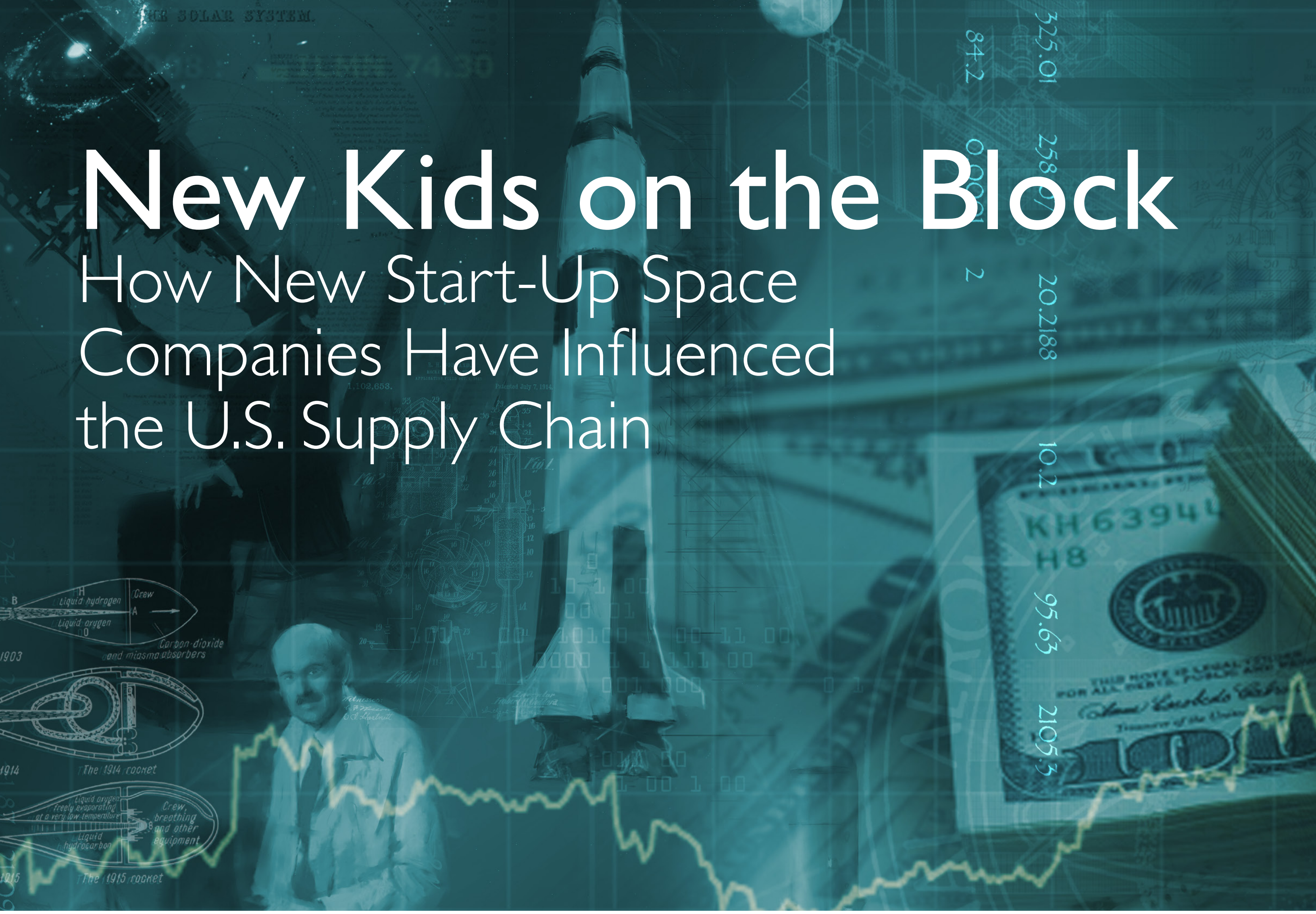
New Kids on the Block

How New Start-Up Space Companies Have Influenced the U.S. Supply Chain



BRYCE

space and technology

Contents

Executive Summary

Start-up space companies have begun to change the space industry supply chain in the United States, though their impact is still limited.

The U.S. space industry supply chain emerged immediately after World War II as the military pursued development of ballistic missiles, built upon the existing aviation supply chain that was forged during World War I. The supply chain expanded further with the introduction of satellites and spacecraft, ultimately supporting a multi-billion dollar industry during the decades that followed.

During the mid-2000s, a new breed of space companies began to grow; start-up space ventures were established with angel investment or venture capital. Most start-ups took a fresh look at existing space markets while leveraging lessons learned from the aerospace industry. Entrepreneurs, some with impressive records of success, developed business plans and sought venture capital from investment firms and angel investors.

Start-up space ventures range from innovative manufacturer-operators building large constellations of very small satellites, to launch vehicle providers ambitiously targeting commercial, civil, and military markets with partially reusable vehicles, to new suppliers providing critical subsystems, assemblies, or components.

This study identifies seven current trends in the space supply chain, shaped (at least in part) by the emergence of start-up space firms.

Vertical integration. Some start-up space firms are vertically integrated, an approach being pursued to ensure supply chain control and keep costs down. For example, Space Exploration Technologies Corporation (SpaceX) manufactures launch vehicles and spacecraft across all tiers, from system integration to additive manufacturing of basic hardware. At the corporate level, vertical integration may carry more risk and have less flexibility if competitive dynamics shift significantly. At the market level, vertical integration carries the risk that some firms will not have access to specialized talent that once supplied critical components, ultimately limiting competition at the highest tier.

Manufacturer-Operators. Many start-up companies were established as manufacturer-operators. These companies design and build the hardware and infrastructure necessary for supporting specific services. Planet, a manufacturer-operator providing data analytics services, has built and deployed over 100 satellites since 2014, each gathering data that the company then translates into data products. Rocket Lab and Virgin Orbit are building launch vehicles, using these to deploy their customer's payloads into orbit.

Maker and Small Team Innovation. Spurred by advances in materials and miniaturized electronics, start-up space companies and universities have expanded the industry beyond traditional space system manufacturing centers in terms of innovations in design, manufacturing, and provision of services. Perhaps the most pronounced example of this trend is in the design and manufacturing of CubeSats. Start-up data companies like Planet and Spire Global selected the CubeSat form factor as a low-cost option for satellite remote sensing, leveraging advances in microelectronics and optics. Launch vehicle innovation has also become more distributed, with many companies developing new vehicles designed to provide small satellite operators with on-demand, cost effective launch options.

Leveraging COTS. Many start-up space companies are using commercial-off-the-shelf (COTS) parts because the components selected are low cost and have proven reliability in other industries like mobile devices. In some instances, the number of flight units is high enough to warrant acceptance of a certain failure rate that does not compromise service.

Warehousing. Warehousing, or maintaining an inventory of space systems, is an emerging strategy pursued by some start-up satellite and launch vehicle companies. The space industry has always been more of an "artisan," built-to-order industry than one characterized by mass production like the automotive industry. This is changing as small satellites, small launch vehicles, and susbsystem level hardware is built and stored, an approach that enables a company to replenish capabilities rapidly as demand for services increase. The warehousing concept reaches back many years, but has only recently been incorporated into business plans.

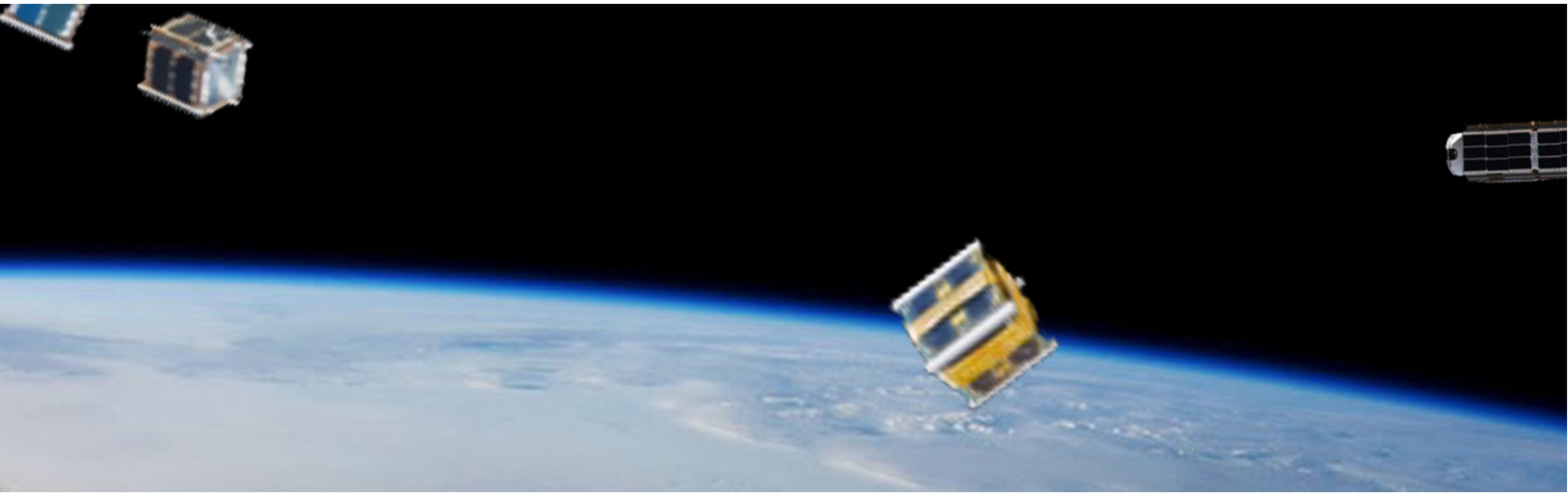
Reusability. The potential for reusable launch vehicles has been considered since the early days of rocketry. In recent years, start-up space companies like Virgin Orbit, Blue Origin, and SpaceX have been iteratively working on launch vehicle reusability. All have successfully demonstrated reusable suborbital launch vehicles to varying degrees. The next ten years will see companies and government agencies continue to develop reusable launch vehicle technologies, with growing operational use. Only after several years of this activity will it be possible to see if reusability has translated into significant cost savings.

