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Summary of Propulsion Technologies: Enabling Sovereign Responsive Access to Space for the Australian Defence Force

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ABSTRACT

Satellite communication, navigation, surveillance and meteorology services are key enablers for the ADF's battlefield awareness and air and missile defence. As the counter-space capabilities of potential adversaries continue to develop, reliance on high-value satellites becomes increasingly risky. Rocket manufacturers and launch service providers are anticipated to offer access to space at a reduced cost and infrastructure footprint compared to traditional methods. The diversity of applicable propulsion technologies has resulted in a range of technology options available to meet a responsive space access capability. This document provides a summary of the current state of the art of major propulsion technologies relevant to Defence responsive access to space, as well as recommendations as to how and where Australia and Defence may best invest to capitalise on advanced technologies to realise sovereign launch capability.

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Executive Summary

Australia, like many modern nations, relies heavily on space-based technologies and its reliance will only continue to increase. Many aspects of everyday life is underpinned by orbiting satellites providing on-demand communication, location services and data exchange with millions of other people around the world. The Australian Defence Force (ADF) uses space-based services for satellite communications, positioning, navigation and timing (PNT), intelligence, surveillance, and meteorology. These services are crucial enablers for battle management systems and air and missile defences. As potential adversaries' counter-space capabilities continue to develop, reliance on high-value satellites for battle space awareness and defence becomes increasingly risky.

There is, however, potential for large augmentation in space based capability, enhanced sovereignty, and much greater resilience to potential failures or adversary counter-space actions. One avenue for such improvement is the development of a sovereign launch capability that could provide rapid re-establishment of crucial ADF and national satellite infrastructure.

Rocket systems and launch service providers are able to, thanks to many advances in technology, offer access to space at a greatly reduced cost and infrastructure footprint. In addition, recent advancements in the capabilities of micro and nano-satellites, small satellite constellations and additive manufacturing present a unique opportunity for Australian industry and Defence to establish an Australian responsive space access capability. This report provides an overview of emerging propulsion technologies and assess the benefits and applicability for responsive space access from an Australian economic and Defence perspective.

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Glossary

ADF	Australian Defence Force
AL	Aluminium
AP	Ammonium perchlorate
ARC	Additive Rocket Corporation
ATBT	Advanced Tactical Booster Technology
BoM	Bureau of Meteorology
BeiDou	China's GPS equivalent
BMS	Battle management systems
CASG	Capability and Sustainment Group
CDSCC	Canberra Deep Space Communication Complex
CT	Computed tomography
DIH	Defence Innovation Hub
DMTC	Defence Materials Technology Centre
DST Group	Defence Science and Technology Group
ELA	Equatorial Launch Australia
ESA	European Space Agency
GLONASS	Russian GPS equivalent
GNSS	European Union GPS equivalent
GPS	Global positioning system
GTO	Geostationary transfer orbit
HTPB	Hydroxyl-terminated polybutadiene
HTPE	Hydroxyl-terminated polyether
IoT	Internet of things
ITAR	International Traffic of Arms Regulations
ISR	Intelligence, surveillance and reconnaissance
ISS	International Space Station
JAXA	Japanese Space Agency
LEO	Low earth orbit
LOX	Liquid oxidiser
Met	Meteorology
MOU	Memorandum of understanding
NASA	National Aeronautics and Space Administration
NGTF	Next Generation Technology Fund
PBAN	Polybutadiene acrylonitrile
PNT	Positioning, navigation and timing
PPS	Precise positioning system
RAM	Resonant acoustic mixing
RDE	Rotating detonation engine
SABRE	Synergetic Air Breathing Rocket Engine
SATCOM	Satellite communications

SMILE	Small European Rocket Launcher for Europe
SRI	Strategic Research Investment
SRM	Solid rocket motor
SSTO	Single stage to orbit
SSO	Sun-synchronous orbit
TRL	Technology readiness level
UHF	Ultra-high frequency
UK	United Kingdom
ULA	United Launch Alliance
UNSW	University of New South Wales
US	United States
USD	United States dollars
WGS	Wideband Global SATCOM

1. Introduction

Australia, like many modern nations, relies heavily on space-based technologies and this reliance will only continue to increase. Many aspects of everyday life are underpinned by orbiting satellites. In the Australian context examples include [1]:

- Communication, especially in remote areas of Australia, where satellites remain an important form of communication
- Location based services, such as global positioning systems (GPS) that is now heavily integrated into smartphones
- Air traffic control
- Data streaming for services such as the National Broadband Network and Foxtel
- Satellite based weather prediction and real-time sharing of meteorological events
- Defence based satellites for communication, positioning, navigation and timing (PNT), surveillance systems, reconnaissance and intelligence gathering
- Australia's scientific community providing monitoring information on many dynamic environments

The rapid emergence of new space access technologies, together with the significant opportunities and strategic risks associated with space systems confers a high priority for Defence research. The Australian Defence Force (ADF) has historically relied on United States (US) launch providers to establish satellites and enable capabilities such as communication, PNT and surveillance. Without the support of US launch providers, the ADF would have diminished modern warfighting capabilities and be unable to access systems such as integrated battlespaces and air-and-missile defences.

The development of an Australian launch capability offers potential for large improvements in space based capability, enhanced sovereignty and much greater resilience by providing rapid re-establishment of crucial ADF and national satellite infrastructure. An Australian designed and launched responsive space access capability is a distinct possibility now in the modern 'NewSpace' era. NewSpace is characterised by a globally emerging private space industry [2] where, unlike traditional rocket and launch services (e.g. United Launch Alliance [ULA] and the National Aeronautics and Space Administration [NASA]), NewSpace focusses on reduced costs and timelines, smaller infrastructure footprint and mobile launch. Some NewSpace companies developing launch services include Vector, Firefly, Gilmour and Rocket Lab [3, 4, 5, 6]. Coupled with the rapid advancements in the capabilities of micro and nano-satellites [7], small satellite constellations and additive manufacturing, it is evident that the monetary investment required for Australian industry and Defence to capitalise on the NewSpace market and achieve a responsive space capability is at an all-time low.

The growth of the space industry has been noteworthy with commercial space having an average compound rate of 13.7% over the last 20 years [8]. In 2015 the global economy for space activities was 323 billion US dollars (USD) [8]. Australia spends 3.1 billion USD on space related services each year with over 11 500 people employed within the industry [8]. This accounts to a 0.8% share of the global space economy [1]. With the establishment of Australia's Space Agency in Adelaide [69] and world-class industrial and academic capabilities in materials science through organisations (such as the Defence Materials Technology Centre (DMTC) [9]), space observation and communication (such as the Canberra Deep Space Communication Complex (CDSCC) [10]) and propulsion technologies (such as those developed through the Defence Science and Technology's (DST) Advanced Tactical Booster Technologies (ATBT) program [11]), Australia is well positioned to grow its share of the global space economy. An Australian designed, manufactured and launched responsive space capability could be the 'lightning rod' to catalyse the rapid expansion of the Australian space industry.

1.1. Definition of 'Responsive Space'

Australia has typically relied on full scale launch vehicles to place large satellites for communication and other space-based requirements into orbit. These launch vehicles have long lead-times for launch, often requiring well over 12 month timeframes, are incredibly heavy due to the large satellite payloads, and are often prohibitively expensive. Whilst the NewSpace era has established a host of launch providers such as SpaceX, Blue Origin and Arianespace who have improved launch time, reduced vehicle weight and overall cost, these are still considered as standard space access due to the still lengthy timelines and large payload masses.

'Responsive space access' is defined by using smaller, more agile technologies to provide micro and nano-satellites (Table 1) to a precise orbit in a time constrained environment at an affordable price. Mobile launch facilities offer highly tailorable orbits allowing, for example, the ADF to provide a communication and surveillance capability in a region of interest ahead of an operation. Australia is well positioned through its extensive government, academia and industry capabilities to provide a responsive access to space capability.

Table 1 - Satellite Definition [7]

Standard and Large Satellites	> 1000 kg
Mini Satellites	< 1000 kg
Micro Satellites	< 100 kg
Nano Satellites	< 10 kg
Pico Satellites	< 1 kg

'Reactive space' access is a rapid response to an event or counter-space activities where the ADF needs time-critical replacement of communications or intelligence, surveillance and reconnaissance (ISR) capabilities. Due to the reactive nature, the payload capability is reduced when compared against that of responsive space access. The differences between standard, responsive and reactive space access are defined below (Table 2).

