.org/media/205392/swf_iridium_cosmos_collision_fact_sheet_updated_2012.pdf

References:

Secure World Foundation, '2007 Chinese Anti-Satellite Test Fact Sheet', updated 23 November 2010, viewed 9 December 2018, https://swfound.org/media/205391/chinese_asat_fact_sheet_updated_2012.pdf.

Secure World Foundation, '2009 Iridium-Cosmos Collision Fact Sheet', updated 10 November 2010, viewed 9 December 2018, https://swfound.org/media/205392/swf_iridium_cosmos_collision_fact_sheet_updated_2012.pdf.

Space debris is defined as "any object placed in space by humans that remains in orbit and no longer serves a useful function or purpose. Objects range from spacecraft to spent launch vehicles stages to components and also include materials, trash, refuse, fragments, or other objects which are overtly or inadvertently cast off or generated"

NASA

From a space debris perspective, the greater operational dangers are in LEO as opposed to GEO due to a range of factors. Objects in orbit must follow the laws of orbital mechanics (unless artificial propulsion is employed). Therefore, objects at the same attitude will have the same relative velocity and thus will maintain physical separation if on the same orbital plane. However, if there is an intersection between orbital planes this is where the danger of collision arises. This danger is greatest in LEO, where there are numerous intersections of orbital planes due to a wide range or orbital inclinations. In GEO, as the satellites are all at the same altitude (36,000 km) and are required to be stationary above the Earth's equator, their orbits are coplanar and therefore they have zero to negligible velocity[35] relative to each other when on station. Hence the probability of collision is very low (as is the likelihood of debris clouds arising from collisions).

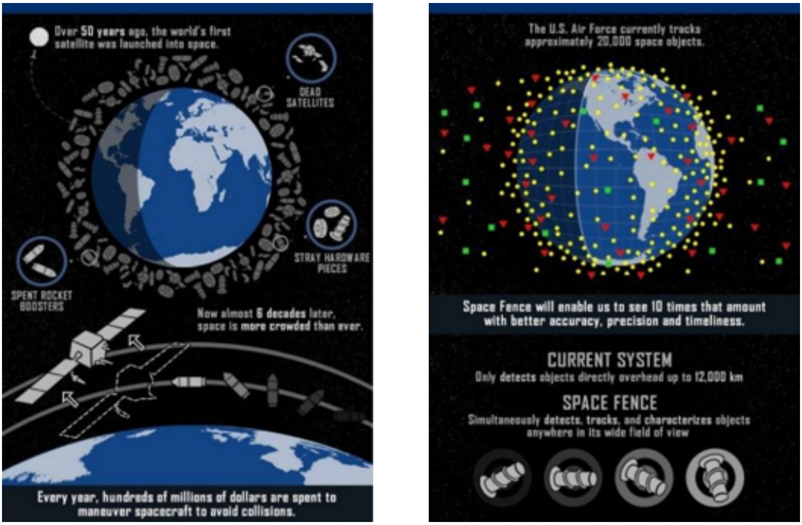
Studies have raised concerns that the growth in orbital debris has become self-perpetuating and risk making parts of space off-limits for future generations. The greater the number of space objects the greater the possibility of the Kessler syndrome – the unstoppable cascade of orbital collisions predicted by NASA scientist Donald Kessler in the late-1970s.

35. The rationale for the non-zero relative velocity is due to GEO satellites using propulsion to take up new positions above different longitude and maintain their orbital position.

The US Department of Defense maintains a highly accurate catalogue of objects in the Earth's orbit that are larger than a softball. The SSN (run by the US Air Force) tracks discrete objects larger than 5-10 cm in diameter in LEO and 30 cm - 1 metre in GEO, with the total number of tracked objects exceeding 21,000. The basis of this SSA is a few 'exquisite' detectors (i.e. powerful telescopes), which rely on complex computational modelling to predict orbital pathways based on non-persistent observation (essentially from one or a small number of viewpoints).

By mid-2019, the Space Fence – a second-generation space surveillance system being built by the US Air Force in partnership with Lockheed Martin on Kwajalein Atoll in the Marshal Islands - should be operational (with the potential for another radar site to be constructed in Western Australia). The Space Fence relies on S-band ground-based radars to detect and track space objects, primarily in LEO. The Space Fence will replace the Air Force Space Surveillance System (or VHF Fence), as the higher wave frequency allows the detection of much smaller microsatellites and debris, facilitating increased timeliness with which operators can detect space threats.

Figure 7: Space Fence overview



Source: https://www.lockheedmartin.com/en-us/products/space-fence.html

SSA is critical to all aspects of satellite operations, including launch to ensure a clear path to orbital position, as well as the ability to check and track satellites once in orbit. SSA in the future is likely to be more challenging with smaller objects in the physical domain that will pose challenges in relation to detection and tracking, noting that one CubeSat looks roughly the same as any other CubeSat. This factor is exacerbated by the fact that these low observable satellites may appear in orbital planes where observers are not expecting them (e.g. CubeSats in GEO). These smaller satellites will likely undertake distributed missions involving multiple satellites (instead of relying on a larger and more easily detectable satellites) and utilise new ways of undertaking existing missions. These factors increase the challenge of SSA, which relies on an element of predictability in relation to satellite movements.