Additive manufacturing. Additive manufacturing, a technique being used by both start-ups and long-established companies, is considered by many in the space industry to be a potential game changer. Perhaps most remarkable given the high-pressure and high-temperature stresses is the use of additive manufacturing to produce liquid rocket engine parts. The Rutherford, an engine being developed by start-up Rocket Lab for its Electron launch vehicle, is almost entirely composed of additive manufactured parts. Though potentially a major technology improvement for the industry, it is still an emerging capability and uncertainties remain about quality control and performance.

Overall, the impact by start-up companies on the supply chain remains uneven, with some segments of the industry and some manufacturing tiers experiencing more immediate change than others. For example, start-up companies in the launch industry have inspired long-established competitors to accelerate technology development to remain competitive. Additive manufacturing is expected to impact lower tiers of the supply chain, especially mixed media printing that can produce complex parts.

COTS and additive manufacturing are two key supply chain trends that have the potential to reduce costs for the National Aeronautics and Space Administration (NASA). Increasingly available COTS products enable NASA and its contractors to tap high-quality, high-volume parts developed for other industries requiring reliable, sophisticated components. NASA has also observed that additive manufacturing is likely to be a game changer. As additive manufacturing techniques improve and become less expensive, the effect on lower tier suppliers will be significant in the coming decades. For NASA to achieve full benefit from both of these trends, it needs to ensure cost-effective mechanisms for meeting reliability and quality standards.

Introduction



Scope and Methods

This project sought to assess the impact of start-up space companies on the supply chain, asking if they have contributed to the production of less expensive, more capable, or quickly available components for space systems. In addition, we considered how start-up space companies may be changing the geography of the space industry.

The study focused on the U.S. space industry, across all five manufacturing tiers (described in detail below). In addition to assessing changes in cost, quality, availability, and geography, the study also sought to delineate the common and unique aspects of the industrial base for venture and angel-funded start-up space companies and the industrial base for long-established competitors and government contractors.[1]

The study included research and a literature review, a survey of launch vehicle and satellite manufacturing firms at all supply chain tiers, and interviews with leading industry professionals and subject matter experts. This information was organized into a structured database and synthesized with analysis of key industry reports, conference proceedings, and other open-source material. We are grateful to the many people who shared their time and expertise with us. The findings reported here reflect the views of Bryce Space and Technology.

The report is based on work supported by a National Aeronautics and Space Administration (NASA) grant under award NNX16AH10G, "The Start-Up Space Supply Chain."[2] The grant, awarded in 2016, supports study of how new start-up space companies have impacted the U.S. space industry supply chain. Bryce Space and Technology also provided resources to support this project.

What is a Start-up Space Company?

This report focuses on the impact of start-up space companies on the U.S. space industry supply chain. Start-up space companies are defined as companies that began as angel- and venture capital-backed start-ups.[3] While some of these companies have sustained themselves through the generation of revenue, many have yet to reach this level of maturity.

From 2000 to 2016, U.S. start-up space ventures reported over $16.6 billion of investment, including $5.1 billion in debt financing. Over 140 angel- and venture-backed space companies have been founded and funded since 2000.[4]

The year 2016 saw sustained, robust investment in start-up space ventures: 114 investors put $2.8 billion into 43 start-up space ventures across 49 deals, slightly outpacing record-breaking investment in 2015. Interestingly, in 2016 there were fewer and larger deals compared to 2015. In addition, the total number of space start-ups reporting new funding also declined about 30 percent from 2015.[5]

For purposes of this study, start-up space companies contrast with long-established companies, which typically have stable revenue streams, business bases, capabilities, and product lines. Established space companies in the United States often include the federal government as an important or primary customer, delivering products and services through highly structured government contracts. These government contractors have systems in place to meet government standards for accounting, reporting, financial management, as well as mandated product and service standards of performance and quality assurance.

Start-up space companies take on many forms. These include manufacturer-operators that both build satellites and provide satellite services; manufacturers producing space launch vehicles not derived from earlier missile designs; companies rapidly building CubeSats or other very small satellites that provide low-cost proof-of-concept for new payloads, capabilities, and services; and many others.

Understanding the Space Supply Chain

The space industry supply chain is the network of companies and suppliers that manufacture and distribute their products to customers. Activities in the supply chain involve the transformation of hardware and materials, components and parts, assemblies, and subsystems into a final, completed system like a satellite or launch vehicle.

The U.S. Department of Commerce (DoC) has a well-practiced approach for investigating the industrial base of high-technology sectors. This approach includes widely disseminated surveys that seek to uncover potential vulnerabilities from the perspective of U.S. competitiveness and national security. Such vulnerabilities could be issues related to single and sole-source suppliers, reliance on large government programs, workforce availability, and so on.

In 2013 the DoC released findings from the U.S. Space Industry Deep Dive assessment conducted in collaboration with the U.S. Air Force (USAF), NASA, and the National Reconnaissance Office (NRO).[6] The study presented here, which differs in scope and purpose, provides timely, additional perspective reflecting the significant changes within the industry more recently, focusing on new firms.

This study uses a tier-by-tier breakdown of the supply chain. The tier-by-tier structure described in this report was initially developed by the Bryce team (then Tauri Group) for a study conducted for the Deputy Assistant Secretary of Defense for Manufacturing and Industrial Base Policy (DASD/MIBP) in 2012. The breakdown was inspired by a report published by the Office of Technology Assessment (OTA).[7] Supply chain tiers describe the relative complexity of products, rather than describing manufacturers. While companies are often identified with a particular tier, it is common for companies to operate at multiple tiers of the supply chain. For example, a single manufacturer can produce final systems as well as lower tier subsystems and assemblies. A vertically integrated firm by definition covers multiple tiers.

Tier 1: System

At the highest level, a Tier 1 system is a completed product, such as a satellite or launch vehicle. A system is often integrated and delivered by a prime contractor, sometimes called an original equipment manufacturer (OEM). For example, United Launch Alliance (ULA) and Space Exploration Technologies Corporation (SpaceX) are prime contractors that manufacture launch vehicles, and Space Systems Loral is a prime contractor that builds satellites.

Tier 2: Subsystems

Subsystems are the major elements of a system. For a satellite, subsystems include attitude determination and control; command and data handling; power; propulsion; structures; thermal; telemetry, tracking and command; and guidance and navigation. Subsystems used in a launch vehicle are propulsion; structures; guidance, navigation, and control; power; payload adapter(s); and payload fairings. As an industry example, Aerojet Rocketdyne manufactures the RS-68A propulsion subsystem for the Delta IV launch vehicle system manufactured by ULA.