Table 2 - Space Access Definitions

Launch Doctrine	**Standard**	**Responsive**	**Reactive**
Timeframe	12+ months	< 12 months	24-96 hours
Orbit	All available orbits	Limited selection due to launcher capability	Mainly restricted to LEO
Payload max mass	> 1000 kg	10 to 1000 kg	< 100 kg
Defence Mission Examples	Persistent communications, ISR/geo-stationary payloads	Establishment of communication networks in regions of interest. Redundancy/upgrade of existing network.	Time-critical replacement of battlefield comms/ISR (potentially temporary)
Commercial Mission Examples	Large geo-stationary communications satellite (i.e. IntelSat), lunar transit, etc	Dedicated launch of small-sat constellation;	Weather and Communication satellites for critical applications (transportation and logistics)

1.2. Types of Satellite Orbits

Satellite orbits are highly varied and greatly depend on the satellite capabilities and intended usage. While many satellite orbits exist, the majority of operational satellites fit into one of of the following main satellite orbits [70]:

- Low Earth Orbit (LEO) - 150 km to 1000 km. Typically used for applications which require higher resolution such as imaging or sensing. Satellites in LEO orbit the Earth approximately every 90 minutes.
- Medium Earth Orbit (MEO) - 1000 km to 36 000 km. Satellites in MEO are typically used for communication and GPS services.
- Geostationary Orbit (GEO) - 36 000 km. GEO satellites remain stationary above a fixed position. Satellites in GEO can be used for communication and GPS services.
- High Earth Orbit - Above GEO, 36 000 to 200 000 km+. High Earth Orbit satellites can be used for wide Earth or deep space observation.
- Polar Orbits - Typical altitude ranges 200 km to 2000 km. Polar orbits pass over the Earth's north and south polar regions several times a day. Polar orbits are ideal for satellites which are used for reconnaissance and wide Earth observation.
- Sun Synchronous Orbits (SSO) - Typical altitude ranges 600 km to 800 km. SSO orbits are similar to Polar orbits where the satellite travels over a region of the Earth's surface at the same local solar time. SSOs are ideal for weather observation, reconnaissance and solar activity monitoring.

2. Space Access Landscape

Space-based commercial applications within Australia have typically relied on standard launch doctrine. While in many cases this was by choice due to the size of the payload, in other cases it is simply due to the low maturation of responsive space access technologies. Mini and micro satellites have previously been launched in clusters with fixed orbits. Commercial space applications will continue to rely predominantly on standard launch doctrine; however with the emergence of responsive and reactive space access many new commercial space-based applications are appearing.

2.1. Commercial Space Applications

Communication retailer Optus operates satellites for enhanced communication within Australia [13]. Optus has commissioned 10 satellites in 30 years and have 5 currently operable that are delivering data and communication services to the Australasian region [13]. In 2003, Optus and the ADF collaborated on Optus C1 as a hybrid commercial and military communications satellite. In most cases, Optus has contracted the launch of their communication satellites to the European Space Agency (ESA) on board the Ariane 5 heavy lift launch vehicle [14].

The Bureau of Meteorology (BoM) has access to Japanese, American, Chinese and European meteorological satellites through the global exchange of meteorological data [15]. In particular, the Japanese Himawari-8 satellite provides a significant portion of the meteorological information to the BOM [15]. This information is accessed via several high-bandwidth satellite data reception sites around Australia and surrounding regions where it is processed and distributed to locations around Australia and worldwide partners, including those in the Defence domain [15].

Australia has relied on international launch providers for large, high capacity satellites and ride-share opportunities for smaller CubeSats; however an Australian responsive space access capability provides unique opportunities for both commercial and Defence applications. Companies such as Australian Fleet Space [12] are building a network of thousands of nanosatellites to provide a global service for the Internet of things (IoT). This network of nanosatellites provides connectivity to cheap, low-power micro sensors and devices that can be deployed in a wide range of areas including animal tracking for conservation and livestock agriculture, global logistics, crop monitoring and soil health to improve farming, oceanic and metrological monitoring, and many other applications [12]. This application is an excellent example of where an Australian responsive space capability would meet a commercial need; as it currently stands Fleet Space must look to international and offshore services to launch their constellation of small satellites.

2.2. Launch Providers and Space Access Capability

Several commercial launch providers are contributing heavily towards the expanding NewSpace market. SpaceX was founded in 2002 and has since become the only private company to delivered cargo to the International Space Station (ISS) and return a spacecraft from LEO [16]. SpaceX's main launch vehicle is the two stage throttleable Falcon 9 liquid fuelled rocket standing 70 m tall with a diameter of 3.7 m, weighing 550 000 kg. The Falcon 9 can deliver 22 800 kg to LEO and 8300 kg to geostationary transfer orbit (GTO) (Figure 1). The Falcon 9 provides significant cost reductions by recovering the first-stage booster. The nine first-stage Merlin engines can be shut-down and restarted during the flight and can throttle during key stages of launch and recovery. Similar to SpaceX, Blue Origin are pursuing reusability with their New Glenn two and three-stage engines standing 86 and 99 m tall respectively [17]. The two-stage New Glenn vehicle is predicted to deliver 13 000 kg of payload to GTO or 45 000 kg to LEO (Figure 1). While both companies have revolutionised space access and kicked off the NewSpace era, neither capability can be characterised as responsive space access.

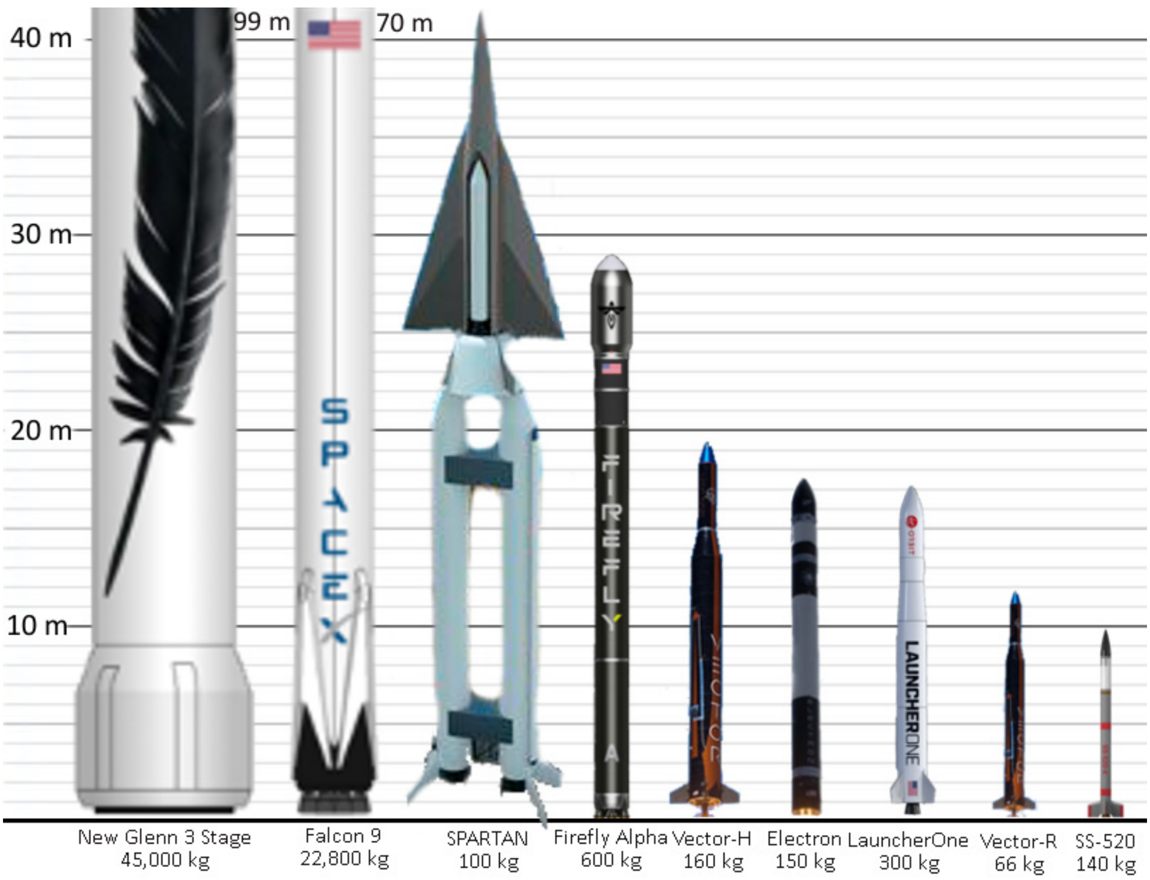

Figure 1 - Comparison of Launch Vehicles Payload Capacity to LEO

Virgin Orbit, a US based company, is developing a space transportation system to deliver small satellites to orbit using their LauncherOne platform, a two-stage liquid-propellant based propulsion system [18]. Virgin Orbit is using a Boeing 747-400 aircraft to air-launch the LauncherOne. The system has a predicted payload capacity of 500 kg to a 230 km LEO and 300 kg to a 500 km SSO (Figure 1). By air-launching, Virgin Orbit can ensure they are truly responsive, launching independently of weather and offering a tailored orbital insertion [18].