Starlink satellite constellation

SpaceX received approval from the Federal Communications Commission (FCC) in March 2018 to provide broadband services in the Ka and Ku bands via a constellation of 4,425 satellites (in LEO – initially at 1150 km, with a later request to deploy 1500 of these satellites to an orbital altitude of 550 km) and via V Band with a separate constellation of 7,518 satellites (in very LEO - between 335 and 346 km) approved in November 2018.

The purpose of these constellations is to provide low latency global broadband internet (Starlink) by the mid-2020s. The key advantage of satellite-based broadband is that it covers entire regions without the need to build extensive land-based internet infrastructure (the ubiquitous cell towers). Rather you just need a satellite dish, which makes it ideal for remote locations. The current key technical limitation is high latency (the time it takes to get a signal from one place to another) because of the orbiting height of the satellites (normally in GEO). By placing the Starlink satellites in LEO this helps reduce latency. The key disadvantage is that bringing a satellite closer to the ground reduces the area its signal can cover, therefore the number of satellites required to provide global coverage is much higher.

On 22 February 2018 SpaceX successfully launched the first two Starlink test satellites (Tintin A and Tintin B) from Vandenberg Air Force Base (California).

References:

Federal Communications Commission, 'FCC Authorises SpaceX to Provide Broadband Satellite Services', 29 March 2018, viewed 9 December 2018, https://www.fcc.gov/document/fcc-authorizes-spacex-provide-broadband-satellite-services.

Loren Grush, The Verge, 'FCC approves SpaceX's plan to launch more than 7,000 internet-beaming satellites', 15 November 2008, viewed 9 December 2018, https://www.theverge.com/2018/11/15/18096943/spacex-fcc-starlink-satellites-approval-constellation-internet-from-space.

Emerging Technologies

SSA from space

To overcome some of the limitations of Earth-based SSA, it is proposed to conduct SSA from space. Space-based optical sensors observe man-made orbiting objects without the disruption of weather, time of day (e.g. daylight) and atmosphere that can limit ground-based systems. Sensors in space can also be more sensitive and can detect dimmer objects including space debris. Space-based SSA assets are typically a single satellite, such as the US Air Force's Space Based Surveillance Block (SBSS) 10 satellite (launched in 2010) and the Advanced Technology Risk Reduction Satellite (launched in 2009). The SBSS satellite orbits at 630 km and can monitor objects as small as a 1 m cube out to GEO. SBSS uses a visible sensor mounted on an agile, two-axis gimbal, which allows ground operators to quickly move the camera between targets without having to expend time and fuel to reposition the entire spacecraft.[36] In 2013, Canada's Sapphire satellite was launched. This satellite uses an optical system to track artificial objects in MEO and GEO orbits. All three satellites provide data to the SSN.

There are also opportunities to use space-based radar satellites for SSA. However, radar does not suffer the same limitations as ground-based optical sensors and so the advantages of space-based radar over its ground-based counterparts are less persuasive for investment in this area. An alternative may be that existing active military radar satellites could be repurposed to provide space-based SSA.

36. Air Force Space Command (US), Space Based Space Surveillance, 22 March 2017, viewed 8 January 2018, https://www.afspc.af.mil/About-Us/Fact-Sheets/Article/249017/space-based-space-surveillance-sbss/.

High Earth Orbit Robotics

An Australian start-up, High Earth Orbit (HEO) Robotics, is proposing to use 6U nanosatellites placed 500 km above geostationary orbit to track GEO assets and debris from high-earth orbit. Earth based optical telescopes need specific lighting conditions to observe GEO assets and space debris (specifically the observation platform needs to be in darkness and the object needs to be illuminated by the Sun). The placement of the HERO spacecraft will increase the amount of time per orbit that GEO satellites can be observed, therefore increasing the extent of SSA and more responsive identification of conjunction risks.

Source: https://www.heo-robotics.com/mission-argus

Reference:

High Earth Orbit Robotics website, various pages, viewed 8 January 2018, http://www.heo-robotics.com/hero.

Challenges

Regulation

A related issue to SSA is the regulatory framework that will support space traffic management. Although an organisation may have the means to detect and predict a conjunction (collision) between two space objects, there is currently no legal basis to compel one of the parties to move an object. The technological difficulties in moving satellites should also not be underestimated, though there is a role for on-orbit satellite servicing that can move the satellite for you. However, such a manoeuvre raises interesting legal issues in relation to liability, particularly if by moving the satellite it impacts on other satellites.

There are currently some voluntary conventions in relation to reducing space debris. In December 2008 the Council of the EU agreed a draft Code of Conduct for outer space activities, which included rules targeted at the reduction of space debris. However, China and Russia proposed a rival treaty and the reluctance of the US to sign-on resulted in negotiations stalling in 2015. Consequently, the UN Committee on the Peaceful Uses of Outer Space has taken the lead on the development of guidelines (a non-legally binding instrument).