Tier 3: Assemblies

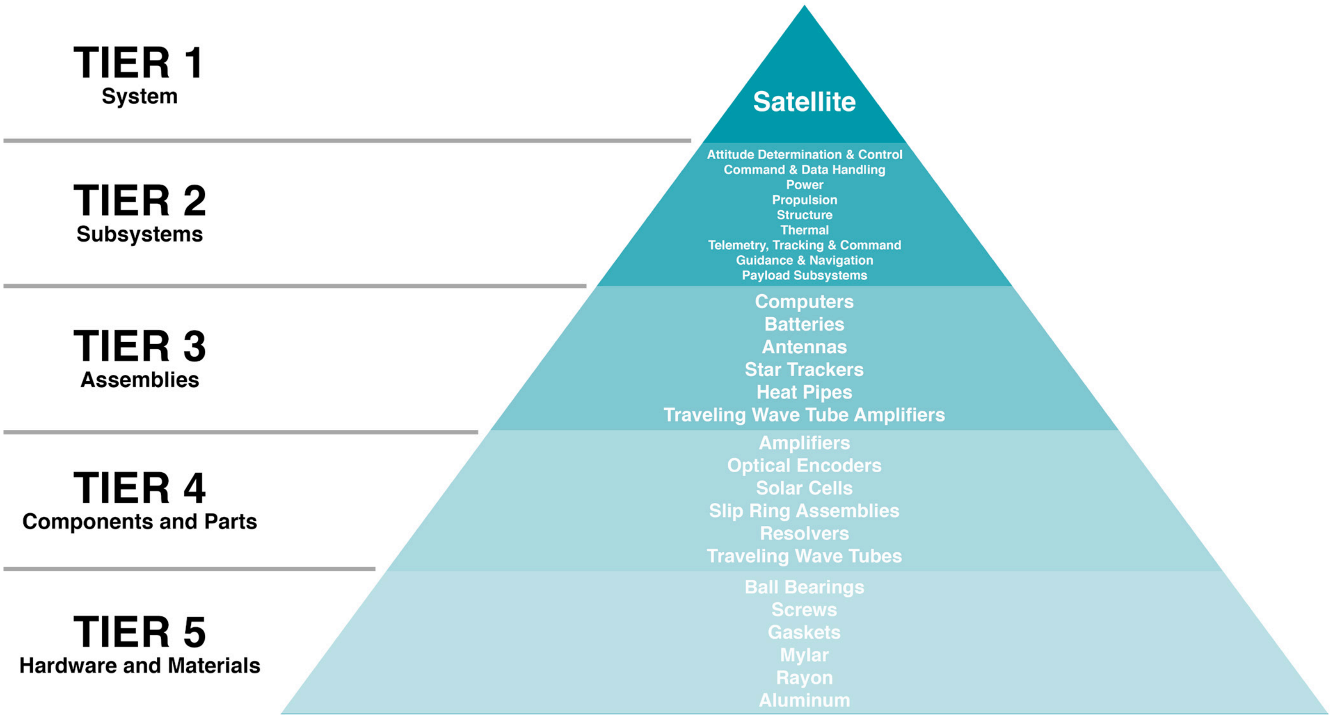
Assemblies are the elements of subsystems. Sometimes, assemblies are described as avionics or "black boxes." Assemblies that may compose a liquid propulsion subsystem include, but are not limited to, a combustion chamber, engine controller, heat exchanger, preburner, propellant manifold, nozzle, and turbopumps. Due to their relative simplicity, solid rocket motors are considered complete propulsion assemblies. As an industry example, Barber-Nichols Inc. designed and manufactured the turbopump assembly for the SpaceX-built Merlin-1D engine, a propulsion subsystem to the Falcon 9. SpaceX ultimately purchased the license to build these turbopumps in-house.

Tier 4: Components and Parts

Components and parts constitute the elements of assemblies. Hundreds to thousands of components and parts are used in the manufacture of satellites and launch vehicles. One Tier 4 supplier, Moog, manufactures a large variety of components and parts for the aerospace industry, such as actuators used in many propulsion subassemblies.

Tier 5: Hardware and Materials

Hardware and materials feed into the manufacture of components and parts. There are thousands to tens of thousands of examples of hardware and materials used in the manufacture of space systems. One example of a Tier 5 supplier, The Timken Company, manufactured the precision ball bearing hardware used in the wheel components developed for NASA's Curiosity rover.



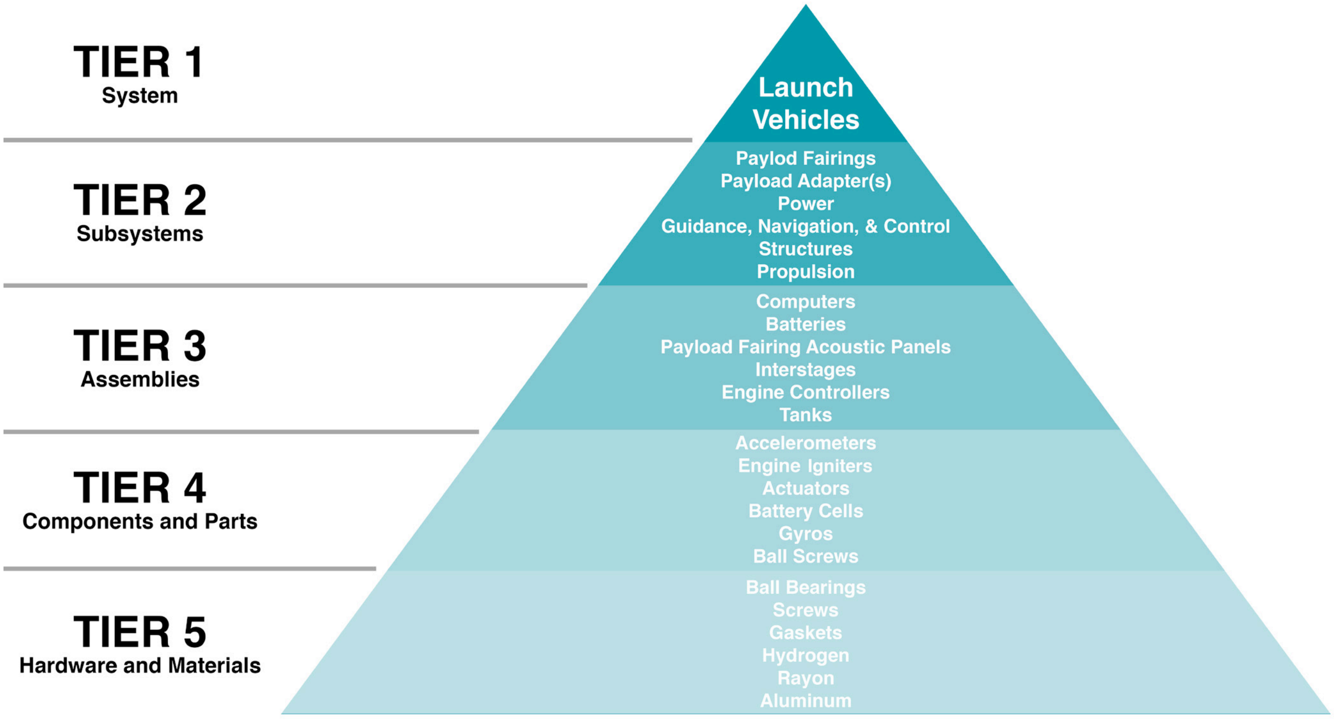


Figure 1. Supply chain tiers for satellites and launch vehicles. Note: Tier 2 is a comprehensive listing of subsystems, while example products are provided for Tier 3 through Tier 5.

Characteristics of the Start-Up Space Supply Chain

Start-up space firms are affecting the U.S. space supply chain, and are also shaped by the established supply chain.

U.S. Space Supply Chain History

The U.S. space industry supply chain traces its origins to the emergence of the aviation industry during World War I. Prime contractors like Boeing, Lockheed, Douglas, and others were established to build aircraft for military and eventually civilian use. These companies tended to be vertically integrated; that is, they would manage the entire supply chain needed for the design and construction of their respective aircraft. Two major waves of mergers and consolidations followed, the first immediately after World War II as military contracts dried up and the second during the 1960s as companies sought cost savings in a heightened competitive environment.[8]

Beginning around 1980, large aerospace companies began to increasingly outsource the manufacturing of lower tier products. A growing network of companies emerged providing subsystems (Tier 2), assemblies (Tier 3), components and parts (Tier 4), and hardware and materials (Tier 5). A third wave of mergers and acquisitions took place in the 1990s, largely driven by the end of the Cold War and greater international competition. The largest among these were Lockheed Corporation and Martin Marietta (1995), Boeing and McDonnell Douglas (1996), and Raytheon and Hughes Aircraft Company (1997).

The 1990s were also a period of significant investment in the space industry. Several companies emerged with the aim of providing communication services via large constellations of satellites, with the more notable of these being Iridium, GlobalStar, ORBCOMM, Teledesic, and ICO. The hundreds of satellites expected to be operational by the turn of the century inspired a surge in the number of competitors in the launch industry, including a wave of builders keen to develop reusable launch systems. The USAF was in the market for new launch vehicles, feeling the timing was right to take advantage of potentially lower launch prices due to high demand by the commercial sector, and partnered with Boeing and Lockheed Martin to develop the Evolved Expendable Launch Vehicle (EELV). The passage of the 1992 Land Remote Sensing Act ushered in a new era in satellite remote sensing, and companies like Space Imaging, WorldView Imaging, and ORBIMAGE were set up to take advantage of the anticipated demand for imagery products. Unfortunately, most companies either went bankrupt or consolidated to survive. Iridium, GlobalStar, and ORBCOMM emerged from bankruptcy and have become viable companies today. Teledesic and others were not so fortunate. Commercial satellite remote sensing was slow to start, with revenues trickling in. As a result, companies merged in phases, so that in the end only DigitalGlobe remained, only to be acquired by Canada-based MDA in 2017. The launch industry underwent major changes, including the emergence of robust Russian providers like International Launch Services (ILS), ISC Kosmotras, Eurockot, Starsem, and others, while the EELV program produced the Atlas V and Delta IV provided by ULA, a joint venture between Boeing and Lockheed Martin. Europe's Arianespace, established in the early 1980s continued to be a major player. All efforts to develop a reusable launch vehicle during this period failed.