RocketLab, a New Zealand/US venture launching off the coast of New Zealand, has developed the Electron series of launch vehicles [6]. RocketLab's Electron vehicles are capable of placing a 150 kg payload in a 500 km SSO (Figure 1). Electron stands 17 m tall with a diameter of 1.2 m and weighs 12 550 kg [19]. Electron has a liquid-propellant propulsion system with carbon composite fairings and additively manufactured engine components to significantly reduce weight and cost of manufacture. The engine can be printed in 24 hours, greatly improving manufacturing time over traditional methods.

Vector Space Systems is a US based launch and microsatellite provider [3]. They have developed two launch vehicles, both liquid-propellant propulsion systems, with carbon fibre fuselages and a mobile launch capability. The Vector-R (Rapid) is a two-stage engine with a predicted payload capacity of 66 kg to LEO or Polar orbit, standing 13 m tall with a diameter of 1.2 m. The Vector-H (Heavy) is also two-stage with a payload capacity of 160 kg to LEO or Polar orbit, standing 18.3 m tall with the same diameter (Figure 1) [3]. Another micro-satellite responsive space access launch provider is the US-based Firefly Aerospace [4]. Their launch vehicle, Firefly Alpha, is capable of delivering 1000 kg to a 200 km LEO or 600 kg to a 500 km SSO. Firefly Alpha is a two-stage liquid-propellant propulsion system standing 29 m tall with a diameter of 2 m (Figure 1). The Firefly utilises carbon fibre components for the airframe and a liner-less cryogenic propellant tank [4]. The combination of small launch vehicles, mobile launch facilities and micro and nano-satellite payloads are well suited to provide a responsive space access capability.

Within Australia, Gilmour Space Technologies is developing a sovereign capability to reach sub-orbital or orbital space using their Ariel and Eris launch vehicles [5]. These vehicles use a hybrid propulsion system consisting of an additively manufactured fuel and liquid oxidiser to provide deeply throttlable thrust profiles for enhanced efficiency compared with liquid propellant propulsion systems. The Ariel vehicle has a predicted payload carrying capacity of 130 kg to 150 km while the Eris vehicle can carry 380 kg to a 350 km LEO (Figure 1) [5]. By utilising additively manufactured fuel, the cost and time of manufacture are both greatly reduced. Black Sky Aerospace is developing a sub-orbital and orbital launch capability in Queensland, Australia [73]. Black Sky Aerospace conducted Australia's first commercial launch of a 5 m long, 80 kg sub-orbital solid propellant rocket motor to an altitude of 20 000 ft [74]. They have a range of sounding rockets, with a proposed altitude up to 300 km in multi-stage configuration. Their proposed orbital services are designed to carry small satellites in a responsive space access capacity to LEO or SSO in 3 or 4 stage solid propellant configurations [73].

Recently, a number of Australian companies have been established with the objective to provide a launching platform for micro and nano-satellites in Australia. Equatorial Launch Australia (ELA) is seeking to provide a commercial spaceport in the Northern Territory [20]. ELA received approval from the Traditional Land Owners and the Northern Land Council to establish the site in 2017. Southern Launch, through negotiations with Australian State, Federal and local land owners, have selected Whalers Bay off the southern coast of Australia to establish a launch facility and provide micro and nano-satellites to a polar earth orbit [21]. Another Australian start-up, Space Ops, has conceptualised the Rocky 1 Launch vehicle to provide access for 10 kg payloads up to 600 km LEO [22]. The Rocky 1 vehicle is stated as a "two-stage liquid-propellant launch vehicle with the capability to return both stages to landing sites within 48 hours for refurbishment".

It is not only commercial launch providers who are making great strides in enabling responsive space access. The Japanese Space Agency (JAXA) developed the SS-520, a three-stage solid propellant 'nano-launcher' which delivered a 3 kg nanosatellite to orbit on 3 February 2018 [23]. The SS-520 is miniscule in size compared to other systems that are currently available, standing just 9.5 m tall with a diameter of 0.5 m and weighing 2600 kg (Figure 1) [23].

In Australian academia, the University of Queensland's Centre for Hypersonics is assessing other options besides traditional liquid and solid systems for responsive space access [24]. Their theoretical system aims to reduce the cost of launch through the development of a reusable space launch platform, SPARTAN. The first stage of the SPARTAN concept is a reusable solid-propellant rocket motor. The second stage is a recoverable, high speed, air-breathing scramjet that propels the SPARTAN to speeds of Mach 10, before the third stage solid-propellant rocket motor containing the payload is launched [25]. The combination of the first and second stage reusability allows for 95% of the system to be reusable. The SPARTAN concept is stated to deliver a 100 kg payload into a 557 km SSO with a take-off weight of 25 700 kg based on preliminary studies (Figure 1) [25].

The current focus of commercial launch providers is to enable access to space in an affordable and timely manner. Many new technologies, manufacturing methods and computational improvements are facilitating a reduction in cost and manufacturing time. Some of the current enabling technologies for responsive and affordable space access include advanced propulsion technologies utilising energy-dense fuels, lightweight and high-strength composite materials, additive manufacturing, mission and system optimisations and recovery of high value components.

3. Australian Defence Space Requirements

The ADF has an ever-increasing reliance on space for communication systems, navigation, intelligence gathering, surveillance, integrated battle management and early warning systems [26].

3.1. Threat Scenario

In the paper 'ADF Space Operations Self-Reliance: An Alternative Universe and the Primacy of Vision', LTCOL Rowlands theorises about the integrated, networked, satellite-reliant ADF in the year 2022 [27]. In the scenario, the ADF has engaged in a joint operation in hostile territory. The ADF has dispatched numerous battle groups in the sea, air and land domains. Each system is networked and digitised via a central battle management system (BMS), providing commanders with communications, PNT, imagery and surveillance.

The operation is proceeding well until all communication and BMSs are lost. A raid of anti-satellite missiles has struck the satellites that were providing commanders with real-time information on the battle space. With the BMS down, the networked air defence systems are operating at reduced capacity, providing the enemy with a window of opportunity to strike high-value assets in the battle group. The ADF has been blinded by an attack that occurred hundreds of kilometres overhead.

LTCOL Rowlands also suggests an alternative future, where a joint space project was established five years earlier deploying hundreds of micro and nano satellites in orbit [27]. In this scenario, the large bandwidth satellites are again struck with anti-satellite missiles, but the previously deployed micro and nano satellites are now present to operate in unison and provide a rapid redundancy and restore several critical information streams to the ADF. The commanders also alert the space agency headquarters in Australia where, within hours, replacement satellites have been launched into a LEO, re-establishing the lost capability and once again providing real-time information to the ADF.

3.2. ADF Space Requirements

The ADF's needs are currently serviced by a range of satellites, launched by foreign partners. Typically, this role has been provided by a small number of large, expensive satellites with high-bandwidth capacities. The ADF's warfighting capabilities are heavily dependent on four space based services [28]:

- Satellite communications (SATCOM)
- PNT
- ISR
- Meteorology (Met)

The ADF utilises the US Wideband Global Satcom (WGS) military satellite network for the bulk of its SATCOM requirements [29]. The ADF funded the WGS-6 satellite that was launched in 2013 and, under the Memorandum-of-Understanding (MOU) with the US, grants Australia access to the previous five WGS satellites [30]. The ADF also utilises the Optus C1 satellite mentioned previously for ultra-high frequency (UHF) communication and data transfer. The *Defence White Paper 2016* announced satellite based communications upgrades including ground-station segments and mobile and deployable land terminals [31].