There is a growing understanding between satellite operators that satellites that orbit above 600 km should have a deorbital solution – perhaps moving into a 'graveyard' orbit. This means that they need a reliable propulsion and communication system that is functional at the end of the satellite's operational life. A conflict can arise between maximising the operational life of a satellite if its payload is still functional to get greater value for money and the need to maintain the reliability of the systems used for the satellite's disposal.

Satellites that orbit from 500 to 600 km will deorbit and usually burn themselves out in the Earth's atmosphere within 10 to 25 years. Satellites orbiting at 300 km have only weeks left before they burn out. Stakeholders noted that currently only about 30 per cent of deorbiting attempts are successful due to the technological challenges. An example of this was that for GEO satellites a graveyard orbit (80 km above the GEO belt) was previously being used but that this orbit was not stable, and objects were gaining speed and popping in and out of the GEO belt. Moving the graveyard orbit further above GEO has seemed to provide a more stable orbit.

Stakeholders equated the emerging orbital situation to that for commercial, recreational and military aircraft that led to the development of standardised air traffic control (ATC) arrangements across the world. Thereby a system of satellite traffic control would probably arise underpinned by the same drivers as that for the ATC system; being providing equitable access to space and minimising the risk of collision. The satellite traffic control system, in the absence of binding international agreements, would likely rely on 'good space citizenship' practices, such as having a deorbital plan. Additionally, improved SSA capabilities would increase the likelihood of any 'rogue' satellite operations being detected.

Opportunities for Australia

Ground station networks

The Square Kilometre Array (SKA) is a large multi-radio telescope project proposed to be built in Australia and South Africa. If built, it would have a total collecting area of approximately one square kilometre. The basic concept is to use passive radar over a very large collection area to provide the world's highest resolution radio telescope with the fastest survey speed in the world (100 times faster than before). The South African component (SKA-mid array) will consist of 200 dish antennas with 12 metre widths. The Australian component (SKA-low array) will consist of 130,000 antennas spread over 65 km in clusters of 256 antennas. It is an international project with well-defined access for international scientific research, with the data it produces to be shared among partner nations – as such, all data will eventually be released to the public. It is also possible that SKA could aid with SSA, noting that due to its open data platform the data it produces will not provide any situational awareness advantage from a military perspective. Construction is expected to start in 2020/21.

Australia is currently home to a C-Band Space Surveillance Radar (used for tracking objects in LEO) and will soon become home to the Space Surveillance Telescope (used for tracking objects in MEO and GEO). These assets are owned by the US and are positioned at the Harold E. Holt Naval Communication Station near Exmouth, Western Australia.

These assets form part of the SSN and are collaborative projects jointly run by the RAAF and the US Air Force. These systems are operated remotely by the No.1. Remote Sensor Unit (1RSU) at RAAF Base Edinburgh. The location of these assets provides access to segments of the sky not generally visible from the northern hemisphere.

Another ground station consideration for Australia is that as the Space Fence is restricted to one (potentially two) locations on the Earth's surface it cannot provide persistent coverage (that is, it loses 'custody' of an orbital object). Stakeholders noted that there is likely to be increasing commercial interest in the provision of SSA to fill the gap between the responsiveness and detail of data provided by government authorities and the needs of satellite operators. These companies would seek to provide supplementary data to reduce the size of the uncertainty bubble around orbital objects (and therefore reduce the need for power expenditure on satellite manoeuvring in relation to conjunction warnings). This supplementary data would also allow satellite operators to perform more efficient station keeping manoeuvres (burns to maintain the optimal orbit to counteract orbital decay caused by the Earth's gravity).

A potential market opportunity therefore exists for ground-based networks, which can provide more persistent coverage through a dispersed, wide-angle sensor network. This aspect has military/national security implications from having an increased ability to detect if a satellite suddenly begins to manoeuvre to change its position. A ground-based network also decreases SSA's reliance on orbital propagation calculations (which by their very nature are complex and thereby introduce a greater risk of error than persistent coverage).

FireOPAL is a joint Curtin University and Lockheed Martin Australia[37] project currently consisting of 15 ground-based observatories in SA and WA. The FireOPAL system is designed to be a cost-effective optical SSA solution that tracks objects in LEO, MEO, and GEO – an optical counterpart to radar systems. Observatories can be mass produced, are simple to deploy and maintain, and can operate autonomously in remote environments for extended periods. Although the imaging systems in an observatory are comparatively low cost and low resolution (compared to larger telescope solutions), multiple, synchronized, triangulated observations deliver highly accurate orbits – comparable to results from exquisite optical sensors. The additional benefit is that a distributed network is disruption tolerant, unaffected by weather, images a large fraction of the sky, and extends the optimal terminator observation period. The goal is to build a global system that can follow objects multiple times per day, is capable of catalogue maintenance for a large proportion of all satellites and is able to detect anomalous events in space as they occur.

Near real-time reporting of results enhances awareness and enables immediate decisions and actions. FireOPAL provides persistent observation, omni-directional with depth, imaging the same object multiple times per day. The system is entirely Australian designed, owned and operated, representing a partnership between an Australian university and an Australian company.