The space industry, which emerged immediately after World War II as the military pursued development of ballistic missiles, built upon the existing aviation supply chain. The supply chain expanded further with the introduction of satellites and spacecraft. By the late 1950s, the term "aerospace" emerged to describe this hybrid industry, with the newly conceived industry immortalized in the genesis of the NASA in 1958.[9]

The Emergence of Start-Up Space Firms

During the mid-2000s, a new breed of space companies began to grow. Most start-ups took a fresh look at existing space markets while leveraging lessons learned from the aerospace industry. Entrepreneurs, some with impressive records of success, developed business plans and sought venture capital from investment firms and angel investors. Reusable launch vehicles, a concept that can be traced to Robert Goddard, were revisited in earnest with some start-ups seeking to develop large launch vehicles that might halve the cost per kilogram to orbit. The aerospace industry experienced an infusion of business talent and capital from the hugely successful computer, software, and data analytics industries. This infusion originated from entrepreneurs pitching detailed plans featuring fleets of small satellites designed to acquire Earth observation data and sell data products rather than raw imagery. Communications companies with plans to deploy orbital constellations, some numbering in the thousands of satellites, also emerged during this time. Finally, with potentially thousands of satellites envisioned by some entrepreneurs in the decades ahead, a number of start-ups formed to build small launch vehicles. These small launch vehicles are designed to put the small satellite operator front and center as a primary payload customer, a novel concept in commercial launch services. Some start-ups even dusted off dreams hatched decades earlier, like non-terrestrial mining and commercial human spaceflight. These firms have begun to reshape aspects of the space supply chain.

Start-up space companies are emerging during a time when information technology is continuing to rapidly expand worldwide. During the past two decades, the Internet has reached more users and become more sophisticated, spawning new industries and global networks. The dramatic evolution of the Internet and low-cost mobile devices follow growing demand for data services supported by communication networks and remote sensing information. Resulting capabilities include location-based services (LBS), which rely on signals from global navigation satellite systems (GNSS) and streaming data, requiring reliable, strong, uninterrupted broadband connections. Machine-to-machine (M2M) is a highly anticipated area that will tap LBS as companies and governments seek to know with greater precision the location and performance condition of expensive machines. Some start-up companies emerged from IT and data analytics centers like San Francisco and Seattle areas to provide real-time data services using globally acquired data. The only way to do that in a cost effective manner was to produce large constellations of small, inexpensive but highly capable satellites. The CubeSat in particular fit the bill for companies like Planet, Spire Global, and others as the basis for technology demonstration and, ultimately, operational satellites.[10]

Start-up companies tap parts of the long-established and mature aerospace supply chain, often specifying different capabilities. They also seek other, non-aerospace suppliers that may be lower cost or more responsive, or have access to mass-produced components. Start-up space firms also expand the supply chain by acting as manufacturers themselves. In some cases, these dynamics have demonstrated a disruptive influence on the space industry.

In particular, **we found seven key supply chain overall trends**, some of which are driven by start-up space companies during the past ten years: use of vertical integration, the rise of satellite manufacturer-operators, regionally distributed innovation, leveraging COTS products, warehousing, reusability, and perhaps most significantly, additive manufacturing.

Trend: Vertical Integration

Some highly visible start-up space firms are vertically integrated. A vertically integrated company is one that internalizes a significant part of the supply chain necessary to manufacture its products. In other words, the operations of a vertically integrated company span the industry tiers or several different technologies within one tier (see Figure 2). Though not a new feature in the aviation industry, vertical integration is a new characteristic for the space industry. In contrast, the automotive industry is comparatively less vertically integrated. OEMs such as General Motors (GM) and Ford Motor Company rely on a vast network of suppliers who are responsible for roughly 70 percent of the vehicles' parts.[11]

In many cases, start-up companies have pursued vertical integration for at least two reasons. One is to contain costs. SpaceX is vertically integrated to ensure control of its supply chain, keep costs down, and efficiently manage development of its launch vehicles and spacecraft. The second is to bypass traditional contracting and procurement approaches. For example, several small prospective satellite operators were not satisfied by proposals submitted by long-established prime contractors, citing what they viewed as undue complexity and a resulting, in their view, unnecessary cost burden. These start-ups decided to pursue manufacturing on their own. To keep costs low, many of these companies discovered the versatility of the CubeSat, a 10-centimeter cubic platform developed for university-level research and education.

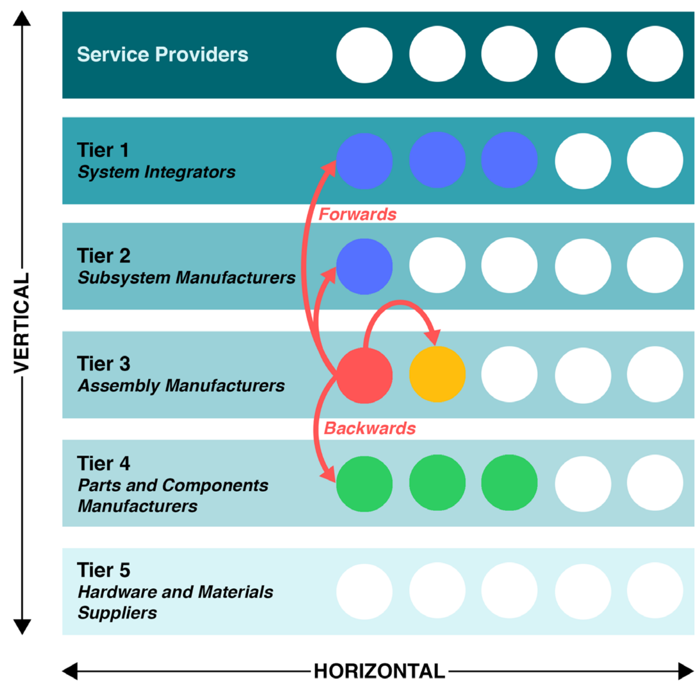
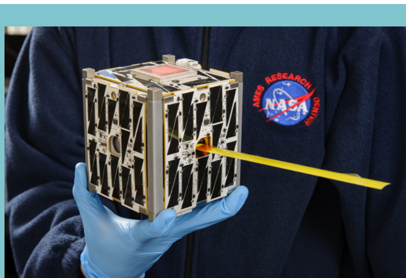


Figure 2. Contrasting vertical and horizontal integration. A company exhibits backward vertical integration (green) when it controls subsidiaries that produce some of the inputs used in the production of its products. A company tends toward forward vertical integration when it controls companies higher in the manufacturing tier hierarchy (blue). Horizontal integration is illustrated in orange.

However, vertical integration does not clearly distinguish start-up space companies from established companies that continue to pursue mergers and acquisitions to drive growth. Established companies, through these mergers and acquisitions, often gain strategically valued capabilities from firms that were previously suppliers supporting development of their Tier 1 systems. A well-known example is the merger of Orbital Sciences Corporation with Alliant Techsystems in 2015. The merger into what is now Orbital ATK enables the company to significantly leverage vertical integration. Its Space Components Division, for example, is a 700-person team and a major supplier of thermal systems, structures, deployable assemblies solid motors, and propulsion tanks across the space industry.[12] Overall, this merger has allowed Orbital ATK to internally build a higher percentage of parts assembled into its final systems.

Vertical integration does have the potential for negative consequences to the individual firm and the wider industry. Vertical integration is a major investment into a particular way of manufacturing and competing. In this way the firm may carry more risk and have less flexibility if competitive dynamics shift significantly. Vertical integration also carries the risk that some firms will not have access to specialized talent that once supplied critical components, ultimately limiting competition at the highest tier.

Trend: Manufacturer-Operators



Cubesats are satellites whose basic building blocks are cube-shaped modules measuring 10 centimeters on each side. Once limited largely to experimental applications, cubesats today are being used for operational missions including imaging, weather-monitoring and communications. *Image: NASA.*

Manufactruer-operators are a type of start-up company that designs, builds, and operates a space system. This is in contrast to most industrial arrangements in the space industry, whereby different companies specialize in manufacturing and providing services. The pursuit of low-cost, fast paced innovative solutions in the data analytics industry has served as a fertile ground for this type of company, where companies like Planet and Spire Global were born.

Start-up data analytics companies aim to efficiently obtain Earth observation data, providing services for a wide variety of customers that seek to design and build their own satellites. As indicated in the previous section, this approach was motivated in part by limitations in the existing supply chain and a desire to keep costs low. This approach was also an effort to attract investment by demonstrating proof of concept through prototype satellites. CubeSats proved to be ideal for this purpose, with the three-unit (3U) configuration popular as an Earth observation platform. Each 3U satellite, which can be built using kit parts, and costs about $300,000 to build and modify.[13] Technology demonstration CubeSats can help validate the technical approach described in a business plan and thus help attract investment. Once adequate investment is secured, funding is spent on the manufacturing of a constellation of operational CubeSats subsequently launched into orbit in clusters. As data is captured following a brief satellite checkout period, revenue is generated. Part of the profit is then applied to replacement satellites.