The ADF makes extensive use of PNT services for accurate and timely control and placement of long range firepower including guided weapons as well as navigation of high value assets in the air, sea and land domains [28]. Australia uses the US NAVSTAR GPS satellites that function for both civilian and military use [32]. GPS services are also provided by Russia (GLONASS), the European Union (GNSS) and China (BeiDou) but are not utilised within the ADF [33]. For military use, the Precise Positioning System (PPS) requires an encrypted key to access precise PNT services. Recently, a joint venture between the University of New South Wales (UNSW Kensington) and DST Group injected GPS technology developed by the university into the Spacecraft for High Accuracy Radar Calibration (SHARC) cube satellite mission. The SHARC CubeSat, launched on Wednesday 19 April 2017, collected detailed positional measurements from space and helped ground based radar networks improve tracking by conducting a series of coordinated fly-bys of military radar stations [34].

The ADF utilise space-based ISR services for imagery, missile threat warnings, BMS, signals and electronic intelligence that, when combined, creates enhanced situational awareness [28]. The *Defence White Paper 2016* announced a $500 million investment to improve Australia's space based ISR capability [31] through: direct and rapid access to partner and commercial space-based capabilities; and enhanced image processing and analysis.

Authors of Australian space reports [1, 8, 26] have made a strong case for the need to develop sovereign capabilities that reduce our reliance on international relationships and puts the focus of the ADF back on self-reliance in the space domain. In doing so, the commercial space sector benefits from enhanced reliance on Australian industry and academia and follows the path that is being set by large commercial space companies such as SpaceX where private industry is driving NewSpace development.

4. Enabling Technologies for Response Space Access

To provide an enhanced capability for affordable, responsive and highly tailorable space access within Australia, many innovative technologies from across government, academia and industry will need to be drawn upon. Recently, the number of launch providers has drastically increased, each offering a new technology or methodology to provide one or more benefits: increased payload mass to orbit, decreased costs, reduced manufacturing time and reduced time to launch. The technologies to enable these advances include:

- Advanced propulsion technologies
- Material science developments
- Improved fuels
- Additive manufacturing
- Mission and system optimisations
- Recovery of high value components

Within Australia, significant research and development efforts are being led by organisations such as DST in areas that are directly relevant to responsive space access. For example, DST's ATBT program [11] was conducted in collaboration with Australian and international industry and developed significant knowledge and expertise in all aspects of solid propellant rocket motor development and utilisation.

4.1. Advanced Propulsion Technologies

The term 'propulsion system' covers many different types of propulsion technologies that can be utilised for responsive space access. New propulsion systems incorporating modern technologies, manufacturing methods and design optimisations have progressed rapidly in recent years, innovating on decades of tried-and-true rocket science. It is therefore critical that any dialogue around Australia's future in a space industry has at its disposal an impartial source of expert information and advice to provide a context for technology options in the NewSpace era. This document exists as one such reference; authored by engineers from DST's Missile and Space Propulsion Group [35]. The following sections provide an overview of modern rocket propulsion concepts relevant to responsive space access, as well as information on their relative strengths, weaknesses and areas of ongoing research.

4.1.1. Solid Propellant Propulsion Systems

Solid propellant rocket motors (SRMs) have long been favoured by the military for their high energy density, long term storability and comparative lack of complexity compared with liquid-based propulsion systems. SRMs are typically used as boosters in space access applications which operate in parallel with the liquid fuel main engine as employed on the NASA space shuttle program. Some vehicles, such as the Japanese SS-520 [23], use a multi-stage SRM for LEO.

Some of the benefits of SRMs include:

- Long storage duration due to chemical stability of the solid propellant
- The lack of on-site fuelling required and the ease of launching without extensive support infrastructure facilitates rapid shelf-to-launch time, thus enabling truly responsive and reactive space access
- Simplified design and manufacture owing to the ease of ignition and operation of SRMs greatly reduces development duration and cost
- High density impulse makes SRM an excellent choice for volume constrained applications

However, for space access, SRMs have traditionally displayed many disadvantages:

- Lack of thrust control (throttling) impacts precision orbit insertion
- Inability to shutoff/restart (without significant engineering) negatively affects safety
- Specific impulse of SRMs is low compared to some other rocket technologies such as liquids so more propellant mass is required to generate the same thrust as a liquid system (Table 3) [36]

Table 3 - Specific Impulse, Density and Density Impulse of Propulsion Types

	Specific Impulse (s)	**Density (g/cm^3)**	**Density Impulse (kg.s/L)**
Solid Rocket Motor	260 - 270	1.85 (HTPB/AP/AL)	481
Liquid Rocket Motor	450 (LOX/H_2) 300 (LOX/RP1)	0.32 (LOX/H_2) 1.03 (LOX/RP1)	146 (LOX/H_2) 310 (LOX/RP1)
Hybrid Rocket Motor	250 - 280	0.93 (HTPB) 0.85 (Parrafin Wax)	254 (HTPB) 238 (Parrafin Wax)

Once solid propellant rocket motors are cast they are live energetics and transport and handling of very large motors presents a significant safety challenge [37]. Recent developments may stand to reduce some of these concerns such as non-destructive health monitoring techniques [37].

4.1.1.1. Solid Propellants

DST has a long history in solid propellant development, perhaps most famously having developed, tested and fielded the SRM in the Nulka decoy [35]. Historically SRMs have been double-base propellants consisting of nitro-glycerine and nitrocellulose, however most modern high performance propellants utilise an oxidiser and metallised fuel bound in a polyurethane-based binder, so-called composite propellants [36].

Oft-used ingredients employed in composite propellants include hydroxyl-terminated polybutadiene (HTPB), hydroxyl-terminated polyether (HTPE) or polybutadiene acrylonitrile (PBAN) as the pre-polymer into which both fuel (e.g. aluminium [Al]) and oxidiser (e.g. ammonium perchlorate [AP]) are mixed. This mixing process is labour intensive, highly sensitive to process control variables [38] and conducted remotely on grounds of safety. Ingredient preparation often necessitates significant on-site equipment to change particle sizes or facilitate quality control procedures, all of which need to be suitably rated for the storage, processors and characterisation of energetic materials. Once the propellant is mixed it is then cast directly into the motor case, which is cured for an extended period (often up to a week) at elevated temperature. Alternatively the propellant can be cast into a 'beaker', cured and then loaded into the rocket motor case (cartridge loaded). Once completed, the rocket motor is ready for final assembly.

The level of infrastructure investment, in-depth expert knowledge and safety requirements surrounding solid propellant is one of the dominating factors that has limited the commercial use of SRMs to those with an already established capability. To circumvent these challenges much of the technological advancement in recent years has focussed on how to improve the safety and reduce the footprint required for manufacture of SRMs.

DST continues to have an active research and development program in high performance SRM propellants [39]. Typically a solid propellant is cast into a rocket motor case and the internal profile is made using extractable mandrels or by post-machining the cured propellant which presents safety challenges. Through the additive manufacturing of energetic material, complex designs can be printed in a timely manner; however there are drawbacks such as reduced energy density and increased cost versus established propellant manufacturing methods. DST is collaborating with industry partners, academia and international defence organisations on the development of advanced additive manufacturing technologies for energetic materials [40, 41, 42].

To greatly reduce the manufacturing time and equipment required, new processing techniques such as resonant acoustic mixing (RAM) can be employed [41]. DST currently has active collaborations with domestic and international industry (e.g. the original equipment manufacturer, Resodyn [71]) and international defence partners. Not only does RAM reduce mixing time from hours to minutes, it enables the inclusion of greater quantities of novel materials such as nano energetics and fuels (improved specific impulse) in solid propellants through low frequency, high intensity acoustic energy to promote rapid mixing without blades or impellers [41]. A contactless mixing process promotes enhanced safety and also allows the in-situ mixing of the propellant in the form of the end-application in question (mass permitting).

DST is collaborating with industry and international defence partners on computed tomography (CT) scanning to provide a robust means of assessing the mechanical integrity and suitability for service of energetic materials and informing transportation and storage safety concerns [43]. This method stands to provide a high resolution, readily manipulated 3D image to assess cracks, de-bonds and voids in SRMs in real-time, alleviating a primary concern for using SRMs for space access.

4.1.1.2. SRM Technology Summary

The domain of solid rockets has and will continue to be primarily for military applications. However, with the concept of responsive and reactive space access becoming a looming requirement, many of the disadvantages of SRMs are being addressed through modern technology, or are less relevant due to a changing doctrine.

