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THE FINAL FRONTIER: THE EMERGENCE OF THE COMMERCIAL SPACE INDUSTRY AND THE LOSS OF SPACE HEGEMONY

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JCSP 42	PCEMI 42
Master of Defence Studies	**Maîtrise en études de la défense**

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CANADIAN FORCES COLLEGE – COLLÈGE DES FORCES CANADIENNES
JCSP 42 – PCEMI 42
2015 – 2016

MASTER OF DEFENCE STUDIES – MAÎTRISE EN ÉTUDES DE LA DÉFENSE

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Word Count: 19 636

Compte de mots: 19 636

The reasonable man adapts himself to the world; the unreasonable one persists in trying to adapt the world to himself. Therefore all progress depends on the unreasonable man. —George Bernard Shaw, *Man and Superman (1903)*

ABSTRACT

The commercial space industry is in upheaval. The *democratization* of space access brought about by new launch operators, acting in more nations, and at lower costs, will threaten Western hegemony in space. The détente reached between the superpowers during the Cold War will be jeopardized as more players enter orbit, enticed by the changing economics of space access and use. The lack of mature international law governing space activities puts pressure on states to regulate their markets. Competition for space-business will lead to disparities in regulation and oversight between states, potentially jeopardizing safety and security. Increasing space use will lead to further orbital congestion, and a rising risk from space debris. Public and private space interests are on the verge of relocating near-Earth objects into our orbit, threatening inadvertent collision. To preserve its primacy in space, the West needs to invest in improved sensors to monitor and characterize space objects; lead development of clear international laws regarding space safety, commerce and use; and, invest in technologies that allow it to influence the space environment (e.g. space planes, heavy lift rockets) in order to defend against new threats.

TABLE OF CONTENTS

CHAPTER 1 – INTRODUCTION

Space. It describes all of the universe less the infinitesimally tiny sliver that we call home – the Earth. For such a small word, it captures all of the majesty and terror that inhabits the skies above us. For the better part of human existence, we have barely understood what the lights in the sky meant, much less visited them. It is only in the past 70 years that we have been able to harness our ingenuity to catapult terrestrial objects into the cosmos. It was only our naïve courage that allowed us to follow with men. The immensity of this challenge could only be borne by the largest and most powerful nations on Earth – the United States (US), the Union of Soviet Socialist Republics (USSR) (now Russia), the People's Republic of China (PRC), Japan, India, and the collective might of the European continent. Of these, only three have successfully launched astronauts, cosmonauts, or taikonauts into orbit. We went to space, lived in artificial satellites, and set foot on the moon.

And then we mostly stopped.

With costs rising, the Cold War waning, and the emergence of cheaper, safer robotic explorers, the impetus to continue with manned space flight waned. Budgets for the US National Aeronautics and Space Administration (NASA) shrank (see Figure 1.1),[1]

[1] According to the US Government Office of Management and Budget (OMB), the percentage of the federal budget spent on NASA peaked at 4.4% in 1966, declined sharply through 1970, and has steadily eroded down 0.5% through 2016. In unadjusted dollars, NASA's budget has largely been on the upswing since 1990, but the data does not account for inflation. Since percentage of federal spending is a better indicator of political support, the first metric is more representative of decreased public space funding since the highs of the 1960's. However, the OMB data does not contain US Department of Defence (DoD) space-specific funding which would need to be incorporated to assess overall US Government space activity. (Source: United States White House, "Historical Tables," *Office of Management and Budget*, accessed on 14 April 2016, https://www.whitehouse.gov/omb/budget/Historicals/, Table 4.1 – Outlays by Agency: 1962-2021 and Table 4.2 – Percentage Distribution of Outlays by Agency: 1962-2021.)

flights of the US space shuttles slowed and then halted; retired to become museum pieces.[2] But while manned use of space declined, commercial and military use of space accelerated. From orbit, satellites have lines-of-sight over huge swathes of the Earth. New capabilities for navigation (e.g. Global Positioning System (GPS), GLONASS, GALILEO or Beidou), communication (e.g. IRIDIUM constellation, INMARSAT, Thuraya), and observation (e.g. RADARSAT, Keyhole) provide unprecedented capability to military, government and commercial users. Space capabilities have contributed to unprecedented improvements in understanding global weather and climate patterns [e.g. National Oceanic and Atmospheric Administration (NOAA) Global Earth Observation System of System (GEOSS)], scientific understanding of the cosmos (e.g. NASA Hubble), and in contributing to global peace and security through space-based monitoring of treaties between nations. There are approximately 1,380 operational satellites actively circling the Earth[3] with approximately 84 rockets launched annually to add satellites to, or to replace, these numbers (see Figure 1.2).[4]

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[2] Robert Z. Pearlman, "NASA's Space Shuttle Program Official Ends After Final Celebration," *Space.com*, 01 September 2011, accessed on 14 April 2016, http://www.space.com/12804-nasa-space-shuttle-program-officially-ends.html.

[3] The Union of Concerned Scientists maintains a "Satellite Database." Based on their database from 01 January 2016, there were 1,381 operating satellites around the Earth. (Source: Union of Concerned Scientists, "UCS Satellite Database," database updated on 01 January 2016, accessed on 14 April 2016, http://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database#.Vw_qYlQrKW8.)

[4] According to data from the "Space Launch Report," there has been an average of 73 launches per year since 1998. However, the overall trend has been upwards since 2004 (low of 54 launches). In the past five years (2011 – 2015), the average has been 84 launches. (Source: Space Launch Report, "Space Launch Report," accessed on 14 April 2016, http://www.spacelaunchreport.com/index.html. Averages taken from "Annual Space Reports" for 1998 until 2015.)

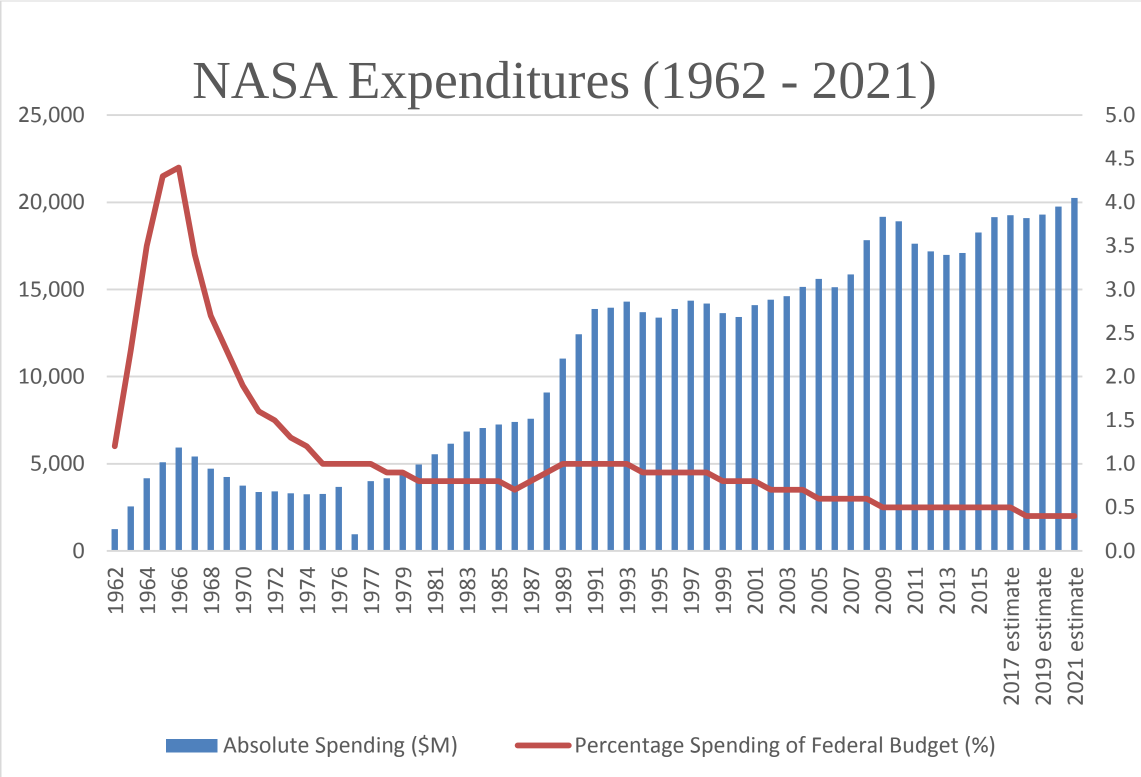

Figure 1.1 - NASA Expenditures (1962 – 2021). (Source: US Office of Management and Budget[5])

The United States, particularly the US military, is the single largest satellite operator in the world.[6] Alongside Russia, the two nations have been operating in space the longest, and have achieved the most milestones.[7] Through their world leading military expenditures, the US Department of Defense (DoD) has led research, development and use

[5] United States White House, "Historical Tables," *Office of Management and Budget*, accessed on 14 April 2016, https://www.whitehouse.gov/omb/budget/Historicals/, Table 4.1 – Outlays by Agency: 1962-2021 and Table 4.2 – Percentage Distribution of Outlays by Agency: 1962-2021.

[6] The US operates 568 satellites out of a global 1,381 total (as of 01 January 2016). By comparison, China is operating 177 and Russia 133. Of the 568 total, 149 are categorized as military. (Source: Union of Concerned Scientists, "UCS Satellite Database," database updated on 01 January 2016, accessed on 14 April 2016, http://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database#.Vw_qYlQrKW8.)

[7] The Soviet Union was the first nation to put a satellite in orbit with *Sputnik* in 1957. They followed with the first person to orbit the Earth with Yuri Garagarin in 1961, and the first spacewalk by Alexei Leonov in 1965. Meanwhile, the US countered by being the first nation to orbit the moon with Apollo 8 in 1968, and the first to land people on the moon with Apollo 11 in 1969.

of space, introducing global imaging and surveillance systems[8], precision navigation and timing services[9], and communication solutions in support of their national interests.[10] In coordination with NASA and other US government departments, the US has built a significant domestic space manufacturing, launch, and services industry.[11] Canada has been a peripheral player in this industry, developing specializations in vision systems, robotics, and remote sensing, but eschewing investment in a nationally controlled launch systems.[12] Since the *Upper Atmosphere and Space Programs in Canada* report published in February 1967, also known as the *Chapman Report*, Canada has been reliant on the Americans for space launch as a national policy.[13]

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[8] The US *CORONA* program placed the first photoreconnaissance satellite in orbit in 1960. (Source: Central Intelligence Agency, "A Look Back… CORONA: The Nation's First Photoreconnaissance Satellite," last updated on 30 April 2013, accessed on 15 April 2016, https://www.cia.gov/news-information/featured-story-archive/2010-featured-story-archive/corona-the-nation2019s-first-photoreconnaissance-satellite.html.)

[9] The US military led the development of satellite based navigation systems as far back as 1959 with the TRANSIT system, launching their first satellite in 1963. However, instability in the satellite clock made precision difficult. The subsequent development and introduction of satellite-based atomic clocks enabled the modern *Global Positioning System (GPS)* to become a reality beginning in 1989. (Source: Catherine Alexandrow, "The Story of GPS," *DARPA: 50 Years of Bridging the Gap*, accessed on 16 April 2016, http://www.darpa.mil/attachments/(2O10)%20Global%20Nav%20-%20About%20Us%20-%20History%20-%20Resources%20-%2050th%20-%20GPS%20(Approved).pdf.)

[10] The US launched their first communication satellite into orbit in 1958. The *Signal Communication by Orbiting Relay Equipment (SCORE)* was a US rebuttal to the Soviet *Sputnik* of the year before. More sophisticated satellites followed in the 1960's and beyond. (Source: Mak King and Michael J. Riccio, "Military Satellite Communications: Then and Now," *Crosslink Magazine*, 01 April 2010, accessed on 16 April 2016, http://www.aerospace.org/crosslinkmag/spring-2010/military-satellite-communications-then-and-now/.)

[11] According to the *Space Foundation*, the US accounts for 54% of all world government spending in 2014, having spent $42.96B that year. (Source: Space Foundation, "The Space Report 2015 – Overiew," accessed on 16 April 2016, http://www.spacefoundation.org/sites/default/files/downloads/The_Space_Report_2015_Overview_TOC_Exhibits.pdf, Exhibit 1.)

[12] Government of Canada, "Canada's Space Sector," accessed on 15 April 2016, http://www.asc-csa.gc.ca/pdf/space_espace_eng.pdf.

[13] Chapman *et al* advocate for a limited domestic launch capability for small satellites, but conclude that larger payloads are better launched by allies "for at least the next decade." (Source: J.H. Chapman *et al*, *Upper Atmosphere and Space Programs in Canada* (Ottawa: Roger Duhamel, F.R.S.C, 1967), 103 – 104.)

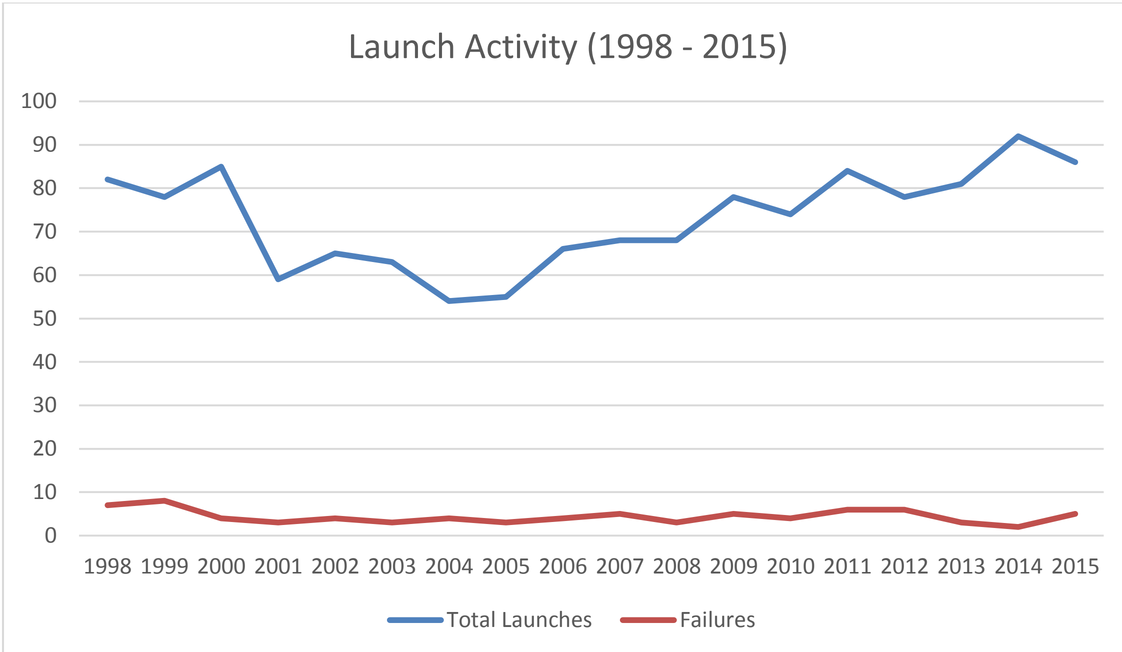

Figure 1.2 – Launch Activity (1998 - 2015) (Source: The Space Launch Report[14])

Costs associated with space system development, launch, and operation have been significant since the beginning. Physics lays out the problem - accelerate objects from the Earth's surface up to a *minimal* velocity of 7.8 km/s, or approximately 23 times the speed of sound (in air, at sea level), tangential to the surface of the Earth, while simultaneously achieving an altitude of approximately 150 kilometers above sea level. This establishes the lowest *stable orbit*. That is to say, an orbit in which the atmospheric drag on the satellite is sufficiently small so as to not slow it down enough to fall out of the sky immediately. To reach the moon, a spacecraft needs to be travelling even faster at approximately 11 km/s while achieving an altitude of approximately 384,400 kilometers (approximately 12 times the diameter of the Earth itself). The thrust required to achieve an acceleration sufficient to lift the body of the rocket itself, plus consumable fuel and any payload to be used or left in

[14] Space Launch Report, "Space Launch Report," accessed on 14 April 2016, http://www.spacelaunchreport.com/index.html.

orbit, is staggering.[15] Historically, only massive aerospace companies such as McDonnell-Douglas, Boeing or Lockheed Martin, operating under contract from the government, were able to develop and maintain space launch capabilities in the US. The European nations developed a consortium, led by France, to develop their own indigenous capabilities as part the European Space Agency.[16] Despite the capabilities Russia inherited from the USSR, that nation has been unable to invest significantly in them in recent decades due to their stagnant economy.[17] Meanwhile, Japan, India and the PRC have developed their own national launch capabilities, while Iran and North Korea harbor their own ambitions as part of their ballistic missile programs.[18]

Historically, with the (partial) exception of the space shuttle, spacecraft and their launchers were designed to be disposable. Once used, they are destroyed on re-entry or left for scrap if they did return to Earth. The shuttle was an attempt to create a fully re-useable space vehicle. It sought to bring down the costs by making space access routine, coupling

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[15] Rockets must produce more thrust (upwards force) than the downward force applied by gravity. This is captured mathematically by the *thrust-to-weight ratio*. This ratio must be greater than one for a rocket to lift-off, and is normally many times larger. SpaceX claims that their *Merlin* engine has a ratio in excess of 150, making it the most efficient booster every built. It produces 170,000 lbs of thrust at liftoff. (Source: Space Exploration Technologies Corporation, "MERLIN Engines," updated on 26 March 2013, accessed on 15 April 2016, http://www.spacex.com/news/2013/03/26/merlin-engines.) By comparison, the GE90 turbofan engine designed for the Boeing 777 produces a world-leading 127,900 lbs of thrust. (Source: General Electric Aviation, "The GE90 Engine," accessed on 15 April 2016, http://www.geaviation.com/commercial/engines/ge90/.)

[16] The forerunners to the ESA were the European Launcher Development Organization (ELDO) and European Space Research Organization (ESRO). They were merged to form the ESA in 1975. (Source: Eric Berger, "Space for Europe and for all humankind: A brief history of the ESA," *Ars Technica*, 31 December 2015, accessed on 06 May 2016, http://arstechnica.com/science/2015/12/space-for-europe-and-for-all-humankind-a-brief-history-of-the-esa/.)

[17] Eric Berger, "For Russia's space program, 2016 may be a make-or-break year," *Ars Technica*, 05 January 2016, accessed on 03 February 2016, http://arstechnica.com/science/2016/01/for-russias-space-program-2016-may-be-a-make-or-break-year/.

[18] Sean Gallagher, "North Korea's "successful" satellite in orbit, but tumbling and useless," *Ars Technica*, 09 February 2016, accessed on 09 February 2016, http://arstechnica.com/information-technology/2016/02/north-koreas-successful-satellite-in-orbit-but-tumbling-and-useless/.

re-usability with high availability to amortize the investments across many more missions. Unfortunately, the program was saddled with sustaining costly legacy infrastructure, subject to Congressional manipulation, faced competition from other launch vehicles, and had significant design deficiencies that required a thorough investigation and partial retrofit to meet safety standards between flights.[19] Taken together, these factors undermined the anticipated savings.

Today, NASA's new heavy lift launch system being designed for flights to near-Earth asteroids and Mars eschews even the partial step forward by the space shuttle.[20] By design, it is fully disposable, even as it incorporates the RS-25 main engine rockets that were re-used from flight-to-flight by the Space Shuttle.[21] US industrial partners continue to purchase and employ the massive engines developed in the last century. Many of these engines are not even American-made, but came out of designs from the Soviet space program.[22] These designs remain highly reliable, but have not noticeably incorporated

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[19] "Space Shuttle history," accessed on 05 May 2016, http://www.century-of-flight.net/Aviation%20history/space/Space%20Shuttle%20history.htm.

[20] The *Space Launch System (SLS)* is the most powerful rocket ever developed by NASA. It is being designed to launch the new *Orion Multi-Purpose Crew Vehicle* beyond the Earth's orbit. The initial (70-metric ton) configuration is expected to produce 8.4 million pounds of thrust at liftoff and carry 154,000 pounds of payload into space An evolved (130 metric ton) configuration will increase thrust to 9.2 million pounds and 286,000 pounds of payload respectively. (Source: National Aeronautics and Space Administration, "Space Launch System," accessed on 15 April 2016, https://www.nasa.gov/pdf/664158main_sls_fs_master.pdf.)

[21] Although the RS-25 engines were re-useable, they were also known for requiring significant refurbishment between flights to ensure safety. (Source: Eric Berger, "As NASA discards reusable engines, Blue Origin and SpaceX push new frontiers," *Ars Technica*, 01 December 2015, accessed on 09 February 2016, http://arstechnica.com/science/2015/12/as-nasa-discards-reusable-engines-blue-origin-and-spacex-push-new-frontiers/.)

[22] The United Launch Alliance (ULA) relies on the RD-180 to power their *Atlas 5* rocket which provides the majority of their government launches. (Source: Warren Ferster, "ULA Execs Say RD-180 Engine Ban Blocks Path to Next-gen Rocket," *SpaceNews*, 22 May 2015, accessed on 19 April 2016, http://spacenews.com/ula-execs-say-rd-180-engine-ban-blocks-path-to-next-gen-rocket/.)

new materials or designs inspired by technological advances in the past twenty years.[23] Innovation in space launch technology is no longer being driven by the Government, or, on their behalf, by their corporate partners.

Into this vacuum, an unusual breed of entrepreneurs have emerged who are looking to undercut legacy space system providers. They are re-thinking space launch systems using modern materials, manufacturing and computation. They are developing solutions that include fully re-useable rockets, seeking to drastically reduce the cost of space access. Already, two of the most well-known and heavily capitalized companies, Space Exploration Technologies Corporation (otherwise known as SpaceX) and Blue Origin, have launched *and* recovered their rockets. In the case of Blue Origin, they have already launched and recovered the same rocket twice within a very short time frame, albeit at sub-orbital velocity and altitude.[24] Meanwhile, SpaceX has done their own launch and recovery following a successful payload delivery to Low Earth Orbit.[25] They claim that the booster suffered minimal damage, although they don't plan on re-launching it again due to the historic nature of the flight.[26] Only four months later, they landed a second rocket, this time on a platform at sea.[27]

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[23] The RD-180 engine was developed by *NPO Energomash* in the 1990's and first tested in 1999. The Soviet Union had pursued a completely different type of rocket technology from the West (i.e. USA, Europe and Japan) which enabled them to achieve much higher efficiency with their engines. (Source: "The Engines That Came In From The Cold," *Equinox*, BBC Channel 4, aired 01 March 2001, posted by Matthew Travis, accessed on 19 April 2016, https://www.youtube.com/watch?v=TMbl_ofF3AM, 37:24 – 49:32.)

[24] Sean O'Kane and Loren Grush, "Blue Origins beats SpaceX to re-launching a reusable rocket," *The Verge*, 22 January 2016, accessed on 03 February 2016, http://www.theverge.com/2016/1/22/10815800/blue-origin-rocket-launch-.

[25] Eric Berger, "With a historic landing, SpaceX launches new age of spaceflight," *Ars Technica*, 21 December 2015, accessed on 03 February 2016, http://arstechnica.com/science/2015/12/by-making-a-historic-landing-spacex-launches-new-age-of-spaceflight/.

[26] Marcia Dunn, "No damage to SpaceX's Falcon rocket following historic landing," *The Associated Press*, 04 January 2016, accessed on 03 February 2016,

While Blue Origin has yet to enter the commercial market in terms of contracting for flights, SpaceX has been launching rockets for clients since August 2008.[28] They have undercut the prices offered by their competitors such as the United Launch Alliance (ULA),[29] the consortium of Boeing and Lockheed Martin that emerged in 2006 out of their separate space flight programs.[30] Boeing and SpaceX are competing for NASA's *commercial crew program*, with SpaceX undercutting the Boeing bid by $1.6B USD for a series of upcoming missions. SpaceX successfully lobbied the government to open up government contracts to new bidders, and convinced them to re-balance the selection criteria between reliability and price. Fixed price contracts are now being awarded by the US government, forcing ULA and other government contractors to become more cost competitive with SpaceX and other start-ups.[31] SpaceX is only the second company (the other being the ULA) certified by the US Air Force (USAF) for National Security Space launches, allowing them to compete for upcoming Department of Defense payloads.[32]

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http://www.ctvnews.ca/sci-tech/no-damage-to-spacex-s-falcon-rocket-following-historic-landing-1.2723268. Additionally, on

[27] Calla Cofield, "SpaceX Sticks a Rocket Landing at Sea in Historic First," *Space.com*, 08 April 2016, accessed on 19 April 2016, http://www.space.com/32517-spacex-sticks-rocket-landing-sea-dragon-launch.html.

[28] Space Exploration Technologies Corporation, "Completed Missions," accessed on 03 February 2016, http://www.spacex.com/missions.

[29] Eric Berger, "ULA executive admits company cannot compete with SpaceX on launch costs," *Ars Technica*, 17 March 2016, accessed on 22 April 2016, http://arstechnica.com/science/2016/03/ula-executive-admits-company-cannot-compete-with-spacex-on-launch-costs/.

[30] United Launch Alliance, "Company History," accessed on 19 April 2016, http://www.ulalaunch.com/history.aspx.

[31] Eric Berger, "Quietly, the new space race between SpaceX and Boeing burns hot," *Ars Technica*, 10 November 2015, accessed on 03 February 2016, http://arstechnica.com/science/2015/11/quietly-the-new-space-race-between-spacex-and-boeing-burns-hot/.

[32] Jason Rhian, "Upgraded SpaceX Falcon 9 certified for National Security Space launches," *Space Flight Insider*, 26 January 2016, accessed on 03 February 2016, http://www.spaceflightinsider.com/organizations/space-exploration-technologies/upgraded-spacex-falcon-9-certified-for-national-security-launches/.

By decreasing the cost of space access, SpaceX and other emerging space launch firms believe that they can create new space-based opportunities for businesses that were previously cost prohibitive. This assumption is predicated on a belief that the demand for space services is elastic, and capable of sufficient growth to justify the investment in new launch vehicles. In parallel, satellite manufacturers and systems integrators are seeking to exploit these opportunities by developing lower cost, smaller volume *microsatellites*. By leveraging advances in miniaturization, power consumption, and power generation, these satellites can be built faster and more cheaply.[33] Coupled with lower cost launch vehicles, capital investment in space-based systems can be dramatically reduced.

In addition to commercial satellite launchers, new companies are also pursuing options for space tourism. The Ansari X Prize was awarded to Aerospace Ventures in 2004 after they successfully conducted two manned sub-orbital flights using *SpaceShipOne* within less than a week.[34] Sir Richard Branson, chairman of the Virgin Group, created *Virgin Galactic* and *The Spaceship Company* to commercialize the technology. Virgin Galactic is planning on providing a two-and-a-half hour sub-orbital flight up to an altitude of approximately 100 kilometers with four minutes of weightlessness for $250,000 USD.[35] Although they suffered a set-back with the loss of one of their test vehicles in 2014, they

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[33] Economist Staff, "Nanosats are go!" *The Economist*, 07 July 2014, accessed on 19 April 2016, http://www.economist.com/news/technology-quarterly/21603240-small-satellites-taking-advantage-smartphones-and-other-consumer-technologies.
[34] Alan Boyle, "SpaceShipOne wins $10 million X Prize," *NBC News*, last updated on 05 October 2004, accessed on 03 February 2016, http://www.nbcnews.com/id/6167761/ns/technology_and_science-space/t/spaceshipone-wins-million-x-prize/#.VrI3JO0rKW-.
[35] William Langewiesche, "Everything You Need to Know About Flying Virgin Galactic," *Vanity Fair*, April 2015, accessed on 19 April 2015, http://www.vanityfair.com/news/2015/03/what-is-it-like-to-fly-virgin-galactic.

continue to press forward with their venture.[36] They have also pivoted to add a satellite launch component to their business model. Unlike SpaceX and Blue Origin, who launch their rockets from the ground, Virgin Galactic is launching their rockets from a modified Boeing 747 flying at altitude.[37] This provides them with some advantages in lift because they can leverage the more energy efficient aerodynamics of an aircraft to overcome some of the Earth's gravity well.[38] Additionally, it can be flown from normal airstrips worldwide vice static spaceports, and can fly above weather that prevents a terrestrial launch.[39] However, the aircraft adds another component to the system which can fail, puts human operators in proximity to the rocket engine, and also limits the gross tonnage of the rocket to what can be lifted aloft by the plane.[40]

Now that opportunities to reach space are multiplying, the use of space is also being reconsidered. With a few exceptions, most space use is focused on improving the situation on the ground.[41] Remote sensing, communications, and position, navigation and time (PNT) systems were all designed to service users on (or near) the surface of the Earth. Due

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[36] Calla Cofield, "Virgin Galactic on Road to Recovery After Fatal SpaceShipTwo Crash," *Space.com*, 30 October 2015, accessed on 19 April 2016. http://www.space.com/30969-virgin-galactic-spaceshiptwo-crash.html.

[37] Kasandra Brabaw, "Meet 'Cosmic Girl': Virgin Galactic's New Satellite Launching Jet (Video)," *Space.com*, 09 December 2015, accessed on 19 April 2016, http://www.space.com/31322-virgin-galactic-cosmic-girl-launcherone-plane.html.

[38] Marti Sarigul-Klijn, and Nesrin Sarigul-Klijn, "A study of air launch methods for RLVs," AIAA Space 2001 Conference and Exposition, Albuquerque, NM, https://wiki.umn.edu/pub/AEM_Air_Launch_Team/LaunchTrajectoryDesign/aiaa2001-4619.pdf. 3.

[39] Jeff Foust, "Air launch, big and small," *The Space Review*, 30 June 2014, accessed on 19 April 2016, http://www.thespacereview.com/article/2543/1.

[40] The mass of the rocket is restricted by the capacity of the aircraft. Based on the flight profile, the ratio of rocket-to-payload will vary. Most air-launched rockets can only achieve payloads sizes of a couple of hundreds of kilograms. The *Stratolauncher*, which is currently under development, would be the largest aircraft ever built, and could achieve up to 6,100 kilograms into low-Earth orbit. However, this is a fraction of the payload that larger rockets can achieve, and still does not address the re-usability of the actual rocket. Costs savings will need to be made up through fuel savings, and launch flexibility in terms of time and space. (Source: Jeff Foust, "Air launch, big and small," *The Space Review*, 30 June 2014, accessed on 19 April 2016, http://www.thespacereview.com/article/2543/1.)

[41] These exceptions are largely space-based astrophysical telescopes and sensors which support basic science and research (e.g. Hubble telescope, Chandra X-Ray Observatory).

to the cost, many of these systems were launched by government users, or larger corporations or commercial interests seeking to service a sophisticated client base. Should the costs decline, smaller organizations and countries may be tempted to launch their own satellites with overlapping, or new capabilities.

New pursuits being investigated include resource extraction from near-Earth asteroid, power generation, orbital space tourism, manufacturing, and habitation. The financial viability of these options hinge on the economics of space access and use. Launching resources from the Earth has been very expensive. Bringing down these costs, or generating resources from space itself, may decrease the costs of inhabiting and using space substantially. Services may emerge that are space-focused vice Earth-focused in terms of their markets. This could create an entirely new, extra-territorial economy in orbit and beyond.

Not discussed yet have been the future options for military use, or the weaponization of space. The West, particularly the US, have used space-based systems as force multipliers, notably during the First Gulf War. Access to space sensors informs their intelligence apparatus, while global communication and navigation give their warfighters an edge in command and manoeuvre. Russia and China have launched, or a preparing to launch, their own systems to supplement their own forces. This military use of space has been long-standing, and with declining costs, may induce other nations into acquiring these capabilities natively.

Weaponization of space has, thus far, remained largely unpursued. The US and the USSR both had programs to investigate and place weapons in space.[42] The USSR tested a *co-orbital anti-satellite* capability as far back as 1968. The test vehicle was not left in orbit, but was intended for a quick launch, interception and destruction of a targeted satellite.[43] Meanwhile, an air-launched anti-satellite capability was investigated and tested successfully by the US in the 1985.[44] Regardless, both nations effectively ceased their programs seeking to place weapon systems into orbit permanently, instead remaining focused on capabilities originating from the ground.[45] More recently, China destroyed their own satellite in 2007 using a ground-based interceptor, highlighting their desire to exert influence in near-Earth orbits.[46] The resulting debris from the collision jeopardized other space objects, colliding with a Russian satellite in 2013.[47] Other, non-kinetic techniques, have been proposed to disable satellites including jamming, laser blinding or

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[42] The best known US program was the *Strategic Defense Initiative (SDI)* that originated in the 1970's, and was announced publically by President Ronald Reagan in 1983. In response, the USSR fast tracked development of orbital battlestations (known as *Skif* and *Kaskad*) to target US satellites. Neither project was successful in achieving their aims. (Source: Amy Teitel, "The laser-toting Soviet satellite that almost sparked a space arms race," *Wired*, 16 May 2013, accessed on 19 April 2016, http://www.wired.co.uk/news/archive/2013-05/16/soviet-laser-satellite/viewall.)

[43] Union of Concerned Scientists, "A History of Anti-Satellite Programs (2012)," February 2012, accessed on 19 April 2016, http://www.ucsusa.org/nuclear-weapons/space-security/a-history-of-anti-satellite-programs#.VxaKvVQrKW8.

[44] Lee Billings, "War in Space May Be Closer Than Ever," *Scientific American*, 10 August 2015, accessed on 19 April 2016, http://www.scientificamerican.com/article/war-in-space-may-be-closer-than-ever/.)

[45] The initial Soviet effort, *Polyus-Skif*, was unsuccessful in achieving orbit when launched in 1987. (Source: Amy Teitel, "The laser-toting Soviet satellite that almost sparked a space arms race," *Wired*, 16 May 2013, accessed on 19 April 2016, http://www.wired.co.uk/news/archive/2013-05/16/soviet-laser-satellite/viewall.) The American's demonstrated the ability to shoot-down a satellite using a missile launched from an F-15 in 1985. They also tested nuclear weapon in the atmosphere before the ban imposed by the 1967 *Outer Space Treaty*. However, there are no other publically acknowledged weapon systems that were placed in orbit by the US. (Source: Lee Billings, "War in Space May Be Closer Than Ever," *Scientific American*, 10 August 2015, accessed on 19 April 2016, http://www.scientificamerican.com/article/war-in-space-may-be-closer-than-ever/.)

[46] Jeremy Singer and Colin Clark, "White House Confirms Chinese Anti-Satellite Weapon Test," *Space.com*, 19 January 2007, accessed on 19 April 2016, http://www.space.com/3367-white-house-confirms-chinese-anti-satellite-weapon-test.html.

[47] Leonard David, "Russian Satellite Hit by Debris from Chinese Anti-Satellite Test," *Space.com*, 08 March 2013, accessed on 19 April 2016, http://www.space.com/20138-russian-satellite-chinese-space-junk.html.

cyber-attack.[48] These techniques are focused on disabling the satellite without contributing to orbital debris. As new space users begin to emerge, competition for orbits and other resources may result in the introduction of new capabilities for space control, including space-based weaponry.

In tandem with new optimism about space use, public interest in space flight and space science is high. The Ansari X Prize sought to encourage the commercialization of sub-orbital flight.[49] The Google Lunar Prize is seeking to incentivize affordable commercial access to the Moon.[50] *MarsOne* is attempting to create the first permanent manned settlement on Mars to jumpstart colonization of the solar system.[51] Elon Musk, the Chief Executive Officer (CEO) of SpaceX, has publically acknowledged that the ultimate mission of his company is to create a self-sustaining colony on Mars by making it economically viable to establish and maintain.[52] Planetary Resources is planning to mine and extract valuable resources of near-Earth asteroids.[53] Science fiction is on the verge of becoming science fact in the next twenty years.