Planet, a manufacturer-operator providing data analytics services to private and government clients, deployed four technology demonstration satellites in 2013. These successful missions helped secure additional investment used to manufacture and operate over 200 operational satellites (called "Doves" and grouped in "Flocks") launched by a variety of vehicles since 2014.

Historically, U.S. prime contractors would build launch vehicles and government agencies would launch them. Since the 1990s, companies have been both building and launching vehicles. For example, ULA both builds and launches Atlas V and Delta IV vehicles. SpaceX, founded in 2002, builds and launches the Falcon 9. The trend has continued, and all start-up companies seeking to build launch vehicles aim to build and launch their products. Other examples include Rocket Lab and Virgin Orbit.

Trend: Maker and Small Team Innovation

Innovation has become more distributed during the past ten years in satellite and launch vehicle development. The key has been the availability of low-cost and easily obtained Computer Aided Design and Drafting (CADD) software combined with satellite kits or small, approachable companies capable of building reliable satellites quickly. Perhaps the most pronounced example of these trends is in the design and manufacture of CubeSats.

Due to the availability of low-cost CubeSat kits and associated hardware via the Internet, satellite innovation is feasible for small teams and individuals. Innovation has also spread beyond the traditional satellite development centers like the Los Angeles and Denver-Boulder areas. In addition, over 225 universities and institutions worldwide are developing CubeSats, effectively increasing the opportunities for satellite technology innovation. The wide distribution of universities with CubeSat programs has also spread innovation.[14] In addition to universities, governments have demonstrated an interest in CubeSats, with countries eager to enter the "space club," picking the CubeSat as an inaugural program. The wide distribution of CubeSat developers, builders, and operators has increased the geographic distribution and diversity of mission approaches, a situation that helps the space industry as a whole.

CubeSats were invented in 1999 by Jordi Puig-Suari of California Polytechnic State University and Bob Twiggs of Stanford University.[15] The simple, low-cost CubeSat form factor was pursued to educate university students on spacecraft design within a four-year period of study. While design and manufacture of a mission could be pursued, launch costs and scheduling remained a challenge and were often simulated. Despite these challenges, some university CubeSats were launched beginning in 2003.

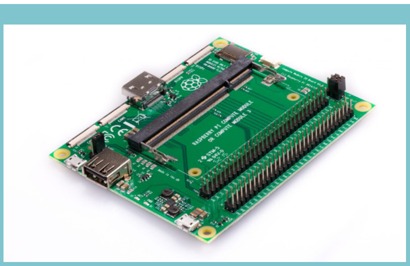
Start-up companies like Planet (formerly Cosmogia), Spire Global (formerly Nanosatisfi), and many others selected the CubeSat form factor as a low cost option to demonstrate capabilities necessary for the eventual development of a fleet of operational satellites. Since 2014 when Planet started launching its CubeSat constellation, the number of CubeSats launched into orbit has ballooned, with hundreds of CubeSats projected for launch each year during the next decade.

Launch vehicle innovation has also become more regionally distributed, with teams developing new vehicles in Mojave, California and Seattle, Washington, with testing facilities built in various areas around Texas and Florida. Nearly 25 new launch vehicles are being developed in the U.S., with the majority being conducted by start-up companies. Most of these vehicles are very small, with capacities to LEO at or below 500 kilograms. Innovations include simplification of design, additive manufacturing techniques for propulsion and structures, and the use of COTS parts for avionics and other assemblies.

Trend: Leveraging COTS

Commercial-off-the-shelf (COTS) components are a popular option for start-up space companies. COTS is attractive because the components selected are low cost and have proven reliability in other industries (especially electronics used in mobile devices). In some instances, the number of flight units is high enough to warrant acceptance of a certain failure rate that does not compromise service.

The use of COTS components is a complement to the strategy of vertical integration discussed above. For start-up space companies, COTS components are a segment within the supply chain that does not need to be internalized because the state-of-the art is being driven forward by other markets. Of course, long-established companies have the option to source COTS components while leveraging their extensive experience ensuring quality control. The challenge for both start-up companies and long-established firms is the same: validate the performance of COTS for the specific application while considering the risk tolerance for the customer and their mission.



The small size of the Raspberry Pi Compute Module makes it ideal for use in CubeSats. *Image: RaspberryPi.*

COTS components are leveraged extensively in the development of CubeSats and other very small satellites (those with masses of 600 kilograms or less).[16] Early on, Planet considered sourcing parts for its Dove satellites through the aerospace suppliers, but elected not to on the basis of cost and performance. Instead, Planet used COTS suppliers, even building their own circuit boards.[17] Some companies and universities have used COTS electronic kits in the development of CubeSats; for example, Spire Global (formerly Nanosatisfi LLC) developed its Ardusat CubeSat using Arduino circuit cards.[18] Others have used Raspberry Pi circuit cards.[19]

The high reliability of microelectronics demonstrated in the manufacture and distribution of millions of mobile devices during the past ten years has translated into a willingness to use them in satellites. Some companies have tested the microelectronics for radiation tolerance or gone the extra step to radiation harden the components for use in space.[20]

Moreover, once COTS microelectronics are used successfully in a CubeSat launched into space, the components are effectively "space-certified," having been operationally demonstrated in a real-world environment. This is another advantage of using low-cost CubeSats as technology demonstration missions.

While the use of COTS microelectronics is not inherently limited to CubeSats, those missions often involve more tolerable conditions for COTS components, such as less radiation exposure in low-Earth orbit, a shorter design life, or lower costs associated with spacecraft failure.

NASA is also working to leverage more COTS components, especially for spacecraft microelectronics. NASA's Electronic Parts and Packaging Program, for example, is evaluating performance and reliability of automotive electronic parts.[21] This program includes testing of chip capacitors, discrete semiconductors, and microcircuits. Not limited to just hardware, COTS also extends to the software and engineering tools required to develop space systems. Satellite manufacturer-operator Planet has noted that the heat transfer analysis tools refined for developing Ford diesel engines can be applied just as well to design problems for Earth observing satellites.[22]

Trend: Warehousing

Warehousing is an emerging strategy being pursued by some start-up satellite and launch vehicle manufacturing companies. The space industry has always been more of an "artisan" industry than one characterized by mass production like the automotive industry. Typically, satellites and spacecraft are manufactured on order and used relatively quickly once built. A satellite sitting on the floor of a high bay is wasted money in part because of storage costs and the lack of return on investment. Launch vehicles can represent an exception to the rule if ballistic missiles are repurposed for space launch; in their original form, these assets were warehoused as part of an arsenal. Storage of multiple complete launch vehicles is impractical, however. Subsystem elements of a large launch vehicle are more easily warehoused, if at all. On the other hand, very small launch vehicles, like those being built by Rocket Lab, Vector Space Systems, and Virgin Orbital can be stored in substantial numbers. This will be a requirement if demand for these vehicles is as high as anticipated by the launch service providers.

The Department of Defense (DoD) has also been exploring the potential of warehousing tactical space assets. The Operationally Responsive Space (ORS) Office under the DoD has been tasked with pursuing efforts to warehouse satellites and launch vehicles that can be rapidly deployed depending on national security needs.[23] Four ORS missions have been conducted since 2008, with a fifth planned in 2017.

Trend: Reusability

The potential for reusable launch vehicles has been considered since the early days of rocketry. The ultimate objective has been a single-stage-to-orbit (SSTO) vehicle that operates similarly to a conventional airplane. While this type of system appears a long way off, NASA, the USAF, and many companies have conducted research and development on reusable launch vehicle systems and related technologies. NASA's Space Transportation System (STS), more commonly known as the Space Shuttle, is the most well known of these is. The Orbiter, which was designed to conduct 100 missions, was not a true reusable vehicle. Rather, the Orbiter was refurbished, having undergone significant inspection and preparation between missions. The STS Solid Rocket Boosters were refurbished up to ten times each.

In recent years, start-up space companies like Virgin Galactic, Blue Origin, and SpaceX, among others, have been iteratively working on launch vehicle reusability. Other efforts, like those pursued by start-ups like Moon Express, Masten Space Systems, and Astrobotic Technology have focused on precision landing, a critical part of point-to-point suborbital transportation and sample return missions. All have successfully demonstrated reusable suborbital launch vehicles to varying degrees.

Virgin Galactic's SpaceShipTwo has been tested in powered flight, though it has not yet reached the Kármán Line, or 100 kilometers in altitude, viewed as the threshold of space.[24] In developing the SpaceShipTwo, Virgin Galactic leveraged experienced gained from SpaceShipOne, designed and built by Scaled Composites to win the Ansari X Prize in 2004.

Blue Origin has successfully flight-tested its New Shepard #2 suborbital vehicle, a vertically launched system that has entered and returned from space on five occasions.