Coupled with large strides in SRM surveillance and storage techniques, SRMs are ideal for reactive space access applications with their ability to be manufactured and stored, and ready for use at a moment's notice with no fuelling infrastructure required. The advent of highly capable micro and nano-satellites has led to a need for smaller and cheaper rocket launchers where the mechanical simplicity and mass production quality of SRMs lends them particularly well to this application for vastly reduced cost of launcher infrastructure as demonstrated by the Japanese SS-520 [23].

RAM manufacturing techniques are simplifying propellant manufacture, enabling the incorporation of higher percentages of solids for performance enhancement and significantly increasing the efficiency of the manufacturing process. Additive manufacturing stands to enable the manufacture of complex propellant geometry designs that allows for very precise motor thrust termination (for orbit control) and performance enhancements through realisation of grain designs which aren't practical with current manufacturing techniques.

It should also be noted that SRM manufacturing capability, unlike the commercially-centred liquid or hybrid propulsion, has a potential market in both defence and civilian/commercial space access. Investment in a sovereign solid rocket capability for responsive space access could also afford a diversification of supply of locally designed, tailored and/or manufactured weapon concepts for the ADF.

4.1.2. Liquid Rocket Propulsion Systems

Liquid propulsion systems are more frequently associated with space access and the technology is most prevalent in current commercial applications. Liquid propulsion systems use liquidised fuel and oxidiser that are mixed and ignited to produce combustion. Liquid systems typically have better performance (Isp) over their solid propellant counterparts [36] and have the ability to throttle and restart, however this comes at the cost of greatly increased complexity. The mechanism for controlling the flow (pressure fed and turbo-pump fed), mixing (bi-axial jet injection and coaxial swirl) and combustion in liquid systems is intricate, so designs contain thousands of parts and development and manufacture is time consuming and expensive [44]. The key features of a liquid system are:

- The ability to throttle and control thrust - allowing for shutoff for either precise orbit insertion or safety in the event of an anomaly
- Long burn duration - burn times for a liquid rocket system are largely decoupled from the physical geometry of the motor, unlike a solid system
- High performance - high Isp enabling very large payload masses. Liquid rockets feature in almost all heavy lift systems to LEO, GEO and beyond.

The drawbacks of liquid propulsion systems include:

- Complex, time-consuming and expensive design and manufacture often requiring tens or hundreds of thousands of parts
- Liquid fuel and oxidiser requires cryogenic cooling, necessitating thick-walled tanks and fuelling of the rocket within hours before launch
- Some fuels such as hypergolics are heavily corrosive, highly toxic, or both and present safety concerns when handling and storing
- Intricacies of handling and storing of propellant constituents restricts launch locations to well established facilities, thus reducing the utility for responsive and reactive space access

The list of propellants available for use in a liquid system is wide and varied, and all contain advantages and disadvantages, such as cryogenic, highly toxic or reduced performance. Because of the complexity of a liquid engine, the selection of propellant is highly integrated to the type of engine design, called a cycle, which is to be used. Options range from staged combustion cycles (like the Space Shuttle) that offer the best performance, but are the most complex, necessitating separate fuel and oxidiser turbo-pumps as well as a pre-combustor (often two) [44], to the simplistic pressure fed cycle where an inert gas is used to displace propellants into the combustion chamber.

Coupled with the cycle selection, materials' compatibility and operating conditions must be considered for their performance impacts. For pressure-fed liquid rocket engines, higher chamber pressures (analogous to thrust and efficiency) result in higher pressure propellant tanks, directly impacting tank thickness and the inert (dead) mass fraction of the whole rocket. This is similarly true for pump-fed liquid rocket engines, where higher chamber pressures results in heavier turbomachinery required.

In addition, due to the combustion temperatures of several propellant combinations many structural materials would not survive operation at the optimal Isp mixture ratio. As such, rocket system designs must utilise regenerative cooling to enable efficient combustion performance. Regenerative cooling uses the fuel as a coolant by pumping it through small chambers around the combustion chamber. This process transfers heat away from the high-temperature structure to the fuel increasing the internal energy of the fuel resulting in enhanced combustion performance. Regenerative cooling has many drawbacks from added pumps and cycles resulting in additional complexity, weight and potential for mechanical failures [36].

In spite of the cost and complexity of liquid rocket systems, they continue to be a focus for development of responsive space applications [3, 4, 5]. To overcome the complexity, start-ups such as RocketLab [6] and Relativity Space [45] are employing additive manufacturing to reduce the number of parts in their engine design, reducing complexity, time and cost of manufacture. In the case of Relativity Space, additive manufacturing has reduced the number of parts in their liquid fuel engine from over 100 000 to fewer than 1000 [45]. SpaceX has utilised the flexibility of liquid propellant propulsion systems to great effect by using throttleable engines to reduce drag on the vehicle as it climbs through maximum dynamic pressure and the restart ability by restarting the engines to recover the 1st stage on a landing pad [16].

4.1.2.1. Liquid Rocket Propellants

Launch vehicle liquid propulsion systems typically use one of two categories of propellants: cryogenic liquids such as hydrogen and oxygen that require storage at low temperatures to maintain their liquid state, or hypergolic fuels such as hydrazine and various oxidisers that spontaneously ignite when their constituents meet. A 3rd type also exists; monopropellant systems that use a catalyst bed and a single fuel. The fuel is decomposed by exposure to the catalyst bed that produces an expansion of gases through the nozzle which results in thrust. However such designs are almost exclusively used as 3rd stage propulsion or in-space propulsion due to their relatively low performance (and simplicity). All have inherent advantages and disadvantages.

Cryogenic propellants have the highest rocket propellant performance (Isp), are readily available, are easily throttled and can be operated at high mass flow rates resulting in higher performance. They have safety concerns due to their stability and low-temperature storage requirements that result in thicker cases for storage tanks, and a low density that necessitates large storage tanks. Cryogenic propellants with dissimilar densities, such as liquid hydrogen and liquid oxygen, greatly complicate the design of the turbo-pump that feeds the combustion chamber due to differing flow rates and required shaft RPM [44] resulting in intricate gearbox designs.

Cryogenic propellants can only be filled in the rocket motor hours before launch so as to remain at low temperatures. Despite the safety improvements liquid systems represent over solids, the act of fuelling the motor with cryogenics has led to disasters and loss of vehicles as recently as 2016 with SpaceX [46]. As such, cryogenic propellants are not appropriate for reactive space access due to their long setup times. However they are becoming increasingly utilised for responsive space access with the advent of modern materials and manufacturing techniques mentioned earlier in this section.

Hypergolic propellants are liquids at room temperature so they have much longer storage durations. Hypergolics are also slightly simpler systems as no ignition system is required, given the fuel and oxidiser spontaneously combust upon mixing. Because of this, they can be indefinitely stopped and restarted with relative ease. They are however less energetic than cryogenic systems and require greater masses of fuel to meet the same thrust as traditional liquid propellants. The major downside of hypergolics is their safety. Fuels such as hydrazine and its derivatives and oxidisers like nitrogen tetroxide are either heavily corrosive, highly toxic, or both [47]. Research efforts in hypergolic propellants are centred on minimising the toxicity of the fuel, finding replacement fuels, increasing the density and specific impulse, reducing the ignition delay and improving the storability [48].

In searching for optimal propellants for a liquid system, researchers have occasionally looked to gel propellant. Gel propellants are liquids whose properties have been modified through the addition of gelling agents resulting in behaviour which resembles solid propellants [49]. Gelled propellants can replace traditional liquid propellant systems while providing similar performance, enhanced safety, density increases and decreases in sloshing and boil-off. An issue with cryogenic liquid propulsion is the short storage time of the fuel. When launching a rocket motor, the liquid propulsion must be filled a few hours before launch to minimise fuel losses and for safety concerns. Gel propellants offer improved longer-term storability compared against liquid propellants, coupled with performance similar to liquids, making them an attractive alternative to both liquid and solid options and ideal for responsive space access. Despite this, research and development on gel propellants is still very much emerging, the science behind droplet formation, gel rheology and combustion is still immature [50]. At the time of publication, no gel propellant propulsion systems have been deployed for commercial space access applications.

It should be noted that other liquid propulsion systems, such as Rotating Detonation Engines (RDEs), are beginning to show promise for space access [52]. A RDE utilises detonation of liquid fuel instead of traditional deflagration, to provide thrust. In doing so, the process is more efficient, allowing greater work to be extracted, and requires only a fraction of the combustor length, allowing more room for payload or fuel, enhancing performance of the system. However, there are many challenges with the utilisation of RDEs in any application, as the fundamental physics are still being investigated. DST along with domestic and international partners is currently investigating the feasibility of RDEs in a range of applications, including responsive access to space.