The successful commercialization of space remains uncertain. Although companies such as SpaceX are profitable and are demonstrating a path to much reduced costs for space access, the emergence of a viable commercial market remains unclear. The economics underlying large scale use of space remain to be proven. Nonetheless, Virgin Galactic,

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[48] Union of Concerned Scientists, "A History of Anti-Satellite Programs (2012)."
[49] Ansari X Prize, "Teams," accessed on 09 February 2016, http://ansari.xprize.org/teams.
[50] Google Lunar X Prize, "About – Overview," accessed on 09 February 2016, http://lunar.xprize.org/about/overview.
[51] Mars One, "Human Settlement on Mars," accessed on 09 February 2016, http://www.mars-one.com/.
[52] Mike Wall, "Now Is the Time to Colonize Mars, Elon Musk Says," *Space.com*, 16 December 2015, accessed on 09 February 2016, http://www.space.com/31388-elon-musk-colonize-mars-now.html.
[53] Planetary Resources, "Planetary Resources – Intro," accessed on 09 February 2016, http://www.planetaryresources.com/#home-intro.

Planetary Resources and their ilk point towards an emerging commercial interest in space that extends beyond the classical examples of space use.

From a Western military perspective, it is essential to investigate the consequences of any shift in space use. The military's dependence on space systems for warfighting can only be assured by investigating and neutralizing potential threats. This is most easily done when they are nascent. These threats may not be strictly limited to increased militarization or weaponization by allies or opponents, but also first, second and higher order effects resulting from broader commercial use. To understand whether these provide opportunities or drawbacks, we need to consider the environment from which they will emerge, and deduce the defence and security implications.

This paper will argue that increased commercial space use presents a risk to Western defence and security. By democratizing access to space services, the West's advantage in space-based sensing, telecommunication and navigation will be neutralized through the emergence of new commercial or small government ventures taking advantage of lower costs. Combined with an immature international legal framework covering space access and use, new risks will emerge that further jeopardize national security interests. Space debris, hypersonic commercial space vehicles, near-Earth space object relocation, and dual-use technologies present emerging threats that will need to be investigated, understood, and countered by a nation's military forces.

CHAPTER 2 - THE ECONOMICS OF SPACE ACCESS AND USE

The economics of space access and use is fundamental to the development of a robust commercial space industry. To understand how that industry may evolve, we need to understand the underlying economic incentives and disincentives that drive commercial activity. Foremost amongst these factors has been the high cost of getting to space itself.[54] If commercial interest in space *is* elastic, it will respond to variability in price. Commercial launch companies are betting on the global market responding to much reduced access costs. Space-based industries for tourism, resource extraction, power generation and manufacturing will only become commercially viable if the fixed costs for getting aloft decline below their expected revenues in a reasonable period of time. More than that, investment in these industries, beyond philanthropic billionaires, requires that the return on investment be risk adjusted. The risks of going to, and operating from space, demand that the risk-weighted rate of return from these ventures surpass what could be achieved through more pedestrian (and terrestrial) ventures.[55]

In a paper entitled "The Political Economy of Very Large Space Projects," Dr. John Hickman evaluated the costs associated with major undertakings in the solar system, from large-scale orbital colonies to terraforming Mars over several centuries.[56] He remarked that most popularizers of these ideas hype the *eventual* benefits of a project, some of which may not emerge for decades or centuries. The requirement for immediate benefits, if any, is

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[54] Although the price is highly variable depending on the type of orbit (low-Earth vs. geosynchronous) and launch vehicle (e.g. light vs. medium vs. heavy lift), it has been approximately $10,000 per pound ($22,000 per kg) to achieve low-Earth orbit in the space shuttle era. (Source: National Aeronautics and Space Administration, "Advanced Space Transportation Program," accessed on 20 April 2016, http://www.nasa.gov/centers/marshall/news/background/facts/astp.html_prt.htm.)

[55] As an economic principle, higher risk should correlate with higher returns. This is known as *Risk Adjusted Return on Capital (RAROC)*.

[56] John Hickman, "The Political Economy of Very Large Space Projects," *Journal of Evolution and Technology* 4, (November 1999): 5.

conveniently ignored.[57] Additionally, the means proposed for funding these projects are often speculative, such as the sale of Martian real estate[58], the *peace dividend* from the end of the Cold War[59], or through other government largesse.[60]

Large scale capital investment that can postpone returns over the long term is more akin to public financing, where the up-front costs can be amortized over decades. Governments can secure much larger pools of capital by leveraging their ability to impose taxes on their populace in perpetuity.[61] Commercial interests are poorly suited for these types of endeavours because of their fiduciary responsibility to their shareholders in the near term. According to Hickman, the returns from large scale investment in space, especially over a multi-decade or multi-century timescale, do not justify the risks for commercial investors. As an example, he conducts a rudimentary calculation on the terraforming of Mars in which he assumes a $200B initial investment, a 700 year timeframe (i.e. the time for the atmosphere to become breathable), and a 5% compounded annual interest rate. This yields an eventual debt of $\$1.36 \times 10^{17}$ billion. Each square meter

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[57] *Ibid.*, 2-3.

[58] The legality of *owning* real estate in outer space will be discussed in greater detail in Chapter 3. (Source: Robert Zubrin and Richard Wagner, *The Case for Mars: The Plan to Settle the Red Planet and Why We Must*. (New York: Simon and Schuster, 1996), 233 - 239, quoted in John Hickman, “The Political Economy of Very Large Space Projects,” *Journal of Evolution and Technology* 4, (November 1999): 2.)

[59] Written before the end of the Cold War, Lovelock and Allaby propose colonizing Mars to become an environmental utopia. (Source: James Lovelock and Michael Allaby, *The Greening of Mars*, (New York: Columbia University Press, 1987): 173-174, quoted in John Hickman, “The Political Economy of Very Large Space Projects,” *Journal of Evolution and Technology* 4, (November 1999): 2.)

[60] In one case, the author’s called for the redistribution of one percent of the US Gross National Product (GNP) to mine Helium-3 on the Moon as a precursor to a colony on Mars. (Source: Harrison H. Schmidt, “The Millenium Project,” in Carol R. Stoker and Carter Emmert eds, *Strategies for Mars: A Guide to Human Exploration*, (San Diego: American Astrophysical Society, 1996): 8-30, quoted in John Hickman, “The Political Economy of Very Large Space Projects,” *Journal of Evolution and Technology* 4, (November 1999): 2.)

[61] Hickman, “The Political Economy of Very Large Space Projects,” 7 – 9.

of Martian real estate would need to return in excess of one billion dollars (in future dollars) to recoup the initial investment.[62]

To carry out a large space project, Hickman identified three tenets that he felt would contribute to success. First, you must "persuade a sponsoring space-faring power or powers with the economic wherewhithal … to absorb as much of the initial costs of the project … as politically possible."[63] Effectively, shift as much cost onto the taxpayer as possible. This requires the mobilization of public support.[64]

As of 2014, the US government was the largest single investor in space,[65] despite the *real* funding for NASA having declined for the past several decades, both as a percentage of the overall federal budget, and when adjusted for inflation.[66] This policy is in-line with recent polling by the Monmouth University Polling Institute showing that most Americans are split evenly on the benefits of space program spending. More than half oppose the multi-billion dollar expenditures earmarked for sending astronauts to the Moon, or other nearby space objects.[67] Fortunately for commercial interests, more than half of

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[62] This analysis makes several assumptions that may ultimately be false. The first is that there would be no means of recuperating the initial investment prior to the conclusion of the 700 years. Second, the selection of the interest rate, initial investment and timeframe are all arbitrary. Third, other income streams may exist beyond the sale of real-estate. Finally, Hickman notes that no inflation was taken into account. (Source: John Hickman, "The Political Economy of Very Large Space Projects," *Journal of Evolution and Technology* 4, (November 1999): 5.)

[63] Hickman, "The Political Economy of Very Large Space Projects," 7.

[64] Hickman draws parallels with the 19th Century naval arms races, colonization of Africa, and the nuclear arms race. (Source: John Hickman, "The Political Economy of Very Large Space Projects," *Journal of Evolution and Technology* 4, (November 1999):7.)

[65] According to *The Space Report 2015*, US government expenditures make-up 13% of the global space market. All other governments in the world only contribute 11% of the total. (Source: Space Foundation, "The Space Report 2015 – Overiew," accessed on 16 April 2016, http://www.spacefoundation.org/sites/default/files/downloads/The_Space_Report_2015_Overview_TOC_Exhibits.pdf, 3.)

[66] See Figure 1.1 – NASA Expenditures.

[67] According to the study, 51% of respondents agreed that increased spending in the space program would be a good investment, but only 42% agreed with spending to put astronauts back on the Moon and other space objects. (Source: Monmouth University Polling Institute, "National: Space Travel in the 21st Century,"

participants also believe that "private companies and individuals should be able to build their own rockets to take people into space."[68] In this environment, getting substantial public support for a very large space project is difficult.

Ironically, public interest in space entertainment seems very high. The Red Bull Stratos project was viewed on-line concurrently by eight million people around the world.[69] The images from Mars rovers *Spirit* and *Opportunity* were both viewed by millions of people globally. Science fiction films *Gravity*, *The Martian* and *Interstellar* have been hugely successful in terms of revenue generated.[70] This should be re-assuring to space tourism companies that can profit from a much smaller segment of the population who are inspired by space travel, and willing to pay for the opportunity. In 2002, Futron/Zogby conducted a *Space Tourism Market Survey*. They forecasted a suborbital market of several thousand tourists per year given an initial price point of $100,000 USD.[71] Although the Virgin Galactic price is two-and-a-half times as big, as of December 2014, they had already received approximately 700 reservations.[72] Based on these numbers,

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released 16 February 2015, accessed on 20 April 2015, http://www.monmouth.edu/assets/0/32212254770/32212254991/32212254992/32212254994/32212254995/30064771087/6314f1fc-8199-44ed-9f8a-ab4b2720bab5.pdf, 1.)

[68] According to the study, 58% of respondents agreed that private companies should be able to take people to space. (Source: Monmouth University Polling Institute, "National: Space Travel in the 21st Century," released 16 February 2015, accessed on 20 April 2015, http://www.monmouth.edu/assets/0/32212254770/32212254991/32212254992/32212254994/32212254995/30064771087/6314f1fc-8199-44ed-9f8a-ab4b2720bab5.pdf, 2.)

[69] Michael Humphrey, "Stratos on YouTube Live Topped 8 Million Concurrent Views," *Forbes*, 14 October 2012, accessed on 09 February 2016, http://www.forbes.com/sites/michaelhumphrey/2012/10/14/red-bull-stratos-live-topped-8-million-concurrent-views-on-youtube/#760e44496633.

[70] According to *Box Office Mojo* (www.boxofficemojo.com), *Gravity* earned $723M worldwide, *The Martian* earned $630M, and *Interstellar* earned $675M.

[71] S. Suzette Beard *et al*, "Space Tourism Market Study," *Futron Corporation*, October 2002, accessed on 09 February 2016, http://www.spaceportassociates.com/pdf/tourism.pdf, 50.

[72] Leonard David, "After SpaceShipTwo Tragedy, How Will Virgin Galactic Return to Flight?" *Space.com*, 24 December 2014, accessed on 09 February 2016, http://www.space.com/28088-virgin-galactic-spaceshiptwo-crash-aftermath.html.

interest on the order of several hundred customers per year seems reasonable, especially if costs decline in the future.

Hickman's second requirement is the establishment of a *Development Authority*, "a semi-sovereign governmental 'entity' … possessing legal ownership over the territory slated for development."[73] This requirement would need to be harmonized with the *1967 Outer Space Treaty* (amongst others) that denies the ability of any nation to declare sovereignty in outer space.[74] However, an *international organization* under the auspices of the United Nations could be designated to act in this capacity.[75] It would be responsible for capitalizing the venture, such as through the sale of bonds, property rights, or taxation.[76] Other academics examining this problem have come to a similar conclusion, stating that "eventually, when true private business operations are feasible on the moon or on asteroid, there will have to be some form of intermediary established to guarantee the right to use the territory."[77] This also contributes to Hickman's third and final requirement, which is "to maximize cash flows to pay for borrowing the capital necessary to begin construction."[78] By guaranteeing loans politically, the *Development Authority* can entice commercial investors to participate in buying up the debt. Combined with political representation of

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[73] Hickman, "The Political Economy of Very Large Space Projects," 8.
[74] United Nations Office for Outer Space Affairs, "Treaty on Principles Governing the Activities of Space in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies," *United Nations*, 19 December 1966, accessed on 10 February 2016, http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html, Article II.
[75] The *International Seabed Authority* established under UNCLOS will be discussed in Chapter 3.
[76] Hickman, "The Political Economy of Very Large Space Projects," 8.
[77] Henry R. Hertzfeld and Frans G. von der Dunk, "Bringing Space Law into the Commercial World: Property Rights without Sovereignty," *Chicago Journal of International Law* 6, no. 1 (Summer 2005): 95.
[78] Hickman, "The Political Economy of Very Large Space Projects," 8.

workers associated with the project (e.g. unions), this creates a public lobby for the continuance of the project in the face of possible setbacks.[79]

Hickman published his paper in 1999. Outside of (possibly) the International Space Station (ISS), no nation has undertaken any very large space projects. The ISS pre-dates Hickman's paper, with the first module being launched in 1998.[80] As an example of Hickman's three tenets, the ISS only really meets his first – that space-faring governments absorb as much cost as can be politically justified. The ISS is a consortium of government entities, led by the US and Russia through their national space agencies. According to the terms of the *Memorandum of Understanding* between NASA and the Russian Space Agency, the participating nations are responsible for the funding associated with their operational responsibilities.[81] There is no formal *Development Authority* or mechanism for recovering investment costs. This is not to say that some nations have not sought to make money off of the ISS. The most obvious example is the sale of space flights to the ISS by the Russian Space Agency beginning in 2001.[82] However, the ISS was not designed to generate revenue, but act as a "laboratory, permanent observatory, transportation node, servicing capability, assembly capability, research and technology capability, storage depot, and staging base."[83] Taken as a step in better understanding how to live and work in

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[79] *Ibid.*, 9.
[80] National Aeronautics and Space Administration, "ISS Assembly Mission 1 A/R," accessed on 20 April 2016, http://www.nasa.gov/mission_pages/station/structure/iss_assembly_1ar.html#.VxfRWVQrKW8.
[81] National Aeronautics and Space Administration, "Memorandum of Understanding between the National Aeronautics and Space Administration of the United States of America and the Russian Space Agency Concerning Cooperation on the Civil International Space Station," signed on 29 January 1998, accessed on 20 April 2016, http://www.nasa.gov/mission_pages/station/structure/elements/nasa_rsa.html.
[82] The US-based company *Space Adventures, Limited* actually contracted for the services of the Russian Space Agency on behalf of their client. (Source: Space Adventures, Limited, "Space Station," accessed on 20 April 2016, http://www.spaceadventures.com/experiences/space-station/.)
[83] Found in Article 2, this is a list of potential capabilities that the evolved ISS could provide. (Source: National Aeronautics and Space Administration, "Memorandum of Understanding between the National Aeronautics and Space Administration of the United States of America and the Russian Space Agency

space, it can be considered as the first step in *any* large space project that sees humans living in space. In that sense, it is a pre-cursor to all future manned space projects.

With Hickman's tenets in mind, are there any very large *commercially-led* space projects on the horizon? At this time, the nearest analogue appears to be an effort to colonize Mars within the century. There are a number of commercial and non-governmental organizations that are investigating efforts to send and sustain a manned presence on the Red Planet. Some of the most notable efforts are the non-profit *Mars One*[84], The Planetary Society's *Human Orbiting Mars* plan[85], the Mars Foundation's *Mars Homestead Project*[86], The Mars Society's *Mars Direct* initiative[87], and SpaceX's *Mars Colonial Transport*.[88] In parallel, NASA is building the *Space Launch System (SLS)* and *Orion Multi-Purpose Crew Vehicle* as the foundation for a publically-funded manned mission to Mars in the 2030 timeframe.[89]

Few of these efforts truly satisfy Hickman's criteria for a very large space project. Most of them are seeking to achieve their efforts with forecasted budgets of only a couple of billion dollars. *Mars One* believes that its first (one-way) mission to land four colonists will cost approximately $6B. Each subsequent landing of four colonists every two years

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Concerning Cooperation on the Civil International Space Station," signed on 29 January 1998, accessed on 20 April 2016, http://www.nasa.gov/mission_pages/station/structure/elements/nasa_rsa.html.)

84 Mars One, "Human Settlement on Mars," accessed on 09 February 2016, http://www.mars-one.com/.

85 The Planetary Society's plan is designed to inform NASA's manned Mars space program, and is not a separate, privately-funded effort. (Source: The Planetary Society, "Humans Orbiting Mars," accessed on 21 April 2016, http://hom.planetary.org/.)

86 Mars Foundation, "Our Mission," accessed on 21 April 2016, http://www.marsfoundation.org/our-mission/.

87 Mars Society, "Mars Direct," accessed on 21 April 2016, http://www.marssociety.org/home/about/mars-direct/.

88 Mike Wall, "Now Is the Time to Colonize Mars, Elon Musk Says," *Space.com*, 16 December 2015, accessed on 09 February 2016, http://www.space.com/31388-elon-musk-colonize-mars-now.html.

89 National Aeronautics and Space Administration, "NASA's Journey to Mars," 01 December 2014, accessed on 21 April 2016, http://www.nasa.gov/content/nasas-journey-to-mars.

will cost an additional $4B.[90] *Mars One* intends on operating as a combination of non-profit foundation, and for-profit company. They are currently funded by donations, but believe that they can develop multiple revenue streams based on media exposure, and intellectual property rights. The for-profit company will be open to investors who will fund the bulk of the mission, with their return on investment coming from the revenue streams. *Mars One* believes that "the revenues from media exposure are estimated at 10 Olympic games between today and the first year after human landing," or approximately $45B through 2028.[91] This seems ambitious. Moreover, it is unknowable until they attempt to negotiate for the sale of these rights. Until they can provide more tangible proof of revenue, it is unlikely that they will see significant commercial investment.

The *Mars Homestead* and *Mars Direct* initiatives have similar problems. Notably, no clear mechanism for generating revenue to spur investment. Like *Mars One*, they appear to be reliant on donations from private sponsors.[92] Moreover, neither presents a timeline or roadmap for accomplishing their plans. Despite their ambitious proposals, they are not serious candidates.

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[90] Mars One, "How much does the mission cost?" accessed on 21 April 2016, http://www.mars-one.com/faq/finance-and-feasibility/how-much-does-the-mission-cost.

[91] *Mars One* claims that the Olympics generates approximately $4.5B in revenue. According to their roadmap, the first manned mission will land on Mars in 2027. (Source: Mars One, "What is the Mars One business model?" accessed on 21 April 2016, http://www.mars-one.com/faq/finance-and-feasibility/what-is-the-mars-one-business-model.)

[92] The Mars Foundation is reliant on private donation and sponsorship. They advertise no plans for how to monetize their mission. (Source: Mars Foundation, "Donate," accessed on 21 April 2016, http://www.marsfoundation.org/donate/.) The Mars Society's *Mars Direct* is based on Robert Zubrin, David A. Baker and Owen Gwynne's 1991 paper "Mars Direct: A Simple, Robust, and Cost Effective Architecture for the Space Exploration Initiative" presented as the 29th Aerospace Sciences Meeting. Like the Mars Foundation, they present no clear mechanism to monetize their mission. (Source: Mars Society, "Donate," accessed on 21 April 2016, http://www.marssociety.org/home/join_us/donate.)

This leaves SpaceX as the lone contender. Unlike *Mars One*, they are a profitable commercial interest.[93] SpaceX CEO, Elon Musk, has been very public and vocal about his desire to colonize Mars.[94] The company's publically stated mission is "to revolutionize space technology, with the ultimate goal of enabling people to live on other planets."[95] Musk believes that by bringing down the cost of space flight, people will be able to afford to move to Mars. Effectively, the colonization effort will be self-funded by the participants themselves. Musk has stated that he believes the cost of a ticket from Earth-to-Mars will eventually sell for around $500,000.[96] The key to bringing down these costs will be making *completely* and *rapidly* re-useable rockets.[97] Unfortunately, despite frequent comments about his desire to colonize Mars, neither Musk, nor SpaceX proper, have publicized how they intend on achieving their goal. Moreover, Musk has failed to meet several self-imposed deadlines for speaking about his plans in the past.[98] Until a credible plan is presented, it is impossible to evaluate his effort against Hickman's tenets.[99]

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[93] John Lippert, "SpaceX Profitable as Musk Pulls in NASA Contracts, Google Cash," *Bloomberg Markets*, 04 March 2015, accessed on 22 April 2016, http://www.bloomberg.com/news/articles/2015-03-04/spacex-profitable-as-musk-pulls-in-nasa-contracts-google-cash.

[94] Mike Wall, "Now Is the Time to Colonize Mars, Elon Musk Says," *Space.com*, 16 December 2015, accessed on 09 February 2016, http://www.space.com/31388-elon-musk-colonize-mars-now.html; or "Elon Musk: Here's How We Can Fix Mars and Colonize It," *Business Insider*, 02 January 2014, accessed on 22 April 2016, http://www.businessinsider.com/elon-musk-colonizing-mars-2014-1.

[95] Space Exploration Technologies Corporation, "About," accessed on 25 April 2016, http://www.spacex.com/about.

[96] Musk believes that the half-million dollar price point will not emerge until around a decade after regular flight has been established. (Source: Kevin Fong, "Scott's Legacy – Episode 2," *BBC Radio 4*, last aired on 22 March 2012, accessed on 22 April 2016, http://www.bbc.co.uk/programmes/b01dhrmj.)

[97] Musk rebuts the space shuttle as re-useable because of the difficulty in refurbishing the vehicle after each flight (rapidity), and the loss of the main booster with each flight (complete re-useability). (Source: Kevin Fong, "Scott's Legacy – Episode 2," *BBC Radio 4*, last aired on 22 March 2012, accessed on 22 April 2016, http://www.bbc.co.uk/programmes/b01dhrmj.)

[98] In his conversation with Kevin Fong, Musk stated he would be ready to speak about his plans in the following year (2013). (Source: Kevin Fong, "Scott's Legacy – Episode 2," *BBC Radio 4*, last aired on 22 March 2012, accessed on 22 April 2016, http://www.bbc.co.uk/programmes/b01dhrmj.). In January 2015, he stated in an *Ask Me Anything (AMA)* on *Reddit* that he hoped to announce his plans before the end of that year (2015). (Source: Elon Musk, "I am Elon Musk, CEO/CTO of a rocket company, AMA!" *Reddit.com*, 06

Setting aside the *very large* space project, we will focus on the more mundane. Namely, what hinders the economic viability of commercial use of space today? We will examine three areas – (1) space access, (2) space vehicle fabrication, and (3) the user base. Or, taken another way - building it, launching it, and monetizing it.

Overcoming the Earth's gravity has long been a major cost driver. Historically, space access has been the purview of the nation state. The economic incentive for investment in basic scientific research and engineering was absent without the backing of government space programs.[100] Without a solid understanding of the space environment, and the associated engineering required to overcome the dangers, entering the space market was a risky proposition. As a consequence, the launch industry became complacent, "because their launches were guaranteed by government contracts that [did] not encourage risk taking."[101] Cost effectiveness was subordinated to safety and reliability.[102]

Today, most launch providers, including the United Launch Alliance (ULA), rely on rocket engines designed in the 1990's. The *Atlas V* (developed by Lockheed-Martin) is

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January 2015, accessed on 22 April 2016, https://www.reddit.com/r/IAmA/comments/2rgsan/i_am_elon_musk_ceocto_of_a_rocket_company_ama/.)

[99] Recent reporting suggests that Musk will present his plans at the 2016 *International Astronauticcal Conference* this September. (Source: Eric Berger, "Elon Musk to unveil Mars plans this year, wants to go to space by 2020," *Ars Technica*, 28 January 2016, accessed on 22 April 2016, http://arstechnica.com/science/2016/01/elon-musk-to-unveil-mars-plans-this-year-wants-to-go-to-space-by-2020/.)

[100] The US space program peaked at 4.4% of the total federal budget in 1966. The US federal budget represented 16.5% of total GDP. This meant the US space program was consuming approximately 0.72% of US GDP. (Source: Federal Reserve Bank of St. Louis, "Federal Net Outlays as Percent of Gross Domestic Product," updated on 25 March 2016, accessed on 22 April 2016, https://research.stlouisfed.org/fred2/series/FYONGDA188S.)

[101] Clemens Rumpf, "Increased competition will challenge ESA's space authority," *The Space Review*, 02 February 2015, accessed on 22 April 2016, http://www.thespacereview.com/article/2687/1.

[102] In discussing their sole-source contracting of the *Evolved Expendable Launch Vehicle (EELV)* to the United Launch Alliance, the US Government Accountability Office reiterated the value of a high rate of success. However, "estimates indicated launch prices were expected to increase at an unsustainable rate," which resulted in a re-examination of bidding criteria. (Source: United States Government Accountability Office, "Letter to the Honourable Carl Levin and the Honourable John McCain regarding The Air Force's Evolved Expendable Launch Vehicle Competitive Procurement," dated 04 March 2014, accessed on 22 April 2016, http://www.gao.gov/assets/670/661330.pdf, 9 (Slide 4).)

powered by the Russian *NPO Energomash* RD-180.[103] It was first test fired in 1999.[104] The *Delta IV* (originally developed by McDonnell-Douglas, now owned by Boeing) is powered by the RS-68 from US manufacturer Aerojet Rocketdyne. It was first test fired in 1998.[105] Both launch vehicles are operated by the ULA, although the company is seeking to phase-out the *Delta IV* due to cost.[106] However, access to RD-180 motors has been jeopardized by Russian-US enmity over Crimea since 2014.[107] This hindered ULA's competitiveness, and saw them fail to bid on an upcoming US Air Force Global Positioning Satellite launch contract.[108] One of their senior executives later admitted that "SpaceX was able to offer launch capabilities for as little as one-third the price of what United Launch Alliance could."[109]

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103 The *Atlas V* uses the Russian RD-180 engine that was first tested in 1999. (Source: Warren Ferster, "ULA Execs Say RD-180 Engine Ban Blocks Path to Next-gen Rocket," *SpaceNews*, 22 May 2015, accessed on 19 April 2016, http://spacenews.com/ula-execs-say-rd-180-engine-ban-blocks-path-to-next-gen-rocket/.)

104 The RD-180 engine was developed by *NPO Energomash* in the 1990's and first tested in 1999. (Source: "The Engines That Came In From The Cold," *Equinox*, BBC Channel 4, aired 01 March 2001, posted by Matthew Travis, accessed on 19 April 2016, https://www.youtube.com/watch?v=TMbl_ofF3AM, 37:24 – 49:32.)

105 Aerojet Rocketdyne, "RS-68 Engine," accessed on 22 April 2016, http://www.rocket.com/rs-68-engine.

106 Mike Gruss, "ULA Targets 2018 for Delta 4 Phase-out, Seeks Relaxation of RD-180 Ban," *SpaceNews*, 03 March 2015, accessed on 22 April 2016, http://spacenews.com/ula-targets-2018-for-delta-4-phase-out-seeks-relaxation-of-rd-180-ban/.

107 Andrea Shalal, "ULA Orders 20 More RD-180 Rocket Engines," *SpaceNews*, 23 December 2015, accessed on 09 February 2016, http://spacenews.com/ula-orders-20-more-rd-180-rocket-engines/.

108 Mike Gruss, "ULA Punts on GPS 3 Launch Contract Long Sought by SpaceX," *SpaceNews*, 16 November 2015, accessed on 22 April 2016, http://spacenews.com/ula-declines-to-bid-on-gps-3-launch-contract-long-sought-by-spacex/.

109 Eric Berger, "ULA executive admits company cannot compete with SpaceX on launch costs," *Ars Technica*, 17 March 2016, accessed on 22 April 2016, http://arstechnica.com/science/2016/03/ula-executive-admits-company-cannot-compete-with-spacex-on-launch-costs/.

Figure 2.1 – SpaceX *Falcon 9* in a controlled descent. (Source: SpaceX[110])

Although these boosters are powerful and reliable, they have not taken advantage of new material science, manufacturing, and computation that has emerged in the new century. Manufacturers such as SpaceX, Blue Origin, and Rocket Lab[111] are building their booster technology from the ground up with *both* cost and reliability being key components in their designs. Much like Musk, CEO of Blue Origin Jeff Bezos is a proponent of re-usability, stating "because space access is so expensive, if you can do it another way, you will… That changes if you can dramatically lower the cost of access, and the only way to do that is reusability."[112] To achieve this goal, Blue Origin's design philosophy is "to

[110] Space X Falcon 9 in a controlled descent with landing legs deployed. Image credited to SpaceX. Taken from http://www.americaspace.com/?p=89910 on 06 May 2016.
[111] Rocket Lab. "Electron." Accessed on 09 February 2016. https://www.rocketlabusa.com/.
[112] Eric Berger, "Astronaut Prime: Here's how Jeff Bezos plans to remake spaceflight," *Ars Technica*, 05 April 2016, accessed on 22 April 2016, http://arstechnica.com/science/2016/04/astronaut-prime-heres-how-jeff-bezos-plans-to-remake-spaceflight/.

choose a medium-performing version of a high-performance architecture."[113] Instead of using the best materials to achieve the highest performance, they use the best materials to achieve a more moderate performance, putting less stress on the system, and facilitating re-usability. Prior to re-launching their *New Shepard* rocket, the refurbishment costs were "in the small tens of thousands of dollars," according to Bezos.[114]

Figure 2.2 - Blue Origin *New Shepard* launching. (Source: Blue Origin[115])

The BE-3 engines used on the *New Shepard* are much smaller than the *Merlin* engines used by SpaceX.[116] However, the *New Shepard* is only intended for sub-orbital

[113] Eric Berger, "Behind the curtain: Ars goes inside Blue Origin's secretive rocket factory," *Ars Technica*, 09 March 2016, accessed on 22 April 2016, http://arstechnica.com/science/2016/03/behind-the-curtain-ars-goes-inside-blue-origins-secretive-rocket-factory/.
[114] *Ibid.*
[115] Blue Origin *New Shepard* launching for the second time. Image credited to Blue Origin. Taken from https://www.blueorigin.com/gallery on 06 May 2016.

tourism, and not orbital insertion of satellites.[117] Nonetheless, Blue Origin have teamed up with ULA to develop new engines for the *Vulcan* rocket, which ULA intends to use in place of the *Atlas V*.[118] The BE-4 is intended to replace the Russian-designed and manufactured RD-180 with two engines, each generating 550,000 pounds of thrust at lift-off.[119] Bezos believes that the privately-funded BE-4 will be developed more cheaply, and more quickly, than competitor Aerojet Rocketdyne, who are providing a back-up engine for the *Vulcan* using public funding.[120]

Much like Blue Origin, Rocket Lab is another upstart engine manufacturer. They are focusing on small satellites going into low-Earth orbit.[121] Like Blue Origin and SpaceX, they have developed their own rocket, the *Electron*, and own engine, the *Rutherford*. Much smaller than even the *New Shepard*, their engine only produces approximately 5,000 pounds of thrust on take-off. However, this is enough to launch

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[116] BE-3 engines produce 110,000 lbs of thrust at launch, compared with 170,000 pounds of thrust for the *Merlin*. (Sources: Blue Origin, "Our Approach to Technology," accessed on 22 April 2016, https://www.blueorigin.com/technology#engine_stories_1, and Space Exploration Technologies Corporation, "MERLIN Engines," updated on 26 March 2013, accessed on 15 April 2016, http://www.spacex.com/news/2013/03/26/merlin-engines.)

[117] Richard Hollingham, "What's the best (and cheapest) way to take a trip to space?" *BBC News*, 22 April 2016, accessed on 22 April 2016, http://www.bbc.com/future/story/20160422-whats-the-best-and-cheapest-way-to-take-a-trip-to-space?ocid=global_future_rss.

[118] Marcia S. Smith, "ULA Wins Big with Two AF Propulsion Contracts, One with Blue Origin, One with Aerojet Rocketdyne," *Space Policy Online*, 29 February 2016, accessed on 22 April 2016, http://www.spacepolicyonline.com/news/ula-wins-big-with-two-af-propulsion-contracts-one-with-blue-origin-one-with-aerojet-rocketdyne.

[119] Blue Origin, "BE-4: America's Next Rocket Engine," accessed on 22 April 2016, https://www.blueorigin.com/be4.

[120] Eric Berger, "Behind the curtain: Ars goes inside Blue Origin's secretive rocket factory," *Ars Technica*, 09 March 2016, accessed on 22 April 2016, http://arstechnica.com/science/2016/03/behind-the-curtain-ars-goes-inside-blue-origins-secretive-rocket-factory/.

[121] Rae Botsford End, "Rocket Lab: The Electron, the Rutherford, and Why Peter Beck Started It in the First Place," *SpaceFlight Insider*, 02 May 2015, accessed on 22 April 2016, http://www.spaceflightinsider.com/missions/commercial/rocket-lab-electron-rutherford-peter-beck-started-first-place/.

approximately 100 kilograms of payload into a 500 kilometer sun-synchronous orbit.[122] They claim to manufacture "all primary components, including the regeneratively cooled thrust chamber, injector, pumps and main propellant valves" using 3D additive printing,[123] and "that the whole engine can be built in just three days."[124] With a price tag of approximately $5 million per launch, as of May 2015, they already had 30 launches booked.[125]

Rocket Lab is not alone in pursuing the small satellite, low-Earth orbit market. Virgin Galactic added their own satellite launch vehicle, called *LauncherOne,* in 2012.[126] Similar to Rocket Lab, they are offering payloads of up to 200 kilograms into a sun-synchronous low-Earth orbit for less than $10M.[127] Unlike the others, Virgin Galactic is launching their rocket from the back of a modified Boeing 747.[128] As an air-launched rocket, they can operate "outside of the US federal launch range system, … can select launch coordinates tailored to [their] customer's specific orbit and can operate independently of many external factors, such as weather, offline radar tracking assets, …

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122 *Ibid.*
123 Rocket Lab, "Rutherford," accessed on 22 April 2016, https://rocketlabusa.com/about-us/propulsion/rutherford/. Rocket Lab is not alone in investigating 3D printed components. NASA has also test high-temperature 3D printed rocket engine parts. (Source: National Aeronautics and Space Administration, "Piece by Piece: NASA Team Moves Closer to Building a 3-D Printed Rocket Engine," 17 December 2015, accessed on 22 April 2016, http://www.nasa.gov/centers/marshall/news/news/releases/2015/piece-by-piece-nasa-team-moves-closer-to-building-a-3-d-printed-rocket-engine.html.)
124 Rae Botsford End, "Rocket Lab: The Electron, the Rutherford, and Why Peter Beck Started It in the First Place."
125 *Ibid.*
126 Chris Bergin and William Graham, "Commercial space flight shows reignited interest in Air Launch System," *NASA Spaceflight*, 13 July 2012, accessed on 23 April 2016, https://www.nasaspaceflight.com/2012/07/commercial-shows-reignited-interest-air-launch-system/.
127 Virgin Galactic, "LauncherOne Performance," accessed on 23 April 2016, http://www.virgingalactic.com/satellite-launch/l1-performance/.
128 Kasandra Brabaw, "Meet 'Cosmic Girl': Virgin Galactic's New Satellite Launching Jet (Video)," *Space.com*, 09 December 2015, accessed on 19 April 2016, http://www.space.com/31322-virgin-galactic-cosmic-girl-launcherone-plane.html.

and traffic jams."[129] Air-launch also allows the aircraft to impart some of its speed to the rocket, and lifts it into less dense atmosphere. This can yield significant performance improvements since most losses due to atmospheric drag are incurred in the first 10 kilometers of ascent.[130] Internet start-up, *OneWeb*, has already contracted with Virgin Galactic to launch hundreds of tiny satellites into orbit to provide ubiquitous, worldwide internet access.[131]

All four companies are single-minded in their pursuit of *inexpensive* access to space. Blue Origin and SpaceX are both seeking complete and rapid re-use of their rockets to reduce costs. Rocket Lab and Virgin Galactic are attempting to achieve cost savings by explicitly building lower-cost options for a niche market. Figure 2.1 identifies the approximate cost per kilogram of sending a payload into either low-Earth orbit (LEO), or Geostationary Transfer Orbit (GTO). When the SpaceX *Falcon Heavy* becomes available, the forecasted cost per kilogram will reach approximately $1,700, or less than $800 per pound, for low-Earth orbit. This is the cost before factoring in the potential re-use of the rocket. SpaceX has previously stated that re-useability will bring down the cost of space access by two orders of magnitude.[132] If successful, the resulting cost per kilogram would be cost competitive with surface shipping around the world.[133]

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[129] Virgin Galactic, "LauncherOne Performance."