In March 2017, SpaceX successfully launched SES-10 aboard a Falcon 9 using a recovered first stage, the first time such an event has taken place in the industry. The company hopes to realize 30-40 percent cost savings per launch vehicle with reusability. From the beginning, SpaceX designed its Falcon 9 launch vehicle to be reusable in an effort to reduce manufacturing costs and launch service price. The company simplified vehicle design, especially in terms of propulsion subsystems, and developed its Grasshopper demonstrator to explore how to return Falcon 9 first stages intact. Following successful flights of Grasshopper, SpaceX included the capability to recover first stages on operational flights of the Falcon 9. Since 2014, the company has successfully recovered Falcon 9 first stages 19 times, 12 times on an ocean barge and seven times on a pad located at Florida's Cape Canaveral Air Force Station (CCAFS).[25]

The next ten years will see companies and government agencies continue to develop reusable launch vehicle technologies, with growing operational use. Only after several years of this activity will there be sufficient data to unequivocally determine that launch vehicle reusability has translated into significant cost savings.

Trend: Additive Manufacturing

Additive manufacturing, often called 3D printing or rapid prototyping, is considered by many in the space industry to be a potential game changer. While additive manufacturing has existed for several years, its use in precision manufacturing for the aerospace industry is in its very early days. Historically, parts produced using additive manufacturing have been exclusively used for prototype parts. Their use as precision parts capable of sustaining temperature and pressure loads common in aerospace applications has only recently been explored.

Both start-up and long-established companies have used additive manufacturing in the development of rocket engines. Following a 2015 contract award by USAF, start-up SpaceX continued development of its Raptor engine, a propulsion subsystem that will burn liquid oxygen (LOX) and liquefied natural gas (LNG). This engine features many parts produced through additive manufacturing. A Raptor engine tested in 2016 contained about 40 percent additive manufactured parts by mass.[26] The Rutherford, a liquid rocket engine being developed by start-up Rocket Lab for its Electron launch vehicle, is almost entirely composed of additive manufactured parts.[27] The Electron was launched into space for the first time in May 2017.

Additive manufacturing is also an ideal method for producing structures used in satellites. Several CubeSats have been constructed using 3D-printed structures. Tethers Unlimited has developed a means to construct CubeSat-scale truss segments using additive manufacturing on-orbit, a process it hopes to demonstrate in the near future. Long-established companies have also introduced additive manufacturing to their factory floors. Aerojet Rocketdyne, a firm with roots back to 1942, has been developing the J-2X engine for the upper stage of NASA's Space Launch System since 2007. This engine was hot fire tested in 2013 with a part manufactured through selective laser melting (SLM), a type of additive manufacturing.[28] Space Systems Loral introduced an antenna tower for use in large communication satellites composed of 37 3D-printed titanium nodes and more than 80 3D-printed graphite struts.[29] Boeing Satellite Systems recently introduced additive manufactured brackets and fittings to its satellites.[30]

Lockheed Martin has noted that the Juno spacecraft built for NASA, which arrived at Jupiter in 2016, included 3D printed components. The company estimates that the technology will eventually streamline satellite production with a 43 percent reduction in cycle time and 48 percent reduction in manufacturing cost.[31] The technology offers a fundamentally new approach to design for manufacturing and the potential to significantly reduce the weight of spacecraft parts.

Though potentially a major technology improvement for the industry, uncertainties remain about quality control and performance. NASA in particular has raised concerns about how one conducts an inspection of parts produced using additive manufacturing. How is an inspection on a part built at the molecular level carried out? Can defects in 3D-printed parts be detected and characterized? Historically, the government has played a critical role in developing standards and qualifications that set a baseline for industry. A recent study published by the National Institute of Standards and Technology (NIST) estimates the estimated annual cost savings and percentage reduction in production costs are $4.1 billion per year, or just over 18 percent of the U.S. manufacturing sector.[32]

How Start-up Companies Have Influenced the U.S. Space Industry Supply Chain

To fully understand how start-up companies have impacted the space industry supply chain, the study gathered survey responses from subject matter experts in the commercial sector and government. The questions reached experts in all five tiers of the supply chain and across the major industry segments building satellite and launch vehicle systems in a survey format. Data was collected using a mix of surveys sent to nearly 300 companies and nearly 50 interviews with industry experts covering supply chain trends, specific technologies within a tier, and emerging manufacturing capabilities.

Survey Responses

Survey questions focused on cost, quality, delivery, geography, and manufacturing technology. Importantly, each question provided respondents the opportunity to provide detailed comments supporting each answer. Overall, the survey revealed that respondents perceive different changes in the supply chain, rather than uniform changes across the industry.

Price Changes

More than one third of respondents observed price decreases. Respondents identified two broad changes. The first change was a gradual decline in costs as current technologies and space components mature. The second change was cost pressure from start-ups who have demonstrated willingness to trade risk for savings when space qualified components are too expensive. One respondent also observed reduced costs from using software applications on commercial servers for ground support equipment to replace earlier, fixed-point solutions. About a third of respondents noted areas of cost increase, including specific materials such as rare metals, plastics, and resins (due to demand created by other industries) as well as transportation and labor costs. Some respondents noted that government regulations on foreign suppliers were also driving costs up. Finally, about a third of respondents pointed to stability in costs, highlighting specialized micro-size parts and other space qualified parts remaining about the same with costs decreasing mostly at the Tier 1 systems level. See Figure 3.

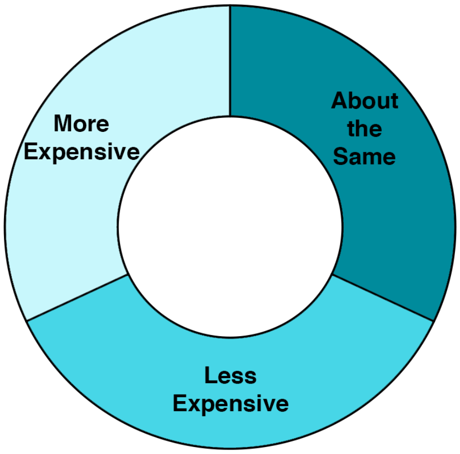


Figure 3. Has the cost of parts stayed the same, increased, or decreased during the past 10 years?

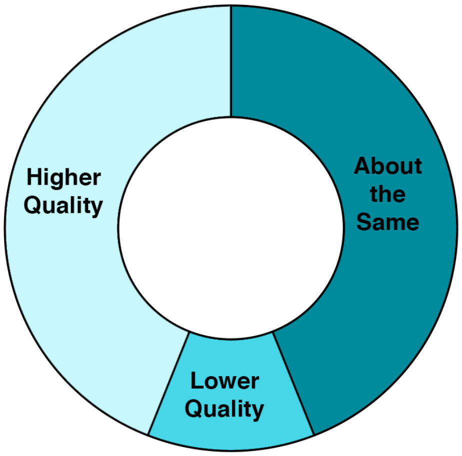


Figure 4. Has quality of parts stayed the same, increased, or decreased during the past 10 years?

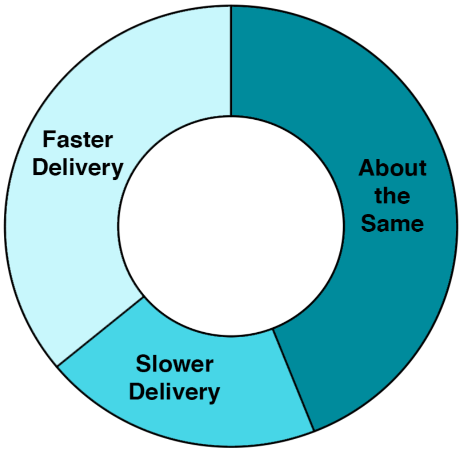


Figure 5. Has delivery time of parts stayed the same, increased, or decreased during the past 10 years?

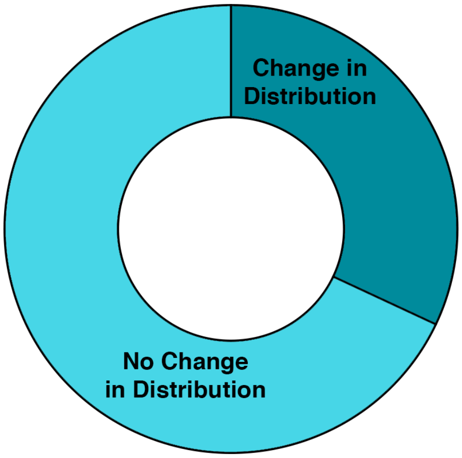


Figure 6. Have you observed any changes to the geographic distribution of your supply chain?

To fully understand how start-up companies have impacted the space industry supply chain, the study gathered survey responses from subject matter experts in the commercial sector and government. The questions reached experts in all five tiers of the supply chain and across the major industry segments building satellite and launch vehicle systems in a survey format. Data was collected using a mix of surveys sent to nearly 300 companies and nearly 50 interviews with industry experts covering supply chain trends, specific technologies within a tier, and emerging manufacturing capabilities.