4.1.2.2. Liquid Rocket Technology Summary

As the pre-eminent propulsion technology for space access, where development had stagnated previously, the era of NewSpace commercial space access has seen an explosion of innovation in the science, design and manufacture of liquid rocket engines. Technology developments in this area include advanced turbo-pumps, improved cooling systems, ignition systems, ceramic materials, injection, mixing and combustion of hydrocarbon fuels [51]. Through application of modern technologies to new, niche markets, new companies, such as RocketLab and SpaceX, are challenging the notion that the rocket science golden era finished at the end of the Apollo program.

The rise of smaller payload masses, combined with rapid advances in battery technology has allowed RocketLab to develop a launcher using electrically powered turbo-pumps capable of lifting 300 kg payloads to LEO [6]. This allows for a simplistic design, devoid of pre-burners and does not expose the turbo-pump to any propellants, negating the highly sensitive area of bearing and seals around a turbopump shaft. The net result is a reduced cost launcher design that was not possible, or required, 20 years ago.

In the context of an Australian Defence responsive space access capability, a liquid rocket solution represents an alternative for responsive, but not necessarily reactive space. The need to fuel a liquid rocket just prior to launch, or use highly toxic hypergolic propellants, does not lend itself to an aspect of responsive or reactive launch that must be able to be geographically flexible and not vulnerable to denial or destruction of critical launch infrastructure. Vector Space, however, are developing a mobile small launcher [3] using a liquid system that may offer a path forward. Use of any US system (rocket motor or mobile launcher) may be subject to International Traffic in Arms Regulations (ITAR) restrictions on rocket technology and unsuitable for use in Australia. This suggests a potential avenue for sovereign development activities.

4.1.3. Hybrid Propulsion Systems

Hybrid propulsion systems use a solid fuel grain and a liquid oxidiser stored in a pressure vessel. When thrust is required, a valve is released and liquid oxidiser flows into the combustion chamber containing the fuel grain, generating a combustion boundary layer on the fuel surface [53]. Hybrid rocket motors have been considered since the 1930s with many developmental efforts directed at improving their performance and understanding the combustion chemistry [54]. Despite this lineage, the development of hybrid motors has proceeded in technology sprints never quite solving all the technical problems in order to proceed into a developed product for market.

The key features of a hybrid propulsion system are:

- Hybrids are inherently safer than SRMs as the fuel and oxidiser are separated and are unlikely to self-initiate in an event [53]
- Hybrids are less complex than liquid fuelled systems as only liquid oxidiser ducting is required and all mixing takes place over the solid fuel grain, reducing the cost and time required to manufacture
- Hybrids have the ability to throttle performance and stop/start combustion by controlling the oxidiser flow value improving the range of applications of the technology [53]

However, a number of drawbacks exist:

- Hybrids generally have a low regression rate, resulting in difficulty achieving high thrust levels. Greater burning surface area and grain complexity are required to achieve the desired mass-flow rates that decrease performance efficiency and volumetric loading.
- Ignition of complex grain surfaces can be difficult and may result in larger or more complex ignition sources when compared against traditional solid propellant igniters
- Residual fuels can build up in the case due to complex fuel grain designs which reduces efficiency
- For a given oxidiser flow rate, the oxygen/fuel ratio changes as the fuel grain regresses so further optimisations are required to reduce the ratio shift which results in inefficiencies
- The method of mixing in hybrid systems can result in lower overall efficiencies than traditional liquid or solid chemical systems [53]

In general, a hybrid can be thought of as avoiding some of the disadvantages of solid and liquid systems, whilst not having overall higher performance in any one area. They have a maximum theoretical Isp higher than SRMs (but lower than liquid rockets) yet in practice this is rarely achieved due to the previously mentioned inefficiencies. This limitation on thrust (acceleration) and combustion inefficiencies has limited the use of hybrids for traditional heavy lift space access applications. With the advent of responsive and reactive space access, utilising lower payload masses that do not require high thrust, hybrid motors are beginning to find a niche where their performance is sufficient and the safety and cost benefits of a hybrid concept allow them to become a competitive solution.

4.1.3.1. Hybrid Rocket Propellant

A hybrid motor is in most cases still a bi-propellant system like a liquid, the key difference being the fuel is a now solid grain, much like an SRM. While the oxidisers chosen can come from the wide range of bi-propellant oxidisers (LOX, H_2O_2, etc.) the fuels are typically rubbers, such as HTPB or polyurethane. The rate at which a rubber fuel with no additives burns is often several orders of magnitude lower than a solid rocket [55]. Coupled with the fact that mixing of fuel and oxidiser occurs on the surface of the fuel grain resulting in a less efficient, non-premixed combustion, these features give rise to the lower thrust capabilities of a hybrid. As a result, much of the research in the last 30 years has focussed on how to improve the regression rates of hybrid propellants to increase thrust and how to improve their structural strength in response to physical loads.

One solution to increasing the thrust of a hybrid is to increase the exposed surface area of the fuel grain. In practice this results in fuel geometries that contain a large number of perforations that increases the mass flow rate of fuel, at the cost of reducing the volumetric efficiency of the system (Figure 2). In addition, the reduced web (amount of material between perforations) weakens the strength of the fuel grain, increasing susceptibility to cracking and structural failure.

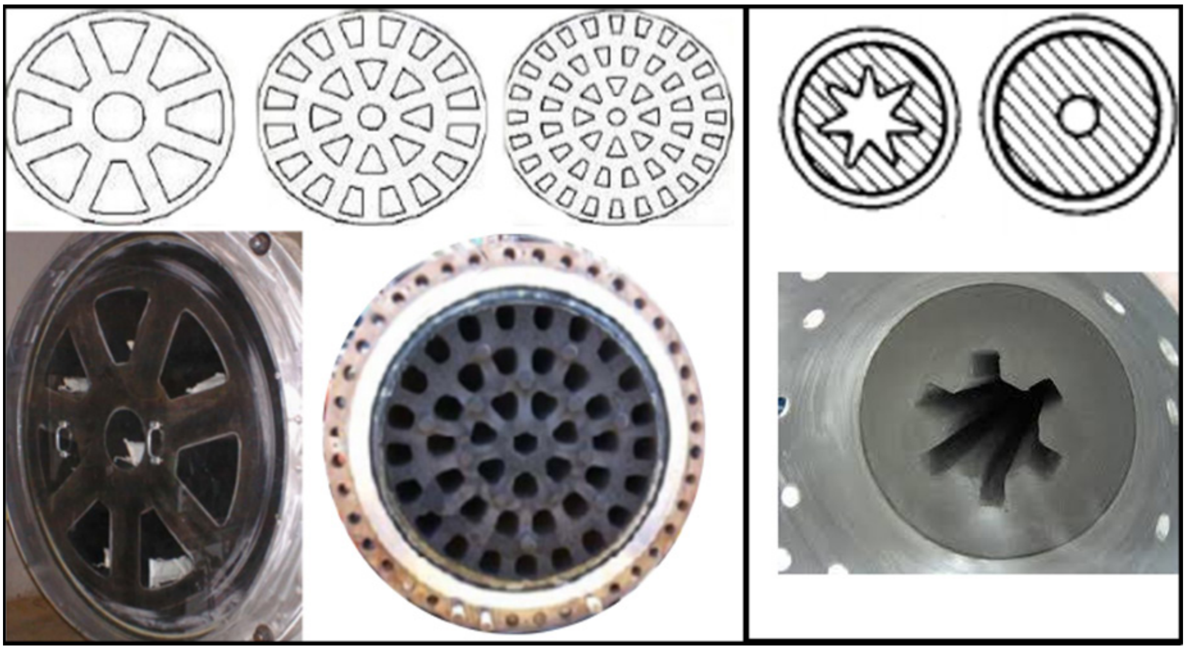

Figure 2 - Comparison of Hybrid (Left) and Solid Propellant Grains (Right) [36, 56]

A solution to enhance the performance of hybrids and improve thrust is to use paraffin wax based fuel that offer burn rates up to four times higher than that of HTPB based fuels [57]. The use of these high regression rate fuels then allows for less geometric perforations, increasing the motor volumetric efficiency and structural performance. However even these fuels require further research as preliminary testing has shown paraffin wax to be a brittle, low strength material and at risk of failure under launch loading conditions [58]. To further increase the performance of a hybrid motor, recent concepts include mixing additives in the fuel grain (such as Al) much like a SRM to increase the energy released and burn rate [58].