[130] Chris Bergin and William Graham, "Commercial space flight shows reignited interest in Air Launch System," *NASA Spaceflight*, 13 July 2012, accessed on 23 April 2016, https://www.nasaspaceflight.com/2012/07/commercial-shows-reignited-interest-air-launch-system/.

[131] Pual Brinkmann, "OneWeb plans to build, launch satellites in Florida, with Virgin Galactic," *Orlando Sentinel*, 18 April 2016, accessed on 23 April 2016, http://www.orlandosentinel.com/business/os-oneweb-virgin-satellites-20160418-story.html.

[132] Doug Bierend, "SpaceX Was Born Because Elon Musk Wanted to Grow Plants on Mars," *Motherboard*, 17 July 2014, accessed on 23 April 2016, http://motherboard.vice.com/read/spacex-is-because-elon-musk-wanted-to-grow-plants-on-mars.

[133] Sam Dinkin, "Increasing the profit ratio," *The Space Review*, 04 January 2016, accessed on 09 February 2016, http://www.thespacereview.com/article/2893/1.

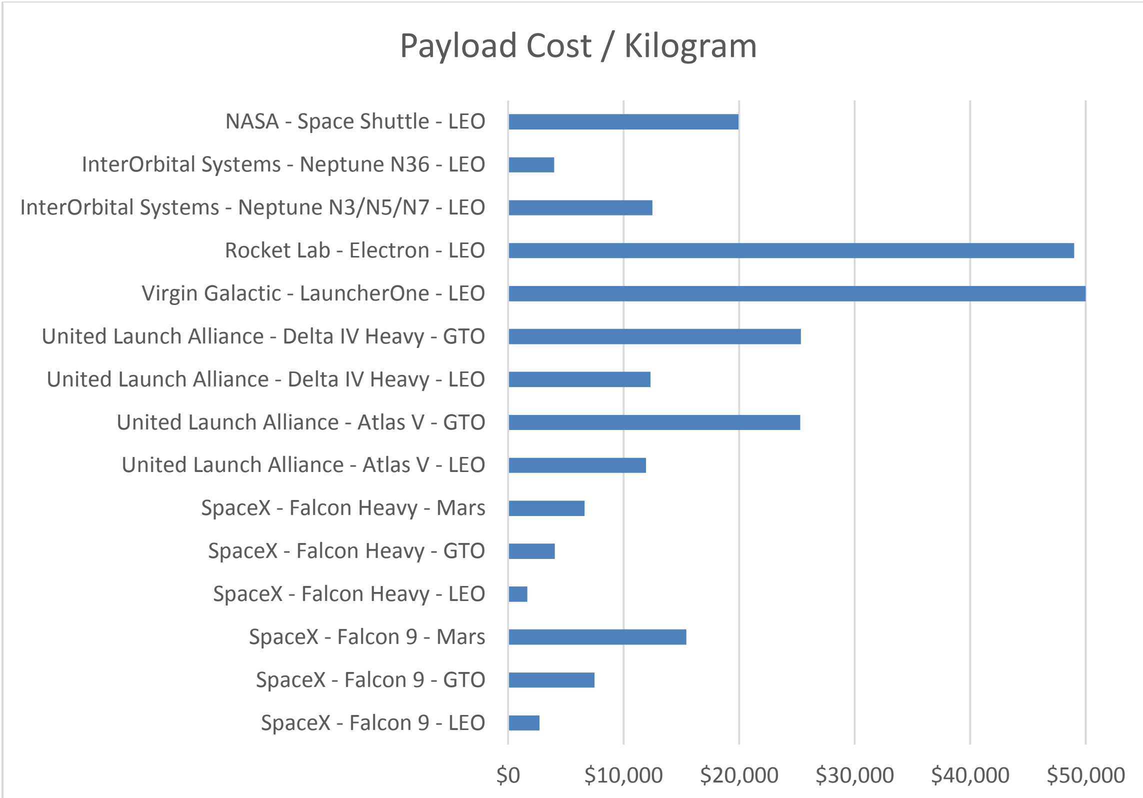

Figure 2.3 - Payload Cost / Kilogram to Orbit (Multiple Sources[134])

[134] Sources - Space Exploration Technologies Corporation, "Capabilities & Services," accessed on 23 April 2016, http://www.spacex.com/about/capabilities; Colin Clark, "ULA Fires Back at SpaceX at Space Symposium; Details Launch Costs," *Breaking Defense*, 20 May 2014, accessed on 23 April 2016, http://breakingdefense.com/2014/05/ula-fires-back-at-spacex-at-space-symposium-details-launch-costs/; United Launch Alliance, "Atlas V," accessed on 23 April 2016, http://www.ulalaunch.com/products_atlasv.aspx; United Launch Alliance, "Delta IV," accessed on 23 April 2016, http://www.ulalaunch.com/products_deltaiv.aspx; Virgin Galactic, "LauncherOne Performance," accessed on 23 April 2016, http://www.virgingalactic.com/satellite-launch/l1-performance/; Rae Botsford End, "Rocket Lab: The Electron, the Rutherford, and Why Peter Beck Started It in the First Place," *SpaceFlight Insider*, 02 May 2015, accessed on 22 April 2016, http://www.spaceflightinsider.com/missions/commercial/rocket-lab-electron-rutherford-peter-beck-started-first-place/; Interorbital Systems, "IOS NEPTUNE System Launch Vehicles," accessed on 08 May 2016. http://www.interorbital.com/interorbital_06222015_012.htm; Interorbital Systems, "NEPTUNE Launch Services," accessed on 08 May 2016, http://www.interorbital.com/interorbital_06222015_003.htm; Dana Andrews, "Space Shuttle 2.0: What did we learn?" *The Space Review*, 11 July 2011, accessed on 08 May 2016, http://www.thespacereview.com/article/1881/1; European Space Agency, "Shuttle Technical Facts," Accessed on 08 May 2016, http://m.esa.int/Our_Activities/Human_Spaceflight/Space_Shuttle/Shuttle_technical_facts.

Manufacturer	Model	Type of Orbit	Max Payload	Cost / Launch	Cost / Kilogram
Rocket Lab	Electron	LEO	100 kg / 220 lbs	$4.9M	$49,000
Virgin Galactic	LauncherOne	LEO	200 kg / 441 lbs	$10M	$50,000
United Launch Alliance	Delta IV Heavy	GTO	13,810 kg / 30,440 lbs	$350M	$25,344
United Launch Alliance	Delta IV Heavy	LEO	28,370 kg / 62,440 lbs	$350M	$12,337
United Launch Alliance	Atlas V (551)	GTO	8,900 kg / 19,620 lbs	$225M	$25,281
United Launch Alliance	Atlas V (551)	LEO	18,850 kg / 41,570 lbs	$225M	$11,936
SpaceX	Falcon Heavy	GTO	22,200 kg / 48,940 lbs	$90M	$4,054
SpaceX	Falcon Heavy	LEO	54,400 kg / 119,930 lbs	$90M	$1,654
SpaceX	Falcon Heavy	Mars	13,600 kg / 29,980 lbs	$90M	$22,388
SpaceX	Falcon 9	GTO	8,300 kg / 18,300 lbs	$62M	$7,470
SpaceX	Falcon 9	LEO	22,800 kg / 50,265 lbs	$62M	$2,719
SpaceX	Falcon 9	Mars	4,020 kg / 8,860 lbs	$62M	$4,559
InterOrbital Systems[135]	Neptune N3/N5/N7	LEO	18 kg / 40 kg / 75 kg	Unknown	$12,500
InterOrbital Systems[135]	Neptune N36	LEO	1000 kg	Unknown	$4,000
NASA	Space Shuttle	LEO	25,060 kg / 55,248 lbs	$500M	$19,952

Table 2.1 – Rocket Models and Capabilities (Multiple Sources[136])

[135] InterOrbital Systems has four launch options available based on the weight of the payload– up to 18 kg, 30 – 40 kg, 75 kg, and 1000 kg. They directly quote the price per kilogram versus providing the maximum payload per rocket. They also appear to be limited to an altitude of only 310 kilometers. (Sources: Interorbital Systems, "IOS NEPTUNE System Launch Vehicles," accessed on 08 May 2016. http://www.interorbital.com/interorbital_06222015_012.htm; and, Interorbital Systems, "NEPTUNE Launch Services," accessed on 08 May 2016, http://www.interorbital.com/interorbital_06222015_003.htm.)

[136] Sources - Space Exploration Technologies Corporation, "Capabilities & Services," accessed on 23 April 2016, http://www.spacex.com/about/capabilities; Colin Clark, "ULA Fires Back at SpaceX at Space Symposium; Details Launch Costs," *Breaking Defense*, 20 May 2014, accessed on 23 April 2016, http://breakingdefense.com/2014/05/ula-fires-back-at-spacex-at-space-symposium-details-launch-costs/;

Space access alone is not the only cost for space-based industry. Manufacturing suitable space vehicles is also a complex, and potentially costly, undertaking. Government satellite projects often run into the billions of dollars and several years of development prior to launch. For instance, the National Oceanic and Atmospheric Administration's (NOAA) next-generation weather system, the Joint Polar Satellite System (JPSS), is a series of five satellites being launched between 2017 and 2031.[137] Each satellite costs between $300M - $500M and takes approximately two-to-three years to manufacture.[138] The overall budget for the project is estimated to be approximately $12.9B.[139] In the case of the JPSS satellites, they are highly specialized and difficult to replace quickly. The cost of losing the satellite is not just the capital cost associated with building another version,

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United Launch Alliance, "Atlas V," accessed on 23 April 2016, http://www.ulalaunch.com/products_atlasv.aspx; United Launch Alliance, "Delta IV," accessed on 23 April 2016, http://www.ulalaunch.com/products_deltaiv.aspx; Virgin Galactic, "LauncherOne Performance," accessed on 23 April 2016, http://www.virgingalactic.com/satellite-launch/l1-performance/; Rae Botsford End, "Rocket Lab: The Electron, the Rutherford, and Why Peter Beck Started It in the First Place," *SpaceFlight Insider*, 02 May 2015, accessed on 22 April 2016, http://www.spaceflightinsider.com/missions/commercial/rocket-lab-electron-rutherford-peter-beck-started-first-place/; Interorbital Systems, "IOS NEPTUNE System Launch Vehicles," accessed on 08 May 2016. http://www.interorbital.com/interorbital_06222015_012.htm; Interorbital Systems, "NEPTUNE Launch Services," accessed on 08 May 2016, http://www.interorbital.com/interorbital_06222015_003.htm; Dana Andrews, "Space Shuttle 2.0: What did we learn?" *The Space Review*, 11 July 2011, accessed on 08 May 2016, http://www.thespacereview.com/article/1881/1; European Space Agency, "Shuttle Technical Facts," Accessed on 08 May 2016, http://m.esa.int/Our_Activities/Human_Spaceflight/Space_Shuttle/Shuttle_technical_facts.

[137] National Oceanic and Atmospheric Administration, "About JPSS," accessed on 25 April 2016, http://www.jpss.noaa.gov/satellites.html.

[138] The first JPSS satellite was contracted to Ball Aerospace at a contract value of approximately $300M. The second satellite contract was award to Orbital ATK with an approximate value of $470M. (Source: Laura Keeney, "Next-gen JPSS-1 weather satellite powers up at Ball in Boulder," *The Denver Post*, 01 July 2015, accessed on 25 April 2016, http://www.denverpost.com/weathernews/ci_28416232/next-gen-jpss-1-weather-satellite-powers-up.)

[139] The US National Oceanic and Atmospheric Administration spent 36.6% of their $5.1B budget in 2013 on satellite programs ($1.87B). The bulk of that funding went to the continued development of the Joint Polar Satellite System (JPSS) which has a forecasted overall cost of $12.9B. (Source: Lauren Morello, "Soaring Satellite Costs Spur US Government to Seek Budget Cuts," *Scientific American*, 21 March 2012, accessed on 25 April 2016, http://www.scientificamerican.com/article/soaring-satellite-costs-spur-us-government-to-seek-budget-cuts/.)

but the secondary costs associated with a loss in service while awaiting replacement.[140] These factors make reliability *the* key concern during launch, which has undermined calls for more cost effectiveness.

By way of comparison, commercial provider Iridium announced in 2010 that they were updating their constellation of communication satellites with a new fleet of 72 operational and in-orbit spares.[141] Cost for the "development, manufacture and launch of the constellation, [was] … anticipated to be approximately $2.9 billion."[142] Fortunately, Iridium has a pre-established customer base, with revenue of approximately $411M in 2015 based on 782,000 subscribers.[143] This gives them an advantage with investors because of their proven capacity to generate income. For new entrants, this is more difficult, especially if they intend on pioneering new markets (e.g. space-based manufacturing) because of the lack of a proven revenue model.

To reduce costs and time, many companies are avoiding fully-customized satellites in favour of standardized form factors. For instance, a single unit (1U) *CubeSat* is a small 10 x 10 x 10 centimeter cube with weight less than one kilogram.[144] Multiple units are combined together as necessary to create more complex structures with each sub-unit respecting the original size and weight restrictions. The *CubeSat* arose out of academia

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[140] According to NOAA officials, weather models depend on data developed by weather satellites. Gaps in coverage can result in significant changes to predictions that can effect responsiveness. (Source: Lauren Morello, "Soaring Satellite Costs Spur US Government to Seek Budget Cuts," *Scientific American*, 21 March 2012, accessed on 25 April 2016, http://www.scientificamerican.com/article/soaring-satellite-costs-spur-us-government-to-seek-budget-cuts/.)

[141] Iridium, "Iridium Announces Comprehensive Plan for Next-Generation Constellation, 02 Jun 2010, accessed on 25 April 2016, http://investor.iridium.com/releasedetail.cfm?releaseid=475071.

[142] *Ibid*.

[143] Peter de Selding, "Iridium, frustrated with Russian red tape, to launch first 10 Iridium Next satellites with SpaceX in July." *Space News*, 25 February 2016, accessed on 25 April 2016, http://spacenews.com/iridium-frustrated-by-russian-red-tape-to-launch-first-10-iridium-next-satellites-with-spacex-in-july/.

[144] Leonard David, "Cubesats: Tiny Spacecraft, Huge Payoffs," *Space.com*, 08 September 2004, accessed on 25 April 2016, http://www.space.com/308-cubesats-tiny-spacecraft-huge-payoffs.html.

with students and professors looking for an inexpensive means of conducting experiments in orbit. Using commercial-off-the-shelf technology, they sought to keep costs down.[145] By standardizing on a size and weight, space launch providers are more easily able to take them as secondary cargo to fill out otherwise vacant space and weight in a rocket launch.[146] In 2004, a single-unit *CubeSat* could be built for approximately $30K, with launch into low-Earth orbit costing approximately $40K.[147] In 2016, InterOrbital Systems is advertising a complete *CubeSat* kit which includes a *free launch* as part of the cost.[148] Their even-smaller *TubeSat* offering was available for only $8K including launch in 2012.[149] Meanwhile, Rocket Lab is also targeting *CubeSat* customers, offering a one-unit launch for between $50K – 90K, and a three-unit launch for between $180 – 250K.[150]

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[145] *Ibid.*

[146] The Poly-PicoSatellite Orbital Deployer (P-POD) can accommodate up to three *CubeSats* and can be carried on an increasing number of launch vehicles. (Source: Jeff Foust, "CubeSats get big," *The Space Review*, 10 September 2012, accessed on 25 April 2016, http://www.thespacereview.com/article/2155/1.)

[147] Leonard David, "Cubesats: Tiny Spacecraft, Huge Payoffs".

[148] Interorbital Systems, "Interorbital Satellite Kits and Launch Services," accessed on 25 April 2015, http://www.interorbital.com/interorbital_06222015_030.htm.

[149] Brian Dodson, "Launch your own satellite for US$8000," *Gizmag*, 22 April 2012, accessed on 25 April 2016, http://www.gizmag.com/tubesat-personal-satellite/22211/.

[150] Rocket Lab, "Space Is Open For Business, Online," accessed on 25 April 2016, https://rocketlabusa.com/space-is-open-for-business-online/.

Figure 2.4 – M-Cubed/COVE-2 *CubeSat* in orbit. (Source: Jet Propulsion Laboratory[151])

The *CubeSat* is not alone in finding a market. According to industry analyst SpaceWorks, the total number of small form factor satellites (< 50 kilograms, also known as *micro, nano, pico* or *femtosatellites* based on their weight[152]) was expected rise from approximately 150 satellites launched per year in 2014 to approximately 300 satellites launched per year in 2016.[153] By 2020, the forecast is between 410 - 543 satellites per

[151] The Michigan Multipurpose Minisatellite (M-Cubed) carrying the CubeSat On-board Processing Validation Experiment (COVE) is a one-unit (1U) *CubeSat* developed to image the earth. It was launched on 05 December 2013 from Vanderberg Air Force Base aboard a *Delta II* rocket. (Source: Jet Propulsion Laboratory, "M-Cubed/COVE-2," accessed on 06 May 2016, http://www.jpl.nasa.gov/cubesat/missions/mcubed.php.)

[152] Based on the categorization of the study, the associated satellite sizes are based on weight with *femtosatellite*: 10 – 100g, *picosatellite*: < 1 kg, *nanosatellite*: 1 – 10 kgs, *microsatellite*: 10 – 100 kg, and *small satellite*: 100 – 500 kgs. (Source: Elizabeth Buchen and Dominic DePasquale, "2014 Nano / Microsatellite Market Assessment." *SpaceWorks Enterprises, Inc*., 2014, accessed on 09 February 2016, http://www.sei.aero/eng/papers/uploads/archive/SpaceWorks_Nano_Microsatellite_Market_Assessment_January_2014.pdf, 5.)

[153] By comparison, between 2009 and 2013, commercial launches were only 20% of the market. Moreover, in absolute terms, there is a forecasted 14-fold increase in the total number of commercial satellites being launched. (Source: Elizabeth Buchen and Dominic DePasquale, "2014 Nano / Microsatellite Market Assessment." *SpaceWorks Enterprises, Inc*., 2014, accessed on 09 February 2016,

year.[154] Of these launches, commercial customers will account for an increasing percentage, accounting for 56% of total sub-50 kilogram satellites launched in the 2014 – 2016 window.[155] In reality, a total of 158 sub-50 kilogram satellites were launched in 2014, beating the estimate.[156] However, the outlook for 2015 was not as positive due to launch failures by Orbital ATK and SpaceX which reduced the opportunities for flight.[157] Nonetheless, of the approximately 300 total satellites launched in 2015, slightly less than half weighed 10 kilograms or less, showing the interest in this class of satellite.[158]

The advantages from standardizing on a satellite form factor were also not lost to the government. The US Department of Defense (DoD) established an *Operationally Responsive Space (ORS)* office in 2007.[159] The ORS has sought to decrease the time required to conceive, design, build, and launch a satellite from several years to several months.[160] Instead of each satellite being a unique design, they have invested in developing a modular platform, known as the *Modular Space Vehicle* (MSV).[161] By

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http://www.sei.aero/eng/papers/uploads/archive/SpaceWorks_Nano_Microsatellite_Market_Assessment_January_2014.pdf, 7.)

[154] Elizabeth Buchen and Dominic DePasquale, "2014 Nano / Microsatellite Market Assessment." *SpaceWorks Enterprises, Inc*., 2014, accessed on 09 February 2016, http://www.sei.aero/eng/papers/uploads/archive/SpaceWorks_Nano_Microsatellite_Market_Assessment_January_2014.pdf, 4 or 7.

[155] Commercial customers only accounted for 8% of *nano/microsatellites* launches between 2009 and 2013. (Source: Elizabeth Buchen and Dominic DePasquale, "2014 Nano / Microsatellite Market Assessment." *SpaceWorks Enterprises, Inc*., 2014, accessed on 09 February 2016, http://www.sei.aero/eng/papers/uploads/archive/SpaceWorks_Nano_Microsatellite_Market_Assessment_January_2014.pdf, 9)

[156] Jeff Foust, "Launch Failures Dent Growth in Small Satellites," *The Space Review*, 12 August 2015, accessed on 25 April 2016, http://spacenews.com/launch-failures-dent-growth-in-small-satellites/.

[157] *Ibid*.

[158] Space Foundation, "The Space Report 2015 – Overiew," accessed on 16 April 2016, http://www.spacefoundation.org/sites/default/files/downloads/The_Space_Report_2015_Overview_TOC_Exhibits.pdf, 2.

[159] Sheila Rupp, "Operationally Responsive Space," *Kirtland Air Force Base*, 22 May 2007, accessed on 09 February 2016, http://www.kirtland.af.mil/news/story.asp?id=123054292.

[160] *Ibid*.

[161] "Modular Space Vehicle (MSV) Bus, United States of America," *Air Force Technology*. Accessed on 09 February 2016. http://www.airforce-technology.com/projects/modular-space-vehicle-msv-bus/.

re-using components between designs, they cut down on time and cost while sacrificing optimal design efficiency.[162] By keeping the final product small, they can take advantage of new opportunities for space launch from new providers (e.g. SpaceX, Virgin Galactic), giving them more options for cost or timeliness.[163]

The final element affecting space use is its monetization. What is the market? What are the opportunities for growth? According to *The Space Report 2015*, global space activity was valued at $330B in 2014, with the bulk (76%) coming from commercial infrastructure, support industries, products and services.[164] This was a 9% increase year-over-year.[165] The largest individual sector was direct-to-home television services, which accounted for nearly three quarters of all spending on space products and services, or approximately $92.4B in total revenue.[166] This market is expected to continue to increase as subscribers from South America, South Asia, Southeast Asia and Sub-Saharan Africa join the global middle class.[167] By 2022, it is expected to generate subscriber revenue of approximately $134.4B.[168]

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162 *Ibid*.
163 Steven Tomaszweksi, "How the US Military is Preparing for Hostile Threats to Its Satellites," *Vice*, 05 May 2015, accessed on 09 February 2016, https://news.vice.com/article/how-the-us-military-is-preparing-for-hostile-threats-to-its-satellites.
164 See Figure 2.2. (Source: Space Foundation, "The Space Report 2015 – Overiew," accessed on 16 April 2016, http://www.spacefoundation.org/sites/default/files/downloads/The_Space_Report_2015_Overview_TOC_Exhibits.pdf, 1.)
165 Space Foundation, "The Space Report 2015 – Overiew," accessed on 16 April 2016, http://www.spacefoundation.org/sites/default/files/downloads/The_Space_Report_2015_Overview_TOC_Exhibits.pdf, 2.
166 *Ibid*, 2.
167 Northern Sky Research, "Global Direct-to-Home Markets, 6th Edition," July 2013, accessed on 25 April 2016, www.nsr.com/upload/research_reports/NSR_DTH6_Brief_1.pdf, 6.
168 *Ibid*, 6.

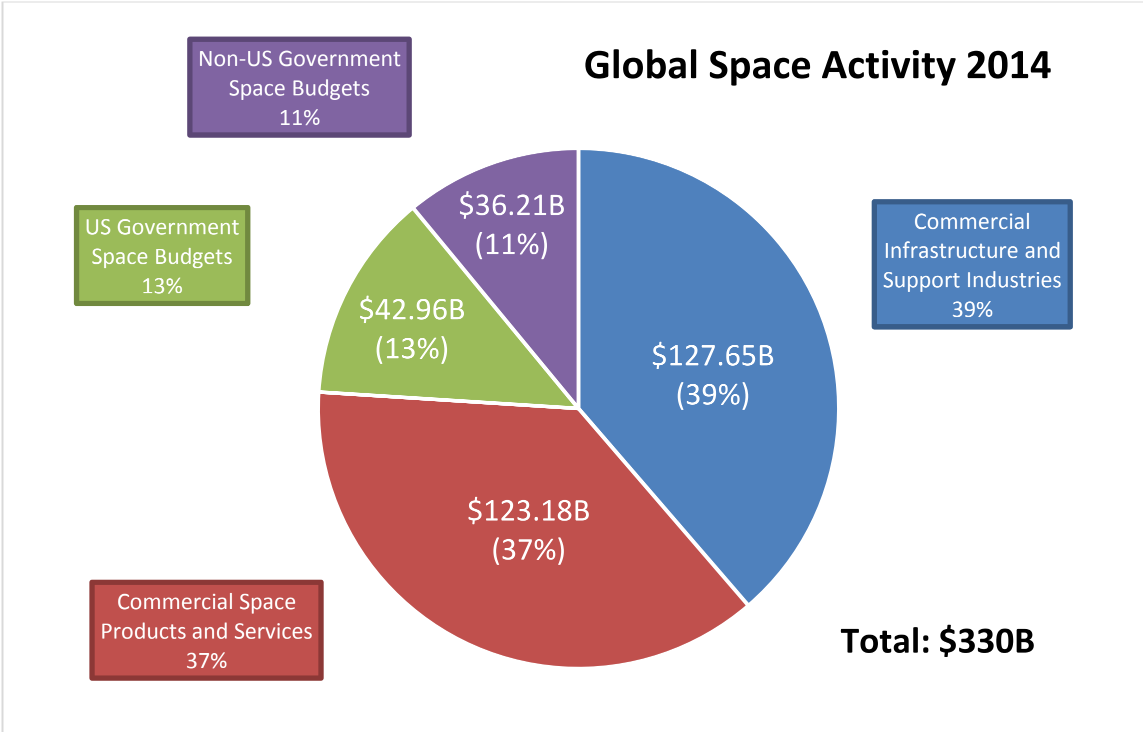

Figure 2.5 - Global Space Market 2014 (Source: The Space Report 2014[169])

The emergence of a new global middle class presents an opportunity for other industries as well. Several companies are seeking to provide global internet access from a constellation of low-Earth orbit satellites. *OneWeb* secured an initial investment of $500M in June 2015, including Virgin Group Chairman, Sir Richard Branson.[170] Their constellation calls for 648 satellites providing overlapping global coverage. User terminals bridge between the satellite, and commercial cellular and wireless devices.[171] They are competing with a SpaceX, Google and Fidelity Investment-backed venture that is seeking to put up to 4,000 satellites into orbit.[172] With an initial investment of $1B, the SpaceX-led

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[169] Space Foundation, “The Space Report 2015 – Overiew,” 1.
[170] Alex Knapp, “Branson-Backed OneWeb Raises $500 Million to Build Satellite Internet,” *Forbes*, 25 June 2015, accessed on 25 April 2016, http://www.forbes.com/sites/alexknapp/2015/06/25/branson-backed-oneweb-raises-500-million-to-build-satellite-internet/#7f31b7065529.
[171] OneWeb, “Solution,” accessed on 25 April 2016, http://oneweb.world/#solution.
[172] Alex Knapp, “Branson-Backed OneWeb Raises $500 Million to Build Satellite Internet.”

venture is also part of Musk's effort to fund a city on Mars. According to Musk, "there is more money associated with satellite manufacturing than with space-launch services… what's needed to create a city on Mars? … a lot of money. So we need things that will generate a lot of money."[173]

Both the direct-to-home satellite television and the telecommunication markets already exist in a fairly mature form today. Lower costs for space access and use will help to expand their reach into new markets, but those markets were just as likely be served regardless as those regions created new middle-class consumers with increasing purchasing power. Global internet is ambitious, but can already be had for a cost through Iridium[174], Intelsat[175] or other providers.

It remains unclear if entirely new markets will emerge. Demand for new services or industries has been slow to develop without evidence of some advantage from doing *it* in space (whatever *it* happens to be).[176] According to Ionan Cozmuta, microgravity-lead in the commercialization office at NASA's Ames Research Centre, "businesses care about their bottom line. They want to know if there is a gravitational impact on their bottom line."[177] Without a clear example of something done better in space, to the point where it could command a premium, new industries remain risky, stifling investment. This has a

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173 Peter de Selding, "SpaceX To Build 4,000 Broadband Satellites in Seattle," *Space News*, 19 January 2015, accessed on 25 April 2016, http://spacenews.com/spacex-opening-seattle-plant-to-build-4000-broadband-satellites/.

174 Iridium services are provided through a number of partners. For instance, RoadPost provides voice, data and SMS services starting at $69 per month. (Source: Roadpost, "Iridium GO! Monthly Plans and Airtime," accessed on 25 April 2016, http://www.roadpost.ca/Iridium-GO-Subscriptions-P809C399.aspx.) For Intelsat, see their website.)

175 Intelsat, "IntelsatOne Flex for Enterprise," accessed on 25 April 2016, http://www.intelsat.com/intelsatone-flex/enterprise/.

176 Jeff Foust, "The challenges of commercializing research in low Earth orbit," *The Space Review*, 04 April 2016, accessed on 25 April 2016, http://www.thespacereview.com/article/2958/1.

177 *Ibid.*

secondary effect on the low-cost space launch industry. Their success is predicated on volume. If volume is slow to materialize because new enterprises are slow to get financed, they may be unable to survive.[178] Is it any wonder that Virgin Galactic Chairman, Sir Richard Branson, and SpaceX CEO, Elon Musk, are investing in new *large volume* satellite companies that will be taking advantage of their other company's launch services? They are hoping to create the very market they seek to serve.

In the meantime, many of these new commercial enterprises will continue to rely on government funding. Unfortunately, the US government has indicated a desire to cede further development of low-Earth orbit to industry, and concentrate their efforts at higher altitudes.[179] The ISS is an annually recurring multi-billion dollar investment that, it is hoped, could be assumed by an industrial consortium beginning in the mid-2020's.[180] At a cost of over $140B USD to manufacture, it is unlikely that industry would be willing to fund a similar capability, even with much lower launch costs.[181] If an industrial consortium does assume control, this would be an example of Hickman's first tenet being satisfied.

Even so, new technologies for space habitation are already being tested. Bigelow Aerospace's Expandable Activity Module (BEAM) was installed on the ISS in April 2016. Unlike the other modules of the ISS, the BEAM is inflatable, giving it a much improved

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178 *Ibid.*

179 Eric Berger, "NASA official warns private sector: We're moving on from low-Earth orbit," *Ars Technica*, 07 December 2015, accessed on 10 February 2016, http://arstechnica.com/science/2015/12/nasa-official-warns-private-sector-were-moving-on-from-low-earth-orbit/.

180 ISS costs $3B per year, rising to $4B in 2020 timeframe. Current funding is expended to run until 2024. (Source: Eric Berger, "NASA official warns private sector: We're moving on from low-Earth orbit," *Ars Technica*, 07 December 2015, accessed on 10 February 2016, http://arstechnica.com/science/2015/12/nasa-official-warns-private-sector-were-moving-on-from-low-earth-orbit/.)

181 Eric Berger, "NASA official warns private sector: We're moving on from low-Earth orbit."

volume-to-weight ratio, lowering the cost of getting it aloft.[182] If successful, it could pave the way for more cost effective solutions for space habitation in the future, making reliance on the ISS moot.[183] For the time being, however, the ISS provides industry with the only habitation module in low-Earth orbit from which to conduct and support any number of activities on a cost recovery basis.

As a final comment on monetization, the US government has also been active in clearing away legal hurdles to space use. In November 2015, the US Congress passed *H.R. 2262, the US Commercial Space Launch Competitiveness Act*.[184] Amongst its sections, it indemnifies space flight operators from legal action by participants[185] and allows for resource extraction from asteroids or other space objects.[186] The former helps the fledgling space tourism sector by minimizing their insurance costs. The latter enables resource extraction companies to acquire and sell their materials, at least within the US market. In this matter, the US government is not alone. The government of Luxembourg announced in February 2016 that they were also creating a legal framework for the exploitation of space-based resources to incentivize investment in outer space mining.[187]

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[182] Thomson Reuters, "NASA installs expandable 'BEAM' module," *CBC News*, 16 April 2016,accessed on 25 April 2016, http://www.cbc.ca/news/technology/beam-module-iss-1.3539160.
[183] *Ibid*.
[184] United States Congress, *Public Law 114-90-Nov. 25, 2015 U.S. Commercial Space Launch Competitiveness Act*, accessed on 27 March 2016, https://www.congress.gov/114/plaws/publ90/PLAW-114publ90.pdf.
[185] *Ibid*, Section 103.
[186] Eric Berger, "Democrats and Republicans agree: If you can mine it in space, it is yours," *Ars Technica*, 10 November 2015, accessed on 10 February 2016, http://arstechnica.com/science/2015/11/democrats-and-republicans-agree-if-you-can-mine-it-in-space-its-yours/.
[187] Veronique Poujol and Marlowe Hood, "Luxembourg's ultimate offshore investment: space mining," *Phys.org*, 03 February 2016, accessed on 10 February 2016, http://phys.org/news/2016-02-luxembourg-ultimate-offshore-investment-space.html.

Clearly, the economic case for increased commercial access and use of space is not obvious. Hickman made the compelling case that, at least in terms of very large space projects, commercial players are at a significant disadvantage. His three tenets – maximum use of public funding, establishment of a development authority, and creation of a revenue stream – have yet to be put to the test in a meaningful way. The ISS may become an example in the future if it is transitioned into private ownership. Meanwhile, non-governmental efforts to colonize Mars fall well short of being feasible.

Looking at the economics behind building, launching, and monetizing space services, we see that new opportunities are emerging. SpaceX and Blue Origin are leading the way in terms of developing fully and rapidly re-useable launch vehicles to significantly reduce costs. Other space launch providers such as Virgin Galactic and Rocket Lab are focusing on the small satellite market in low-Earth orbit, building less capable, but less expensive, rockets to service these markets. Standardization in small satellite design, such as the *CubeSats*, is lowering costs for manufacturing and simplifying launch options. Meanwhile, the emergence of a global middle class in South Asia, Sub-Saharan Africa, and South America is creating new markets for new and existing service providers.

Unfortunately, these factors have not yet contributed to the creation of new space-based industries such as manufacturing, or power generation. The benefits of going to space for these (and other) services still remain theoretical, and the evidence to support investment is uncertain. More research will need to happen before there is a major commitment to their establishment.[188] Fortunately, the US government seems interested in

[188] Jeff Foust, "The challenges of commercializing research in low Earth orbit," *The Space Review*, 04 April 2016, accessed on 25 April 2016, http://www.thespacereview.com/article/2958/1.

clearing away legal hurdles associated with space access and use. Hopefully, they will continue to encourage industry through continued investment, and legislation, to undermine uncertainty. In the meantime, the incentives for space access and use are improving, and we may be on the verge of a rapid acceleration in use, at least for some services.

CHAPTER 3 - SPACE LAW

Commercial interests in space, like on Earth, benefit from a robust legal and regulatory framework. Uncertainty is to be avoided because it undermines confidence. If investors cannot accurately account for possible outcomes, they are less likely to provide funding, or will demand a higher rate of return. Given the costs associated with developing and operating a commercial space enterprise,[189] only companies that can avail themselves freely of the markets to secure financing, manufacturing, and launch capabilities are likely to prevail. Consequently, clear regulations about what can, and cannot, be done in space are an important element in incentivizing space activities. Space law needs to evolve to provide legal clarity over space-based ventures. Understanding the interplay between international and national law as they relate to the use and exploitation of space and space-based resources is critical to evaluating the eventual success of the global space market.