37. Another current ground network project with SSA applications is the Murchison Widefield Array (MWA), which is led by Curtin University in collaboration with Silentium Defence (amongst other partners). The MWA is a low-frequency radio telescope designated as a precursor instrument for the SKA.

TECHNOLOGIES SUPPORTING SPACE CAPABILITIES

Trends

Growth in space debris services

There are several techniques to reduce the impact of space debris on operational satellites. Objects located in LEO deorbit due to either steady orbital decay or as a deliberate satellite deorbiting manoeuvre to lower their orbit height to a point where atmospheric drag can operate in a much shorter timeframe. Eventually the LEO satellite will reach an altitude at which they burn-up in the atmosphere (depending on size). Operational satellites located in GEO are expected to be able to move themselves into a 'graveyard orbit' at the end of the operational lifespan to minimise the impact of space debris on operational satellites.

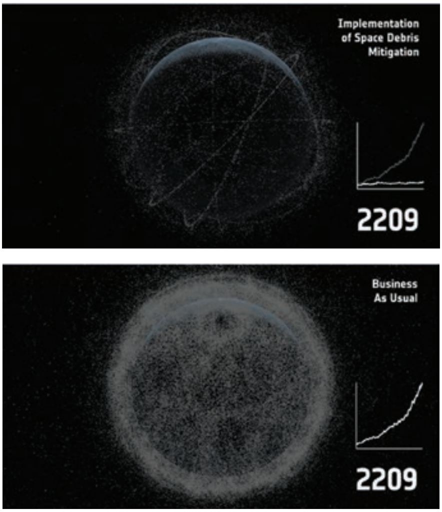
In relation to Active Debris Removal (ADR), the European Space Agency (ESA) is focused on the number of collisions avoided rather than the reduction in volume of space debris. The ESA have proposed the following selection principles for developing a criticality index for removal:

- high mass (potentially create the largest debris cloud in the event of a collision);
- high collision probabilities (e.g. they should be in densely populated regions of LEO and have a high cross-sectional area); and
- be in high altitudes (e.g. between 800 – 1000 km at high inclinations[87], where the orbital lifetime of the resulting fragments is lengthy).[39]

38. Objects at an altitude of 600 km deorbit in about 25 years, while those at 800 km need about two centuries to deorbit.
39. European Space Agency, 'Active Debris Removal', updated 14 April 2017, viewed 7 January 2019, https://www.esa.int/Our_Activities/Operations/Space_Debris/Active_debris_removal.

The ADR focus will be on orbital 'hotspots', where there is a concentration of critical-size objects in narrow orbit bands, thereby facilitating multi-target removal missions.[40] ESA simulations have indicated that the LEO environment can be stabilised with the removal of 5-10 objects per year.

Figure 8. ESA space debris modelling



Source: https://www.esa.int/Our_Activities/Operations/Space_Debris/Active_debris_removal

An option for managing space debris is the use of high-powered lasers to push an object off its orbit. This technique uses photon pressure to achieve a orbital velocity change, with the greater the power applied the greater the corresponding orbital change. This action doesn't remove the threat, rather it reduces the risk of a collision with a specific satellite. This technology is intended to be

40. High-ranking hotspots are 1000 km and 82o inclination, 800 km and 98 o inclination and 850 km and 71 o inclination. European Space Agency, 'Active Debris Removal', updated 14 April 2017, viewed 7 January 2019, https://www.esa.int/Our_Activities/Operations/Space_Debris/Active_debris_removal.

applied in LEO to push space debris away from colliding with operational satellites. The main customers for this space environment management service are assessed to be satellite owners who don't want to use the limited fuel they have onboard their satellites to manoeuvre. It is assessed that they would rather pay to have the object that is going to collide with their satellite moved onto another orbital plane.

Other options for space debris removal include space nets and harpoons to capture LEO satellites. However, many pieces of space debris, such as third stage rockets, have highly elliptical orbits that would require a lot of fuel to be expended to match these orbits to attempt a capture.

On-orbit servicing is at the technology demonstrator stage and will have the most utility for GEO satellites, where fuel is often the key determinant of operational life (noting that the earlier limitations for GEO satellites arising from inadequate solar radiation shielding have now been largely overcome). On-orbit servicing requires a satellite to match the relative speed of another space object and then pull alongside it where it can refuel the satellite and conduct maintenance (including removing and installing pop-out modules). While the same technology can be used for the smaller objects in LEO, they are moving much faster (GEO satellites orbit at approximately 11,000 km/h). Additionally, LEO satellites are in a range or orbital planes (as opposed to GEO, which are in a single orbital plane (35,786 km above the Earth)). Therefore, more fuel is needed for servicing LEO satellites as the on-orbit servicer would potentially need to move between orbital planes. So, while on-orbit servicing of LEO satellites is possible, there are a range of technical challenges that would need to be overcome before it becomes commercially viable.