4.1.3.2. Hybrid Rocket Technology Summary

Gilmour Space Technologies are using additively manufactured fuel grains to reduce the manufacturing time and cost for responsive space access [5]. Hybrid technology enables the Eris orbital launcher to throttle through inefficient regions of ascent saving fuel and increasing payload capacity.

Internationally, fourteen European companies and institutes are developing a 'Small Innovative Launcher for Europe (SMILE)' for responsive launch of micro and nano-satellites [59]. The preliminary design is based on a two-stage, liquid and hybrid propulsion system to reduce cost and improve the launch cycle cadence. Some of the technologies being exploited for responsive and affordable space access include ceramic components, additively manufactured injectors, green storable propellants and hybrid propulsion [59]. A hybrid propulsion system was selected to maintain acceptable levels of acceleration by throttling through ascent and for the restart capability to enable accurate orbit insertion and further deorbit manoeuvres.

Hybrid rocket motors suffer from drawbacks that limit their performance and usefulness in many applications, as discussed above. However, many of these concerns can be alleviated by exploiting the design freedoms enabled by additive manufacturing techniques. Tooling (such as moulds and mandrels) is unable to manufacture propellant grains with axially varying bores and must adhere to traditional methods of propellant grain design. Some of the designs that are realisable by using additive manufacturing include helical, submerged and radial ports (Figure 3). By utilising non-traditional grain designs, such as star-shaped swirl, the burning surface area and regression rate can be greatly increased and the resulting vortices can promote improved fuel-oxidiser mixing and improved efficiency [55]. Recent advances in underpinning technologies and additive manufacturing are enabling the use of hybrid systems for responsive space access.

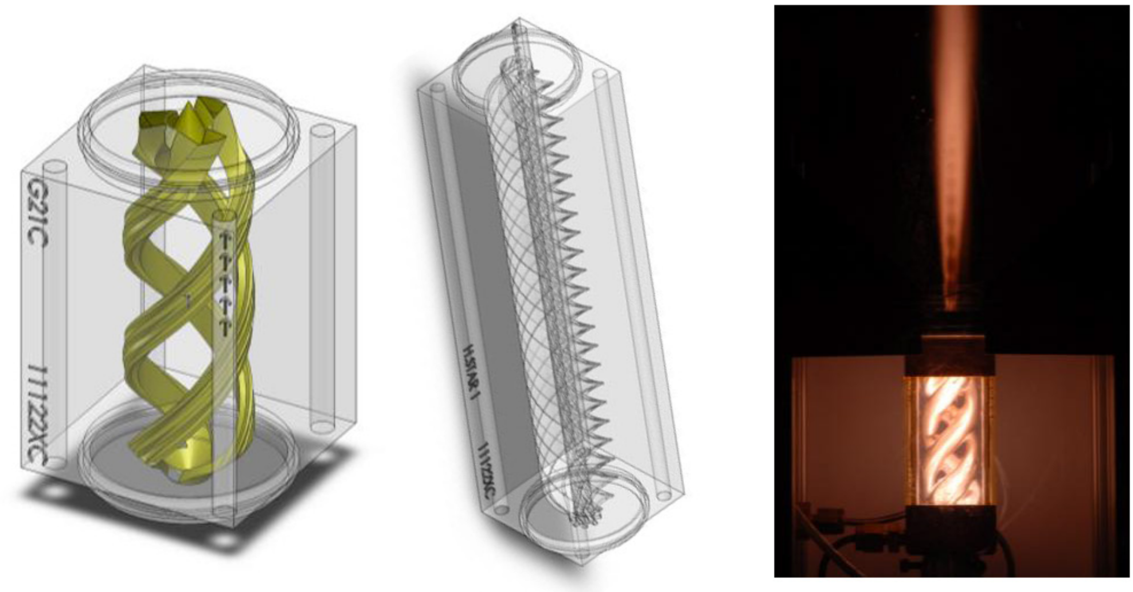

Figure 3 - Helical Port Hybrid Grain Design [60]

4.1.4. Air-breathing Propulsion Systems

Air-breathing propulsion systems, such as turbojets, ramjets and scramjets, utilise atmospheric oxygen for combustion alleviating the need to carry oxidiser and supporting components resulting in significant weight reductions even with the additional fore-body weight requirements. They are typically used in regions of the atmosphere where there is still sufficient oxygen to sustain combustion but where the atmospheric drag is relatively low. Air-breathing propulsion systems provide relatively low thrust but excel in long-range cruise applications, sustaining existing vehicle velocity over long durations. Development of tri-mode rocket/air-breathing/rocket systems are being investigated for responsive space access. Once a first stage booster has achieved appropriate speeds, a launch system can operate in air-breathing mode before changing modes as altitude increases and oxygen decreases to a purely rocket based propulsion system for the final ascent to space [37]. The Australian SPARTAN launch vehicle concept proposes a 2nd stage scramjet to accelerate the system to Mach 10 before releasing a SRM 3rd stage that performs a pitch manoeuvre and gains altitude, reaching orbit [25]. Detonation based systems such as RDEs can also operate in air-breathing modes and may be suitable in such an application [52].

The benefits for air-breathing propulsion systems include:

- Excellent Isp performance which translates into efficiencies over a range of Mach numbers depending on the propulsion system
- Significant mass reductions by removing on-board oxidisers when compared against liquid propellant propulsion systems

However, air-breathing propulsion systems have many drawbacks:

- Low thrust generation does not lend itself to heavy-lift space access applications, so trajectory modification and inefficient manoeuvres are required
- Atmospheric oxygen for combustion necessitates the need to stay in the atmosphere for longer, losing efficiency due to drag
- Air-breathing scramjet engines are at a low technology readiness level (TRL) and are unable to be appropriately deployed in this application at this time. Significant research and development is required before a scramjet is utilised for space access.
- Some high speed air-breathing systems require an initial velocity to achieve inlet compression for combustion. A preceding stage is therefore required for operation of the air-breathing propulsion system.

While concepts exist for using air-breathing propulsion for space access a combination of fundamental performance limitations and/or low TRL suggests they are not viable in the near term for space access. However, with additional research it is likely that an air-breathing propulsion system or combined cycle system such as the UK SABRE engine [61] will form part of the 'holy grail' for space access; a single vehicle to orbit where stages are not discarded, and the system is fully reusable.

4.2. Material Developments

Reduction in material weight of a launch vehicle provides significant benefits in terms of payload capacity or a marked reduction in fuel requirements and total cost. Many modern rockets are being manufactured using light-weight, high-strength composite materials in place of traditional heavy metals, such as the composite cases used by RocketLab's Electron vehicle [6] and SpaceX's Falcon 9 [16].

For liquid systems, rocket motor cases are required to contain large volumes of liquid fuel and oxidiser at high pressure and at cryogenic temperatures through heavy launch loads. For SRMs, the case is subject to large internal pressures at extremely high temperatures in addition to the chemical and mechanical effects associated with the burning of solid propellant. The higher the operating pressures of the rocket motor, the higher the Isp. Rocket motor developers must strive to achieve a 'sweet spot' between operating conditions, inert mass and system performance. Recently, rocket motor manufacturers are turning towards high strength composite materials such as carbon fibre which drastically reduces weight while providing comparative structural performance. DST has an active research program in this area and has demonstrated high strength carbon fibre cases through material testing and static firings [62, 63].

Rocket motor nozzles are typically manufactured from multiple materials selected for their material properties and the application of the engine. For example, solid propellant rocket motors require ruggedised nozzles to survive both the chemical environment and the mechanical impact of metallic particles. Depending on the level of erosion at the throat which is deemed acceptable, materials can range from simple graphite to heavy metals such as Tungsten or Titanium which provide minimal erosion at a significant penalty to weight and cost. Thermal transfer must also be considered so liners are used which reduce the level of heat transfer into surrounding components. Aluminium, steel or composite materials then provide the final structural support required to withstand the internal and external loads present during ascent. A rocket motor nozzle can constitute up to 10% of the rocket motors total weight [64]. Incorporating light-weight and high strength materials into the nozzle design can provide significant weight reduction. DST has an active research area investigating novel materials for SRM nozzles [11].