Space law is largely founded on the UN treaties initially established in the late 1960's following the success of the US and Soviet space programs. Arising as they did during the Cold War, these treaties were conceived in part to dissuade the two superpowers from unilaterally pursuing objectives in space that could lead to an escalation of conflict on Earth. US President Eisenhower was a proponent of the peaceful use of space, creating NASA in 1958 to separate civilian space exploration from military pursuits.[190] When addressing the UN General Assembly in 1960, he first proposed the creation of an outer

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[189] See Chapter 2 for more discussion.

[190] Shira Teitel, "The Outer Space Treaty Promised Peace in Space," *Discovery News*, 10 October 2013, accessed on 26 April 2016, http://news.discovery.com/space/history-of-space/the-outer-space-treaty-promised-peaceful-exploration-of-space-131010.htm.

space treaty modeled on the principles of the *Antarctic Treaty*.[191] The United Nation's took up the issue of outer space in the early 1960's, passing the *Declaration of Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space* in 1963.[192] This resolution laid the foundation for future treaties and declarations with respect to possession and use of outer space by states and their citizens, stating "outer space and celestial bodies are not subject to national appropriation or claim of sovereignty by means of use or occupation, or by any other means."[193] Further declarations made clear that states bear responsibility for their actions in space, and the actions of *non-governmental entities* through "authorization and continuing supervision by the state concerned."[194] Non-governmental entity has been interpreted in the US to mean natural persons, corporations or non-governmental organizations whom are subject to US law.[195] Recent case law in the US has reinforced this interpretation, although a decision by the US Federal Courts did not definitively rule out the possibility of private ownership of lunar or celestial property, "merely… that they are prohibited from appropriating [it.]"[196] For instance, as per Hickman's second tenet, an internationally sanctioned *Development Authority*, empowered with ownership over a space object, could allow for a private sale leading to ownership without appropriation.

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[191] United States Department of State, "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies," accessed on 26 April 2016, http://www.state.gov/t/isn/5181.htm.

[192] United Nations Office of Outer Space Affairs, "Resolution Adopted by the General Assembly. 1962 (XVIII). Declaration of Legal Principles Governing Activities of States in the Exploration and Use of Outer Space," *United Nations*, 13 December 1963, accessed on 22 March 2016, http://www.unoosa.org/oosa/en/ourwork/spacelaw/principles/legal-principles.html.

[193] *Ibid*, Principle #3.

[194] *Ibid*, Principle # 5.

[195] Robert Kelly, "Nemitz v. United States, A Case of First Impression: Appropriation, Private Property Rights and Space Law Before The Federal Courts of the United States," *Journal of Space Law* 30, no.2 (Fall 2004): 308, http://www.spacelaw.olemiss.edu/JSL/Back_issues/JSL%2030-2.pdf.

[196] *Ibid*.

As a declaration, the principles were not binding on the UN membership. The first international space treaty codified by the UN was the *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies* (more commonly known as the *Outer Space Treaty*) that was passed in 1966.[197] It reaffirmed the principles already enshrined within the declaration, while adding additional detail, and expanding the treaty to prohibit the extension of weapons of mass destruction into space.[198] The treaty does not prevent the *conventional weaponization* of space, but does impose limitations on the placement of forces. Weaponization is also considered separately from the *militarization* of space, with the latter being the use of space for military purposes (less the placement of weapon systems). Article IV of the treaty makes clear that "the establishment of military bases, installations and fortifications, the testing of any type of weapons and the conduct of military manoeuvres on celestial bodies shall be forbidden."[199]

The militarization of space continued unimpeded in the US and the USSR, with both parties pursuing space-based surveillance, communication and navigation systems. The weaponization of space reached its theoretical apogee in the West with the US Strategic Defense Initiative (SDI) of the Reagan Administration. Known derogatively as *Star Wars*, it was the pinnacle of publically acknowledged space weapon aspiration, establishing an anti-intercontinental ballistic missile shield in space through directed-energy weapons, kinetic energy weapons, and surveillance, acquisition and

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[197] United Nations Office for Outer Space Affairs, "Treaty on Principles Governing the Activities of Space in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies," *United Nations,* 19 December 1966, accessed on 10 February 2016, http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html.
[198] *Ibid*, Article IV.
[199] *Ibid*, Article IV.

tracking systems, amongst other technologies.[200] As a concept, it was eventually undone by the limitations of the available technology, the cost, and the collapse of the enemy against whom it was aimed. In the 1990's, it was re-oriented by the Bush and the Clinton administrations, eventually focusing on the more limited problem of Theatre Ballistic Missile Defence (TBMD).[201]

Given the reliance of western nations on satellite-based systems for communication, navigation and intelligence gathering, Russia and the People's Republic of China (henceforth referred to as China) are pursuing programs to neutralize or destroy these capabilities in the event of conflict. The most recent publically acknowledged effort was by China in 2007 when they destroyed one of their own satellites, a *Fengyun* series weather satellite, through a head-on collision on 11 January.[202] However, China is alleged to have conducted further tests in 2010, 2013, 2014 and 2015 under the guise of ballistic missile defence interceptor testing.[203] Of concern, their 2013 ballistic missile almost reached geosynchronous orbit, demonstrating a threat to military communication, intelligence, and navigation satellites in a future conflict.[204] Meanwhile, Russia carried out

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[200] SDI included a nuclear-bomb powered X-ray laser which would also have violated the *Outer Space Treaty*. (Source: Dietrich Schroeer, "The Present Status of the Strategic Defense Initiative," in *Space and Nuclear Weaponry in the 1990's*, eds. Carlo Schaerf, Giuseppe Longo and David Carlton (Hampshire: The MacMillan Press Ltd, 1992): 4.)

[201] Robert J. Bunker, "Strategic Defense Initiative," in *Europe Since 1945: An Encyclopedia*, ed. Bernard A. Cook (New York, NY: Garland Publishing, 2001): 1197. Accessed on 22 March 2016. http://scholarship.claremont.edu/cgi/viewcontent.cgi?article=1395&context=cgu_fac_pub.

[202] BBC Staff, "China confirms satellite downed," *BBC News*, 23 January 2007, accessed on 22 March 2016, http://news.bbc.co.uk/2/hi/asia-pacific/6289519.stm.

[203] Bill Gertz, "China Tests Anti-Satellite Missile," *The Washington Free Beacon*, 09 November 2015, accessed on 22 March 2016, http://freebeacon.com/national-security/china-tests-anti-satellite-missile/.

[204] *Ibid*.

their own successful anti-satellite missile test in November 2015.[205] As the USSR, they also have a heritage with anti-satellite programs going all the way back to the 1960's.[206]

As of 2015, the *Outer Space Treaty* is in force across most nations (ratified in 103 states)[207], and governs the actions of those states and their populace in accessing space, and exploiting its resources. Since 1967, it has been joined by four additional treaties. They are maintained by the United Nations Office for Outer Space Affairs (UNOOSA) which is mandated with "[promoting] international cooperation in the peaceful uses of outer space."[208] UNOOSA formed the *Committee on the Peaceful Uses of Outer Space* in 1959 to "govern the exploration and use of space for the benefit of all humanity: for peace, security and development."[209] It contributed to the development of the *Outer Space Treaty,* the four additional treaties, and the five principles that govern outer space.[210] The additional treaties are:

a. the 1968 *Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space* (also known as the *Rescue Agreement*)[211];
b. the 1972 *Convention on International Liability for Damage Caused by Space Objects* (also known as the *Liability Convention*)[212];

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205 *Ibid.*
206 Union of Concerned Scientists, "A History of Anti-Satellite Programs (2012)."
207 United Nations Office of Outer Space Affairs, "Status of International Agreements relating to activities in outer space as of 01 January 2015," *United Nations*, 08 April 2015, accessed on 23 March 2016, http://www.unoosa.org/pdf/limited/c2/AC105_C2_2015_CRP08E.pdf, 10.
208 United Nations Office of Outer Space Affairs, "United Nations Office of Outer Space Affairs – Homepage," *United Nations*, accessed on 23 March 2016, http://www.unoosa.org/.
209 United Nations Office of Outer Space Affairs, "Committee on the Peaceful Uses of Outer Space," *United Nations*, accessed on 23 March 2016, http://www.unoosa.org/oosa/en/ourwork/copuos/index.html.
210 *Ibid.*
211 United Nations Office of Outer Space Affairs, "Agreement on the Rescue of Astronauts, the Return of Astronauts, and the Return of Objects Launched into Outer Space," *United Nations*, 19 December 1967, accessed on 23 March 2016, http://www.unoosa.org/pdf/gares/ARES_22_2345E.pdf.

c. the 1975 *Convention on Registration of Objects Launched into Outer Space* (also known as the *Registration Convention*)[213]; and

d. the 1979 *Agreement Governing the Activities of States on the Moon and Other Celestial Bodies* (also known as the *Moon Treaty*).[214]

As of 2015, the *Outer Space Treaty* had been ratified by the most nations, followed closely by the *Rescue* and *Liability Treaties*, while the *Registration Convention* lagged behind with only 62 nations. This is not unexpected however, given that most nations have not launched objects into space requiring them to be registered. However, the *Moon Treaty* has only be ratified or recognized by 16 nations.[215] Of those, only India and France are space-faring, and they have only signed, but not ratified the treaty. Consequently, while it has been put forward by the UN for ratification, its articles are not universally recognized as valid. As will be discussed later, this is significant when it comes to resource recovery from the Moon, or other celestial bodies.

In addition to the five treaties, the UNOOSA has also promulgated five principles of space use:

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[212] United Nations Office of Outer Space Affairs, "Convention on International Liability for Damage Caused by Space Objects," *United Nations*, accessed on 23 March 2016, http://www.unoosa.org/pdf/gares/ARES_26_2777E.pdf.

[213] This treaty didn't enter into force until the following year (1976). (Source: United Nations Office of Outer Space Affairs, "Convention on Registration of Objects Launched into Outer Space," *United Nations*, accessed on 23 March 2016, http://www.unoosa.org/pdf/gares/ARES_29_3235E.pdf.)

[214] This treaty didn't enter into force until 11 July 1984. (Source: United Nations Office of Outer Space Affairs, "Agreement Governing Activities of States on the Moon and Other Celestial Bodies," *United Nations*, accessed on 23 March 2016, http://www.unoosa.org/pdf/gares/ARES_34_68E.pdf.)

[215] United Nations Office of Outer Space Affairs, "Status of International Agreements relating to activities in outer space as of 01 January 2015," *United Nations*, 08 April 2015, accessed on 23 March 2016, http://www.unoosa.org/pdf/limited/c2/AC105_C2_2015_CRP08E.pdf, 10.

a. the 1963 *Declaration of Legal Principles Governing the Activities of the States in the Exploration and Uses of Outer Space*[216];

b. the 1982 *Principles Governing the Use of States of Artificial Earth Satellites for International Direct Television Broadcasting*[217];

c. the 1986 *Principles Relating to Remote Sensing of the Earth from Outer Space*[218];

d. the 1992 *Principles Relevant to the Use of Nuclear Power Sources in Outer Space*[219]; and,

e. the 1996 *Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States, Taking into Particular Accounts the Needs of Developing Countries*[220].

Of these, the 1963 *Declaration of Legal Principles* has been subsumed into the *Outer Space Treaty*. The extension of satellite-based direct television broadcast into new markets was discussed in Chapter 2, and is unlikely to generate legal issues pertinent to defence or

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[216] United Nations Office of Outer Space Affairs, "Resolution Adopted by the General Assembly. 1962 (XVIII). Declaration of Legal Principles Governing Activities of States in the Exploration and Use of Outer Space," *United Nations*, 13 December 1963, accessed on 22 March 2016, http://www.unoosa.org/oosa/en/ourwork/spacelaw/principles/legal-principles.html.

[217] United Nations Office of Outer Space Affairs, "Resolution Adopted by the General Assembly 37/92. Principles Governing the Use by States of Artificial Earth Satellites for International Direct Television Broadcasting," *United Nations*, 10 December 1982, accessed on 23 March 2016, http://www.unoosa.org/oosa/en/ourwork/spacelaw/principles/dbs-principles.html.

[218] United Nations Office of Outer Space Affairs, "Resolution Adopted by the General Assembly 41/65. Principles Relating to Remote Sensing of the Earth from Outer Space," *United Nations*, 03 December 1986, accessed on 23 March 2016, http://www.unoosa.org/oosa/en/ourwork/spacelaw/principles/remote-sensing-principles.html.

[219] United Nations Office of Outer Space Affairs, "Resolution Adopted by the General Assembly 47/68. Principles Relevant to the Use of Nuclear Power Sources in Outer Space," *United Nations*, 14 December 1992, accessed on 23 March 2016, http://www.unoosa.org/oosa/en/ourwork/spacelaw/principles/nps-principles.html.

[220] United Nations Office of Outer Space Affairs, "Resolution Adopted by the General Assembly 51/122. Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States, Taking into Particular Account the Needs of Developing Countries," *United Nations*, 13 December 1996, accessed on 23 March 2016, http://www.unoosa.org/oosa/en/ourwork/spacelaw/principles/nps-principles.html.

security. The 1986 *Principles Relating to Remote Sensing* limits the definition of remote sensing as being "for the purpose of improving natural resources management, land use and the protection of the environment."[221] This impacts commercial use, but exempts the military. The 1992 *Principles Relevant to the Use of Nuclear Power Sources* may be applicable to commercial interests. *Mars Direct* calls for the establishment of a nuclear power plant on Mars prior to the arrival of any astronauts.[222] Satellites have also used nuclear reactors in the past for power,[223] although most use solar panels today, including the ISS.[224] The principle allows for the use of nuclear power to be operated – "(i) on interplanetary missions, (ii) in sufficiently high orbits, … (c) in low-Earth orbits if they are stored in sufficiently high orbits after the operational part of their mission."[225] This may pose a future safety and security challenge.[226] Finally, the 1996 *Declaration on International Cooperation* reiterates that the "exploration and use of outer space… shall be carried out for the benefit and interest of all States… [and] particular account should be taken of the needs of developing countries."[227] Cooperative ventures "should be fair and

[221] United Nations Office of Outer Space Affairs, "Resolution Adopted by the General Assembly 41/65. Principles Relating to Remote Sensing of the Earth from Outer Space," Principle 1.

[222] Mars Society, "Mars Direct," accessed on 21 April 2016, http://www.marssociety.org/home/about/mars-direct/.

[223] Leonard David, "50 Years of Nuclear-Powered Spacecraft: It All Started with Satellite Transit 4A," *Space.com*, 29 June 2011, accessed on 26 April 2016, http://www.space.com/12118-space-nuclear-power-50-years-transit-4a.html.

[224] The ISS has approximately one acre of solar panels generating between 75 – 90 kilowatts. (Source: National Aeronautics and Space Administration, "About the Space Station: Facts and Figures," accessed on 26 April 2016, http://www.nasa.gov/mission_pages/station/main/onthestation/facts_and_figures.html.)

[225] United Nations Office of Outer Space Affairs, "Resolution Adopted by the General Assembly 47/68. Principles Relevant to the Use of Nuclear Power Sources in Outer Space," Principle 3, Section 2, Sub-para a. (i) – (iii).

[226] Nuclear reactors (or their by-products) have been used in space for more than half-a-century. We already understand the risk associated with their use in space. Widespread use may lead to an increased risk of accident. (Source: Leonard David, "50 Years of Nuclear-Powered Spacecraft: It All Started with Satellite Transit 4A," *Space.com*, 29 June 2011, accessed on 26 April 2016, http://www.space.com/12118-space-nuclear-power-50-years-transit-4a.html.)

[227] United Nations Office of Outer Space Affairs, "Resolution Adopted by the General Assembly 51/122. Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States, Taking into Particular Account the Needs of Developing Countries," Paragraph 1.

reasonable and they should be in full compliance with the legitimate rights and interests of the parties concerned, as, for example, with intellectual property rights."[228] The spirit of this principle is captured in the *Memorandum of Understanding* between NASA, the RSA, and their partners, regarding the establishment and operation of the ISS.[229]

A key feature of the 1963 *Declaration of Legal Principles*, the 1967 *Outer Space Treaty*, and the 1979 *Moon Treaty* were their statements concerning *ownership* of space resources. All three documents prohibit states from declaring sovereignty over the Moon or other celestial objects. On Earth, property rights confer some measure of control over its use, and the resources located above and below.[230] All land within a nation is either publically held by the government, or privately held with ownership enforced through domestic law. In outer space, there is no overarching authority with responsibility for managing property rights. In the parlance of Hickman, there is no *Development Authority*. It is perhaps telling that the *Antarctic Treaty* upon which the *Outer Space Treaty* is based also prohibited new claims of sovereignty in Antarctica,[231] and "had no provisions for granting property rights or regulating economic activity."[232] Unlike the Arctic, where

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[228] *Ibid.*, Paragraph 2.
[229] In addition to defining responsibilities, the *MoU* also discussed the sharing of intellectual property developed on the ISS between nations. (Source: National Aeronautics and Space Administration, "Memorandum of Understanding between the National Aeronautics and Space Administration of the United States of America and the Russian Space Agency Concerning Cooperation on the Civil International Space Station," signed on 29 January 1998, accessed on 20 April 2016, http://www.nasa.gov/mission_pages/station/structure/elements/nasa_rsa.html.)
[230] The specific rights afforded to an owner depend on the state. In Canada, these rights are governed by federal and provincial laws, or international treaties. (Source: Alberta Land Institute, "A Guide to Property Rights in Alberta," accessed on 26 April 2016, http://www.albertalandinstitute.ca/public/download/documents/10432, 9.)
[231] Signatories with existing claims toward Antarctica were deemed not to have renounced, prejudiced or reduced them by signing the treaty. (Source: United Nations Office for Disarmament Affairs, "Antarctic Treaty," *United Nations*, 01 December 1959, accessed on 26 April 2016, http://disarmament.un.org/treaties/t/antarctic/text, Article IV.)
[232] Rand Simberg, "Property Rights in Space," *The New Atlantis*, Number 37 (Fall 2012). Accessed on 26 April 2016. http://www.thenewatlantis.com/publications/property-rights-in-space.

property rights are better established, investment in resource extraction under the Antarctic continent has languished.[233]

The 1963 *Declaration of Legal Principles* and the 1967 *Outer Space Treaty* do not *explicitly* forbid individual appropriation of property.[234] One legal interpretation put forward is that "establishing a permanent settlement… or any use involving consumption or taking with the intention of keeping for one's own exclusive use would amount to appropriation."[235] Effectively, *de facto* ownership can be established by a private interest through physical control of the location or resource. Under the terms of the *Outer Space Treaty*, states "shall bear international responsibility for national activities in outer space… whether such activities are carried out by governmental agencies or by non-governmental agencies, and for assuring that national activities are carried out in conformity with the provision set forth in the present treaty."[236] This places the onus on national governments to legislate the rules and responsibilities under which their national space industry will operate. *De facto* ownership seems to be supported under Chapter 513 of the *US Commercial Space Launch Competitiveness Act*, which states that "a United States citizen engaged in commercial recovery of an asteroid resource or a space resource… shall be entitled to any asteroid resource or space resource recovered."[237] The analogy has been

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233 *Ibid*.

234 The *Moon Treaty* amplifies the prohibition on state sovereignty by explicitly denying property rights to "any state, international intergovernmental or non-governmental organization, national organization or non-governmental entity or of any natural person." (Source: United Nations Office of Outer Space Affairs, "Agreement Governing Activities of States on the Moon and Other Celestial Bodies," *United Nations*, accessed on 23 March 2016, http://www.unoosa.org/pdf/gares/ARES_34_68E.pdf, Article 11, paragraph 3.)

235 Stephen Grove, "Interpreting Article II of the Outer Space Treaty." *Fordham Law Review* 37, issue 3 (1969): 352, accessed on 26 April 2016, http://ir.lawnet.fordham.edu/cgi/viewcontent.cgi?article=1966&context=flr.

236 United Nations Office for Outer Space Affairs, "Treaty on Principles Governing the Activities of Space in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies," Article VI.

237 United States Congress, *Public Law 114-90-Nov. 25, 2015 U.S. Commercial Space Launch Competitiveness Act*, Section 51303.

made to fishing in international waters. Boats are still subject to the national laws of the state under whose flag they sail, but they have the right to ownership over whatever they catch.[238] Other experts believe that the legislation violates the *Outer Space Treaty*, and could lead to conflict with other space faring nations in the future, such as China or Russia.[239] As one academic remarked, "states can take actions at will and there are no defined rules governing their activities, which ultimately leads to the devastating result of a 'gold rush' by space-faring states."[240]

The idea of establishing *de facto* property rights has been explored further by some commentators. Economist Sam Dinkin argued that the US could lead the world by establishing *pseudo* property rights in space.[241] Under his scenario, US citizens and corporations would need approval from the US Government to conduct their activities within some well-defined area of outer space (e.g. on a specific asteroid, within a demarcated section of the Moon). Since each state is mandated to regulate their internal market,[242] the US would be within their rights to limit the activities for their citizens, effectively creating *pseudo* property rights specific to their populace. The *Outer Space Treaty* also requires that other states consult with one another when their activities may be

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[238] Dominic Basulto, "How property rights in outer space may lead to a scramble to exploit the moon's resources," *The Washington Post*, 18 November 2015, accessed on 26 April 2015, https://www.washingtonpost.com/news/innovations/wp/2015/11/18/how-property-rights-in-outer-space-may-lead-to-a-scramble-to-exploit-the-moons-resources/.

[239] Rob Davies, "Asteroid mining could be space's new frontier: the problem is doing it legally," *The Guardian*, 06 February 2016, accessed on 26 April 2016, http://www.theguardian.com/business/2016/feb/06/asteroid-mining-space-minerals-legal-issues.

[240] Yun Zhao, "An International Space Authority: A Governance Model for a Space Commercialization Regime," *Journal of Space Law* 30 no. 2, (Fall 2004): 282, http://www.spacelaw.olemiss.edu/JSL/Back_issues/JSL%2030-2.pdf.

[241] Sam Dinkin, "Property rights and space commercialization," *The Space Review*, 10 May 2004, accessed on 27 March 2016, http://www.thespacereview.com/article/141/1.

[242] United Nations Office for Outer Space Affairs, "Treaty on Principles Governing the Activities of Space in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies," Article VI.

in conflict.[243] Hence, should another State or their citizens have an interest in the same area of space, they would obligated to consult with the US beforehand. Although this does not preclude the other state from authorizing their own activity in the same area, it does give the US the opportunity to leverage other instruments of national power to uphold their interests, or those of their citizens.

Notwithstanding the legal confusion, this has not prevented some companies from pursuing ambitious plans. Planetary Resources[244] and Deep Space Industries[245] are both targeting asteroids for resource extraction. Mineral-rich asteroids are believed to exist that have high concentrations of pure minerals and metals that are difficult to find and recover from Earth, such as members of the platinum group used for electronics.[246] Other asteroids are believed to contain high concentrations of ice that can be split into hydrogen and oxygen to act as fuel, or nickel, iron and cobalt that can be processed in space to manufacture new structures.[247] These minerals can be returned to Earth for sale, or be used to reduce costs for the in-orbit economy by replacing consumables that otherwise need to be shipped from Earth, such as water or fuel.[248] They are joined by Moon Express, which is looking to mine minerals from the surface of the Moon, including platinum, rare Earth elements, and Helium-3.[249] Moon Express is also seeking to win the $10M Google Lunar XPrize by being the first private lander to travel 500 meters on the surface of the Moon, and

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[243] United Nations Office for Outer Space Affairs, "Treaty on Principles Governing the Activities of Space in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies," Articles IX – XI.
[244] Planetary Resources, "Planetary Resources – Intro," accessed on 09 February 2016, http://www.planetaryresources.com/#home-intro.
[245] Deep Space Industries, "Deep Space Industries – Homepage," accessed on 27 March 2016, https://deepspaceindustries.com/.
[246] *Ibid.*
[247] *Ibid.*
[248] Sarah Cruddas, "The truth about asteroid mining," *BBC News*, 05 January 2016, accessed on 26 April 2016, http://www.bbc.com/future/story/20160103-the-truth-about-asteroid-mining.
[249] Moon Express, "Moon Express," accessed on 26 April 2016, http://www.moonexpress.com/.

beam back images.[250] Despite uncertainty over the legality of their finds, all three companies are optimistic about their opportunities.[251]

While mining minerals in space for use on Earth may be undercut by the discovery of a terrestrial source, the in-orbit economy has the built-in advantage of the cost premium for getting material into orbit. Space flight still depends on hydrogen and oxygen-based compounds for fuel, oxidization, atmosphere and water. These are key components for sustaining life in orbit, or keeping space vehicles (including satellites) fueled to do course corrections over the course of their lifetime. In the near term, the best case price for getting a metric ton of water into low-Earth orbit is approximately $1.7M aboard the, as yet unproven, SpaceX *Falcon Heavy*.[252] The ISS propulsion module consumes between 8,000 pounds and 19,000 pounds of fuel per year, depending on altitude, to maintain its orbit, which would cost approximately $3.6M – 8.7M.[253] Furthermore, these margins increase as the altitude rises (e.g. SpaceX *Falcon Heavy* costs $4,245 per kilogram to GTO). Instead of bringing water and fuel from the planet, they could be provided from near-Earth asteroids or the Moon. However, if the cost of space access decreases sharply (e.g. through re-usability), these rates would fall. Fortunately, so would the investment in establishing the space mining industry. However, it is difficult to assess the impact on the financial viability of the industry with the data available. We don't know the relationship between launch costs, and the cost per kilogram of returning water (or another mineral) from an

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[250] Kathryn Nave, "Space mining will take a giant leap in 2016," *Wired*, 05 January 2016, accessed on 26 April 2016, http://www.wired.co.uk/news/archive/2016-01/05/space-mining-a-reality-in-2016.

[251] Planetary Resources refers to water as a "trillion dollar market in space." (Source: Planetary Resources, "The Trillion Dollar Market: Fuel In Space From Asteroids," 06 Jun 2014, accessed on 26 April 2016, http://www.planetaryresources.com/2014/06/fuelspace/.)

[252] Based on $1.7K per kilogram. See Figure 2.1.

[253] Based on $1.7K per kilogram. See Figure 2.1. (Source: National Aeronautics and Space Administration, "Higher Altitude Improves Station's Fuel Economy," accessed on 26 April 2016, http://www.nasa.gov/mission_pages/station/expeditions/expedition26/iss_altitude.html.)

asteroid or the Moon to Earth orbit. None of the space mining companies have publically released their estimates. A speculative assessment of returns from a small, high-density, platinum-rich asteroid suggests that it could generate billions of dollars in returns at current market rates. This would seemingly justify the cost of their recovery even if other minerals were not financially viable.[254]

The problem for resource extraction doesn't end there. Another complicating factor for space mining is a clause in the *Moon Treaty* regarding the resources of outer space as being the *common heritage of mankind (CHM)*.[255] This is interpreted to mean that all inhabitants of the Earth should benefit from any financial windfall that may arise from their use, and that they should be safeguarded on behalf of all the Earth's inhabitants. No single nation or enterprise has unilateral authority to seize and exploit the Moon or any celestial bodies without recompense to the rest of the world. Fortunately for commercial enterprises, the *Moon Treaty* is effectively unratified, and its claim over the resources of outer space is without legal merit outside of the handful of nations that have signed and ratified.[256] The *Outer Space Treaty* is more vague, indicating only that "the exploration and use of outer space… shall be carried on for the benefit and in the interests of all countries, irrespective of their degree of economic and scientific development, and shall be

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[254] At the time of the article, a pure, 10-meter diameter platinum asteroid would yield a return of approximately $600B. In the intervening years, the costs of platinum has fallen to approximately $1,000 per troy ounce (from the $1,600 quoted in the article). This would reduce the maximum return to approximately $375B (or 67.5% of the original return). (Source: Simone Foxman, "The crazy economics of mining asteroids for gold and platinum," *Quartz*, 25 January 2013, accessed on 26 April 2016, http://qz.com/47232/the-crazy-economics-of-mining-asteroids-for-gold-and-platinum/.)

[255] United Nations Office of Outer Space Affairs, "Agreement Governing Activities of States on the Moon and Other Celestial Bodies," *United Nations*, accessed on 23 March 2016, http://www.unoosa.org/pdf/gares/ARES_34_68E.pdf, Article 18.

[256] United Nations Office of Outer Space Affairs, "Status of International Agreements relating to activities in outer space as of 01 January 2015," *United Nations*, 08 April 2015, accessed on 23 March 2016, http://www.unoosa.org/pdf/limited/c2/AC105_C2_2015_CRP08E.pdf, 10.

the province of all mankind."[257] However, some scholars have interpreted *province of all mankind* "to be the functional and legal equivalent of 'common heritage of all mankind.'"[258] If this interpretation becomes common international law, then there is a compensatory component to the exploitation of space resources that is not yet clear.

Common heritage of mankind has been used once before in international law. As part of the United Nations Convention on the Law of the Sea (UNCLOS), the deep seabed and its associated resources are the *common heritage of mankind*.[259] To protect these resources on behalf of all mankind, UNCLOS established the *International Seabed Authority* in 1994 "with a view of administering the resources of the [seabed]."[260] Unfortunately, in terms of the deep seabed, countries had diverging views on the application of the UNCLOS agreement. Given the substantial upfront capital investment to undertake deep sea operations, the terms initially offered under UNCLOS made the ventures too risky for many qualified bidders.[261] The 1994 Agreement that implemented the seabed provisions within the Convention addressed many of the shortfalls in the original text, including market-based mechanisms for technology transfer, reduced fees, the removal of production ceilings, and increased lease timetables.[262] These new measures were supposed to increase certainty for investors, making deep seabed operations more viable. However, as of 2009, only eight licenses had been issued, and all of them were to

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[257] United Nations Office for Outer Space Affairs, "Treaty on Principles Governing the Activities of Space in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies," Article I.
[258] Yun Zhao, "An International Space Authority: A Governance Model for a Space Commercialization Regime," 279.
[259] United Nations, "United Nations Convention on the Law of the Sea," *United Nations*, accessed on 25 March 2016. http://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf, Article 136.
[260] *Ibid.*, Article 157.
[261] Yun Zhao, "An International Space Authority: A Governance Model for a Space Commercialization Regime," 286 – 287.
[262] Yun Zhao, "An International Space Authority: A Governance Model for a Space Commercialization Regime," 286 – 287.

governmental or quasi-governmental agencies.[263] Matters have improved somewhat since then, with seven exploration licenses issued in 2014, including to several commercial enterprises.[264] If CHM does become common international law for outer space resources then lessons learned from the ISA should be applied to an *International Space Authority* to foster investment and innovation.

The problems of ownership in space do not impact all space activity equally. Telecommunication and remote sensing today, and potentially power generation and zero-gravity manufacturing tomorrow, don't depend on sovereignty or property rights to be profitable. They do depend on access to suitable terrestrial orbits however, and this is not governed by any of the UN treaties. Instead, orbits are indirectly managed through the International Telecommunications Union Radiocommunication Sector (ITU-R) who control the uplink and downlink frequencies required for their use. The ITU-R's "primary objective is to ensure interference free operations of radiocommunication systems."[265] For space systems, they "[develop and manage] space-related assignment and allotment plans and [provide] mechanisms for the development of new satellite services by locating suitable orbital slots."[266] The ITU-R works with states to manage the radio frequency spectrum to ensure that space-based services can operate with limited interference over different territories. Separation parameters based on angle, altitude and frequency are

[263] Economist Staff, "The unplumbed riches of the deep," *The Economist*, 14 May 2009, accessed on 27 April 2016, http://www.economist.com/node/13649273.
[264] David Shukman, "Deep see mining licences issued," *BBC News*, 23 July 2014, accessed on 27 April 2016, http://www.bbc.com/news/science-environment-28442640.
[265] International Telecommunication Union Radiocommunication Sector, "Welcome to ITU-R," *International Telecommunication Union*, 27 January 2011, accessed on 25 March 2016, http://www.itu.int/net/ITU-R/index.asp?category=information&rlink=itur-welcome&lang=en.
[266] *Ibid.*

employed to ensure that satellites in orbit do not interfere with each other due to errors in antenna pointing, beam width, or overlapping frequencies.

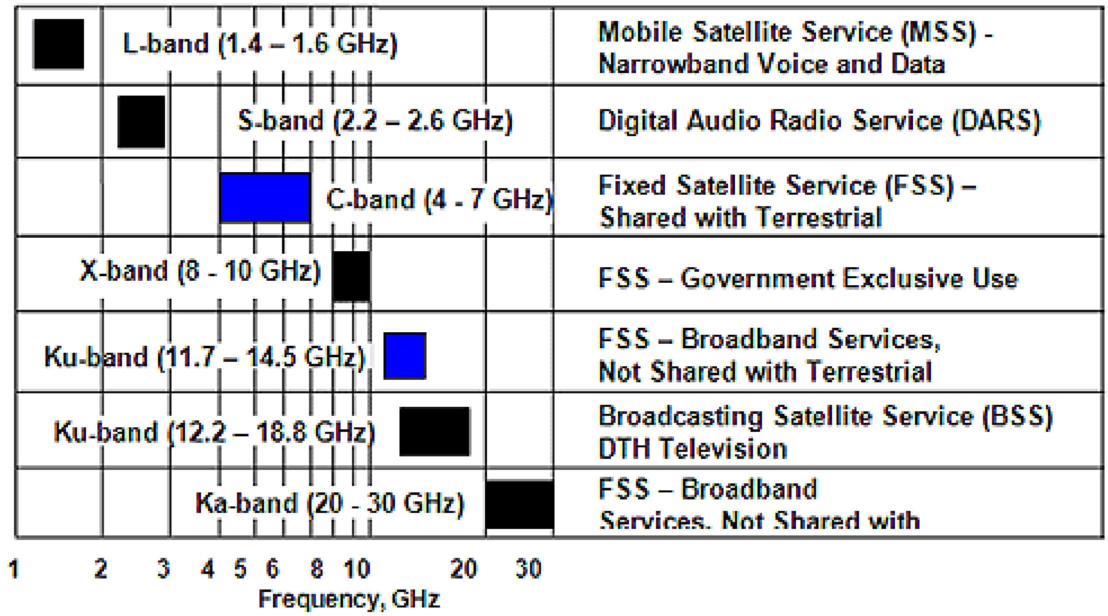

Figure 3.1 - Satellite Frequency Bands (Source: JSAT International[267])

As of 2008, for satellites looking to employ C and Ku-band communication for their operation, most orbital slots suitable for operation were in use, or had been designated for use by an upcoming satellite.[268] Higher frequencies in the Ka-band were being explored to enable new satellites to operate. Higher frequencies have the advantage of being more directional, allowing for easier re-use around the globe, but they are more easily attenuated by rain, fog, or other atmospheric effects.

Over time, the parameters governing orbital separation have evolved to account for improved technology. For highly competitive markets like North America and Europe,

[267] JSAT International, "Frequency," accessed on 26 April 2016, http://www.jsati.com/why-satellite-what-frequency.asp.

[268] Mark Holmes, "Hot Orbital Slots: Is There Anything Left?" *Satellite Today*, 01 March 2008, accessed on 25 March 2016, http://www.satellitetoday.com/publications/via-satellite-magazine/features/2008/03/01/hot-orbital-slots-is-there-anything-left/.

orbital slots suitable for their territories are already congested. The US Federal Communication Commission (FCC) successfully lobbied the ITU-R for a reduction in the orbital angle between satellites from 3^o to 2^o in order to create more spots for satellite providers,[269] increasing competition and opportunity in the US market.[270] Notwithstanding, there is no international legal prohibition that prevents a user from parking their satellite in another's orbit. To date, orbital theft has not occurred, although some nations have retained orbital slots by leaving satellites in orbit past their useful lifespan.[271] Given that the current space-faring nations have a stake in ensuring the safety and security of satellites in orbit, it is unlikely that they would wittingly participate in this type of action. However, if space launch capabilities become more widespread, less scrupulous nations may be less conscientious.