RemoveDEBRIS experiment

In April 2018 a SpaceX Dragon capsule delivered a 100 kg satellite designed by the Surry Space Centre at the University of Surrey (UK) and co-funded by the European Commission to the International Space Station, and then deployed into orbit by the NanoRacks Kaber system in June 2018.

The RemoveDEBRIS satellite will conduct the first experiments to demonstrate ADR in space. The satellite carries three types of technologies used for space debris capture and active de-orbiting:

- a harpoon – which will be fired into a fixed target (10 x 10 cm) extended from the main satellite by a boom to a distance of 1.5 m and contains a flip-out locking mechanism that prevents the harpoon (attached by a tether to the satellite) from pulling out;
- a net – this will be launched from the satellite to capture two CubeSats, previously ejected from the main satellite (which will naturally deorbit in a few months); and
- a drag sail – which will be deployed from the main satellite and will speed up the deorbiting process.

The experiment will also test a LiDAR (light detection and ranging) system for optical navigation that will help future 'chaser' satellites better aim at their targets. The LiDAR system determines the distance to a target by illuminating the target with a pulsed laser light and then measuring the time it takes for the light to return to the transmitter.

The team decided to take up into orbit their own 'space junk' due to legal issues that don't permit the manipulation of space objects that belong to someone else – even if the objects are no longer functional.

The net was successfully deployed on 16 September 2018.

References:

Tereza Pultarova, Space.com, 'This Space Junk Removal Experiment Will Harpoon & Net Debris in Orbit', 6 April 2018, viewed 30 November 2018, https://www.space.com/40221-space-junk-debris-sweeper-experiment.html.

University of Surrey, 'Surrey Space Centre – Space Missions: RemoveDEBRIS', undated, viewed 7 January 2018, https://www.surrey.ac.uk?/surrey-space-centre/missions/removedebris.

AI support on-data processing and satellite manoveuring

A key challenge with satellite imagery used for surveillance and reconnaissance activities is the huge amount of data produced from Earth observation satellites. This presents two challenges: first is getting the data from the satellite to the ground, for which you may require a high bandwidth downlink. The second is processing and analysis of the raw data once received. These challenges are driving developments in 'Edge Processing', whereby data is processed at the origin point (e.g. in space onboard a satellite) and it is only the results of the analysis (rather than the raw data) that are sent to the ground station before undergoing further processing and then are sent to the customer. These challenges are also driving advances in artificial intelligence (AI) such as machine learning to increase the processing of data in space. Machine learning relates to an algorithm's ability to find patterns in data to improve the machine's outcome – that is, to use existing data to predict unknowns.

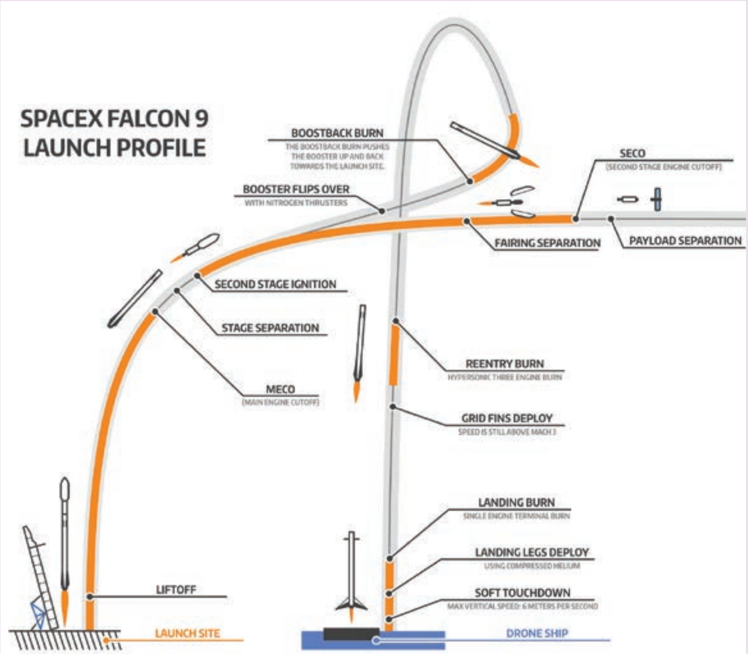
Improvements in AI will enable satellites to undertake more autonomous operations instead of requiring to be sent corrections to instructions from ground stations. While the transmission time from Earth to a satellite in LEO is less than second (if they have a connection), the transmission time for a satellite deployed to Mars can be as long as 40 minutes. Additionally, human operators need to detect a change and then decide to alter a satellite's operating profile; AI would be able to undertake such actions virtually instantaneously without the need for human intervention. An example of how such technology can be employed is the United States' Earth Observation (EO1) satellite launched in the early 2000s. Its onboard AI functionality has direct applications to satellite motion control, which requires complex geometric and kinematical location information to be processed in relation to orbit adjustment, autonomous navigation and, if coupled with a space debris sensor, collision avoidance.