Quality

Nearly half of respondents to the survey noted gradual improvements in quality throughout the supply chain. Respondents attributed this improvement to incremental gains in performance and tighter tolerances, better communication of requirements, encouraged standardization and use of general purpose systems, and the growing focus on reusability. On the other hand, a minority response indicated a decline in quality emphasized shrinking availability that results from vertical integration and low volume government demand. Far more respondents identified either an increase in quality or no change. See Figure 4.

Delivery Speed

Faster delivery time was another change observed, noted by over a third of respondents (Figure 5), most of which are start-up companies. This change was attributed to implementing new software tools and just-in-time strategies for managing inventory. Other respondents noted that lead times remain long for specialized components where reliability is paramount and where low volume results in minimal competition. One respondent noted that slower than expected delivery time was a real motivation for pursuing further vertical integration. As many respondents, a mix of start-up and long-established companies, found delivery time about the same as those who had found it faster. While centralized manufacturing can speed production by reducing the number of hands the technology passes through, other factors like the location of integration and unexpected subcontractor delays can offset these gains.

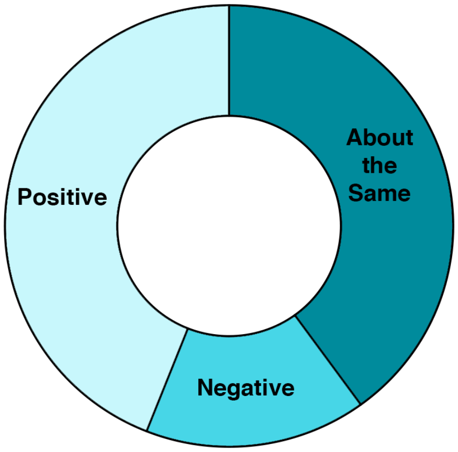


Figure 7. Is your impression that changes to the supply chain during the past 10 years have been positive or negative?

Geography

The majority of respondents have not yet observed significant changes in the geography of the space supply chain, despite the growth of start-up space companies in places such as Seattle and the San Francisco Bay Area (Figure 6). Respondents noted that the supply base remains located near the primary customers. One identified change was the use of U.S. based distributors for certain offshore vendors of critical space components.

Manufacturing

Government and industry respondents did identify several important changes in manufacturing technology. Improvements have been enabled through new semiconductor manufacturing technology, stereo lithography, and 3D printing. Respondents also noted process improvements that enable higher quality and the rapid incorporation of lessons learned. Examples mentioned by respondents included standards for the exchange of manufacturing information and improved software tools for managing design changes and the bill of materials.

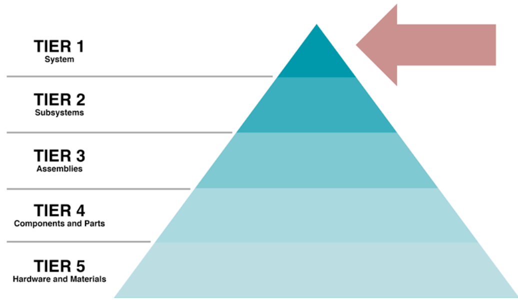
Many respondents concluded with an overall positive take on the changes in the space supply chain (Figure 7). Respondents noted there is willingness to test and space-qualify new materials and parts. For others, changes in supply chain driven by new space companies are not yet evident or are predicted to be less significant. While some respondents noted there are more suppliers addressing a wider range of needs, another respondent had the opposite take. This respondent highlighted vertical integration and a shrinking industrial base as a significant, negative change in the supply chain. To better understand these differing perspectives, the next section takes a focused, tier-by-tier look at the space industry supply chain.

Tier-by-Tier Highlights

With an overview of the start-up space industry supply chain provided in the previous paragraphs, the following section highlights interesting findings by tier. Unless otherwise cited, survey respondents and interviewees provided details described in this section.

Tier 1: System

Prime contractors are responsible for the manufacture of completed systems (that is, Tier 1 products) like satellites, spacecraft, and launch vehicles. These companies come



in many sizes. They can have the capability to develop very large and complex systems, such as those manufactured by The Boeing Company or SpaceX. Conversely, prime contractors can produce relatively small systems, such as very small satellites built by Planet and York Space Systems.

Prime Contractors Feel the Pressure to Keep System Cost Down

In most cases, prime contractors like Boeing, Lockheed Martin, Orbital ATK, and SpaceX have the capability to manufacture elements of a system down to the Tier 3 level, while still depending on Tier 4 and Tier 5 suppliers for components, parts, hardware, and materials. Some, like Rocket Lab, have the means to produce Tier 4 and Tier 5 elements using additive manufacturing. These are examples of vertical integration, an approach designed to enable the prime contractor to manage as much of the supply chain as possible in an effort to avoid disruptions and keep costs down.

Manufacturing costs remain a constant challenge for prime contractors given constant pressure by customers to keep the system delivery price down. Participating in a competitive marketplace also motivates prime contractors to implement cost saving measures. Factors that have a tendency to increase costs include inflation, rising prices of rare earth elements and other elemental materials used in space applications, rising transportation costs, and government regulations precluding foreign supplier participation.

In the space industry, non-recurring engineering (NRE) associated with research, development, test, and evaluation (RDT&E) happens as a matter of course at the system level. NRE can cost hundreds of millions of dollars for an aircraft or automobile, for example. However, an aircraft or automobile manufacturer knows that following the NRE phase, hundreds to millions of units will be sold, enabling the recouping of investment and contributing to profit. In the space industry, there is no follow-on production of this magnitude, and NRE cost takes many years to recover, if ever.

Prime Contractors are Maintaining a High Standard of Quality

Overall, the quality of products provided to prime contractors remains high. The high quality typical of the space industry results from several factors, some of which are changing due in part to the entry of start-up space companies. Since the dawn of the Space Age, strict quality control has been essential to the manufacturing of space hardware because the system cannot easily be repaired or maintained once delivered to orbit or a celestial body. Space qualification standards and requirements have been adopted from experience gained by NASA and the USAF, with refinement and deliberation by organizations like the American Institute of Aeronautics and Astronautics (AIAA), The Aerospace Corporation, and others. More effective software-supported supply chain management and engineering engagement to clarify requirements has further enhanced quality.

Rigorous quality control and less “touch labor” have meant that failures due to manufacturing are very rare, particularly in terms of satellites deployed to geosynchronous orbit (GEO). For commercial GEO communication satellites, service reliability is close to 100 percent.

Some prime contractors have gone to suppliers outside the space industry. In those cases, the prime contractors apply a layer of quality control to make sure a part is "space qualified." Though not the best model for high-volume production due to the potential for schedule delays, this approach has not been identified as a problem.

In recent years, both long-established and start-up space companies have introduced additive manufacturing, paperless media systems, and automation to support the building of systems. Some start-up satellite manufacturers have pursued a unique approach that effectively trades risk with volume. Large satellite constellations, like those being pursued by Planet, Spire Global, and Satellogic, feature very small satellites manufactured in an assembly line fashion. This mass production model means that the era of rapidly built, disposable satellites may be dawning. Disposable does not mean poorly built, however. These satellites have been designed to optimize small volumes in efficient ways, leveraging advanced electronics and materials. However, the large numbers produced mean that on-orbit failure of a few is likely. In these cases, the business plan and design of the constellation factor into this potential for failure, building redundancy into the architecture instead of an individual satellite. This approach means that the cost burden shifts from research and development to production, which is proportionally less expensive.[33]

The launch industry has also evolved in terms of quality control, especially in recent years. The introduction of computer-aided design and manufacturing, additive manufacturing, automation, and mass-minimizing manufacturing techniques have all improved quality. The minimization of factory overhead and idle capabilities and the use of advanced materials to improve rigidity and reduce launch vehicle mass have improved quality as well. These improvements have also led to greater launch vehicle capability, lower launch service prices, and better reliability.

There is concern that in some cases, prime contractors are seeking to commoditize non-commodity components, thereby removing engineers from this process. This effort to reduce costs has shown some negative impact on quality and delivery. While this may save money in the short run, there is high potential to increase cost in the long run because of schedule delays.

Signs of Faster Delivery of Parts to Prime Contractors

From the perspective of prime contractors, the delivery speed of parts has remained about the same.

A key factor in delivery speeds is the demand for non-space qualified parts by some start-up prime contractors. Typically, parts destined for use in satellites and launch vehicles must be space-qualified, a process that is time-intensive and expensive. For Tier 4 and Tier 5 suppliers, demand for space-qualified parts is relatively low compared to similar parts supplied to non-space customers. Space qualification of parts takes time to conduct and is delivered in small lots according to demand. These conditions translate into long lead times. In an effort to mitigate long lead times, satellite manufacturers seeking to produce large numbers of systems are acquiring parts certified under United States Military Standard (MIL-STD), which is considered adequate enough for space use.