In much the same way that there is legal uncertainty about the rights of commercial entities in space, there are many questions about how the rights of nations are extended into space. According to the *Outer Space Treaty*, the nation responsible for launching an object into space retains ownership over it (known as the *launching State*).[272] This allows for the

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[269] Orbital angle is the angular distance made between two satellites tracing the same orbit in the sky. Since radio frequency beams spread out as they advance, there is a risk that a transmission directed at one satellite will also be received by the second. This creates unintentional interference that impacts the performance of the second satellite. Based on the frequency (which affects the rate at which the RF beam spreads), altitude, and directionality of the antennas, the ITU selects an orbital angle that limits the interference between satellites operating in the same part of the sky. For higher frequencies, directionality is improved, potentially allowing for smaller orbital angles for satellites operating in these bands.

[270] Mark Holmes, "Hot Orbital Slots: Is There Anything Left?"

[271] *Tongasat*, formed in the Kingdom of Tongo in the late 1980's, currently has a 30+ year old communication satellite sitting in a highly valuable geostationary orbit. Given its age, it's highly unlikely that the satellite is very effective. They are believed to be squatting on the orbit until they can get someone to pay them for the slot. (Source: Dwayne A. Day, "Tough Little Spinner." *The Space Review*, 28 February 2011, accessed on 26 April 2016, http://www.thespacereview.com/article/1787/1.)

[272] The definition of *launching state* includes the state responsible for the launch itself, and the state responsible for contracting the launch (if different). (Source: United Nations Office of Outer Space Affairs, "Convention on International Liability for Damage Caused by Space Objects," *United Nations*, accessed on 23 March 2016, http://www.unoosa.org/pdf/gares/ARES_26_2777E.pdf, Article I – definition of "launching State.")

extension of that nation's legal framework into space within the confines of the satellite or space craft in question. Given that only a handful of nations possess a space launch capability, they may be doing so on behalf of another nation, or a business interest located therein.

Under the terms of the *Outer Space Treaty*, states are responsible for regulating their own domestic market.[273] This includes the safety standards and regulations concerning spacecraft. The *Liability Convention* places the onus for damages on both the state from whose territory the space object was launched, and the state who procured the launch.[274] Damages resulting from a failed launch are apportioned between the participating states based on their contributory negligence. At the level of the UN treaties, there is no explicit recognition of liability residing on the citizen or corporation who may have undertaken the launch. The liability of the state for the actions of their citizens or corporations must be enshrined in domestic legislation to offset the risk being run by the state in allowing them to launch space objects. In the US, Section 107 of the *US Space Launch Competitiveness Act* addresses the requirement for liability waivers associated with launch or re-entry services by amending previous regulations.[275] At present, given that the space-faring nations are all well-developed economies with good standing in the international community, they are expected to take their responsibilities for safety in space seriously. They have a vested interest in preserving the effective and efficient use of space because of the national economic incentives. However, competition for space-business

[273] United Nations Office for Outer Space Affairs, "Treaty on Principles Governing the Activities of Space in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies," Article VI.
[274] United Nations Office of Outer Space Affairs, "Convention on International Liability for Damage Caused by Space Objects," *United Nations*, accessed on 23 March 2016, http://www.unoosa.org/pdf/gares/ARES_26_2777E.pdf, Article I – definition of "launching State."
[275] United States Congress, *Public Law 114-90-Nov. 25, 2015 U.S. Commercial Space Launch Competitiveness Act*, Section 107.

may lead to disparities in regulation and oversight between states, potentially jeopardizing safety and security. Much like orbital theft, less scrupulous nations may not apply the same rigour to an emergent space industry. The space launch equivalent of a Panama or Liberia as a flag nation for cargo vessels may eventually emerge because of weak regulation or enforcement of safety standards by that nation.[276] North Korea, for instance, launched a satellite into low-Earth Orbit in February 2016.[277] Given their pariah standing in the international community, they are not likely to be swayed by the interests of others should they choose to undertake space operations that defy international conventions.[278]

Liability is also an issue for the sale of space objects. The *Liability Treaty* makes no distinctions about the owner of a space object, only the *launching State*.[279] If a space object is sold from one nation to another, there is not an automatic transfer of liability under the UN treaty. Instead, liability is transferred "by incorporating derogation clauses into the contract of sale, but such constructions might be cumbersome and ultimately detrimental to the commercial utilization of space."[280] Corporations may use shell companies, or other tactics, to limit their liabilities regardless. Furthermore, some nations may be negligent in oversight or enforcement. However, although this introduces another layer of uncertainty,

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[276] In fact, Panama's location near the equator gives it an advantage as a potential launch location. (Source: BBC Staff, "Why so many shipowners find Panama's flag convenient," *BBC News*, 05 August 2014, accessed on 27 April 2016, http://www.bbc.com/news/world-latin-america-28558480.)

[277] Mike Wall, "North Korea Launches Satellite to Space," *Space.com*, 08 February 2016, accessed on 26 April 2016, http://www.space.com/31860-north-korea-satellite-launch.html.

[278] In their defence, North Korean reportedly did advise the ITU and the UN of their intention to launch a satellite in February 2016. (Source: Hyung-Jin Kim, "Agency: North Korea plans satellite launch this month," *Phys.org*, 02 February 2016, accessed on 26 April 2016, http://phys.org/news/2016-02-agency-north-korea-satellite-month.html.)

[279] United Nations Office of Outer Space Affairs, "Convention on International Liability for Damage Caused by Space Objects," *United Nations*, accessed on 23 March 2016, http://www.unoosa.org/pdf/gares/ARES_26_2777E.pdf.

[280] Henry R. Hertzfeld and Frans G. von der Dunk, "Bringing Space Law into the Commercial World: Property Rights without Sovereignty," *Chicago Journal of International Law* 6, no. 1 (Summer 2005): 89 – 90.

this problem has not halted sales in the past.[281] But, it may stifle matters, especially for buyers without a pedigree in the space business.

For the time being, given the limited number of national and commercial space launch operators, they possess quite a bit of power to dictate the terms of a launch. This became a problem for Canada when it sought to launch RADARSAT II in the early 2000's. RADARSAT II was a public-private collaboration between the Canadian Government through the Canadian Space Agency (CSA), and MacDonald, Detwiller and Associates (MDA).[282] Like its predecessor, RADARSAT I, RADARSAT II provides worldwide coverage using synthetic aperture radar imagery that can sense through all weather conditions.[283] As a public-private enterprise, it sells its products on the market to commercial users, in addition to providing products to the Government of Canada.[284] The original RADARSAT was launched by the US Government on a Delta II rocket from Vanderberg Air Force Base US in November 1995.[285] When the Canadian Government sought to launch its successor in the early 2000's, the capabilities of the satellite and the availability of its products to private interests caused security problems with the US. In accordance with the treaty, "Agreement Concerning the Operation of Commercial Remote Sensing Satellites," signed by the US and Canada in 2000, each nation was responsible for exercising national security controls over private imagery satellites operated by their

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[281] In 2014, Google bought a satellite operator including their satellites. (Source: Robinson Meyer, "Google owns a satellite now," *The Atlantic*, 10 June 2014, accessed on 27 April 2016, http://www.theatlantic.com/technology/archive/2014/06/why-google-bought-satellite-startup-skybox/371531/.)

[282] Canadian Space Agency, "RADARSAT-2," accessed on 27 April 2016, http://www.asc-csa.gc.ca/eng/satellites/radarsat2/.

[283] Canadian Space Agency, "Applications," accessed on 27 April 2016, http://www.asc-csa.gc.ca/eng/satellites/radarsat2/applications.asp.

[284] Canadian Space Agency, "Ordering RADARSAT-2 data," accessed on 27 April 2016, http://www.asc-csa.gc.ca/eng/satellites/radarsat2/order-contact.asp.

[285] Earth Observation Portal, "RADARSAT-1," accessed on 27 April 2016, https://directory.eoportal.org/web/eoportal/satellite-missions/r/radarsat-1.

nationals.[286] The US mandated that Canada provide *shutter control* over RADARSAT II as a pre-condition for launch. In response, the Canadian Parliament passed "Bill C-25: An Act Governing the Operation of Remote Sensing Space Systems," on 25 November 2005, giving them positive control over RADARSAT imagery in the event of a crisis.[287] Regardless, additional issues plagued the relationship. Mechanical and technical incompatibilities between the Delta II rocket and RADARSAT-2 emerged.[288] MDA was also unhappy that the US was launching the satellite in exchange for data, which the company was planning to sell to them.[289] In the end, the US backed out of the launch, and RADARSAT-2 was launched by the Russians in 2007.[290]

Under the terms of the *Remote Sensing Treaty* with the US in 2000, Canada was obligated to pass legislation giving them the right to restrict access to RADARSAT imagery. Nonetheless, Canada's initial reliance on the US space launch infrastructure gave the latter significant leverage to see that this was brought about. Setting aside the security considerations, Canada could have sought a launch capability from another nation such as the Europeans, Indians, or Chinese, but would have been out-of-pocket for the launch costs. In the end, they had to do so anyway, adding an estimated $191M to the total mission

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[286] Jason Bates, "Canadian Bill Would Align Remote Sensing Law with U.S.," *Space.com*, 07 February 2005, accessed on 25 March 2016, http://www.space.com/770-canadian-bill-align-remote-sensing-law.html.
[287] Parliament of Canada, "Bill C-25: An Act Governing the Operation of Remote Sensing Space Systems," *Government of Canada*, 25 November 2005, accessed on 25 March 2016, http://www.lop.parl.gc.ca/About/Parliament/LegislativeSummaries/bills_ls.asp?ls=C25&Parl=38&Ses=1. Clause 14 mandates shutter control. Clause 15 mandates priority access.
[288] Ottawa Citizen, "Russia entrusted with Canada's top satellite secrets," *Canada.com*, 18 Januray 2006, accessed on 27 April 2016, http://www.canada.com/story_print.html?id=5dfd910e-125e-495a-a180-27fc68522918&sponsor=.
[289] Marc Boucher, "Is Canadian Sovereignty at Risk by a Lack of an Indigenous Satellite Launch Capability?" *Space Ref Canada*, 04 January 2011, accessed on 27 April 2016, http://spaceref.ca/national-security/is-canadian-sovereignty-at-risk-by-a-lack-of-satellite-launching-capability.html.
[290] Canadian Space Agency, "RADARSAT-2."

cost.[291] Some commentators have suggested that Canada needs a domestic launch capability, at least for small satellites.[292] In 2010, the CSA conducted a study into this matter. However, by 2014, head of the CSA, retired General Walter Natynczyk opposed development of a domestic capability, citing budgetary concerns.[293]

With the emergence of new launch competitors around the world (privately or otherwise), Canada should have more flexibility in negotiating with the US in the future. Companies like Virgin Galactic will have the flexibility to move their operations worldwide. They will not be tied to fixed infrastructure at a spaceport. This gives them the flexibility to sidestep national regulations by choosing to launch from elsewhere in the world. A future Canadian satellite could be launched from an airport in Canada for these reasons.[294]

It is clear that, at the international level, confusion remains over some aspects of commercial space use. The UN space treaties and principles were developed in a bi-polar world, with only a limited numbers of states capable of developing a space program at that time. Given that the costs could only be borne by industrialized nations, the treaties were conceived to govern the relationship between states, and not private enterprises or individuals. This has led to confusion over the right of *ownership* in outer space, given the prohibition on declarations of sovereignty in many of the space treaties. Hickman's

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[291] Marc Boucher, "Is Canadian Sovereignty at Risk by a Lack of an Indigenous Satellite Launch Capability?" *Space Ref Canada*, 04 January 2011, accessed on 27 April 2016, http://spaceref.ca/national-security/is-canadian-sovereignty-at-risk-by-a-lack-of-satellite-launching-capability.html.

[292] *Ibid*; and David Pugliese, "Does Canada need its own rockets to launch satellites?" *Ottawa Citizen*, 24 July 2014, accessed on 27 April 2016, http://ottawacitizen.com/news/national/does-canada-need-its-own-rockets-to-launch-satellites.

[293] David Pugliese, "Does Canada need its own rockets to launch satellites?"

[294] Location on the globe does have an impact on the type of initial orbit that can be achieved, so selecting a Canadian location for launch may not be ideal depending on the orbit being sought.

concept of a *Development Authority* seems quite pertinent. Some academics have drawn parallels to the *International Seabed Authority* within UNCLOS as a potential solution. Others have discussed *de facto* or *pseudo* property rights, with corporations or individuals essentially declaring themselves the owner over resources that they physically control, or that are granted by their government. They have been aided in their arguments by the US and Luxembourg who both passed legislation granting their citizens the right to take and sell resources from space, possibly in violation of *Outer Space Treaty*. Regardless, this uncertainty has not hindered investment in a handful of space mining companies intent on harvesting resources from the Moon and near-Earth asteroids within the next decade.

In addition to complications over ownership, no international treaties (UN or otherwise) control near-Earth orbits. The ITU exerts indirect control over orbital slots through their role in ensuring frequency de-confliction around the globe. Without their assistance, satellites would be in jeopardy of unintentional interference, degrading their operations and limiting their utility. Even so, other than self-interest on the part of the launching nations to preserve safety in orbit, there is no legal prohibition preventing a malign actor from stealing a valuable orbit from another player.

For the time being, outer space remains a little bit of *The Wild West*. We can conceive of a better regulated environment, but the impetus to address these problems has been limited. This lack of clarity may actually be an advantage. It gets dreamers to invest in ventures that promise big returns, optimistic that any legal entanglements will be resolved in their favour. In success or failure, their efforts may lay the foundation for future exploration.

CHAPTER 4 - DEFENCE AND SECURITY IN SPACE

Having examined the legal and economic aspects of the emerging commercial space industry, the question remains – what does this mean for defence and security? Under the *Outer Space Treaty*, space objects launched by a nation remain the property of that nation while in orbit.[295] In principle, any responsibilities a nation has to protect the property of its citizens should be naturally extended into space. Terrestrially, protection of one's citizens or corporate interests is not usually enforced by that state's armed forces. International law and diplomacy are the tools employed to reinforce behavioural norms and punish transgressors. A nation reserves its military might for its strategic national interests.

From the US perspective, and those of its key allies (including Canada), access to global telecommunications, position, navigation and time (PNT) services, and remote sensing capabilities, are critical to their defence and security. Loss of access to these services would be detrimental to the effectiveness of these forces, undermining capabilities that depend on them for their effectiveness, such as unmanned aerial vehicles (UAVs),[296] situational awareness systems,[297] or precision guided munitions.[298] This dependency explains the interest by the Russians and Chinese in developing military capabilities that

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[295] United Nations Office for Outer Space Affairs, "Treaty on Principles Governing the Activities of Space in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies," Article VIII.

[296] UAVs may rely on satellite communication to connect with their ground station. (Source: Sandra I Erwin, "Pentagon Eyes Deals With Satellite Industry to Fill Demand for Drone Communications," *National Defense Magazine*, May 2013, accessed on 27 April 2016, http://www.nationaldefensemagazine.org/archive/2013/May/pages/PentagonEyesDealsWithSatelliteIndustryToFillDemandforDroneCommunications.aspx.)

[297] For example, Northrup Grumman's Blue Force Tracker. (Source: Richard J. Dunn, III, "Blue Force Tracking," *Northrop Grumman*, accessed on 27 April 2016, http://www.northropgrumman.com/aboutus/analysiscenter/documents/pdfs/bft-afghanistan-and-iraq-exper.pdf.)

[298] PCTEL Connected Solutions, "Precision Guided Munitions and the Historic Role of GPS," accessed on 27 April 2016, http://www.antenna.com/artifacts/20101021MunitionsGuidance-GPS_final.pdf.

could remove or degrade them in a future conflict.[299] From a strategic perspective, the US must preserve its ability to access and operate in space to maintain its military advantage.

Article IV of the *Outer Space Treaty* complicates matters. It states that "the establishment of military bases, installations and fortifications, the testing of any type of weapons and the conduct of military manoeuvres on celestial bodies shall be forbidden."[300] This limits the ability of the US (and Russia or China) to test and place weapon systems in orbit, even if only for defensive purposes. As more nations extend their influence into space, who will be responsible for enforcing the treaty, and imposing law and order in space? Does this treaty apply to law enforcement functions? Must the UN or some other internationally sanctioned organization take up responsibility for defence and security in space? Can the UN Security Council interpret its mandate to enforce international peace and security in orbit? These questions do not arise specifically from an increased *commercial* use of space, but rather from an overall increase in space use generally. This chapter will constrain itself to those matters that arise as a logical consequence of increased commercial use of space. Particularly, what new threats or hazards may arise?

We've already touched on a handful threats and hazards in previous chapters. First, orbital congestion is increasing, especially in low-Earth orbit. As discussed in Chapter 2, an estimated 300 small satellites (< 50 kilograms) are expected to be launched in 2016, rising to between 400 – 500 satellites per year by 2020.[301] New telecommunication and

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[299] See Chapter 3 for a discussion of recent Russian and Chinese anti-satellite efforts.
[300] United Nations Office for Outer Space Affairs, "Treaty on Principles Governing the Activities of Space in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies," Article IV.
[301] Elizabeth Buchen and Dominic DePasquale, "2014 Nano / Microsatellite Market Assessment." *SpaceWorks Enterprises, Inc*., 2014, accessed on 09 February 2016, http://www.sei.aero/eng/papers/uploads/archive/SpaceWorks_Nano_Microsatellite_Market_Assessment_January_2014.pdf, 7.

direct broadcast (e.g. television, radio) satellites are being introduced to provide services for the emerging middle class in Sub-Saharan Africa, South America, and Asia.[302] These satellites need to share access to the radio frequency spectrum which is deconflicted by the ITU. As technology improves, beam shaping and advanced coding techniques will decrease the power required, and reduce unintentional interference between satellites.[303] This will allow for the orbital angular separation to fall below 2^o, allowing for even more satellites to be placed into the same orbital track. This was already done once at the request of the US Federal Communication Commission.[304] This increases the risk of an accidental collision due to an improper orbital insertion or orbital adjustment. Any resulting collision would create a debris field that would result in even more space objects in close proximity with which to start a chain reaction.

NASA scientist Donald J. Kessler proposed the concept of *collisional cascading* in 1978 (also known as *Kessler Syndrome*) in which the density of space objects in low-Earth orbit is sufficient to create a self-sustaining cascade of collisions, with each individual collision fueling one or more.[305] Of the space objects currently being tracked, the majority of the total is debris, and the majority of the debris came from only two collisions.[306] The

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[302] See Chapter 2 on direct-to-home satellite television broadcast.
[303] Satellites already use beam-shaping to create *spot beams*, limiting the size of the area being serviced by the signal. Adaptive phased areas antennas allow for these beams to be *steered* through time-phasing of the signal elements. By improving the directionality of the beam, lower power can be employed. Similarly, advanced coding techniques can make use of increased computing power for improved error detection and correction codes (EDAC) without compromising transmission speeds.
[304] See Chapter 3 discussion on the ITU-R.
[305] Karl Tate, "Space Junk Explained: How Orbital Debris Threatens Future of Spaceflight (Infographic)," *Space.com*, 01 October 2013, accessed on 28 March 2016, http://www.space.com/23039-space-junk-explained-orbital-debris-infographic.html.
[306] See Figure 4.1. (Source: Karl Tate, "Space Junk Explained: How Orbital Debris Threatens Future of Spaceflight (Infographic)," *Space.com*, 01 October 2013, accessed on 28 March 2016, http://www.space.com/23039-space-junk-explained-orbital-debris-infographic.html.)

first was the intentional anti-satellite test by the Chinese in 2007.[307] The second was the unintentional collision of US and Russian satellites in 2009.[308, 309] Both created several thousand new space objects of varying sizes and speed. As of 2013, the largest single piece of space debris is the ENVISAT satellite. Launched by the European Space Agency (ESA) in 2002, it was a commercial Earth observation satellite.[310] Contact with the satellite was unexpectedly lost in on 08 April 2012, leaving ENVISAT in a slowly decaying orbit expected to last for up to another 150 years.[311] ESA scientists assessed the probability of a collision in that time frame at 30%, assuming that orbital congestion does not increase.[312] More recently, the Japanese Aerospace Exploration Agency (JAXA) lost contact with their newly launched space telescope, *Hitomi*, on 27 March 2016. Space sensors observed debris emanating from the satellite, suggesting that it may have been subject to a collision, or an explosion from the *Hitomi* itself. Regardless, for the time being, it is just another piece of space junk clogging up a useful orbit.[313]

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[307] BBC Staff, “China confirms satellite downed,” *BBC News*, 23 January 2007, accessed on 22 March 2016, http://news.bbc.co.uk/2/hi/asia-pacific/6289519.stm.

[308] Becky Iannotta and Tariq Malik, “US Satellite Destroyed in Space Collision,” *Space.com*, 11 February 2009., accessed on 27 April 2016, http://www.space.com/5542-satellite-destroyed-space-collision.html.

[309] This collision also led to claims between Iridium and the Russian government under the *Liability Convention*. Russia claimed they were unable to manoeuver Cosmos 2251, and moreover, were under no obligation to de-orbit the satellite. Iridium counter-claimed that they were under no obligation to move either, even if they had been aware of the collision in advance. As of 2012, the situation had not been resolved. (Source: Michael Listner, “Iridium 33 and Cosmos 2251 three years later: where are we now?” *The Space Review*, 13 February 2013, accessed on 27 April 2016, http://www.thespacereview.com/article/2023/1.)

[310] European Space Agency, “What is ENVISAT?” accessed on 28 March 2016, https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/envisat.

[311] Karl Tate, “Space Junk Explained: How Orbital Debris Threatens Future of Spaceflight (Infographic),” *Space.com*, 01 October 2013, accessed on 28 March 2016, http://www.space.com/23039-space-junk-explained-orbital-debris-infographic.html.

[312] Orbital congestion will increase. (Source: Peter de Selding, “ESA Enlists Outside Help for Envisat Recovery Effort,” *Space News*, 13 April 2012, accessed on 27 April 2016, http://spacenews.com/esa-enlists-outside-help-envisat-recovery-effort/.)

[313] Stephen Clark, “Japan’s newest space telescope goes silent,” *Spaceflightnow.com*, 28 March 2016, accessed on 08 April 2016, https://spaceflightnow.com/2016/03/27/japans-newest-space-telescope-goes-silent/.

Setting aside the apocalyptic predictions of Dr. Kessler, debris routinely threatens other space objects. As the quantity of debris rises, the requirement to track it, either terrestrially or through collision avoidance systems on satellites increases. Orbital adjustments to avoid debris consume fuel which either increases the cost for the satellite, or reduces its useable lifespan. If too many collisions occur, entire orbital paths could become unnavigable. Fortunately, most US intelligence and military telecommunication satellites operate above low-Earth Orbit, and would be least affected by their collisions. However, as commercial enterprises move outwards over time, these risks will rise.

The US Strategic Command operates a space surveillance system designed to identify and track space objects including debris.[314] As of 2014, the Joint Space Operations Centre was tracking more than 16,000 objects in orbit,[315] with approximately 95 percent of those objects being debris, inactive satellites or expended rocket bodies.[316] Canada is also a participant in this *Space Surveillance Network*, contributing a dedicated satellite to the effort in 2014.[317] As more collisions occur, this inventory of objects will continue to grow. Moreover, the size of the debris being tracked is limited by the resolution of the sensor, so 16,000 only sets the lower limit on orbital debris, with smaller pieces

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[314] United States Strategic Command, "US STRATCOM Space Control and Space Surveillance," *US STRATCOM*, January 2014, accessed on 27 March 2016, https://www.stratcom.mil/factsheets/11/Space_Control_and_Space_Surveillance/.
[315] *Ibid.*
[316] See Figure 4.1 for breakdown.
[317] Department of National Defence, "Sapphire satellite system is declared fully operational," 30 January 2014, accessed on 27 April 2016, http://www.forces.gc.ca/en/news/article.page?doc=sapphire-satellite-system-is-declared-fully-operational/hr1thk2x.

currently unreported.[318] Satellites in orbit need to manoeuvre to avoid collisions, or be built suitably rugged or redundant so that they can survive them.

In 2007, the UN promulgated *Space Debris Mitigation Guidelines* that arose out of their Inter-Agency Space Debris Coordination Committee.[319] It recommended a "Space Debris Mitigration Plan be established and documented for each program and project," which included "a plan for disposal of the spacecraft … at end of mission," and steps taken to mitigate the potential for debris, or orbital break-ups.[320] However, adoption of these guidelines going forward would only serve to reduce the problem in the future. It does nothing to address the current situation with debris. Unfortunately, this situation is complicated by Article VIII of the *Outer Space Treaty* which states that the launching state "shall retain jurisdiction and control over such object… while in outer space."[321] Unlike the ocean, there is no right to salvage of derelict satellites.[322] Space debris can only be removed with the consent of the owner, regardless of its status, including fragments of the original object.[323] Furthermore, under the *Liability Convention*, if the remediation effort resulted in further debris, the state under whom the remediator was regulated would inherit some measure of liability.[324]

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[318] Sensors only monitor objects of size greater than approximately 10 centimeters in diameter. (Source: United States Air Force, "Space Surveillance," accessed on 27 April 2016, http://www.au.af.mil/au/awc/awcgate/usspc-fs/space.htm.)

[319] United Nations Office of Outer Space Affairs, "IADC Space Debris Mitigation Guidelines," September 2007, accessed on 27 April 2016, http://www.unoosa.org/documents/pdf/spacelaw/sd/IADC-2002-01-IADC-Space_Debris-Guidelines-Revision1.pdf.

[320] *Ibid*, Section 4 and 5.

[321] United Nations Office for Outer Space Affairs, "Treaty on Principles Governing the Activities of Space in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies," Article VIII.

[322] Michael Listner, "Legal issues surrounding space debris remediation," *The Space Review*, 06 August 2012, accessed on 27 April 2016, http://www.thespacereview.com/article/2130/1.

[323] *Ibid*.

[324] *Ibid*.

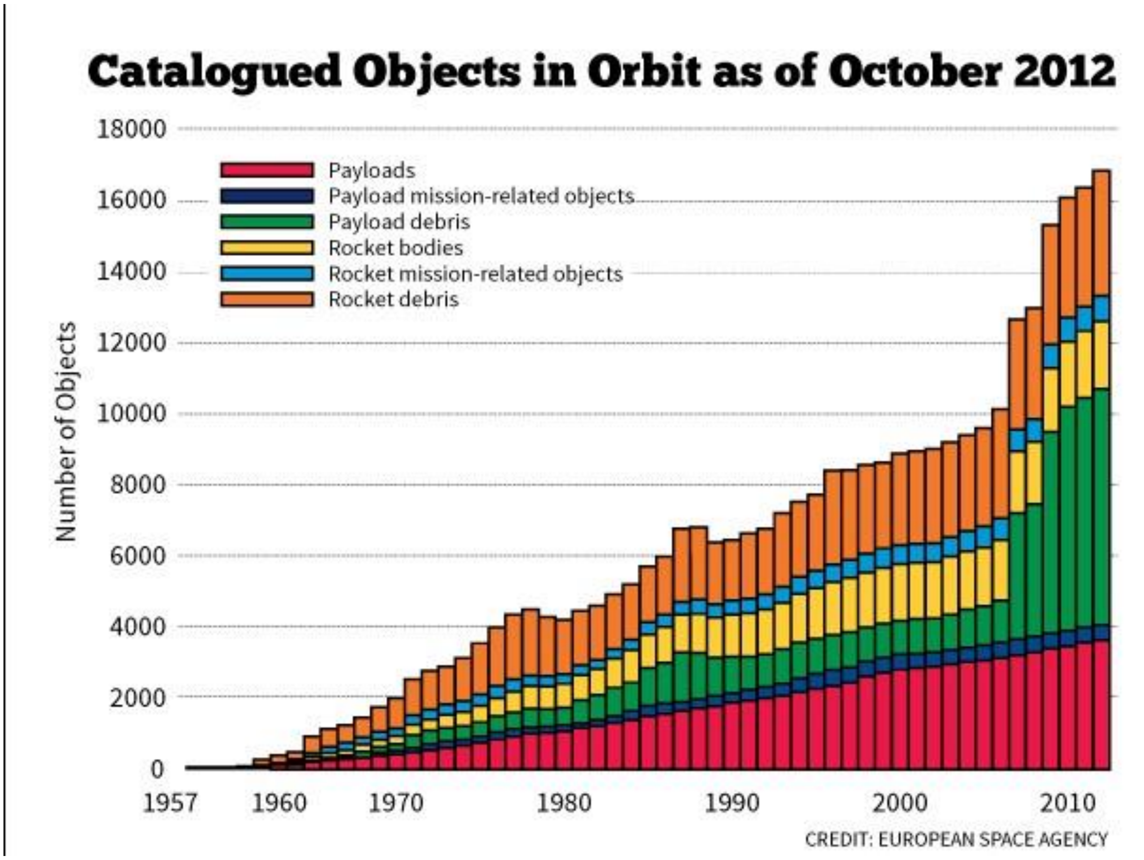

Figure 4.1 - Space Debris by Type (Source: European Space Agency[325])

As Russia commented in 2012, there is no international obligation to *clean up* after oneself when a satellite's use is discontinued.[326] Good stewardship sees satellites being de-orbited so that they burn up in the Earth's atmosphere, or are placed into a parking orbit far away from other satellites (also known as a *graveyard orbit*.) The industry for deliberate orbital debris collection is nascent. A handful of commercial companies are pursuing different technologies and business models for success. L'Ecole Polytechnique

[325] Excerpted from the infographic. (Source: Karl Tate, "Space Junk Explained: How Orbital Debris Threatens Future of Spaceflight (Infographic)," *Space.com*, 01 October 2013, accessed on 28 March 2016, http://www.space.com/23039-space-junk-explained-orbital-debris-infographic.html.)

[326] Michael Listner, "Iridium 33 and Cosmos 2251 three years later: where are we now?" *The Space Review*, 13 February 2013, accessed on 27 April 2016, http://www.thespacereview.com/article/2023/1.

Federale de Lausanne (EPFL) in Switzerland is developing a satellite recovery system called *CleanSpace One*. It is funded by the Swiss government through the Swiss Space Centre, and has been tasked initially with de-orbiting the Swiss-owned satellite, *SwissCube*. *SwissCube* is a *CubeSat* weighing less than one kilogram and with a volume of approximately 10 cm^3. The small size and weight allow for the recovery satellite to be equally small, but also makes automated detection, recognition and approach of the satellite a challenge.[327] *CleanSpace One* works by extending a mouth-like net around the satellite as it approaches, slowly contracting it to capture the *SwissCube*.[328]

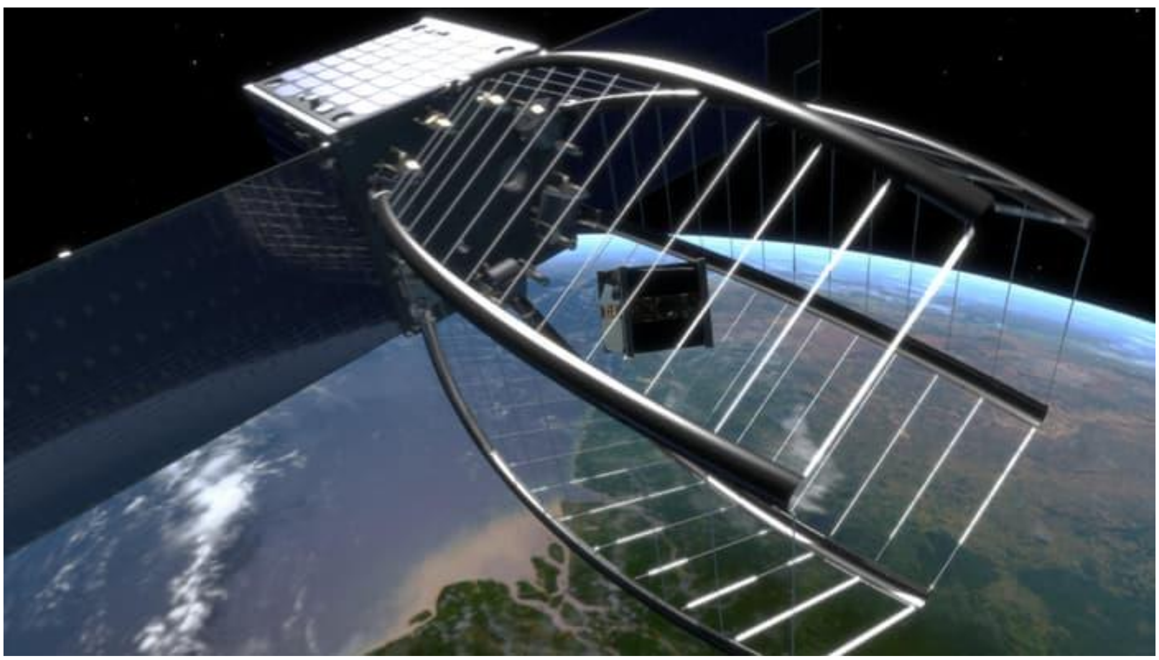

Figure 4.2 - CleanSpace One capturing SwissCube. (Source: Gizmag[329])

[327] *SwissCube* is known to be tumbling, continuously changing its relative orientation with respect to the intercepting satellite, complicating the rendezvous by changing how the satellite is perceived by the automated sensors. (Source: Ecole Polytechnique Federale de Lausanne, "Space Engineering Centre EPFL ESPACE – CleanSpaceOne," accessed on 28 March 2016, http://espace.epfl.ch/CleanSpaceOne_1.)
[328] Ben Coxworth, "EPFL's CleanSpace One satellite will 'eat' space junk," *Gizmag.com*, 07 July 2015, accessed on 28 March 2016, http://www.gizmag.com/cleanspace-one-orbital-debris-satellite/38348/.
[329] *Ibid*.

EPFL has the advantage of being a non-profit endeavor. It currently has approximately $15 million Swiss Francs budgeted for the effort.[330] However, the capture of the *SwissCube* is also intended as a technology demonstrator, allowing them to pursue additional business in the future.[331] However, since the technology works by burning up both the capture and captured satellites in the atmosphere, the *per debris captured* cost is likely to remain quite high. It is an unlikely contender for widespread and cost effective removal of space debris, especially if it needs to be tailored specifically to the size of the debris captured.

Also unclear is the funding mechanism for debris removal beyond governmental altruism. An industry for space debris collection needs to be built, but the commercial incentive remains murky. How should orbital debris removal be funded? It could arise as a premium on space launch, be mandated nationally or internationally, or may arise naturally from market forces as debris-filled orbits become valuable in their own right. As the risk of damage from debris increases, the cost for insurance will rise in response. Conceivably, the cost of removing the debris could reach parity with the premiums, and there would be market motivation to pursue the activity.[332]

The European Space Agency stated in 2013 that “space debris poses an increasing threat to economically and scientifically vital orbital regions… The replacement cost for the approximately 1000 active satellites in orbit [as of 2013] is estimated to be around

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[330] Rob Coppinger, “Space Junk Cleanup Satellite Launching on Swiss Space Plan in 2018,” *Space.com,* 02 October 2013, accessed on 28 March 2016, http://www.space.com/23049-space-junk-satellite-swiss-space-plane.html.
[331] *Ibid.*
[332] Insurance would still be required for other purposes (e.g. loss on launch), so the equivalency would need to arise specifically from the risk due to space debris.

€100B."[333] The ESA has a program called *Clean Space* dedicated to reducing the overall impact of space activity on the Earth, both terrestrially and through debris reduction efforts in orbit.[334] Unfortunately, while laudable, they have not created an economic incentive for widespread clean-up to take place.

The technology behind debris removal itself is also worth consideration as a potential threat. Space capture technology is not only feasible against decommissioned or inoperable satellites, but could also be employed against active ones. An active satellite would still have fuel for maneuvering, making it a more difficult target to capture. In theory, the space surveillance network or another collision detection mechanism would provide warning to enable evasion. However, these systems are designed to operate against targets that are not actively seeking to hide themselves. A satellite using stealth technology could mask itself, appearing as a much smaller target, if not being effectively unseen on approach. Russia is rumoured to have launched an interceptor satellite in May 2014.[335] It was originally thought to be debris until it commenced manoeuvres to rendezvous with the rocket chassis from which it was launched.[336] This type of deceptive insertion masks the threat, and highlights the requirement for space surveillance systems to positively identify space objects.