Falcon 9 machine learning

The Falcon 9 rocket booster is 40 metres in height and weighs over 20 tonnes. It is steered back to land precisely on a launch pad at Cape Canaveral or SpaceX's autonomous drone ship using only its internal computers. There were some enabling technologies, such as the use of thrust control to control and slow the descent of the rocket booster, which eliminated the parachute drift normally associated with spacecraft returning to Earth. However, the key technological advance was the use of a convex optimisation algorithm to determine the optimal path to the landing target without running out of fuel. In simple terms, this involves considering all the possible options for the descent as a geometric shape and in seconds choosing the optimal way down from this data set. Real-time computer vision is fed into the on-board computer to enable the rocket to alter its course (known as 'dispersions') in reaction to changes in its environment (for example, the rocket has the awareness to avoid buildings). An additional aspect of the AI is the timing of a 'safing' sequence, whereby unused propellant is vented from the rocket's tanks.

A recent example of the operation of the onboard AI occurred on 6 December 2018, during an attempted relanding at Cape Canaveral. As the rocket descended there was a problem with one of the grid fins. As the rocket could not be sure of a stable landing it guided itself away from the touchdown zone on land and instead touched down on water just offshore (although landing vertically it subsequently tipped over). This occurred as a result of an inbuilt safety feature that prevents the rocket landing on land unless the rocket is working as intended.

Falcon 9 Launch profile

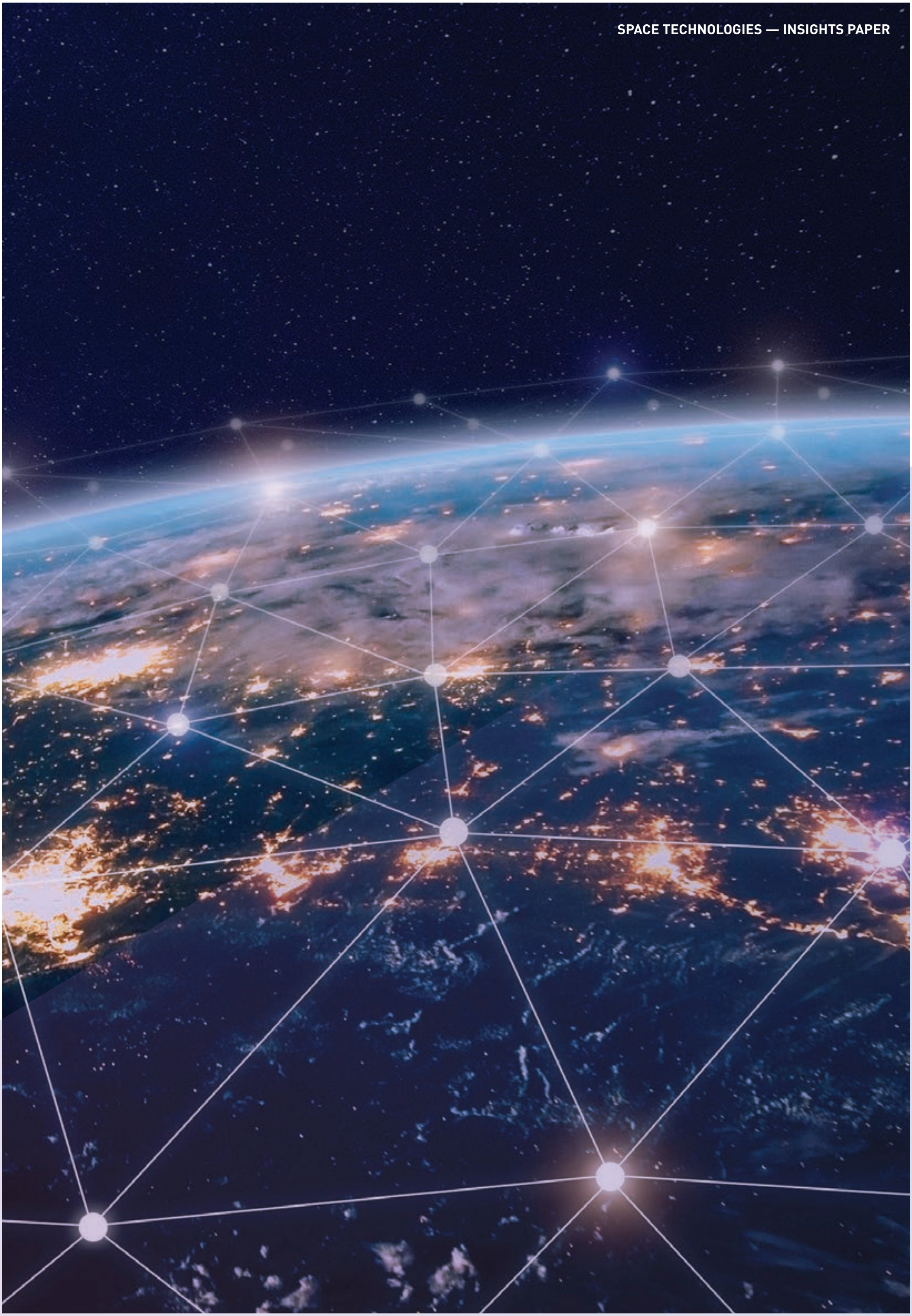


Source: http://justatinker.com/Future/

References:

Tim Fernholz, Quartz, 'SpaceX's self-landing rocket is a flying robot that's great at math', 22 February 2017, viewed 12 December 2018, https://qz.com/915702/the-spacex-falcon-9-rocket-you-see-landing-on-earth-is-really-a-sophisticated-flying-robot/.