4.3. Additive Manufacturing

Additive manufacturing creates 3D objects by printing layer upon layer of materials until the object is formed. The materials used in this process include plastics, polymers, inks, metals and recently energetic materials [72]. The nature of the feed stock employed dictates the types of additive manufacturing employed [68].

This process drastically reduces the manufacturing time and cost of complex parts and is being increasingly utilised to enable responsive space access. Startup companies such as Additive Rocket Corporation (ARC) utilise additive manufacturing to design, optimise and manufacture liquid propellant rocket engines for a fraction of the time and cost [65]. The number of parts in a liquid system can also be drastically reduced as the manufacturing method no longer prohibits the design of complex pipework and injection systems.

DST has active research programs in the area of novel energetic materials and manufacturing techniques necessary to fully exploit the benefits afforded by these materials [41]. New materials are being realised through research into nano-sized energetic materials which provides benefits in energy output coupled with reduced vulnerability to external stimuli; research into RAM to afford greater propellant energy-density is being undertaken and also the additive manufacturing of energetics is being explored. DST is developing a design and optimisation capability that exploits the techniques of additive manufacturing of energetics to provide desired performance gains [42]. This is applicable for responsive space access as additive manufacturing enables high performance solid propellant grain designs which are not feasible with current casting techniques (see hybrids above).

4.4. Rocket Motor Design and Optimisation

Thanks to the current state of computational power, rocket motor analysis and design has begun to wholly incorporate optimisation techniques to improve the timeliness and accuracy of conceptual motor design. Optimisation of rocket motors is typically difficult and numerically intensive as there can be thousands of design variables. Optimisation techniques are revolutionising traditional rocket motor design by enabling the evaluation of millions of rocket motor designs, assigning a criteria value against each design and re-evaluating the design based on the population trend. Critically, this can be coupled with specific trajectory design and, in some cases, optimisation of the desired motor trajectory. This concept of integrated trajectory and motor design gives rise to a new way of approaching rocket design where materials, performance and traditional rocket design criteria (inert mass, Isp, etc.) are considered and traded against the actual mission performance requirements.

DST is leading the development and use of new design tools that combine modular component-based motor design and trajectory optimisation that can highlight where specific motor technologies combined with system level optimisation have the potential to drastically improve the mission performance for a range of rocket missions [66]. This process can have significant benefits in the design of space launch vehicles by maximising both payload weight and overall performance [67].

4.5. Reusability of Components

Traditional space access has been prohibitively expensive due, in large part, to the loss of the launch vehicles after each flight. However, the cost of space access is now being significantly reduced by reusing expensive rocket motor components. For example, launch vehicles such as SpaceX's Falcon 9 and Falcon Heavy [16] and Blue Origin's New Glenn [17] are able to recover the first stage and refit for future use.

Some of the technologies enabling reusability include previously mentioned materials improvements such as carbon fibre materials developments and manufacturing processes stemming from commercial aviation – a vast market where every kilogram saved equates to large fuel savings over the life of an aircraft. However, many others have resulted from areas ancillary to rocket propulsion. The ability to return the SpaceX boosters back to land is as much a product of advances in high performance computing, control system optimisations and artificial computer vision to enable the precise guidance, navigation, control, and landing. Optimisation techniques coupled with the low cost of computing power allows full rocket system designs to be exercised by the thousands, greatly reducing the barrier to entry for start-up companies and advanced computer simulations are reducing the number of costly physical testing required during development.

4.6. Pertinence of Responsive Space Access Technologies

The previous sub-points cover some of the technology areas that are required to further enhance responsive, affordable access to space. However, some technology developments have less of an impact than others for an ADF's responsive space access capability. DST's Missile and Space Propulsion Group has observed a sudden surge in the number of novel and innovative technologies that are being couched to enhance responsive space access. Given limited resources, prioritisation on the research and development areas that are likely to provide the greatest benefits for the ADF is critical for Australia, and DST is in a unique position to provide input into this process.

If the ADF requires a sovereign space launch capability that can launch Defence payloads into orbit rapidly, for low-cost and at short notice, the maturation and development of launch technologies is critical. It is the opinion of the authors that the following three technology areas have the greatest potential return on investment, and provides additional benefits when implemented together due to their highly synergistic nature.

- Additive manufacturing of propellants and structures:
    - Additive manufacturing enables significant increase in design complexity whilst maintaining manufacturability, manufacturing at reduced cost, enhanced tailorability over energy release and increased material durability (through improved cooling and heat transfer of inert components).
- Development of lightweight and high strength composite materials:
    - Reduction of weight is crucial to providing affordable and responsive space access. Composite material development has benefits in all areas of the launch vehicle and enables heavier payloads or reductions in fuel required.
- Design and mission optimisation:
    - Design and mission optimisation allows for reductions in system complexity and overall weight, enhanced performance through focused mission objectives and advanced rocket motor design techniques.

5. Recommendations for Future Australian Space Access Capability Development

The ADF has an ever increasing dependency on space-based services (e.g. enhanced BMS and integrated air and missile defence services). To ensure the continued availability of real-time mission data, it would be beneficial for the ADF to investigate a sovereign launch capability, utilising Australian commercial providers and research and development in launch technologies from industry, academia and government agencies such as DST. A similar model has been established through the SMILE sovereign launch capability, drawing the knowledge and expertise of fourteen companies and organisations across Europe. Defence is taking positive steps in this regard with space as a key priority of the Next Generation Technology Fund (NGTF) and space systems Strategic Research Investment (SRI) programs, where research from these initiatives aims to produce an enduring and resilient Defence capability. However, these initiatives have for the most part been focused on space based payloads instead of development of responsive or reactive launch capabilities.

While much of the required technology to develop and operate a sovereign launch capability exists in the US, many of the relevant technologies are prohibited for use in Australia due to ITAR restrictions. In many cases it may be more appropriate and beneficial to leverage or establish in-country technical expertise and facilities to enable responsive space access. In addition, establishing a sovereign capability within Australia enables stakeholders to suitably tailor the solution to best suit Australia's economic, National Security and Defence requirements.

It is the opinion of the authors that the following would aid in the establishment of a sovereign space access capability:

- Investigate the feasibility of a launch capability by utilising the expertise and manufacturing capability of Australian industry, academia and Defence (similar to the European SMILE concept)
- Leverage existing proposals for sovereign launch facilities (ELA, Southern Launch, Gilmour Space Technologies, Black Sky Aerospace and Space Ops)
- Use existing technology funds (NGTF/Defence Innovation Hub [DIH]) to establish collaborative programs aimed at establishing a sovereign responsive space access capability
- Explore options for micro-launcher concepts based on solid rocket propulsion technology, due to existing manufacturing base in country and dual civilian/Defence relevance of SRM systems

6. Conclusion

The rapid emergence of new space access technologies, together with the significant opportunities and Australian collaboration potential with space systems offers a new priority for Defence research. There is potential for large improvements in space based capability, enhanced sovereignty and much greater resilience to potential failures or adversary counter-space actions. One avenue for such improvement is the development of a sovereign launch capability that could provide rapid re-establishment of crucial ADF and national satellite infrastructure.

Internationally, a surging number of companies are demonstrating advanced propulsion technologies coupled with rapid advancements in the capabilities of micro and nano-satellites, small satellite constellations and additive manufacturing. It is important to ensure any investment in launch technologies is appropriate for Australia's economic and Defence requirements. This document provides an expert summary of the current state of the art of major propulsion technologies and what areas are most relevant to establishing an Australian responsive space access capability.

With world-class industrial and academic capabilities in materials science, space observation and communication, and propulsion technologies, Australia is well positioned to grow its share of the global space economy. An Australian designed and launched responsive space capability could be the 'lightning rod' to catalyse the rapid expansion of the Australian space industry.

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17. ABSTRACT Satellite communication, navigation, surveillance and meteorology services are key enablers for the ADF's battlefield awareness and air and missile defence. As the counter-space capabilities of potential adversaries continue to develop, reliance on high-value satellites becomes increasingly risky. Rocket manufacturers and launch service providers are anticipated to offer access to space at a reduced cost and infrastructure footprint compared to traditional launch. The diversity of applicable propulsion technologies has resulted in a range of technology options available to meet a responsive space access capability. This document provides a summary of the current state of the art of major propulsion technologies relevant to Defence responsive access to space, as well as recommendations as to how and where Australia and Defence may best invest to capitalise on advanced technologies to realise sovereign launch capability.				