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[333] European Space Agency, "Global Experts Agree Action Needed on Space Debris," created on 25 April 2013, accessed on 05 April 2016, http://www.esa.int/Our_Activities/Operations/Space_Debris/Global_experts_agree_action_needed_on_space_debris.

[334] European Space Agency, "Clean Space," accessed on 04 April 2016, http://www.esa.int/Our_Activities/Space_Engineering_Technology/Clean_Space.

[335] Tyler Rogoway, "That's No Moon! Did Russia Deploy An Experimental Killer Satellite?" *Foxtrot Alpha*, 21 November 2014, accessed on 28 March 2016, http://foxtrotalpha.jalopnik.com/thats-no-moon-did-russia-deploy-an-experimental-killer-1661535449.

[336] *Ibid.*

Separate from the risk of grappling or physically capturing another satellite, proximity through interception also enables radio frequency eavesdropping or jamming, and physical observation of another satellite's surface. This gives the perpetrator options for categorizing or neutralizing different space objects. This *dual use* for interceptor satellites make monitoring their development and deployment a concern for any military interested in preserving space control.

The US military is aware of this threat, and declassified plans for a constellation of orbital rendezvous satellites in 2014.[337] Known as the *Geosynchronous Space Situational Awareness Program*, the four satellite will reside in near-geosynchronous orbit to monitor and classify other space objects, including interception to resolve ambiguity.[338] The first pair of satellites were launched in 2014, and declared operational in 2015.[339]

The US and her allies are not alone in exploiting space to give them an operational advantage on the battlefield. Other nations have been swift to follow their lead in developing competing commercial or military systems that provide satellite-based telecommunications, position, navigation and time (PNT), or remote sensing. The Soviet Union launched the first satellite of the *Globalnaya Navigazionnaya Sputnikovaya Sistema* or Global Navigation Satellite System (GLONASS) in 1982.[340] Like GPS, it provides global position, navigation and timing coverage. Russia has funded its continued

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[337] Lee Billings, "War in Space May Be Closer Than Ever," *Scientific American*, 10 August 2015, accessed on 19 April 2016, http://www.scientificamerican.com/article/war-in-space-may-be-closer-than-ever/.
[338] United States Air Force Space Command, "Geosynchronous Space Situational Awareness Program (GSSAP)," last updated on 15 April 2015, accessed on 27 April 2016, http://www.afspc.af.mil/library/factsheets/factsheet.asp?id=21389.
[339] Mike Gruss, "US Air Force Declares GSSAP Surveillance Sats Operational," *SpaceNews*, 08 October 2015, accessed on 27 April 2016. http://spacenews.com/u-s-air-force-declares-gssap-surveillance-sats-operational/.
[340] "GLONASS GPS," *Space Today Online*, accessed on 27 April 2016, http://www.spacetoday.org/Satellites/GLONASS.html.

development in recent years, and their receiver technology is starting to be incorporated into dual GPS-GLONASS receivers for use in commercial devices.[341] Meanwhile, the Chinese have been developing their own PNT system, known as Beidou. They have several satellites already in orbit, and a forecasted full operational capability in 2020.[342] Finally, the European GALILEO system is designed to provide Europe with a "highly accurate, guaranteed global positioning system under civilian control."[343] It alleviates European concerns over US control of GPS. Moreover, it is designed to be interoperable with GPS and GLONASS, enabling GALILEO to leverage the existing investments in portable receivers. The ESA is forecasting initial services in 2016, with final completion in 2020.[344] Since the US military maintains the ability to selectively degrade GPS coverage in given areas around the globe, GLONASS and Beidou, in particular, will provide alternate solutions for nations or users who choose to operate in these degraded areas.

In parallel with the first space race, the US and USSR both developed a suite of Intercontinental Ballistic Missiles (ICBMs) that enabled them to lob nuclear warheads on ballistic trajectories anywhere in the world. The Strategic Defense Initiative (SDI) of the 1980's was an effort by the US to neutralize ICBMs before they could strike the continental US. If successful, this would have undermined nuclear deterrence based on the doctrine of *Mutually Assured Destruction (MAD)* by allowing the US to survive a Soviet nuclear strike. Although SDI failed, it did lead to the development of more limited Ballistic Missile

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[341] PJ Jacobowitz, "GPS and GLONASS: 'Dual-Core' Location For Your Phone," *Qualcomm*, 15 December 2011, accessed on 08 April 2016, https://www.qualcomm.com/news/onq/2011/12/15/gps-and-glonass-dual-core-location-your-phone.
[342] Stephen Clark, "Successful launch expands China's Beidou navigation system," *Spaceflight Now*, 02 February 2016, accessed on 08 April 2016, https://spaceflightnow.com/2016/02/02/successful-launch-expands-chinas-beidou-navigation-system/.
[343] European Space Agency, "What is GALILEO?" Accessed on 08 April 2016, http://m.esa.int/Our_Activities/Navigation/The_future_-_Galileo/What_is_Galileo.
[344] *Ibid.*

Defence (BMD) capabilities.[345] Missile defence was first heralded during the 1990 – 1991 Gulf War when Patriot missiles were used to counter the Scud missile threat from the Iraqi Armed Forces against Israel and Saudi Arabia.[346] Although the public narrative trumpeted their success, a subsequent re-evaluation concluded that they were largely ineffective.[347] The President George H.W. Bush and President Clinton administrations continued to pursue development against short and medium range ballistic missiles. This led to a mix of capabilities in the form of the sea-based Aegis Ballistic Missile Defense System, the Patriot Advanced Capability 3 (PAC3) and Terminal (previously, Theatre) High Altitude Air Defence (THAAD) system.[348] Under the President George W. Bush administration, a continental missile defence system was initiated in 2001, leading to the Ground-Based Midcourse Defence (GMD) system, intended to target intercontinental ballistic missiles (ICBMs) directed at the US homeland.[349] Although it is unable to stop a barrage of ICBMs, it is intended to counter limited threats from rogue nations such as North Korea. Canada has been reluctant to get involved in ballistic missile defence for political reasons, eschewing the opportunity back in 2005 under the Liberal government of Paul Martin.[350]

Several space launch operators are currently planning on using a commercial aircraft as the launch platforms for a space plane. For instance, Virgin Galactic's

[345] Additional discussion of SDI and TBMD can be found in Chapter 3.
[346] Fred Kaplan, "Patriot Games," *Slate*, 24 March 2003, accessed on 27 April 2016, http://www.slate.com/articles/news_and_politics/war_stories/2003/03/patriot_games.html.
[347] *Ibid*.
[348] Steven Pifer, "The limits of US missile defense," *The Brookings Institute*, 30 March 2015, accessed on 27 April 2016, http://www.brookings.edu/research/opinions/2015/03/30-us-missile-defense-limits-pifer.
[349] *Ibid*.
[350] CBC News, "Martin will reject missile defence: report," *CBC News*, 22 February 2005, accessed on 08 April 2016, http://www.cbc.ca/news/canada/martin-will-reject-missile-defence-report-1.519736.

SpaceShipTwo is being launched from their specialized *White Knight Two* aircraft.[351] Other space plane operators include Swiss Space Systems (S3) and their SOAR platform[352], and the XCOR Aerospace Lynx spacecraft[353], both of which are planned to be launched using modified commercial aircraft.[354] Given the mobility of the launch platforms to take-off and land around the world, and to orient themselves in any direction once airborne, this gives these spacecraft a great deal of flexibility in terms of their ballistic trajectory. The space planes will also travel much higher, and much faster than conventional aircraft. For instance, *SpaceShipTwo* may only reach a sub-orbital altitude of approximately 100 kilometers above the surface of the Earth, but this is almost five times the operational ceiling of a conventional fighter aircraft.[355] Moreover, using their rocket motor, *SpaceShipTwo* will also be travelling at supersonic speeds well in excess of conventional fighters.[356] By comparison, the much smaller Lynx II spacecraft will also reach an operating ceiling of approximately 100 kilometers above the Earth.[357] Their

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[351] Virgin Galactic, "Human Spaceflight – Our Vehicles," *Virgin Galactic*, accessed on 08 April 2016, http://www.virgingalactic.com/human-spaceflight/our-vehicles/.
[352] Rob Coppinger, "Swiss Company to Launch Robotic Mini-Shuttle in 2017," *Space.com*, 01 April 2013, accessed on 28 April 2016, http://www.space.com/20449-swiss-private-rocket-plane-2017.html.
[353] XCOR Aerospace, "Lynx Spacecraft," accessed on 28 April 2016, http://aerospace.xcor.com/reusable-launch-vehicles/lynx-spacecraft/.
[354] Kasandra Brabaw, "Meet 'Cosmic Girl': Virgin Galactic's New Satellite Launching Jet (Video)," *Space.com*, 09 December 2015, accessed on 19 April 2016, http://www.space.com/31322-virgin-galactic-cosmic-girl-launcherone-plane.html.
[355] The F22 Raptor has an advertised operational ceiling of approximately 60,000ft or ~ 20 kilometers. (Source: Nick Statt, "Virgin Galactic aircraft cruises to supersonic speeds," *CNet*, 05 September 2013, accessed on 08 April 2016, http://www.cnet.com/news/virgin-galactic-aircraft-cruises-to-supersonic-speeds/.)
[356] *SpaceShipTwo* will achieves speeds of 2,500 mph. By comparison, the F22 Raptor has a maximum advertised speed of 2,468 km/h (1500 mph). The SR71 Blackbird only had an advertised maximum speed of 2200 mph. (Source: Nick Statt, "Virgin Galactic aircraft cruises to supersonic speeds," *CNet*, 05 September 2013, accessed on 08 April 2016, http://www.cnet.com/news/virgin-galactic-aircraft-cruises-to-supersonic-speeds/.)
[357] Karl Tate, "How XCOR's Lynx Space Plane Works (Infographics)," *Space.com*, 01 March 2016, accessed on 28 April 2016, http://www.space.com/32104-how-xcor-s-lynx-space-plane-works-infographic.html.

rocket engines will propel them into orbit at Mach 2.9.[358] Although they plan on gliding back to Earth, they can still re-engage their engines to achieve even greater speeds on the descent.[359]

Figure 4.3 - SpaceShipTwo. (Source: Virgin Galactic[360])

Given the role of the military in ensuring national aerospace defence (e.g. NORAD) or overseas on operations (e.g. establishing air control or supremacy), a maneuverable space plane with high altitude and speed is a significant threat. Whether through hijacking a commercial flight, or deliberate development by another nation, even just the kinetic energy from colliding a space plane into a stationary object would be immense. As a threat, they most closely match a ballistic missile, but are more

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358 *Ibid.*
359 *Ibid.*
360 SpaceShipTwo. Image credited to Virgin Galactic. Taken from http://www.virgingalactic.com/human-spaceflight/our-vehicles/ on 06 May 2016.

maneuverable due to their larger aerodynamic control surface. Conventional solutions for responding to this threat need to be re-examined to ensure that they can effectively intercept and engage these new types of atmospheric vehicle. BMD or other solutions targeted against high-speed, high-altitude threats may need to be more widely available to counter these threats. Setting aside the risk from hijacking, technology transfer to other nations through sale, theft, or espionage, risks making this capability available to adversaries. Notably, China is already believed to be pursuing a hypersonic glide vehicle (known as the WU-13) with high speed and maneuverability intended to defeat conventional missile defence systems in this manner.[361]

The US is also developing their own space plane technology in the form of the classified X-37B program. Operated by the US Air Force, "the primary objectives of the X-37B are twofold: reusable spacecraft technologies… and operating experiments which can be returned to, and examined on Earth."[362] Unlike its space tourism cousins, the X-37B can operate in orbit for protracted periods of time.[363] Like the US Space Shuttle, it has a cargo bay that can transport different payloads. Based on this capability, it is speculated that the X-37B can be employed as a remote laboratory for sensitive science experiments, an observation platform for use against other space objects, or as an

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[361] Richard D. Fisher Jr., "US officials confirm sixth Chinese hypersonic manoeuvring strike vehicle test," *IHS Janes*, 27 November 2015, accessed on 28 April 2016, http://www.janes.com/article/56282/us-officials-confirm-sixth-chinese-hypersonic-manoeuvring-strike-vehicle-test.

[362] United States Air Force, "X-37B Orbital Test Vehicle," *US Air Force*, 17 April 2015, accessed on 08 April 2016, http://www.af.mil/AboutUs/FactSheets/Display/tabid/224/Article/104539/x-37b-orbital-test-vehicle.aspx.

[363] Leonard David, "US Military's Top-Secret X-37B Space Plane Mission Nears 3-Month Mark," *Space.com*, 13 August 2015, accessed on 28 April 2016, http://www.space.com/30245-x37b-military-space-plane-100-days.html.

interception platform that can grapple and capture them.[364] From orbit, it may also be capable of intercepting sub-orbital spacecraft in support of aerospace defence. Much like NORAD maintains aircraft on alert to respond to an emergency arising from commercial aviation, a fleet of X-37B along suitable orbital tracks could respond to an emergency arising from commercial (or hostile) space operations.

Would the use of the X-37B in this role violate Article IV of the *Outer Space Treaty*?[365] Arguably, it is not a base, installation or fortification. However, it would probably need to possess a weapon to disable a hostile space plane, but this would not necessarily need to be tested in space (assuming interception is done sufficiently close to the Earth as to be *not space*[366]). It would probably be considered a military manoeuver, but it is not actually *on* a celestial body. In short, less the prohibition on testing, use of the X-37B or a similar conventional solution from space should be in compliance with the *Outer Space Treaty*. Of course, this assumes that the US (or Russia or China) would choose to remain compliant in the face of threats that were not conceived at the time of authorship.

We previously remarked that the use of the military for national security reasons arises in response to threats to national strategic interests. Separate from preserving its ability to militarize space, what other national strategic interests exist within space which the US would want to protect?

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[364] Kiona Smith-Strickland, "What's the X-37 Doing Up There?" *Smithsonian Air & Space Magazine*, February 2016, accessed on 08 April 2016, http://www.airspacemag.com/space/spaceplane-x-37-180957777/?no-ist.

[365] Article IV states "The establishment of military bases, installations, fortifications, the testing of any type of weapons and the conduct of military manoeuvres on celestial bodies shall be forbidden." (Source: United Nations Office for Outer Space Affairs, "Treaty on Principles Governing the Activities of Space in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies," *United Nations*, 19 December 1966, accessed on 10 February 2016, http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html, Article IV.)

[366] The actual definition of *outer space* has never been conclusively agreed upon in international law.

As discussed previously, the US has heavily invested in space-based telecommunication, remote sensing, and PNT solutions. Their military is reliant on these capabilities for warfighting. Their industry has built substantial commercial solutions based around their continued availability. Loss of these capabilities would be detrimental to national defence and security, and would significantly impact the US (and world) economies. Fortunately, many of these systems are designed to be redundant, so the loss of any one (or a handful of) satellite is not likely to cause significant repercussions. For example, as of March 2016, the GPS constellation consisted of over 31 satellites flying in medium-Earth orbit, up from the original 24 satellite configuration.[367] Similarly, in addition to several military telecommunication satellites, there are numerous commercial providers who can provide competing coverage in the event of an emergency.

Does commercialization of space change this equation? Expanded use of space for telecommunication, remote sensing, or PNT is unlikely to warrant further concern by the government beyond whatever has already been discussed.[368] Although the US military makes use of commercial services, they maintain core capabilities upon which to fall back. However, one should expect them to react strongly to any actions taken to neutralize or destroy key elements of their space systems.

In terms of new commercial industries, resource extraction merits further investigation because it involves the potential transport of significant quantities of material into Earth orbit. Because of the fuel costs associated with continued ferrying of material

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[367] United States Government, "Space Segment," accessed on 28 April 2016, http://www.gps.gov/systems/gps/space/.
[368] For instance, the US is concerned with remote sensing of their facilities. See Chapter 3 for further discussion.

from an asteroid to Earth orbit, it has been proposed that the asteroid itself should be *nudged* into orbit around the Earth, effectively creating a second Moon. Orbital mechanics is very sensitive to small deviations in speed and angle[369], meaning that objects in orbit are constantly making adjustments to maintain their position.[370] Moving any large object into orbit with the Earth is a cause for concern. Although it may seem difficult to believe that this is feasible, the sensitivity of orbital mechanics to small changes can also work to our advantage. Investigations into the opposite problem, namely ensuring that asteroid do not intersect with the Earth's orbit, have shown that even a small satellite placed in orbit around an asteroid can operate as a *gravity tractor*, slowly pulling the asteroid onto a new trajectory by changing the centre of mass of the conjoined system.[371] Even changing the solar albedo of an asteroid by spraying it with a reflective substance (e.g. reflective powder or paint) would result in a small increase in pressure from the solar wind that would cause a deviation in the asteroid's orbit over time.[372]

Moving massive objects into orbit around the Earth seems like a risky endeavor, especially during the nascent stages of our expansion into space. However, there is no legal prohibition preventing someone from doing this, and also no ability to stop them if they

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[369] Many-body systems (such as multiple objects orbiting each other) are mathematically unsolvable. For three or more interacting bodies, no general solution to the problem is known. Even the long term stability of the solar system is unknown. Furthermore, the orbital parameters are unstable. Small deviations in speed and direction can have significant consequences on the resulting orbit.

[370] As discussed in Chapter 2, the ISS requires between 8,000 and 19,000 pounds of fuel per year to maintain their orbit. (Source: National Aeronautics and Space Administration, "Higher Altitude Improves Station's Fuel Economy," accessed on 26 April 2016, http://www.nasa.gov/mission_pages/station/expeditions/expedition26/iss_altitude.html.)

[371] The deviation is a function of the relative masses between the satellite and the asteroid, and the time space over which it is allowed to operate. (Source: Edward T. Lu and Stanley G. Love, "Gravitational Tractor for Towing Asteroids," *Nature* 438 (10 November 2005): 177 – 178.)

[372] Jennifer Chu, "Paintballs may deflect an incoming asteroid," *MIT Press*, 26 October 2012, accessed on 08 April 2016, http://news.mit.edu/2012/deflecting-an-asteroid-with-paintballs-1026.

choose to pursue it.[373] In fact, NASA is planning their own *asteroid redirect mission* in the 2020's in which they intend on capturing a near-Earth asteroid, and placing it in orbit around the Moon to allow for sustained study. As NASA states on their official webpage for the program, the mission "will demonstrate planetary defense techniques to deflect dangerous asteroids and protect Earth if needed in the future."[374] They will also "choose an asteroid for capture with a size and mass that cannot harm the Earth, because it would burn up in the atmosphere."[375] These two statements are fascinating because they speak to be balance of risk versus reward that arises with any effort to relocate space objects in the vicinity of the Earth. NASA is clearly betting that the risk of causing an accidental collision is quite low, but not altogether zero.

For commercial enterprises, there are no *best practices* established yet for governing how this type of activity should be undertaken. Like NASA, limiting orbital insertion to lunar orbits, or the Lagrange Points in the Sun-Earth system may be a thoughtful first step. However, because these orbits are further away from the Earth, they raise the cost associated with resource extraction, which may dissuade some. And the question still remains how to protect against deliberate or accidental relocation of space objects that threaten to collide with the Earth. International agreements governing the movement of space objects in the vicinity of Earth seems like a logical first step. However, these agreements need to be enforced, and a response capability to address accidental or intentional movement of a space object into a detrimental orbit needs to be established.

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[373] A nation could choose to deny permission to launch, but this would need to be repeated around the world to result in a complete prohibition. It's also unclear whether any nation could legally prevent a launch arising from international waters.
[374] National Aeronautics and Space Administration, "What is NASA's Asteroid Redirect Mission?" *Asteroid Redirect Mission*, accessed on 04 April 2016.
[375] *Ibid.*

To achieve success against these threats, the detection of alterations in near-Earth asteroids or other space objects needs to be improved. The existing Space Surveillance Network is not suitable for deeper space observations required to support this endeavor, and existing funding by the US government on near-Earth asteroid detection has been marginal. The NASA Near Earth Object Program had a budget of only $4M in 2009, although it has since expanded to $40M in 2014.[376] A Planetary Defense Coordination Office was established by NASA in January 2016 to oversee and coordinate the increased scope of the Near Earth Object Program, including the aforementioned asteroid redirect mission, and international efforts to detect and track asteroid that intersect with the Earth's orbit.[377] To date, NASA and the international community have only identified approximately 90% of asteroids larger than one kilometer, and approximately 25% of mid-sized asteroids (~ 140 meters).[378] For comparison, the unexpected meteor that traced a path through the sky over Chelyabinsk, Russia on 15 February 2013 was only 20 meters wide, but created the equivalent of a 500 kiloton blast when it broke apart in the atmosphere approximately 27 kilometers above the Earth.[379] It went unnoticed because of its small size and trajectory when approaching the Earth.[380] According to one estimate,

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[376] Emily Reynolds, "New NASA office will protect the Earth from asteroids," *Wired UK*, 11 January 2016, accessed on 04 April 2016, http://www.wired.co.uk/news/archive/2016-01/11/nasa-asteroid-program.

[377] Jet Propulsion Laboratory, "NASA Office to Coordinate Asteroid Detection, Hazard Mitigation," *National Aeronautics and Space Administration*, 07 January 2016, accessed on 04 April 2016, http://www.jpl.nasa.gov/news/news.php?feature=4816.

[378] *Ibid*.

[379] Dan Vergano, "Russian Meteor's Air Blast Was One for the Record Books," *National Geographic*, 06 November 2013, accessed on 04 April 2016, http://news.nationalgeographic.com/news/2013/11/131106-russian-meteor-chelyabinsk-airburst-500-kilotons/.

[380] The meteor was coming from the direction of the Sun, blinding most sensors that could have observed its approach.

there are approximately 20 million asteroids of this size in near-Earth orbit that could wreak similar havoc in the future.[381]

Asteroid defence has garnered some public advocacy. The non-governmental B612 Foundation was created to "[work] towards protection of Earth from asteroid impacts… and to inform decision-making on planetary defense issues."[382] They are hoping to build their own infrared space telescope, called *Sentinel*, to assist in these efforts.[383] However, much like many of the Mars colonization efforts,[384] their donation-based approach to funding has fallen short.[385]

In addition to much improved monitoring capabilities, an ability to respond to asteroid threats in a tangible manner must emerge. Preferably, this capability would already be resident in orbit, making it immediately available, and avoiding the time and risk associated with a launch. However, if we improve the quality of our detection, we can buy ourselves additional time to respond, giving us more options. In particular, the gravity tractor relies on the inverse correlation of time and mass to be effective (i.e. more satellite mass decreases the time for deflection).[386] Similarly, solar albedo is also difficult to employ in an emergency because there is an upper limit on the reflectivity, and we can't control the strength of the solar wind. Augmenting the albedo with a solar sail would improve matters by increasing the surface area on which the solar wind can act, but it is a

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[381] P.G. Brown *et al*, "Letter: A 500-kiloton airburst over Chelyabinsk and an enhanced hazard from small impactors," *Nature* 503, issue 7474 (14 November 2013): 241.
[382] B612 Foundation, "Our Mission," accessed on 28 April 2016, https://b612foundation.org/our-mission/.
[383] *Sentinel* would be an infrared telescope satellite in orbit around the sun, allowing it to observe asteroid threats at a different angle than from the Earth. (Source: B612 Foundation, "The Sentinel Mission," accessed on 28 April 2016, https://b612foundation.org/sentinel/.)
[384] See Chapter 2 for further discussion on the financial difficulties surrounding Mars colonization.
[385] Jeff Foust, "B612 Presses Ahead with Asteroid Mission Despite Setbacks," *Space News*, 20 October 2015, accessed on 28 April 2016, http://spacenews.com/b612-presses-ahead-with-asteroid-mission-despite-setbacks/.
[386] The larger the mass of the satellite, the less time it takes to cause a given deviation.

more technically complex solution. Other solutions under investigation include breaking apart the space object using conventional or nuclear weapons such that the fragments are scattered into new orbits or will be small enough to burn up in the Earth's atmosphere[387], or by attaching reaction drives to the object to push it into another orbit.[388] As interest in relocating space objects continues to rise, serious consideration on how to respond to potential problems needs to mature as well.

Aside from the existential risks that may arise from asteroid relocation, are there other examples of a national space interest that could come about through further commercialization? Yes, if further elements of our terrestrial national infrastructure are extended into space. For instance, as observable consequences of climate change become more apparent, a transition is occurring between energy sources that generate greenhouse gases, and lower impact renewables in the form of solar, wind, tidal, and geothermal energy.[389] Solar power has seen significant investment in technology and adoption in the past decade which has raised its effectiveness, but it will always remain limited by the rotation of the Earth.[390] However, satellites operating above the Earth can maintain

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[387] For further information, see the 1998 summer movie blockbusters *Armageddon* (https://www.youtube.com/watch?v=kg_jH47u480) and *Deep Impact* (https://www.youtube.com/watch?v=9cqDWRIv7Mg); or, Douglas Messier, "Nuking Dangerous Asteroids Might Be the Best Protection, Expert Says," *Space.com*, 29 May 2013, accessed on 28 April 2016, http://www.space.com/21333-asteroid-nuke-spacecraft-mission.html.

[388] NASA's *asteroid redirect mission* seems them capturing the asteroid inside a *capture bag*, and then using the engines on the redirect vehicle to push it into orbit. (Source: National Aeronautics and Space Administration, "Asteroid Redirect Mission Reference Concept," accessed on 28 April 2016, https://www.nasa.gov/pdf/756122main_Asteroid%20Redirect%20Mission%20Reference%20Concept%20Description.pdf, 3.)

[389] Karl Mathiesen, "What is holding back the growth in solar power?" *The Guardian*, 31 January 2016, accessed on 28 April 2016, http://www.theguardian.com/sustainable-business/2016/jan/31/solar-power-what-is-holding-back-growth-clean-energy.

[390] Northern Europe only has a capacity factor of 15%. Capacity factor is the ratio between actual output, and theoretical maximum output over time. (Source: Karl Mathiesen, "What is holding back the growth in solar power?" *The Guardian*, 31 January 2016, accessed on 28 April 2016,

constant exposure to the sun, and beam power to the Earth wirelessly to satisfy our terrestrial demands.

Research in this area has been underway since the 1970's. The Department of Energy and NASA initially studied the problem under the *Satellite Power System Concept Development and Evaluation Program* from 1978 until 1981.[391] In 1999, NASA revisited the problem through the *Space Power Exploratory Research and Technology Program*.[392] It was mandated to study the problem and provide a research and technology roadmap for a 10 – 100 gigawatt space power system.[393] In the final project report, the Committee concluded that "ultimate success" in achieving cost-competitive power generation relied on "dramatic reductions in the cost of transportation from Earth to GEO."[394] At the time, they were seeking costs of $220 per kilogram to LEO, and $800 per kilogram to GEO, in order to achieve projected costs of 10 – 20 cents per kilowatt-hour.[395] This objective remains elusive, requiring that current best-case space launch costs improve by approximately another order of magnitude.[396] Even given these difficulties, NASA is not alone in their investigation. The Japanese Aerospace Exploration Agency has also been

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http://www.theguardian.com/sustainable-business/2016/jan/31/solar-power-what-is-holding-back-growth-clean-energy.)

[391] National Space Society, "Satellite Power System Concept Development and Evaluation Program," accessed on 10 April 2016, http://www.nss.org/settlement/ssp/library/doe.htm.

[392] National Research Council, *Laying the Foundation for Space Solar Power: An Assessment of NASA's Space Solar Power Investment Strategy* (Washington, DC: The National Academies Press, 2001). Accessed on 28 April 2016, http://www.nap.edu/read/10202/chapter/1.

[393] National Research Council, *Laying the Foundation for Space Solar Power: An Assessment of NASA's Space Solar Power Investment Strategy*, Executive Summary, 1.

[394] National Research Council, *Laying the Foundation for Space Solar Power: An Assessment of NASA's Space Solar Power Investment Strategy*, Committee Assessment, 2.

[395] National Research Council, *Laying the Foundation for Space Solar Power: An Assessment of NASA's Space Solar Power Investment Strategy*, Chapter 4, 15.

[396] For instance, the SpaceX *Falcon Heavy* would need to decline from $1,700 per kilogram to LEO to approximately $170 per kilogram to LEO.

interested in this concept for several years, and recently demonstrated the wireless transmission of power via microwave transmission in 2015.[397]

Space-based power generation has the advantage of increased efficiency over ground-based since approximately 30% of all solar energy is absorbed by the atmosphere enroute to the surface.[398] By converting the solar energy into a laser or microwave beam for transmission to the Earth, this energy absorption can be mitigated.[399] A satellite in geostationary orbit has (near) continuous exposure to the sun, meaning that solar power can be used while the terrain over which it is orbiting is in the dark. Satellites in lower Earth orbits would need to be sun-synchronous to maintain their exposure, but would not remain stationary over their ground stations.[400] Space solar power also requires significant commitments in land to build the terrestrial receivers.[401] One commentator suggested that "about 3.4% of the contiguous United States would be needed for receiving stations and safety perimeter"[402] to provide 100% of all forecasted US power needs in the year 2100.[403] Moreover, he predicts that as much as "five to ten percent of the US gross domestic product

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397 Evan Ackerman, "Japan Demoes Wireless Power Transmission from Space-Based Solar Farms," *Spectrum Magazine*, 16 March 2015, accessed on 10 April 2016, http://spectrum.ieee.org/energywise/green-tech/solar/japan-demoes-wireless-power-transmission-for-space based-solar-farms.

398 United States Department of Energy, "Space-based Solar Power," 06 March 2014, accessed on 28 April 2016, http://www.energy.gov/articles/space-based-solar-power.

399 Although there are losses associated in the conversion from solar-to-microwave/laser-to-DC that need to be included as well.

400 United States Department of Energy, "Space-based Solar Power."

401 Rectifying antennas would need a diameter between 3 – 10 kilometers depending on wavelength. A rectifying antenna converts EM energy into direct current (DC). (Source: United States Department of Energy, "Space-based Solar Power," 06 March 2014, accessed on 28 April 2016, http://www.energy.gov/articles/space-based-solar-power.)

402 Mike Snead, "US terrestrial non-fossil fuel energy vs. space solar power," *The Space Review*, 14 March 2016, accessed on 28 April 2016, http://www.thespacereview.com/article/2941/1.

403 *Ibid.*

[will be required] for the remainder of this century"[404] to accommodate the transition. This is unlikely.[405]

Regardless, space-based power generation, using solar or other means (e.g. nuclear plants in orbit) is interesting from a military perspective because it extends national infrastructure into space. Loss of power can have a dire and direct consequence on people. Establishing robustness and redundancy in the system to address intentional or unintentional damage would be critical. From a military perspective, defending this infrastructure from attack would also be essential to ensuring the energy independence of a nation. The physical threats from ground-based or space-based interception, and destruction or degradation remain a principal concern. Protection from space-based hazards such as asteroids, solar flares, or coronal mass ejections also require detection and reaction. The military's ability to detect, characterize and respond to these threats will require continued investment in sensors, and reactive space vehicles either in orbit, or available for launch on short notice.

As commercial use of space rises, we can expect to see more instances of many existing space services already in operation – telecommunication, remote sensing, and PNT. The security risks associated with these services are already largely understood, and we will face challenges from increased adversary use of technology previously limited to the domain of the military. As more competition emerges, costs decline, and non-Western aligned nations emerge with sophisticated space capabilities, the capability overmatch of Western forces through use of space will be undermined.

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[404] Mike Snead, "Federal legislation to jumpstart space solar power," *The Space Review*, 04 April 2016, accessed on 28 April 2016, http://www.thespacereview.com/article/2956/1.
[405] Quite unlikely.

More interesting are the military considerations that emerge from new forms of space use. Space tourism is creating space planes with unprecedented speed and altitude. As they begin to operate in our national aerospace, they present a threat to our ability to ensure air supremacy. Existing ballistic missile defence systems may already be in a position to respond to these threats, but they are limited in their deployment. In orbit, dual-use of space interceptors designed for debris retrieval and disposal can also target operational infrastructure, providing a covert anti-satellite capability. With orbital congestion forecasted to increase, and the risk of collision rising concurrently, the requirement for debris collection and disposal becomes even more important. To combat the threat, early warning of space objects in the vicinity of key satellites and space systems will be essential to preserve freedom of manoeuvre. Characterizing space objects to detect this capability in advance will be key.

However, all of these threats pale in comparison with the existential threat of an asteroid collision with the Earth. Resource extraction efforts may involve the relocation of near-Earth asteroids into orbit around the Earth, Moon or another suitable location (e.g. Lagrange Point). Any effort to relocate a sizeable object should be treated with caution. Even NASA, who are planning their own asteroid redirection effort, are being circumspect in their selection to ensure that the asteroid would break-up in the atmosphere were the unexpected to occur. Given our lack of experience moving celestial objects, and in the absence of any legal restraints or constraints, deep space observation of near-Earth objects and their movement is critical to providing a timely response to any threat. That response needs to be developed in parallel with efforts to exploit asteroids, and several options are already being investigated by the space community. Ensuring defence and security in space, as on Earth, will depend on situational awareness, preparation, and the proper tools to permit a flexible response.

CHAPTER 5 – CONCLUSION

The space industry is going through an upheaval. Inspired in part by the Ansari X Prize in the early 2000's, private interest and investment in space ventures has grown. Industry stalwarts like Boeing and Lockheed Martin are being upended by new ventures backed by billionaires keen to re-make the space launch economy through lower costs. Upstart SpaceX's *Falcon 9* already has the lowest cost-per-kilogram to reach LEO and GTO.[406] Their upcoming *Falcon Heavy* will lower the costs even further by a factor of two-to-three depending on the orbit.[407] The older *Atlas V* and *Delta IV* rockets being flown by the United Launch Alliance are not cost competitive.[408] This will get even worse if SpaceX achieves further cost savings through re-usability.

Already, SpaceX and Blue Origin have demonstrated the ability to launch and land their first stages safely back on Earth. Blue Origin has gone so far as to launch and land the same rocket three times, all within a span of five months.[409] Meanwhile, SpaceX, flying higher and faster, have also succeeded with three separate rockets, including two recent landings at sea.[410] CEO of SpaceX, Elon Musk, claims that complete and rapid re-usability

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[406] See Figure 2.1

[407] See Figure 2.1. Cost to LEO will drop by approximately half. The cost to GTO will drop by approximately a third.

[408] Eric Berger, "ULA executive admits company cannot compete with SpaceX on launch costs," *Ars Technica*, 17 March 2016, accessed on 22 April 2016, http://arstechnica.com/science/2016/03/ula-executive-admits-company-cannot-compete-with-spacex-on-launch-costs/.

[409] The first landing was on 23 November 2015. The second landing took place on 22 January 2016. The third landing was on 02 April 2016. (Source: Tariq Malik, "Jeff Bezos' Blue Origin Launches and Lands Private Rocket for Third Time," *Space.com*, 02 April 2016, accessed on 29 April 2016, http://www.space.com/32453-blue-origin-launches-and-lands-rocket-third-time.html.)