Loren Grush, The Verge, 'For the first time ever, a SpaceX Falcon 9 rocket fails to stick a ground landing', 5 December 2018, viewed 12 December 2018, https://www.theverge.com/2018/12/5/18127630/spacex-falcon-9-rocket-landing-failure-ground-cape-canaveral.



Emerging Technologies

Cognitive radio

Cognitive radio is the infusion of AI into space communication networks to meet demand and increase efficiency by reducing the requirement to rely on human-controlled radio systems to communicate with Earth. With the growth in the overall number of satellites RF congestion is likely to increase, which in turn necessitates dynamic spectrum management to maximise the efficient use of the available spectrum. Cognitive radio uses AI to automatically employ underutilised portions ('white spaces') of the RF spectrum without the need for intervention by a human operator. These 'white spaces' are licenced but, at a specific point in time, unused segments of the spectrum. The FCC permits a cognitive radio to use these specific frequencies (for example, portions of the spectrum allocated to cell service, satellite radio, Bluetooth, Wi-Fi) while unused by the licenced primary user until that user becomes active again. In effect, cognitive radio employs frequency-hopping techniques to switch from one white space to another as they become available.

Another potential application for cognitive radio would be utilising alternative data paths to the ground as well as prioritising and routing data through multiple paths simultaneously to avoid interference. Cognitive radio could also increase the efficiency of scheduling for ground station downlinks by a more responsive allocation based on projected demand.

The machine learning aspects of cognitive radio could leverage historical data to identify and remove superfluous data and optimise data packet transmission through spectrum monitoring and analysis of available downlinks.

A key technological challenge is the development of high-quality spectrum-sensing devices and supporting algorithms for exchanging spectrum-sensing data between nodes. While this is a key challenge for terrestrial cognitive radio devices as well, an added technological challenge for space-based cognitive radios is identifying and adapting to space weather. The aim would be to circumvent the harmful effects of space weather by transmitting outside the range of spectrum interference and even shutting down elements of the satellite temporarily to mitigate radiation damage during severe space weather events.[41]

Challenges

Data processing

Currently there is very limited data processing conducted in space and as a result ground stations are getting sent large amounts of data. The ground station then needs to process this data before sending it onto the customer. Considerable development effort is being directed towards the development of processing, exploitation and dissemination (PED) capabilities for space data.

41. Danny Baird, NASA, 'NASA Explores Artificial Intelligence for Space Communications', 9 December 2017, viewed 12 December 2018, https://www.nasa.gov/feature/goddard/2017/nasa-explores-artificial-intelligence-for-space-communications.

These development projects are focused on using machine learning and AI to expedite the extraction of useable intelligence from the huge amount of data produced by satellites to support strategic and operational decision makers. For example, in 2016, NASA was producing 12.1 TB of data every day from thousands of sensor and system dotted across the Earth and space. As NASA moves to the use of optical lasers for high speed/high capacity data transmissions, some missions could generate as much as 24 TB of data in a single day. On top of this, is NASA's data archive of 24 PB (or 24,000,000 GB). By the mid-2020s, NASA expects this data archive to double to 50 PB as it launches new missions to analyse Earth and other planets.[42]

Opportunities For Australia

Autonomous mining expertise

Several stakeholders noted that Australia has the two largest mining companies in the world based on market capitalisation (BHP Billiton and Rio Tinto), both of which have significant experience in remote location operations and deployment of autonomous technology. These factors would likely provide Australia with a domestic advantage in relation to asteroid mining.

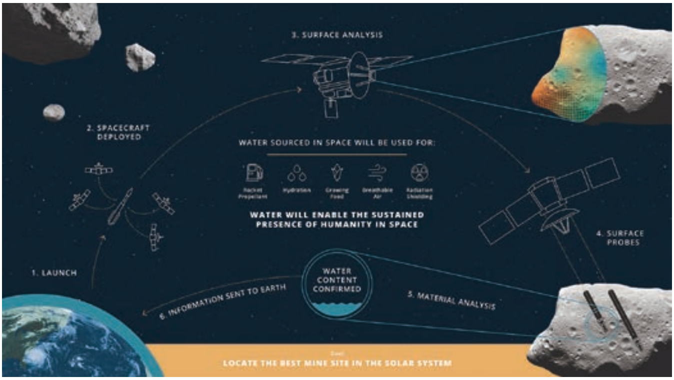
42. Colm Gorey, SiliconRepublic, 'The volume of data NASA has to manage is mind-boggling', 26 October 2017, viewed 8 January 2018, https://www.siliconrepublic.com/enterprise/nasa-data-figures.

Asteroids fall into three classes based on their spectral type – a classification based on the analysis of light reflected off their surface.