[410] Calla Cofield, "SpaceX Sticks a Rocket Landing at Sea in Historic First," *Space.com*, 08 April 2016, accessed on 19 April 2016, http://www.space.com/32517-spacex-sticks-rocket-landing-sea-dragon-launch.html; and, Mike Wall, "Wow! SpaceX Nails Rocket Landing At Sea Again," *Space.com*, 06 May 2016, accessed on 06 May 2016, http://www.space.com/32811-spacex-rocket-landing-jcsat-14-launch.html.

will lower the cost by two orders of magnitude, putting the eventual cost at tens of dollars per kilogram.[411]

With much lower costs to reach space, space enthusiasts believe that use of space will accelerate, yielding entirely new industries. Space launch trends have been on the upswing since 2001,[412] although they're still well below the volume launched annually between 1960 and 1980.[413] Increasing standardization in small satellites, such as the *CubeSat*, has lowered manufacturing costs. Combined with launch operators focusing on this market (e.g. Rocket Lab, Virgin Galactic, InterOrbital Systems), the volume of small satellites in orbit is growing by several hundred per year.[414] New ventures by Virgin Group Chairman, Sir Richard Branson, and SpaceX CEO, Elon Musk, are planning on launching almost 5,000 new low-Earth orbit satellites to provide global internet.[415] This would more than triple the current number of operational satellites in orbit.[416]

Emerging middle classes in South America, Sub-Saharan Africa, and South Asia are growing markets for satellite services, particularly direct-to-home satellite television.[417] Global orbits for C and Ku-band satellites were already reaching saturation

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[411] Doug Bierend, "SpaceX Was Born Because Elon Musk Wanted to Grow Plants on Mars," *Motherboard*, 17 July 2014, accessed on 23 April 2016, http://motherboard.vice.com/read/spacex-is-because-elon-musk-wanted-to-grow-plants-on-mars.

[412] See Figure 1.1.

[413] Claude Lafleur, "Spacecraft stats and insights," *The Space Review*, 05 April 2010, accessed on 29 April 2016, http://www.thespacereview.com/article/1598/1.

[414] Elizabeth Buchen and Dominic DePasquale, "2014 Nano / Microsatellite Market Assessment." *SpaceWorks Enterprises, Inc*., 2014, accessed on 09 February 2016, http://www.sei.aero/eng/papers/uploads/archive/SpaceWorks_Nano_Microsatellite_Market_Assessment_January_2014.pdf, 7.

[415] See Chapter 2 for further discussion.

[416] According to the Union of Concerned Scientist, there were 1,381 operating satellites in orbit as of 31 December 2015. (Source: Union of Concerned Scientists, "UCS Satellite Database," database updated on 01 January 2016, accessed on 14 April 2016, http://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database#.Vw_qYlQrKW8.)

[417] Northern Sky Research, "Global Direct-to-Home Markets, 6th Edition," July 2013, accessed on 25 April 2016, www.nsr.com/upload/research_reports/NSR_DTH6_Brief_1.pdf, 6.

in 2008.[418] Commercial providers of traditional satellites services such as telecommunication, remote sensing, and PNT will see their markets expand as new customers increase their purchasing power relative to the West. However, new space industries have been slower to emerge. The scientific evidence supporting the economic advantage for doing most activities in space is still missing.[419] Commercial enterprises focused on mining minerals from asteroids and the Moon have seen the most significant development.

Space resource extraction is an uncertain venture. Economically, it is unclear if they can generate a viable return on investment by securing minerals from celestial objects.[420] They are optimistic about the in-orbit economy, providing fuel and water to spacecraft already in orbit, and leveraging the cost premium associated with launching material from Earth.[421] However, this could be undercut if space launch costs decline into the tens of dollars per kilogram. It also presumes that future spacecraft will continue to rely on reaction engines.[422]

Resource extraction is also plagued with legal uncertainty. The *Outer Space Treaty* prohibits national appropriation or declarations of sovereignty by States over objects in

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[418] Mark Holmes, "Hot Orbital Slots: Is There Anything Left?" *Satellite Today*, 01 March 2008, accessed on 25 March 2016, http://www.satellitetoday.com/publications/via-satellite-magazine/features/2008/03/01/hot-orbital-slots-is-there-anything-left/.

[419] Jeff Foust, "The challenges of commercializing research in low Earth orbit," *The Space Review*, 04 April 2016, accessed on 25 April 2016, http://www.thespacereview.com/article/2958/1.

[420] Sarah Cruddas, "The truth about asteroid mining," *BBC News*, 05 January 2016, accessed on 26 April 2016, http://www.bbc.com/future/story/20160103-the-truth-about-asteroid-mining.

[421] Planetary Resources, "The Trillion Dollar Market: Fuel In Space From Asteroids," 06 Jun 2014, accessed on 26 April 2016, http://www.planetaryresources.com/2014/06/fuelspace/.

[422] NASA recently studied a reactionless drive based on radiation pressure within a cavity. If scalable, it would create an entirely new propulsion paradigm. (Source: Dario Borghino, "NASA says puzzling new space drive can generate thrust without propellant," *Gizmag*, 02 August 2014, accessed on 29 April 2016, http://www.gizmag.com/cannae-reactionless-drive-space-propulsion/33210/.)

outer space.[423] Legal scholars and commentators are split over whether this makes private ownership of space impossible, and whether there is a compensatory component for the rest of the world (e.g. *common heritage of mankind* provisions).[424] Regardless, the governments of the US and Luxembourg have enacted legislation that authorizes their citizens to seize and sell resources from space.[425] US companies Planetary Resources, Deep Space Industries, and Moon Express are forging ahead.

Increased use of space will compound the existing problem of space debris. As of 2014, there was already 16,000 objects of size greater than 10 centimeters in diameter being tracked by US Space Command's *Space Surveillance Network*.[426] Most of these came from only two collision in 2007 and 2009.[427] The UN is advocating for new guidelines to limit the growth of space debris in the future.[428] However, this does not address the existing problem. It is further compounded by the *Liability Convention* which prohibits the seizure of another nation's space objects, including debris. Switzerland is funding the removal of their own derelict satellites, and hope to use the effort as a

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[423] United Nations Office for Outer Space Affairs, "Treaty on Principles Governing the Activities of Space in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies," Article II.
[424] See Chapter 3 for a more detailed discussion.
[425] Eric Berger, "Democrats and Republicans agree: If you can mine it in space, it is yours," *Ars Technica,* 10 November 2015, accessed on 10 February 2016, http://arstechnica.com/science/2015/11/democrats-and-republicans-agree-if-you-can-mine-it-in-space-its-yours/; and, Veronique Poujol and Marlowe Hood, "Luxembourg's ultimate offshore investment: space mining," *Phys.org,* 03 February 2016, accessed on 10 February 2016, http://phys.org/news/2016-02-luxembourg-ultimate-offshore-investment-space.html.
[426] United States Strategic Command, "US STRATCOM Space Control and Space Surveillance," *US STRATCOM*, January 2014, accessed on 27 March 2016, https://www.stratcom.mil/factsheets/11/Space_Control_and_Space_Surveillance/.
[427] See further discussion in Chapter 4. In Figure 4.1, we also see a sharp increase in space debris after each collision.
[428] United Nations Office of Outer Space Affairs, "IADC Space Debris Mitigation Guidelines," September 2007, accessed on 27 April 2016, http://www.unoosa.org/documents/pdf/spacelaw/sd/IADC-2002-01-IADC-Space_Debris-Guidelines-Revision1.pdf.

technology demonstrator for future business.[429] Unfortunately, a commercial incentive to do this more broadly is not yet apparent.

The technology associated with debris collection is also a concern. In particular, technology allowing for the orbital interception of space debris can also be used against active satellites. The Soviet Union had a co-orbital interception program in the 1970's,[430] and the Russian's may have launched a covert capability in 2014.[431] To address these threats, proper characterization of space objects is essential. As of 2014, the US had supplemented their *Space Surveillance Network* with two near-geostationary satellites to assist with this effort, including the option for physical interception of a satellite being investigated.[432]

The *Space Surveillance Network* is limited to monitoring objects in near-Earth orbit. Resources extraction companies are considering the relocation of near-Earth asteroids into orbit around the Earth (or Moon). There is no international legal prohibition against moving objects in space. Even NASA is planning for an asteroid redirect mission in the 2020's.[433] Funding for deep space observation of asteroids and other celestial objects

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429 Ben Coxworth, "EPFL's CleanSpace One satellite will 'eat' space junk," *Gizmag.com*, 07 July 2015, accessed on 28 March 2016, http://www.gizmag.com/cleanspace-one-orbital-debris-satellite/38348/.

430 Union of Concerned Scientists, "A History of Anti-Satellite Programs (2012)," February 2012, accessed on 19 April 2016, http://www.ucsusa.org/nuclear-weapons/space-security/a-history-of-anti-satellite-programs#.VxaKvVQrKW8.

431 Tyler Rogoway, "That's No Moon! Did Russia Deploy An Experimental Killer Satellite?" *Foxtrot Alpha*, 21 November 2014, accessed on 28 March 2016, http://foxtrotalpha.jalopnik.com/thats-no-moon-did-russia-deploy-an-experimental-killer-1661535449.

432 United States Air Force Space Command, "Geosynchronous Space Situational Awareness Program (GSSAP)," last updated on 15 April 2015, accessed on 27 April 2016, http://www.afspc.af.mil/library/factsheets/factsheet.asp?id=21389.

433 National Aeronautics and Space Administration, "What is NASA's Asteroid Redirect Mission?" *Asteroid Redirect Mission*, accessed on 04 April 2016.

has been marginal until recently.[434] The explosion of a small asteroid of Chelyabinsk, Russia in 2012 raised concerns over the threat posed. NASA created a Planetary Defense Coordination Office in January 2016 to oversee and coordinate the increased scope of the Near Earth Object Program.[435] New technology to respond to threats from space objects needs to be developed in parallel. Several options, including gravity tractors, kinetic impactors, and nuclear weapons, are being considered by the scientific community.[436]

Another emerging threat is the development of commercial space planes. Virgin Galactic's *SpaceShipTwo* and XCOR's Lynx II aircraft both fly higher and faster than conventional aircraft.[437] Unlike ballistic missiles, they have larger control surfaces making them more maneuverable. Existing ballistic missile defence technologies may need to be adapted to respond to them. BMD may also need to be more widely available depending on the scope of space plane operations. Finally, the spread of this technology to other nations will need to be curtailed until the threat is better characterized. China is already working on a hypersonic glide vehicle with similar characteristics.[438] US development of X-37B space plane may be part of a future solution, assuming it does not violate Article IV of the *Outer Space Treaty*.

This *democratization* of space access through more launch operators, across more nations, operating at lower costs, will threaten Western hegemony in space. We have had

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434 Only $4M in 2009. (Source: Emily Reynolds, "New NASA office will protect the Earth from asteroids," *Wired UK*, 11 January 2016, accessed on 04 April 2016, http://www.wired.co.uk/news/archive/2016-01/11/nasa-asteroid-program.)

435 Jet Propulsion Laboratory, "NASA Office to Coordinate Asteroid Detection, Hazard Mitigation," *National Aeronautics and Space Administration*, 07 January 2016, accessed on 04 April 2016, http://www.jpl.nasa.gov/news/news.php?feature=4816.

436 See Chapter 4 for more discussion.

437 See Chapter 4 for more discussion.

438 Kiona Smith-Strickland, "What's the X-37 Doing Up There?" *Smithsonian Air & Space Magazine*, February 2016, accessed on 08 April 2016, http://www.airspacemag.com/space/spaceplane-x-37-180957777/?no-ist.

fifty years of undisputed access to outer space. The détente reached between the superpowers during the Cold War has allowed the space-faring nations to devote their efforts to economic and scientific advancement vice weaponization. However, as more players enter orbit, the opportunity for mischief increases. The lack of mature international law governing private actions puts the pressure on states to regulate their markets. Competition for space-business will lead to disparities in regulation and oversight between states, potentially jeopardizing safety and security. Development of new technologies threaten our national security. Increasing space use will lead to further orbital congestion, and a rising risk from space debris. We're also on the verge of relocating near-Earth objects into our orbit, threatening inadvertent collision. Fortunately, even the ambitious timeframe for most of these activities does not see them emerging until the middle of the next decade. However, as Bill Gates observed, "we always overestimate the change that will occur in the next two years, and underestimate the change that will occur in the next ten. Don't let yourself be lulled into inaction."[439]

To preserve its primacy in space, the West needs to invest in improved sensors to monitor and characterize space objects, both in Earth orbit, and in near-Earth orbits. It should lead development of clear international laws regarding space commerce (including property rights and liability), the relocation of space object in the vicinity of the Earth[440], and global safety standards for space launch and spacecraft operation.[441] Finally, the West must continue to invest in technologies that allow it to influence the space environment (e.g. space planes, heavy lift rockets). In order to defend against threats arising from space,

[439] Bill Gates, *The Road Ahead* (Toronto, Ontario: Penguin Canada, 1996).
[440] This seems like a very bad idea without more oversight.
[441] To prohibit orbital theft, or deter weak *flag states* from emerging.

it needs an assortment of space capabilities so that it has capacity and flexibility in the future. We must not be lulled into inaction.

BIBLIOGRAPHY

Books

Bunker, Robert J. "Strategic Defense Initiative." In *Europe Since 1945: An Encyclopedia*, ed. Bernard A. Cook, 1197. New York, NY: Garland Publishing, 2001. Accessed on 22 March 2016. http://scholarship.claremont.edu/cgi/viewcontent.cgi?article=1395&context=cgu_fac_pub.

Dolman, Everett C. *Astropolitik: Classical Geopolitics in the Space Age*. Portland, Oregon: Frank Cass Publishers, 2002.

Gates, Bill. *The Road Ahead*. Toronto, Ontario: Penguin Canada, 1996.

Gray, Colin S. *Modern Strategy*. Oxford, England: Oxford University Press, 1999.

Motz, James Clay. *The Politics of Space Security*. Stanford, California: Stanford University Press, 2008.

National Research Council. *Laying the Foundation for Space Solar Power: An Assessment of NASA's Space Solar Power Investment Strategy*. Washington, DC: The National Academies Press, 2001. Accessed on 28 April 2016. http://www.nap.edu/read/10202/chapter/2.

Schroeer, Dietrich. "The Present Status of the Strategic Defense Initiative." In *Space and Nuclear Weaponry in the 1990's*, eds. Carlo Schaerf, Giuseppe Longo and David Carlton, 3-38. Hampshire: The MacMillan Press Limited, 1992.

Vance, Ashlee. *Elon Musk: Tesla, SpaceX, and the Quest for a Fantastic Future*. New York, NY: HarperCollins Publishers, 2015.

Videos/Audio

"The Engines That Came In From The Cold." *Equinox*, BBC Channel 4. Aired 01 March 2001. Posted by Matthew Travis. Accessed on 19 April 2016. https://www.youtube.com/watch?v=TMbl_ofF3AM.

"Elon Musk: Here's How We Can Fix Mars and Colonize It." *Business Insider*, 02 January 2014. Accessed on 22 April 2016. http://www.businessinsider.com/elon-musk-colonizing-mars-2014-1.

Fong, Kevin. “Scott’s Legacy – Episode 2.” *BBC Radio 4*, last aired on 22 March 2012. Accessed on 22 April 2016. http://www.bbc.co.uk/programmes/b01dhrmj.

Articles

Andrews, Dana. “Space Shuttle 2.0: What did we learn?” *The Space Review,* 11 July 2011. Accessed on 08 May 2016. http://www.thespacereview.com/article/1881/1.

Brown, P.G. *et al*, “Letter: A 500-kiloton airburst over Chelyabinsk and an enhanced hazard from small impactors.” *Nature* 503, issue 7474 (14 November 2013): 238 – 241. Published online 06 November 2014. Accessed on 04 April 2016. http://www.nature.com/articles/nature12741.epdf?referrer_access_token=H6yVWqEn8Q30Xd4SVvHHKdRgN0jAjWel9jnR3ZoTv0PyqszVJsMboh07BaZDfmONTF1Nmpe0JFsDi60k_DCn-ys0Kuc6PbSq6U0b6JSmVFuLJLBQEIINDyaLMH910LFvsHTuINRAgsXeSPTK2QRsHSBnGln19A1B6Q4ThkyhSImZE5joXxefg1slfXPnt5LuJyuvcnENCosvHQECP0owjb4qjdMjz-fSev71XyYpOca3rhS2IN-al_sSD9noUFvX&tracking_referrer=news.nationalgeographic.com.

Grove, Stephen. “Interpreting Article II of the Outer Space Treaty.” *Fordham Law Review* 37, vol. 3 (1969): 349 – 354. Accessed on 26 April 2016. http://ir.lawnet.fordham.edu/cgi/viewcontent.cgi?article=1966&context=flr.

Hertzfeld, Henry R. and Frans G. von der Dunk. “Bringing Space Law into the Commercial World: Property Rights without Sovereignty.” *Chicago Journal of International Law* 6, no. 1 (Summer 2005): 81 – 99.

Hickman, John. “The Political Economy of Very Large Space Projects.” *Journal of Evolution and Technology* 4, (November 1999): 1 – 14.

Kelly, Robert. “Nemitz v. United States, A Case of First Impression: Appropriation, Private Property Rights and Space Law Before The Federal Courts of the United States.” *Journal of Space Law* 30, no.2 (Fall 2004): 297 – 310. http://www.spacelaw.olemiss.edu/JSL/Back_issues/JSL%2030-2.pdf.

Lu, Edward T. and Stanley G. Love. “Gravitational Tractor for Towing Asteroids.” *Nature* 438 (10 November 2005): 177 – 178.

Sarigul-Klijn, Marti and Nesrin Sarigul-Klijn. "A study of air launch methods for RLVs." AIAA Space 2001 Conference and Exposition, Albuquerque, NM. https://wiki.umn.edu/pub/AEM_Air_Launch_Team/LaunchTrajectoryDesign/aiaa2001-4619.pdf.

Simberg, Rand. “Property Rights in Space.” *The New Atlantis*, Number 37 (Fall 2012): 20 – 31. Accessed on 26 April 2016. http://www.thenewatlantis.com/publications/property-rights-in-space.

Zhao, Yun. “An International Space Authority: A Governance Model for a Space Commercialization Regime.” *Journal of Space Law* 30 no.2 (Fall 2004): 277 – 296.

Online Publications

Ackerman, Evan. “Japan Demoes Wireless Power Transmission from Space-Based Solar Farms.” *Spectrum Magazine*, 16 March 2015. Accessed on 10 April 2016. http://spectrum.ieee.org/energywise/green-tech/solar/japan-demoes-wireless-power-transmission-for-spacebased-solar-farms.

Amos, Jonathan. “Mars for the ‘average person’.” *BBC News*, 20 March 2012. Accessed on 22 April 2016. http://www.bbc.com/news/health-17439490.

Basulto, Dominic. “How property rights in outer space may lead to a scramble to exploit the moon’s resources.” *The Washington Post*, 18 November 2015. Accessed on 26 April 2015. https://www.washingtonpost.com/news/innovations/wp/2015/11/18/how-property-rights-in-outer-space-may-lead-to-a-scramble-to-exploit-the-moons-resources/.

Bates, Jason. “Canadian Bill Would Align Remote Sensing Law with U.S.” *Space.com*, 07 February 2005. Accessed on 25 March 2016. http://www.space.com/770-canadian-bill-align-remote-sensing-law.html.

BBC Staff. “China confirms satellite downed.” *BBC News*, 23 January 2007. Accessed on 22 March 2016. http://news.bbc.co.uk/2/hi/asia-pacific/6289519.stm.

BBC Staff. “Why so many shipowners find Panama’s flag convenient.” *BBC News*, 05 August 2014. Accessed on 27 April 2016. http://www.bbc.com/news/world-latin-america-28558480.

Beard, S. Suzette *et al*. “Space Tourism Market Study.” *Futron Corporation*, October 2002. Accessed on 09 February 2016. http://www.spaceportassociates.com/pdf/tourism.pdf.

Berger, Eric. “Democrats and Republicans agree: If you can mine it in space, it’s yours.” *Ars Technica*, 10 November 2015. Accessed on 10 February 2016. http://arstechnica.com/science/2015/11/democrats-and-republicans-agree-if-you-can-mine-it-in-space-its-yours/.

Berger, Eric. “Quietly, the new space race between SpaceX and Boeing burns hot.” *Ars Technica*, 10 November 2015. Accessed on 03 February 2016. http://arstechnica.com/science/2015/11/quietly-the-new-space-race-between-spacex-and-boeing-burns-hot/.

Berger, Eric. “As NASA discards reusable engines, Blue Origin and SpaceX push new frontiers.” *Ars Technica*, 01 December 2015. Accessed on 09 February 2016. http://arstechnica.com/science/2015/12/as-nasa-discards-reusable-engines-blue-origin-and-spacex-push-new-frontiers/.

Berger, Eric. “NASA official warns private sector: We’re moving on from low-Earth orbit.” *Ars Technica*, 07 December 2015. Accessed on 10 February 2016. http://arstechnica.com/science/2015/12/nasa-official-warns-private-sector-were-moving-on-from-low-earth-orbit/.

Berger, Eric. “With a historic landing, SpaceX launches new age of spaceflight.” *Ars Technica*, 21 December 2015. Accessed on 03 February 2016. http://arstechnica.com/science/2015/12/by-making-a-historic-landing-spacex-launches-new-age-of-spaceflight/.

Berger, Eric. “For Russia’s space program, 2016 may be a make-or-break year.” *Ars Technica*, 05 January 2016. Accessed on 03 February 2016. http://arstechnica.com/science/2016/01/for-russias-space-program-2016-may-be-a-make-or-break-year/.

Berger, Eric. “Elon Musk to unveil Mars plans this year, wants to go to space by 2020.” *Ars Technica*, 28 January 2016. Accessed on 22 April 2016. http://arstechnica.com/science/2016/01/elon-musk-to-unveil-mars-plans-this-year-wants-to-go-to-space-by-2020/.

Berger, Eric. “Astronaut Prime: Here’s how Jeff Bezos plans to remake spaceflight.” *Ars Technica*, 05 April 2016. Accessed on 22 April 2016. http://arstechnica.com/science/2016/04/astronaut-prime-heres-how-jeff-bezos-plans-to-remake-spaceflight/.

Berger, Eric. “Behind the curtain: Ars goes inside Blue Origin’s secretive rocket factory.” *Ars Technica*, 09 March 2016. Accessed on 22 April 2016. http://arstechnica.com/science/2016/03/behind-the-curtain-ars-goes-inside-blue-origins-secretive-rocket-factory/.

Berger, Eric. “ULA executive admits company cannot compete with SpaceX on launch costs.” *Ars Technica*, 17 March 2016. Accessed on 22 April 2016.

http://arstechnica.com/science/2016/03/ula-executive-admits-company-cannot-compete-with-spacex-on-launch-costs/.

Berger, Eric. “Space for Europe and for all humankind: A brief history of the ESA.” *Ars Technica*, 31 December 2015. Accessed on 06 May 2016. http://arstechnica.com/science/2015/12/space-for-europe-and-for-all-humankind-a-brief-history-of-the-esa/.

Bergin, Chris and William Graham. “Commercial space flight shows reignited interest in Air Launch System.” *NASA Spaceflight*, 13 July 2012. Accessed on 23 April 2016. https://www.nasaspaceflight.com/2012/07/commercial-shows-reignited-interest-air-launch-system/.

Bierend, Doug. “SpaceX Was Born Because Elon Musk Wanted to Grow Plants on Mars.” *Motherboard*, 17 July 2014. Accessed on 23 April 2016. http://motherboard.vice.com/read/spacex-is-because-elon-musk-wanted-to-grow-plants-on-mars.

Billings, Lee. “War in Space May Be Closer Than Ever.” *Scientific American*, 10 August 2015. Accessed on 19 April 2016. http://www.scientificamerican.com/article/war-in-space-may-be-closer-than-ever/.

Borghino, Dario. “NASA says puzzling new space drive can generate thrust without propellant.” *Gizmag*, 02 August 2014. Accessed on 29 April 2016. http://www.gizmag.com/cannae-reactionless-drive-space-propulsion/33210/.

Boucher, Marc. “Is Canadian Sovereignty at Risk by a Lack of an Indigenous Satellite Launch Capability?” *Space Ref Canada*, 04 January 2011. Accessed on 27 April 2016. http://spaceref.ca/national-security/is-canadian-sovereignty-at-risk-by-a-lack-of-satellite-launching-capability.html.

Boyle, Alan. “SpaceShipOne wins $10 million X Prize.” *NBC News*, last updated on 05 October 2004. Accessed on 03 February 2016.

Brabaw, Kasandra. “Meet ‘Cosmic Girl’: Virgin Galactic’s New Satellite Launching Jet.” *Space.com*, 09 December 2015. Accessed on 19 April 2016. http://www.space.com/31322-virgin-galactic-cosmic-girl-launcherone-plane.html.

Brinkmann, Paul. “OneWeb plans to build, launch satellites in Florida, with Virgin Galactic.” *Orlando Sentinel*, 18 April 2016. Accessed on 23 April 2016. http://www.orlandosentinel.com/business/os-oneweb-virgin-satellites-20160418-story.html.

Buchen, Elizabeth and Dominic DePasquale. “2014 Nano / Microsatellite Market Assessment.” *SpaceWorks Enterprises, Inc*. 2014. Accessed on 09 February 2016. http://www.sei.aero/eng/papers/uploads/archive/SpaceWorks_Nano_Microsatellite_Market_Assessment_January_2014.pdf.

CBC News. “Martin will reject missile defence: report.” *CBC News*, 22 February 2005. Accessed on 08 April 2016. http://www.cbc.ca/news/canada/martin-will-reject-missile-defence-report-1.519736.

Chu, Jennifer. “Paintballs may deflect an incoming asteroid.” *MIT Press*, 26 October 2012. Accessed on 08 April 2016. http://news.mit.edu/2012/deflecting-an-asteroid-with-paintballs-1026.

Clark, Colin. “ULA Fires Back at SpaceX at Space Symposium; Details Launch Costs.” *Breaking Defense*, 20 May 2014. Accessed on 23 April 2016. http://breakingdefense.com/2014/05/ula-fires-back-at-spacex-at-space-symposium-details-launch-costs/.

Clark, Stephen. “Japan’s newest space telescope goes silent.” *Spaceflight Now*, 28 March 2016. Accessed on 08 April 2016. https://spaceflightnow.com/2016/03/27/japans-newest-space-telescope-goes-silent/.

Clark, Stephen. “Successful launch expands China’s Beidou navigation system.” *Spaceflight Now*, 02 February 2016. Accessed on 08 April 2016. https://spaceflightnow.com/2016/02/02/successful-launch-expands-chinas-beidou-navigation-system/.

Cofield, Calla. “SpaceX Sticks a Rocket Landing at Sea in Historic First.” *Space.com*, 08 April 2016. Accessed on 19 April 2016. http://www.space.com/32517-spacex-sticks-rocket-landing-sea-dragon-launch.html.

Cofield, Calla. “Virgin Galactic on Road to Recovery After Fatal SpaceShipTwo Crash.” *Space.com*, 30 October 2015. Accessed on 19 April 2016. http://www.space.com/30969-virgin-galactic-spaceshiptwo-crash.html.

Coppinger, Rob. “Space Junk Cleanup Satellite Launching on Swiss Space Plan in 2018.” *Space.com*, 02 October 2013. Accessed on 28 March 2016. http://www.space.com/23049-space-junk-satellite-swiss-space-plane.html.

Coppinger, Rob. “Swiss Company to Launch Robotic Mini-Shuttle in 2017.” *Space.com*, 01 April 2013. Accessed on 28 April 2016. http://www.space.com/20449-swiss-private-rocket-plane-2017.html.

Coxworth, Ben. “EPFL’s CleanSpace One satellite will ‘eat’ space junk.” *Gizmag.com*, 07 July 2015. Accessed on 28 March 2016. http://www.gizmag.com/cleanspace-one-orbital-debris-satellite/38348/.

Cruddas, Sarah. “The truth about asteroid mining. “*BBC News*, 05 January 2016. Accessed on 26 April 2016. http://www.bbc.com/future/story/20160103-the-truth-about-asteroid-mining.

David, Leonard. “After SpaceShipTwo Tragedy, How Will Virgin Galactic Return to Flight?” *Space.com*, 24 December 2014. Accessed on 09 February 2016. http://www.space.com/28088-virgin-galactic-spaceshiptwo-crash-aftermath.html.

David, Leonard. “Russian Satellite Hit by Debris from Chinese Anti-Satellite Test.” *Space.com*, 08 March 2013. Accessed on 19 April 2016. http://www.space.com/20138-russian-satellite-chinese-space-junk.html.

David, Leonard. “Cubesats: Tiny Spacecraft, Huge Payoffs.” *Space.com*, 08 September 2004. Accessed on 25 April 2016. http://www.space.com/308-cubesats-tiny-spacecraft-huge-payoffs.html.

David, Leonard. “50 Years of Nuclear-Powered Spacecraft: It All Started with Satellite Transit 4A.” *Space.com*, 29 June 2011. Accessed on 26 April 2016. http://www.space.com/12118-space-nuclear-power-50-years-transit-4a.html.

David, Leonard. “US Military’s Top-Secret X-37B Space Plane Mission Nears 3-Month Mark.” *Space.com*, 13 August 2015. Accessed on 28 April 2016. http://www.space.com/30245-x37b-military-space-plane-100-days.html.

Davies, Rob. “Asteroid mining could be space’s new frontier: the problem is doing it legally.” *The Guardian*, 06 February 2016. Accessed on 26 April 2016. http://www.theguardian.com/business/2016/feb/06/asteroid-mining-space-minerals-legal-issues.

Day, Dwayne A. “Tough Little Spinner.” *The Space Review*, 28 February 2011. Accessed on 26 April 2016. http://www.thespacereview.com/article/1787/1.

De Selding, Peter. “Falling Satellite Insurance Premiums Put Market at Risk of Major Upheaval.” *Space News*, 02 March 2012. Accessed on 10 February 2016. http://spacenews.com/falling-satellite-insurance-premiums-put-market-risk-major-upheaval/.

De Selding, Peter. “Iridium, frustrated with Russian red tape, to launch first 10 Iridium Next satellites with SpaceX in July.” *SpaceNews*, 25 February 2016. Accessed on 25 April 2016.

http://spacenews.com/iridium-frustrated-by-russian-red-tape-to-launch-first-10-iridium-next-satellites-with-spacex-in-july/.

De Selding, Peter. “SpaceX To Build 4,000 Broadband Satellites in Seattle.” *SpaceNews*, 19 January 2015. Accessed on 25 April 2016. http://spacenews.com/spacex-opening-seattle-plant-to-build-4000-broadband-satellites/.

De Selding, Peter. “ESA Enlists Outside Help for Envisat Recovery Effort.” *SpaceNews*, 13 April 2012. Accessed on 27 April 2016. http://spacenews.com/esa-enlists-outside-help-envisat-recovery-effort/.

Dinkin, Sam. “Increasing the profit ratio.” *The Space Review*, 04 January 2016. Accessed on 09 February 2016. http://www.thespacereview.com/article/2893/1.

Dinkin, Sam. “Property rights and space commercialization.” *The Space Review*, 10 May 2004. Accessed on 27 March 2016. http://www.thespacereview.com/article/141/1.

Dinkin, Sam. “Don’t wait for property rights.” *The Space Review*, 12 July 2004. Accessed on 27 March 2016. http://www.thespacereview.com/article/179/1.

Dodson, Brian. “Launch your own satellite for US$8000.” *Gizmag*, 22 April 2012. Accessed on 25 April 2016. http://www.gizmag.com/tubesat-personal-satellite/22211/.

Dunn, Marcia. “No damage to SpaceX’s Falcon rocket following historic landing.” *The Associated Press*, 04 January 2016. Accessed on 03 February 2016. http://www.ctvnews.ca/sci-tech/no-damage-to-spacex-s-falcon-rocket-following-historic-landing-1.2723268.

Economist Staff. “Nanosats are go!” *The Economist*, 07 July 2014. Accessed on 19 April 2016. http://www.economist.com/news/technology-quarterly/21603240-small-satellites-taking-advantage-smartphones-and-other-consumer-technologies.

Economist Staff. “The unplumbed riches of the deep.” *The Economist*, 14 May 2009. Accessed on 27 April 2016. http://www.economist.com/node/13649273.

End, Rae Botsford. “Rocket Lab: The Electron, the Rutherford, and Why Peter Beck Started It in the First Place.” *SpaceFlight Insider*, 02 May 2015. Accessed on 22 April 2016. http://www.spaceflightinsider.com/missions/commercial/rocket-lab-electron-rutherford-peter-beck-started-first-place/.

Erwin, Sandra I. “Pentagon Eyes Deals With Satellite Industry to Fill Demand for Drone Communications.” *National Defense Magazine*, May 2013. Accessed on 27 April 2016.

http://www.nationaldefensemagazine.org/archive/2013/May/pages/PentagonEyesDealsWithSatelliteIndustryToFillDemandforDroneCommunications.aspx.

Ferster, Warren. "ULA Execs Say RD-180 Engine Ban Blocks Path to Next-gen Rocket." *SpaceNews*, 22 May 2015. Accessed on 19 April 2016. http://spacenews.com/ula-execs-say-rd-180-engine-ban-blocks-path-to-next-gen-rocket/.

Fisher Jr., Richard D. "US officials confirm sixth Chinese hypersonic manoeuvring strike vehicle test." *IHS Janes*, 27 November 2015. Accessed on 28 April 2016. http://www.janes.com/article/56282/us-officials-confirm-sixth-chinese-hypersonic-manoeuvring-strike-vehicle-test.

Foust, Jeff. "Air launch, big and small." *The Space Review*, 30 June 2014. Accessed on 19 April 2016. http://www.thespacereview.com/article/2543/1.

Foust, Jeff. "CubeSats get big." *The Space Review*, 10 September 2012. Accessed on 25 April 2016. http://www.thespacereview.com/article/2155/1.

Foust, Jeff. "Launch Failures Dent Growth in Small Satellites." *The Space Review*, 12 August 2015. Accessed on 25 April 2016. http://spacenews.com/launch-failures-dent-growth-in-small-satellites/.

Foust, Jeff. "The challenges of commercializing research in low Earth orbit." *The Space Review*, 04 April 2016. Accessed on 25 April 2016. http://www.thespacereview.com/article/2958/1.

Foust, Jeff. "Closing the case for reusable launchers." *The Space Review*, 11 April 2016. Accessed on 25 April 2016. http://www.thespacereview.com/article/2963/1.

Foust, Jeff. "B612 Presses Ahead with Asteroid Mission Despite Setbacks." *SpaceNews*, 20 October 2015. Accessed on 28 April 2016. http://spacenews.com/b612-presses-ahead-with-asteroid-mission-despite-setbacks/.

Foxman, Simone. "The crazy economics of mining asteroids for gold and platinum." *Quartz*, 25 January 2013. Accessed on 26 April 2016. http://qz.com/47232/the-crazy-economics-of-mining-asteroids-for-gold-and-platinum/.

Gallagher, Sean. "North Korea's "successful" satellite in orbit, but tumbling and useless." *Ars Technica*, 09 February 2016. Accessed on 09 February 2016. http://arstechnica.com/information-technology/2016/02/north-koreas-successful-satellite-in-orbit-but-tumbling-and-useless/.

Gertz, Bill. "China Conducts Test of New Anti-Satellite Missile." *The Washington Free Beacon*, 14 May 2013. Accessed on 22 March 2016. http://freebeacon.com/national-security/china-conducts-test-of-new-anti-satellite-missile/.

Gertz, Bill. “China Tests Anti-Satellite Missile.” *The Washington Free Beacon*, 09 November 2015. Accessed on 22 March 2016. http://freebeacon.com/national-security/china-tests-anti-satellite-missile/.

Gertz, Bill. “Russia Flight Tests Anti-Satellite Missile.” *The Washington Free Beacon*, 02 December 2015. Accessed on 26 April 2016. http://freebeacon.com/national-security/russia-conducts-successful-flight-test-of-anti-satellite-missile/.

Gruss, Mike. “ULA Targets 2018 for Delta 4 Phase-out, Seeks Relaxation of RD-180 Ban.” *SpaceNews*, 03 March 2015. Accessed on 22 April 2016. http://spacenews.com/ula-targets-2018-for-delta-4-phase-out-seeks-relaxation-of-rd-180-ban/.

Gruss, Mike. “ULA Punts on GPS 3 Launch Contract Long Sought by SpaceX.” *SpaceNews*, 16 November 2015. Accessed on 22 April 2016. http://spacenews.com/ula-declines-to-bid-on-gps-3-launch-contract-long-sought-by-spacex/.

Gruss, Mike. “US Air Force Declares GSSAP Surveillance Sats Operational.” *SpaceNews*, 08 October 2015. Accessed on 27 April 2016. http://spacenews.com/u-s-air-force-declares-gssap-surveillance-sats-operational/.

Hollingham, Richard. “What’s the best (and cheapest) way to take a trip to space?” *BBC News*, 22 April 2016. Accessed on 22 April 2016. http://www.bbc.com/future/story/20160422-whats-the-best-and-cheapest-way-to-take-a-trip-to-space?ocid=global_future_rss.

Holmes, Mark. “Hot Orbital Slots: Is There Anything Left?” *Satellite Today*, 01 March 2008. Accessed on 25 March 2016. http://www.satellitetoday.com/publications/via-satellite-magazine/features/2008/03/01/hot-orbital-slots-is-there-anything-left/.

Humphrey, Michael. “Stratos on YouTube Live Topped 8 Million Concurrent Views.” *Forbes*, 14 October 2012. Accessed on 09 February 2016. http://www.forbes.com/sites/michaelhumphrey/2012/10/14/red-bull-stratos-live-topped-8-million-concurrent-views-on-youtube/#760e44496633.

Iannotta, Becky and Tariq Malik. “US Satellite Destroyed in Space Collision.” *Space.com*, 11 February 2009. Accessed on 27 April 2016. http://www.space.com/5542-satellite-destroyed-space-collision.html.

Jones, Sam. “Satellite wars.” *Financial Times Magazine,* 20 November 2015. Accessed on 09 February 2016. http://www.ft.com/intl/cms/s/2/637bf054-8e34-11e5-8be4-3506bf20cc2b.html.

Kaplan, Fred. “Patriot Games.” *Slate*, 24 March 2003. Accessed on 27 April 2016. http://www.slate.com/articles/news_and_politics/war_stories/2003/03/patriot_games.html.

Keeney, Laura. “Next-gen JPSS-1 weather satellite powers up at Ball in Boulder.” *The Denver Post*, 01 July 2015. Accessed on 25 April 2016. http://www.denverpost.com/weathernews/ci_28416232/next-gen-jpss-1-weather-satellite-powers-up.

Kim, Hyung-Jin. “Agency: North Korea plans satellite launch this month.” *Phys.org*, 02 February 2016. Accessed on 26 April 2016. http://phys.org/news/2016-02-agency-north-korea-satellite-month.html.

King, Mak and Michael J. Riccio. “Military Satellite Communications: Then and Now.” *Crosslink Magazine,* 01 April 2010. Accessed on 16 April 2016. http://www.aerospace.org/crosslinkmag/spring-2010/military-satellite-communications-then-and-now/.

Knapp, Alex. “Branson-Backed OneWeb Raises $500 Million to Build Satellite Internet.” *Forbes*, 25 June 2015. Accessed on 25 April 2016. http://www.forbes.com/sites/alexknapp/2015/06/25/branson-backed-oneweb-raises-500-million-to-build-satellite-internet/#7f31b7065529.

Lafleur, Claude. “Spacecraft stats and insights.” *The Space Review*, 05 April 2010. Accessed on 29 April 2016. http://www.thespacereview.com/article/1598/1.

Langewiesche, William. “Everything You Need to Know About Flying Virgin Galactic.” *Vanity Fair*, April 2015. Accessed on 19 April 2015. http://www.vanityfair.com/news/2015/03/what-is-it-like-to-fly-virgin-galactic.

Lippert, John. “SpaceX Profitable as Musk Pulls in NASA Contracts, Google Cash.” *Bloomberg Markets*, 04 March 2015. Accessed on 22 April 2016. http://www.bloomberg.com/news/articles/2015-03-04/spacex-profitable-as-musk-pulls-in-nasa-contracts-google-cash.

Listner, Michael. “Iridium 33 and Cosmos 2251 three years later: where are we now?” *The Space Review*, 13 February 2013. Accessed on 27 April 2016. http://www.thespacereview.com/article/2023/1.

Listner, Michael. “Legal issues surrounding space debris remediation.” *The Space Review*, 06 August 2012. Accessed on 27 April 2016. http://www.thespacereview.com/article/2130/1.

Malik, Tariq. “Jeff Bezos’ Blue Origin Launches and Lands Private Rocket for Third Time.” *Space.com*, 02 April 2016. Accessed on 29 April 2016. http://www.space.com/32453-blue-origin-launches-and-lands-rocket-third-time.html.

Mathiesen, Karl. “What is holding back the growth in solar power?” *The Guardian*, 31 January 2016. Accessed on 28 April 2016. http://www.theguardian.com/sustainable-business/2016/jan/31/solar-power-what-is-holding-back-growth-clean-energy.

Messier, Douglas. “Nuking Dangerous Asteroids Might Be the Best Protection, Expert Says.” *Space.com*, 29 May 2013. Accessed on 28 April 2016. http://www.space.com/21333-asteroid-nuke-spacecraft-mission.html.

Meyer, Robinson. “Google owns a satellite now.” *The Atlantic*, 10 June 2014. Accessed on 27 April 2016. http://www.theatlantic.com/technology/archive/2014/06/why-google-bought-satellite-startup-skybox/371531/.

Monmouth University Polling Institute. “National: Space Travel in the 21st Century.” Released 16 February 2015. Accessed on 20 April 2015. http://www.monmouth.edu/assets/0/32212254770/32212254991/32212254992/32212254994/32212254995/30064771087/6314f1fc-8199-44ed-9f8a-ab4b2720bab5.pdf.

Morello, Lauren. “Soaring Satellite Costs Spur US Government to Seek Budget Cuts.” *Scientific American*, 21 March 2012. Accessed on 25 April 2016. http://www.scientificamerican.com/article/soaring-satellite-costs-spur-us-government-to-seek-budget-cuts/.

Nave, Kathryn. “Space mining will take a giant leap in 2016.” *Wired*, 05 January 2016. Accessed on 26 April 2016. http://www.wired.co.uk/news/archive/2016-01/05/space-mining-a-reality-in-2016.

Northern Sky Research. “Global Direct-to-Home Markets, 6th Edition.” July 2013. Accessed on 25 April 2016. www.nsr.com/upload/research_reports/NSR_DTH6_Brief_1.pdf.

O’Kane, Sean and Loren Grush. “Blue Origins beats SpaceX to re-launching a reusable rocket.” *The Verge*, 22 January 2016. Accessed on 03 February 2016. http://www.theverge.com/2016/1/22/10815800/blue-origin-rocket-launch-.

Ottawa Citizen. "Russia entrusted with Canada's top satellite secrets." *Canada.com*, 18 January 2006. Accessed on 27 April 2016. http://www.canada.com/story_print.html?id=5dfd910e-125e-495a-a180-27fc68522918&sponsor=.

PCTEL Connected Solutions. "Precision Guided Munitions and the Historic Role of GPS." Accessed on 27 April 2016. http://www.antenna.com/artifacts/20101021MunitionsGuidance-GPS_final.pdf.

Pearlman, Robert Z. "NASA's Space Shuttle Program Official Ends After Final Celebration." *Space.com*, 01 September 2011. Accessed on 14 April 2016. http://www.space.com/12804-nasa-space-shuttle-program-officially-ends.html.

Pifer, Steven. "The limits of US missile defense." *The Brookings Institute*, 30 March 2015. Accessed on 27 April 2016. http://www.brookings.edu/research/opinions/2015/03/30-us-missile-defense-limits-pifer.

Poujol, Veronique and Marlowe Hood. "Luxembourg's ultimate offshore investment: space mining." *Phys.org*, 03 February 2016. Accessed on 10 February 2016. http://phys.org/news/2016-02-luxembourg-ultimate-offshore-investment-space.html.

Pugliese, David. "Does Canada need its own rockets to launch satellites?" *Ottawa Citizen*, 24 July 2014. Accessed on 27 April 2016. http://ottawacitizen.com/news/national/does-canada-need-its-own-rockets-to-launch-satellites.

Reynolds, Emily. "New NASA office will protect the Earth from asteroids." *Wired UK*, 11 January 2016. Accessed on 04 April 2016. http://www.wired.co.uk/news/archive/2016-01/11/nasa-asteroid-program.

Rhian, Jason. "Upgraded SpaceX Falcon 9 certified for National Security Space launches." *Space Flight Insider*, 26 January 2016. Accessed on 03 February 2016. http://www.spaceflightinsider.com/organizations/space-exploration-technologies/upgraded-spacex-falcon-9-certified-for-national-security-launches/.

Rogoway, Tyler. "That's No Moon! Did Russia Deploy An Experimental Killer Satellite?" *Foxtrot Alpha*, 21 November 2014. Accessed on 28 March 2016. http://foxtrotalpha.jalopnik.com/thats-no-moon-did-russia-deploy-an-experimental-killer-1661535449.

Rumpf, Clemens. "Increased competition will challenge ESA's space authority." *The Space Review*, 02 February 2015. Accessed on 22 April 2016. http://www.thespacereview.com/article/2687/1.

Shalal, Andrea. "ULA Orders 20 More RD-180 Rocket Engines." *SpaceNews*, 23 December 2015. Accessed on 09 February 2016. http://spacenews.com/ula-orders-20-more-rd-180-rocket-engines/.

Shukman, David. "Deep see mining licences issued." *BBC News*, 23 July 2014. Accessed on 27 April 2016. http://www.bbc.com/news/science-environment-28442640.

Singer, Jeremy and Colin Clark. "White House Confirms Chinese Anti-Satellite Weapon Test." *Space.com*, 19 January 2007. Accessed on 19 April 2016. http://www.space.com/3367-white-house-confirms-chinese-anti-satellite-weapon-test.html.

Smith, Marcia S. "ULA Wins Big with Two AF Propulsion Contracts, One with Blue Origin, One with Aerojet Rocketdyne." *Space Policy Online*, 29 February 2016. Accessed on 22 April 2016. http://www.spacepolicyonline.com/news/ula-wins-big-with-two-af-propulsion-contracts-one-with-blue-origin-one-with-aerojet-rocketdyne.

Smith-Strickland, Kiona. "What's the X-37 Doing Up There?" *Smithsonian Air & Space Magazine,* February 2016. Accessed on 08 April 2016. http://www.airspacemag.com/space/spaceplane-x-37-180957777/?no-ist.

Snead, Mike. "US terrestrial non-fossil fuel energy vs. space solar power." *The Space Review,* 14 March 2016. Accessed on 28 April 2016. http://www.thespacereview.com/article/2941/1.

Snead, Mike. "Federal legislation to jumpstart space solar power." *The Space Review*, 04 April 2016. Accessed on 28 April 2016. http://www.thespacereview.com/article/2956/1.

Space Foundation. "The Space Report 2015 - Overiew." Accessed on 16 April 2016. http://www.spacefoundation.org/sites/default/files/downloads/The_Space_Report_2015_Overview_TOC_Exhibits.pdf.

Statt, Nick. "Virgin Galactic aircraft cruises to supersonic speeds." *CNet*, 05 September 2013. Accessed on 08 April 2016. http://www.cnet.com/news/virgin-galactic-aircraft-cruises-to-supersonic-speeds/.

Stein, Mark A. "Elbowing for a Piece of Space: The parking lot for satellites is getting jammed. So a shoving match has broken out between Tonga and Indonesia as nations and companies fight for choice spots in the communications network." *Los Angeles Times*, 20 September 1993. Accessed on 10 February 2016. http://articles.latimes.com/1993-09-20/news/mn-37280_1_satellite-operator/2.

Tate, Karl. “Space Junk Explained: How Orbital Debris Threatens Future of Spaceflight (Infographic).” *Space.com*, 01 October 2013. Accessed on 28 March 2016. http://www.space.com/23039-space-junk-explained-orbital-debris-infographic.html.

Tate, Karl. “How XCOR’s Lynx Space Plane Works (Infographics).” *Space.com*, 01 March 2016. Accessed on 28 April 2016. http://www.space.com/32104-how-xcor-s-lynx-space-plane-works-infographic.html.

Teitel, Amy. “The laser-toting Soviet satellite that almost sparked a space arms race.” *Wired*, 16 May 2013. Accessed on 19 April 2016. http://www.wired.co.uk/news/archive/2013-05/16/soviet-laser-satellite/viewall.

Teitel, Shira. “The Ouse Space Treaty Promised Peace in Space.” *Discovery News*, 10 October 2013. Accessed on 26 April 2016. http://news.discovery.com/space/history-of-space/the-outer-space-treaty-promised-peaceful-exploration-of-space-131010.htm.

Thomson Reuters. “NASA installs expandable ‘BEAM’ module.” *CBC News*, 16 April 2016. Accessed on 25 April 2016. http://www.cbc.ca/news/technology/beam-module-iss-1.3539160.

Tomaszweksi, Steven. “How the US Military is Preparing for Hostile Threats to Its Satellites.” *Vice*, 05 May 2015. Accessed on 09 February 2016. https://news.vice.com/article/how-the-us-military-is-preparing-for-hostile-threats-to-its-satellites.

Vergano, Dan. “Russian Meteor’s Air Blast Was One for the Record Books.” *National Geographic*, 06 November 2013. Accessed on 04 April 2016. http://news.nationalgeographic.com/news/2013/11/131106-russian-meteor-chelyabinsk-airburst-500-kilotons/.

Wall, Mike. “Now Is the Time to Colonize Mars, Elon Musk Says.” *Space.com*, 16 December 2015. Accessed on 09 February 2016. http://www.space.com/31388-elon-musk-colonize-mars-now.html.

Wall, Mike. “North Korea Launches Satellite to Space.” *Space.com*, 08 February 2016. Accessed on 26 April 2016. http://www.space.com/31860-north-korea-satellite-launch.html.

Wall, Mike. “Wow! SpaceX Nails Rocket Landing At Sea Again.” *Space.com*, 06 May 2016. Accessed on 06 May 2016. http://www.space.com/32811-spacex-rocket-landing-jcsat-14-launch.html.

Governmental Publications

Alexandrow, Catherine. “The Story of GPS.” *DARPA: 50 Years of Bridging the Gap.* Accessed on 16 April 2016. http://www.darpa.mil/attachments/(2O10)%20Global%20Nav%20-%20About%20Us%20-%20History%20-%20Resources%20-%2050th%20-%20GPS%20(Approved).pdf.

Canadian Space Agency. “RADARSAT-2.” Accessed on 27 April 2016. http://www.asc-csa.gc.ca/eng/satellites/radarsat2/.

Canadian Space Agency. “Applications.” Accessed on 27 April 2016. http://www.asc-csa.gc.ca/eng/satellites/radarsat2/applications.asp.

Canadian Space Agency. “Ordering RADARSAT-2 data.” Accessed on 27 April 2016. http://www.asc-csa.gc.ca/eng/satellites/radarsat2/order-contact.asp.

Canadian Space Agency. “Canada’s Space Sector.” Accessed on 15 April 2016. http://www.asc-csa.gc.ca/pdf/space_espace_eng.pdf.

Central Intelligence Agency. “A Look Back… CORONA: The Nation’s First Photoreconnaissance Satellite.” Last updated on 30 April 2013. Accessed on 15 April 2016. https://www.cia.gov/news-information/featured-story-archive/2010-featured-story-archive/corona-the-nation2019s-first-photoreconnaissance-satellite.html.

Chapman, J.H. *et al*. *Upper Atmosphere and Space Programs in Canada*. Ottawa: Roger Duhamel, F.R.S.C, 1967.

Department of National Defence. “Sapphire satellite system is declared fully operational.” 30 January 2014. Accessed on 27 April 2016. http://www.forces.gc.ca/en/news/article.page?doc=sapphire-satellite-system-is-declared-fully-operational/hr1thk2x.

European Space Agency. “Clean Space.” Accessed on 04 April 2016. http://www.esa.int/Our_Activities/Space_Engineering_Technology/Clean_Space.

European Space Agency. “Global Experts Agree Action Needed on Space Debris.” Created on 25 April 2013. Accessed on 05 April 2016. http://www.esa.int/Our_Activities/Operations/Space_Debris/Global_experts_agree_action_needed_on_space_debris.

European Space Agency. “What is ENVISAT?” Accessed on 28 March 2016. https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/envisat.

European Space Agency. “What is GALILEO?” Accessed on 08 April 2016. http://m.esa.int/Our_Activities/Navigation/The_future_-_Galileo/What_is_Galileo.

European Space Agency. “Shuttle Technical Facts.” Accessed on 08 May 2016. http://m.esa.int/Our_Activities/Human_Spaceflight/Space_Shuttle/Shuttle_technical_facts.

Federal Reserve Bank of St. Louis. “Federal Net Outlays as Percent of Gross Domestic Product.” Updated on 25 March 2016. Accessed on 22 April 2016. https://research.stlouisfed.org/fred2/series/FYONGDA188S.

International Telecommunication Union Radiocommunication Sector. “Welcome to ITU-R.” *International Telecommunication Union*, 27 January 2011. Accessed on 25 March 2016. http://www.itu.int/net/ITU-R/index.asp?category=information&rlink=itur-welcome&lang=en.

National Aeronautics and Space Administration. “Space Launch System.” Accessed on 15 April 2016. https://www.nasa.gov/pdf/664158main_sls_fs_master.pdf.

National Aeronautics and Space Administration. “Advanced Space Transportation Program.” Accessed on 20 April 2016. http://www.nasa.gov/centers/marshall/news/background/facts/astp.html_prt.htm.

National Aeronautics and Space Administration. “Memorandum of Understanding between the National Aeronautics and Space Administration of the United States of America and the Russian Space Agency Concerning Cooperation on the Civil International Space Station.” Signed on 29 January 1998. Accessed on 20 April 2016. http://www.nasa.gov/mission_pages/station/structure/elements/nasa_rsa.html.

National Aeronautics and Space Administration. “ISS Assembly Mission 1 A/R.” Accessed on 20 April 2016. http://www.nasa.gov/mission_pages/station/structure/iss_assembly_1ar.html#.VxfRWVQrKW8.

National Aeronautics and Space Administration. “NASA’s Journey to Mars.” 01 December 2014. Accessed on 21 April 2016. http://www.nasa.gov/content/nasas-journey-to-mars.

National Aeronautics and Space Administration. “Piece by Piece: NASA Team Moves Closer to Building a 3-D Printed Rocket Engine.” 17 December 2015. Accessed on 22 April 2016. http://www.nasa.gov/centers/marshall/news/news/releases/2015/piece-by-piece-nasa-team-moves-closer-to-building-a-3-d-printed-rocket-engine.html.

National Aeronautics and Space Administration. "About the Space Station: Facts and Figures." Accessed on 26 April 2016. http://www.nasa.gov/mission_pages/station/main/onthestation/facts_and_figures.html.

National Aeronautics and Space Administration. "Higher Altitude Improves Station's Fuel Economy." Accessed on 26 April 2016. http://www.nasa.gov/mission_pages/station/expeditions/expedition26/iss_altitude.html.

National Aeronautics and Space Administration. "Asteroid Redirect Mission Reference Concept." Accessed on 28 April 2016. https://www.nasa.gov/pdf/756122main_Asteroid%20Redirect%20Mission%20Reference%20Concept%20Description.pdf.

National Aeronautics and Space Administration. "What is NASA's Asteroid Redirect Mission?" *Asteroid Redirect Mission*. Accessed on 04 April 2016.

National Oceanic and Atmospheric Administration. "About JPSS." Accessed on 25 April 2016. http://www.jpss.noaa.gov/satellites.html.

National Space Society. "Satellite Power System Concept Development and Evaluation Program." Accessed on 10 April 2016. http://www.nss.org/settlement/ssp/library/doe.htm.

Parliament of Canada. "Bill C-25: An Act Governing the Operation of Remote Sensing Space Systems." *Government of Canada*, 25 November 2005. Accessed on 25 March 2016. http://www.lop.parl.gc.ca/About/Parliament/LegislativeSummaries/bills_ls.asp?ls=C25&Parl=38&Ses=1.

Rupp, Sheila. "Operationally Responsive Space." *Kirtland Air Force Base*, 22 May 2007. Accessed on 09 February 2016. http://www.kirtland.af.mil/news/story.asp?id=123054292.

The World Bank. "Data: United States." Accessed on 22 April 2016. http://data.worldbank.org/country/united-states.

United Nations. "United Nations Convention on the Law of the Sea." *United Nations*. Accessed on 25 March 2016. http://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf.

United Nations Office for Disarmament Affairs. "Antarctic Treaty." *United Nations*, 01 December 1959. Accessed on 26 April 2016. http://disarmament.un.org/treaties/t/antarctic/text.

United Nations Office for Outer Space Affairs. "Treaty on Principles Governing the Activities of Space in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies." *United Nations*, 19 December 1966. Accessed on 10 February

2016.
http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html.

United Nations Office of Outer Space Affairs. “Resolution Adopted by the General Assembly. 1962 (XVIII). Declaration of Legal Principles Governing Activities of States in the Exploration and Use of Outer Space.” *United Nations*, 13 December 1963. Accessed on 22 March 2016.
http://www.unoosa.org/oosa/en/ourwork/spacelaw/principles/legal-principles.html.

United Nations Office of Outer Space Affairs. “Status of International Agreements relating to activities in outer space as of 01 January 2015.” *United Nations*, 08 April 2015. Accessed on 23 March 2016.
http://www.unoosa.org/pdf/limited/c2/AC105_C2_2015_CRP08E.pdf.

United Nations Office of Outer Space Affairs. “Agreement on the Rescue of Astronauts, the Return of Astronauts, and the Return of Objects Launched into Outer Space.” *United Nations*, 19 December 1967. Accessed on 23 March 2016.
http://www.unoosa.org/pdf/gares/ARES_22_2345E.pdf.

United Nations Office of Outer Space Affairs. “Committee on the Peaceful Uses of Outer Space.” Accessed on 26 April 2016.
http://www.unoosa.org/oosa/en/ourwork/copuos/index.html.

United Nations Office of Outer Space Affairs. “IADC Space Debris Mitigation Guidelines.” September 2007. Accessed on 27 April 2016.
http://www.unoosa.org/documents/pdf/spacelaw/sd/IADC-2002-01-IADC-Space_Debris-Guidelines-Revision1.pdf.

United Nations Office of Outer Space Affairs. “United Nations Office of Outer Space Affairs – Homepage.” *United Nations*. Accessed on 23 March 2016.
http://www.unoosa.org/.

United Nations Office of Outer Space Affairs. “Committee on the Peaceful Uses of Outer Space.” *United Nations*. Accessed on 23 March 2016.
http://www.unoosa.org/oosa/en/ourwork/copuos/index.html.

United Nations Office of Outer Space Affairs. “Convention on International Liability for Damage Caused by Space Objects.” *United Nations*. Accessed on 23 March 2016.
http://www.unoosa.org/pdf/gares/ARES_26_2777E.pdf.

United Nations Office of Outer Space Affairs. “Convention on Registration of Objects Launched into Outer Space.” *United Nations*. Accessed on 23 March 2016.
http://www.unoosa.org/pdf/gares/ARES_29_3235E.pdf.

United Nations Office of Outer Space Affairs. "Agreement Governing Activities of States on the Moon and Other Celestial Bodies." *United Nations*. Accessed on 23 March 2016. http://www.unoosa.org/pdf/gares/ARES_34_68E.pdf.

United Nations Office of Outer Space Affairs. "Resolution Adopted by the General Assembly 37/92. Principles Governing the Use by States of Artificial Earth Satellites for International Direct Television Broadcasting." *United Nations*, 10 December 1982. Accessed on 23 March 2016. http://www.unoosa.org/oosa/en/ourwork/spacelaw/principles/dbs-principles.html.

United Nations Office of Outer Space Affairs. "Resolution Adopted by the General Assembly 41/65. Principles Relating to Remote Sensing of the Earth from Outer Space." *United Nations*, 03 December 1986. Accessed on 23 March 2016. http://www.unoosa.org/oosa/en/ourwork/spacelaw/principles/remote-sensing-principles.html.

United Nations Office of Outer Space Affairs. "Resolution Adopted by the General Assembly 47/68. Principles Relevant to the Use of Nuclear Power Sources in Outer Space." *United Nations*, 14 December 1992. Accessed on 23 March 2016. http://www.unoosa.org/oosa/en/ourwork/spacelaw/principles/nps-principles.html.

United Nations Office of Outer Space Affairs. "Resolution Adopted by the General Assembly 51/122. Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States, Taking into Particular Account the Needs of Developing Countries." *United Nations*, 13 December 1996. Accessed on 23 March 2016. http://www.unoosa.org/oosa/en/ourwork/spacelaw/principles/nps-principles.html.

United States Congress. *Public Law 114-90-Nov. 25, 2015 U.S. Commercial Space Launch Competitiveness Act.* Accessed on 27 March 2016. https://www.congress.gov/114/plaws/publ90/PLAW-114publ90.pdf.

United States Department of Energy. "Space-based Solar Power." 06 March 2014. Accessed on 28 April 2016. http://www.energy.gov/articles/space-based-solar-power.

United States Department of State. "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies." Accessed on 26 April 2016. http://www.state.gov/t/isn/5181.htm.

United States Government. "Space Segment." Accessed on 28 April 2016. http://www.gps.gov/systems/gps/space/.

United States Government Accountability Office. "Letter to the Honourable Carl Levin and the Honourable John McCain regarding The Air Force's Evolved Expendable Launch

Vehicle Competitive Procurement." Dated 04 March 2014. Accessed on 22 April 2016. http://www.gao.gov/assets/670/661330.pdf.

United States White House. "Historical Tables." *Office of Management and Budget*. Accessed on 14 April 2016. https://www.whitehouse.gov/omb/budget/Historicals/.

Webpages

Aerojet Rocketdyne. "About." Accessed on 09 February 2016. http://www.rocket.com/about.

Aerojet Rocketdyne. "RS-68 Engine." Accessed on 22 April 2016. http://www.rocket.com/rs-68-engine.

Alberta Land Institute. "A Guide to Property Rights in Alberta." Accessed on 26 April 2016. http://www.albertalandinstitute.ca/public/download/documents/10432.

Ansari X Prize. "Teams." Accessed on 09 February 2016. http://ansari.xprize.org/teams.

B612 Foundation. "Our Mission." Accessed on 28 April 2016. https://b612foundation.org/our-mission/.

B612 Foundation. "The Sentinel Mission." Accessed on 28 April 2016. https://b612foundation.org/sentinel/.

Blue Origin. "Our Approach to Technology." Accessed on 22 April 2016. https://www.blueorigin.com/technology#engine_stories_1.

Blue Origin. "BE-4: America's Next Rocket Engine." Accessed on 22 April 2016. https://www.blueorigin.com/be4.

Deep Space Industries. "Deep Space Industries – Homepage." Accessed on 27 March 2016. https://deepspaceindustries.com/.

Deep Space Industries. "Space Resources." Accessed on 26 April 2016. https://deepspaceindustries.com/space-resources/.

Dunn III, Richard J. "Blue Force Tracking." *Northrop Grumman*. Accessed on 27 April 2016. http://www.northropgrumman.com/aboutus/analysiscenter/documents/pdfs/bft-afghanistan-and-iraq-exper.pdf.

Earth Observation Portal. "RADARSAT-1." Accessed on 27 April 2016. https://directory.eoportal.org/web/eoportal/satellite-missions/r/radarsat-1.

Ecole Polytechnique Federale de Lausanne. “Space Engineering Centre EPFL ESPACE – CleanSpaceOne.” Accessed on 28 March 2016. http://espace.epfl.ch/CleanSpaceOne_1.

General Electric Aviation. “The GE90 Engine.” Accessed on 15 April 2016. http://www.geaviation.com/commercial/engines/ge90/.

“GLONASS GPS.” *Space Today Online*. Accessed on 27 April 2016. http://www.spacetoday.org/Satellites/GLONASS.html.

Google Lunar X Prize. “About – Overview.” Accessed on 09 February 2016. http://lunar.xprize.org/about/overview.

Intelsat. “IntelsatOne Flex for Enterprise.” Accessed on 25 April 2016. http://www.intelsat.com/intelsatone-flex/enterprise/.

Interorbital Systems. “Interorbital Satellite Kits and Launch Services.” Accessed on 25 April 2015. http://www.interorbital.com/interorbital_06222015_030.htm.

Interorbital Systems. “IOS NEPTUNE System Launch Vehicles.” Accessed on 08 May 2016. http://www.interorbital.com/interorbital_06222015_012.htm.

Interorbital Systems. “NEPTUNE Launch Services.” Accessed on 08 May 2016. http://www.interorbital.com/interorbital_06222015_003.htm.

Iridium. “Iridium Announces Comprehensive Plan for Next-Generation Constellation.” 02 Jun 2010. Accessed on 25 April 2016. http://investor.iridium.com/releasedetail.cfm?releaseid=475071.

Jacobowitz, PJ. “GPS and GLONASS: ‘Dual-Core’ Location For Your Phone.” *Qualcomm,* 15 December 2011. Accessed on 08 April 2016. https://www.qualcomm.com/news/onq/2011/12/15/gps-and-glonass-dual-core-location-your-phone.

Jet Propulsion Laboratory. “NASA Office to Coordinate Asteroid Detection, Hazard Mitigation.” *National Aeronautics and Space Administration,* 07 January 2016. Accessed on 04 April 2016. http://www.jpl.nasa.gov/news/news.php?feature=4816.

Jet Propulsion Laboratory. “M-Cubed/COVE-2.” Accessed on 06 May 2016. http://www.jpl.nasa.gov/cubesat/missions/mcubed.php.

JSAT International. “Frequency.” Accessed on 26 April 2016. http://www.jsati.com/why-satellite-what-frequency.asp.

Mars Foundation. “Our Mission.” Accessed on 21 April 2016. http://www.marsfoundation.org/our-mission/.

Mars Foundation. “Donate.” Accessed on 21 April 2016. http://www.marsfoundation.org/donate/.

Mars One. “Human Settlement on Mars.” Accessed on 09 February 2016. http://www.mars-one.com/.

Mars One. “Mars One Astronauts.” Accessed on 21 April 2016. http://www.mars-one.com/mission/mars-one-astronauts.

Mars One. “How much does the mission cost?” Accessed on 21 April 2016. http://www.mars-one.com/faq/finance-and-feasibility/how-much-does-the-mission-cost.

Mars One. “What is the Mars One business model?” Accessed on 21 April 2016. http://www.mars-one.com/faq/finance-and-feasibility/what-is-the-mars-one-business-model.

Mars Society. “Mars Direct.” Accessed on 21 April 2016. http://www.marssociety.org/home/about/mars-direct/.

Mars Society. “Donate.” Accessed on 21 April 2016. http://www.marssociety.org/home/join_us/donate.

“Modular Space Vehicle (MSV) Bus, United States of America.” *Air Force Technology*. Accessed on 09 February 2016. http://www.airforce-technology.com/projects/modular-space-vehicle-msv-bus/.

Moon Express. “Moon Express.” Accessed on 26 April 2016. http://www.moonexpress.com/.

Musk, Elon. “I am Elon Musk, CEO/CTO of a rocket company, AMA!” *Reddit.com*, 06 January 2015. Accessed on 22 April 2016. https://www.reddit.com/r/IAmA/comments/2rgsan/i_am_elon_musk_ceocto_of_a_rocket_company_ama/.

OneWeb. “Solution.” Accessed on 25 April 2016. http://oneweb.world/#solution.

Orbital ATK. “Pegasus.” Accessed on 28 April 2016. https://www.orbitalatk.com/flight-systems/space-launch-vehicles/pegasus/.

Planetary Resources. “Planetary Resources - Intro.” Accessed on 09 February 2016. http://www.planetaryresources.com/#home-intro.

Planetary Resources. “The Trillion Dollar Market: Fuel In Space From Asteroids.” 06 Jun 2014. Accessed on 26 April 2016. http://www.planetaryresources.com/2014/06/fuelspace/.

Roadpost. “Iridium GO! Monthly Plans and Airtime.” Accessed on 25 April 2016. http://www.roadpost.ca/Iridium-GO-Subscriptions-P809C399.aspx.

Rocket Lab. “Electron.” Accessed on 09 February 2016. https://www.rocketlabusa.com/.

Rocket Lab. “Rutherford.” Accessed on 22 April 2016. https://rocketlabusa.com/about-us/propulsion/rutherford/.

Rocket Lab. “Space Is Open For Business, Online.” Accessed on 25 April 2016. https://rocketlabusa.com/space-is-open-for-business-online/.

Space Adventures, Limited. “Space Station.” Accessed on 20 April 2016. http://www.spaceadventures.com/experiences/space-station/.

Space Exploration Technologies Corporation. “Completed Missions.” Accessed on 03 February 2016. http://www.spacex.com/missions.

Space Exploration Technologies Corporation. “MERLIN Engines.” Updated on 26 March 2013. Accessed on 15 April 2016. http://www.spacex.com/news/2013/03/26/merlin-engines.

Space Exploration Technologies Corporation. “Capabilities & Services.” Accessed on 23 April 2016. http://www.spacex.com/about/capabilities.

Space Exploration Technologies Corporation. “About.” Accessed on 25 April 2016. http://www.spacex.com/about.

Space Launch Report. “Space Launch Report.” Accessed on 14 April 2016. http://www.spacelaunchreport.com/index.html.

“Space Shuttle history.” Accessed on 05 May 2016. http://www.century-of-flight.net/Aviation%20history/space/Space%20Shuttle%20history.htm.

The Planetary Society. “Humans Orbiting Mars.” Accessed on 21 April 2016. http://hom.planetary.org/.

Union of Concerned Scientists. “UCS Satellite Database.” Database updated on 01 January 2016. Accessed on 14 April 2016. http://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database#.Vw_qYlQrKW8.

Union of Concerned Scientists. “A History of Anti-Satellite Programs (2012).” February 2012. Accessed on 19 April 2016.

http://www.ucsusa.org/nuclear-weapons/space-security/a-history-of-anti-satellite-programs#.VxaKvVQrKW8.

United Launch Alliance. "Company History." Accessed on 19 April 2016. http://www.ulalaunch.com/history.aspx.

United Launch Alliance. "Atlas V." Accessed on 23 April 2016. http://www.ulalaunch.com/products_atlasv.aspx.

United Launch Alliance. "Delta IV." Accessed on 23 April 2016. http://www.ulalaunch.com/products_deltaiv.aspx.

United States Air Force. "X-37B Orbital Test Vehicle." *US Air Force*, 17 April 2015. Accessed on 08 April 2016. http://www.af.mil/AboutUs/FactSheets/Display/tabid/224/Article/104539/x-37b-orbital-test-vehicle.aspx.

United States Air Force Air University. "Space Surveillance." Accessed on 27 April 2016. http://www.au.af.mil/au/awc/awcgate/usspc-fs/space.htm.

United States Air Force Space Command. "Geosynchronous Space Situational Awareness Program (GSSAP)." Last updated on 15 April 2015. Accessed on 27 April 2016. http://www.afspc.af.mil/library/factsheets/factsheet.asp?id=21389.

United States Strategic Command. "US STRATCOM Space Control and Space Surveillance." *US STRATCOM*, January 2014. Accessed on 27 March 2016. https://www.stratcom.mil/factsheets/11/Space_Control_and_Space_Surveillance/.

Virgin Galactic. "Human Spaceflight – Our Vehicles." *Virgin Galactic*. Accessed on 08 April 2016. http://www.virgingalactic.com/human-spaceflight/our-vehicles/.

Virgin Galactic. "LauncherOne Performance." Accessed on 23 April 2016. http://www.virgingalactic.com/satellite-launch/l1-performance/.

XCOR Aerospace. "Lynx Spacecraft." Accessed on 28 April 2016. http://aerospace.xcor.com/reusable-launch-vehicles/lynx-spacecraft/.