- C-type. These are carbonaceous asteroids and probably consist of clay and stony silicate rocks. These asteroids have a high abundance of water bound up as hydrated clay materials, as well as organic carbon and phosphorous.
- S-type. These are salicaceous asteroids and appear to be made of silicate materials and nickel-iron. These asteroids contain a significant fraction of metal, mostly iron, nickel and cobalt but also a fair amount of trace elements, such as gold, platinum and rhodium.
- M-type. These are metallic asteroids and appear to be made up of nickel iron with a higher amount of trace elements.

There are over 16,000 near-Earth asteroids that share a similar orbit to Earth. A US company, Planetary Resources (founded in 2012), has estimated that there are over two-trillion tonnes of water available on near-Earth asteroids that could be used for a variety of purposes (see graphic over page).

Figure 9: Planetary Resources deep space exploration mission



Source: https://pri-wpengine.netdna-ssl.com/wp-content/uploads/2017/08/PR_P34Infographic_v7-WEB.jpeg

Even for trace materials such as gold and platinum, the cost associated with asteroid mining is unlikely in the foreseeable future to be a viable commercial alternative to earth-extraction/recycling. Rather, the main economic opportunities are projected to be in the extraction and utilisation of resources from asteroids for use in space to avoid the high costs of transporting these materials (such as water) into space. It is noted that there is currently significant legal ambiguity concerning the rights of nations and commercial entities to mine asteroids.

Rio Tinto autonomous mining

Rio Tinto's 'Mine of the Future' project commenced in 2008 with key automation elements being:

- AutoHaul autonomous freight train system – first successful run in July 2018 with three locomotives carrying 28,000 tonnes of iron ore over 280 km from mining operations in Tom Price to the port at Cape Lambert. By October 2018, there was an average of 34 autonomous trains running per day.
- Autonomous Haulage System (AHS) outfitted on fleet of haul trucks at Rio's Pilbara operations. AHS allows trucks to be operated by a supervisory system and central controller rather than a driver. It uses pre-defined GPS courses to automatically navigate haul roads and intersections and the system knows the actual locations, speeds and direction of all vehicles at all times. Rio is the world's largest owner and operator of AHS trucks, with 80 currently in operation at the Pilbara sites, increasing to more than 140 by the end of 2019.
- Autonomous Drilling System (ADS) to drill production blast holes. This capability was first demonstrated in 2008 and within a decade the 11 ADS-enabled drills had drilled more than 5,000 kms. The ADS enables an operator using a single console at a location remote from the machinery to operate multiple drill rigs.

Autonomous operations are remotely monitored at Rio Tinto's Perth Operations Centre more than 1500 km away. This is a state-of-art facility that enables all of Rio's mines, ports and rail systems to be operated from a single location.

Rio Tinto's autonomous haulage vehicles

Source: http://www.riotinto.com/media/media-releases-237_23802.aspx

References:

Rio Tinto, 'Mine of the Future', updated, viewed 7 January 2019, https://www.riotinto.com/australia/pilbara/mine-of-the-future-9603.aspx.

Rio Tinto, 'Rio Tinto to expand autonomous fleet as part of $5 billion productivity drive', 18 December 2017, viewed 7 January 2019, http://www.riotinto.com/media/media-releases-237_23802.aspx.

Ewen Hosie, Australian Mining, 'Rio Tinto finalises Pilbara autonomous train deployment', 7 January 2019, viewed 7 January 2019, https://www.australianmining.com.au/news/rio-tinto-finalises-pilbara-autonomous-train-deployment/.

Appendix 1: SME Interviews

Title/Name	Position
Mr Travis Bessell	National Security and ISR Division, DST
Dr Ray Oermann	National Security and ISR Division, DST
Dr Gerald Bolding	Cyber and Electronic Warfare Division, DST
Mr Matthew McKinna	Weapons and Combat Systems Division, DST
Dr David Lingard	National Security and ISR Division, DST
Dr Alex Grant	CEO and co-founder, Myriota
Dr Andrew Barton	CTO, Fleet Space Technologies
Mr Brett Biddington	Principle, Biddington Research
Mr Adam Gilmour	CEO and founder, Gilmour Space Technologies
Professor Craig Smith	CEO, EOS Space Systems
Professor Phil Bland	Professor of Planetary Science, School of Earth and Planetary Sciences, Curtin University
Professor Russell Boyce	Chair for Space Engineering at UNSW Canberra

Title/Name	Position
Professor Andrew Dempster	Director of the Australian Centre for Space Engineering Research, UNSW
Dr Francis Bennet	Assistant Professor at ANU College of Science, ANU
Dr Sarah Pearce	Deputy Director of CSIRO Astronomy and Space Science, CSIRO
Wing Commander Tracy Douglas	Strategic Policy Division, Department of Defence
Group Captain Darren May	Information Warfare Division, Department of Defence
Wing Commander Duncan Blake	Military Strategic Commitments Division, Department of Defence
Wing Commander Richard Harrison	Force Integration Division, Department of Defence

Notes

Notes

Australian Government

Department of Defence

Science and Technology

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