Vertical integration is also employed by some prime contractors to mitigate delays in delivery of certain parts. Several manufacturers surveyed for this study indicated they developed certain components internally to help control the production schedule. For small start-up companies focusing on high performance, cost effective solutions that follow a tight schedule dictated by a business plan, technology demonstration also drives internal development of key components. For the long-term, however, having a robust supply chain reduces internal inventory, workforce costs, and end-item costs.

Prime Contractors Tend to Favor Nearby/Regional Suppliers Where Feasible

In general, prime contractors tend to rely on suppliers that are geographically close to reduce logistical burden, and thus delivery times and costs. One start-up prime contractor indicated that it relies heavily on suppliers in its local area, which it believed represented a modest expansion of the overall U.S. space industry supply chain. This practice is likely repeated elsewhere in the country by start-ups established in areas of the country not traditionally considered centers of space industrial activity. In addition, some prime contractors use COTS components—hardened for space applications—to expand the supplier base beyond the typical parts and component suppliers that have traditionally participated in this sector.

One large, long-established satellite manufacturer pointed out that there seems to be a greater number of lower tier suppliers to support the building of small satellites in particular. Long-established companies are interested in participating in this expanding part of the supply chain, but movement has been slow.

System Reusability and Maintenance will Increase Demand for Certain Parts and Consumables

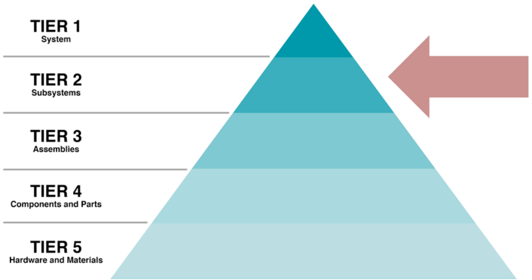
Launch vehicle reusability has been explored for decades, with the U.S. government's Space Shuttle coming closest to full realization by operating as a partially reusable, or refurbishable, system from 1981 to 2011. Start-up space companies like SpaceX, Blue Origin, and Virgin Galactic have been developing reusable launch vehicles since the dawn of the 21st century. During the past five years, these companies have demonstrated reusable launch vehicle systems with varying degrees of success. Since December 2015, SpaceX has successfully landed spent Falcon 9 first stages immediately following separation of the second stage and Blue Origin's New Shepard #2 has successfully flown five suborbital missions since November 2015. Virgin Galactic has been testing its SpaceShipTwo system since 2013, though a failure in October 2014 that resulted in loss of the vehicle has delayed rocket-powered flights of a second flight article until late 2017. Launch vehicle reusability means that systems designed to be one-use-only systems are now being replaced by systems designed to survive all environments of flight. From a supply chain perspective, this shift translates into new standardized quality control requirements for reusable components, post-flight inspection, and routine maintenance that will require consumables and replacement parts.

Reusability is also being introduced into satellite and spacecraft manufacturing, leveraging lessons learned from technology development missions aboard the International Space Station (ISS) and ISS cargo resupply since 2010. Satellite servicing, which has been successfully demonstrated aboard ISS via NASA's Robotic Refueling Mission (RRM) and is also being pursued by the Defense Advanced Research Projects Agency (DARPA) under its Robotic Servicing of Geosynchronous Satellites' (RSGS) program, means that satellites could have their lives extended through maintenance and refueling. While demonstrating technologies like proximity operations, capture, cutting, and grasping fittings is critical, standardizing satellite buses and procedures is also needed to maximize potential. On-orbit additive manufacturing has also been explored aboard ISS using printers provided by U.S.-based company Made In Space. The long-term objective is to provide crews in space with the ability to manufacture parts on-site, precluding the need to ship parts from Earth to the space-based destination.

Reusable cargo spacecraft have been launched to the ISS since 2010 by SpaceX using the company's Dragon vehicle. Dragon, which is capable of carrying cargo to and from the ISS, is designed to be recovered, refurbished, and reused following splashdown. The first ten SpaceX missions conducted under NASA's Cargo Resupply Services (CRS) contract used ten individual Dragon spacecraft. On the eleventh mission, conducted in June 2017, SpaceX launched the Dragon used for a CRS mission conducted in 2014. Recovery and refurbishment of Dragon, as well as the company's Falcon 9 first stages, introduces a new aspect to the supply chain, that of purchasing and stockpiling consumables and replacement parts. While NASA's Space Shuttle Program was supported by a similar supply chain for more than three decades, this program was entirely funded by the federal government. For the start-up companies pursuing this capability, the intention is to include reusability in revenue generating models.

Prime Contractors are Introducing New Manufacturing Technologies and Approaches to Remain Competitive

Long-established prime contractors have been implementing new technologies and approaches to system manufacturing, doing so in a manner designed to seamlessly evolve without significantly disrupting manufacturing activity. In contrast, start-up space companies were established using these new technologies and approaches from the beginning. Examples of new technologies include additive manufacturing, microelectronics, and the production of large-scale composite structures. In terms of new approaches, examples include the use of ISO 10303 (commonly called the Standard for the Exchange of Product, or STEP) for the management of product manufacturing information and the use of COTS parts.



Tier 2: Subsystems

Satellite subsystem builders are responsible for the manufacture of subsystems like attitude determination and control (ADC); command and data handling (CDH); power; propulsion; structures; thermal management; telemetry, tracking, and command (TT&C); guidance and navigation; and subsystems related to the satellite payload.[34] Launch vehicle Tier 2 subsystems include propulsion; structures; guidance, navigation, and control; power; payload adapters; and payload fairings. Though prime contractors can and do design and build subsystems, examples of companies that focus on providing subsystems are Aerojet Rocketdyne and Raytheon.

United Launch Alliance (ULA) Selects Start-ups Blue Origin and XCOR Aerospace for Propulsion Subsystems

Long-established companies like ULA, a joint venture between Boeing and Lockheed Martin) have shown a willingness to sign contracts with start-up space companies for subsystems. In this particular example, ULA contracted with Blue Origin in 2014 for the provision of BE-4 engines as part of the propulsion subsystem of ULA's Vulcan launch vehicle. ULA chose the BE-4 over the AR1 being developed by Aerojet Rocketdyne, a company with roots reaching back to the beginning of the Space Age. Though ULA has since entered into a public-private partnership with the USAF to continue producing the AR1, the BE-4 was selected as the baseline engine of Vulcan because Blue Origin was further along in the development of its engine.[35]

ULA also contracted with start-up XCOR Aerospace for the development of an upper stage engine for the Vulcan's Advanced Cryogenic Evolved Stage (ACES). XCOR, which has put development of its Lynx vehicle on hiatus to focus on development of rocket engines, is developing its 8H21 engine under this contract, leveraging a partnership with ULA that stretches back to 2008.[36]

Cost Pressures from Prime Contractors Trickle Down to Subsystem Manufacturers

The pressure on prime contractors to lower system costs has added pressure on subsystem builders to lower costs in turn. Manufacturing volume and rate are key drivers of cost for companies that provide subsystems. These drivers are most evident in the manufacture of small satellites where reliability and lifetime are not driving factors. The relatively inelastic demand and low volume for subsystems used in large space systems translates into high costs. In contrast, the demand generated by start-up companies for many small satellites to support large constellations and the small launch vehicles designed to carry them is more elastic. This increased elasticity will likely drive costs lower. Subsystems for these satellites and launch vehicles will feature highly reliable (but not necessarily space-qualified) COTS parts and parts produced using additive manufacturing. These characteristics reduce costs but also introduce the potential for lower reliability and lifetime. This potential is factored into business plans and accounts for the steady rate of satellite replenishment for companies like Planet and Spire Global, among others.

In terms of space-qualified parts, a mix of start-up and long-established satellite and launch vehicle subsystem manufacturers indicated that they have not seen evidence of a decrease in prices.

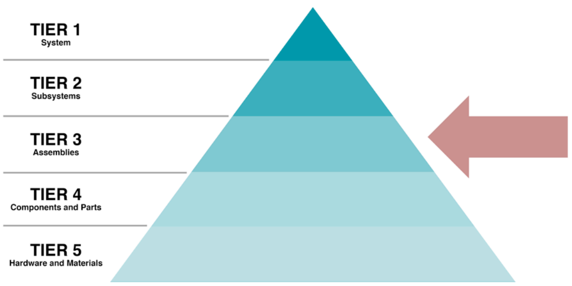
Subsystem Manufacturers Say Quality of Parts from Suppliers Has Improved Because of Other Industries

Tier 2 manufacturers consider the quality of parts being supplied by lower tiers as high, with indications that in some cases parts have improved in terms of higher performance and tighter tolerances. However, some subsystem manufacturers are concerned that space-qualified parts required by the government in particular have become more difficult to find. This is apparently due in part to low demand; the low volume and high cost to produce space-qualified parts is not attractive for small companies. In contrast, demand from start-up companies for parts that are not space-qualified has increased, as the focus is less on reliability and more on lowering system costs. Subsystem manufacturers supporting government programs have also indicated that their customers are reticent to change requirements.

Start-up Space Subsystem Manufacturers Employing Additive Manufacturing

According to many subsystem manufacturers surveyed for this report, additive manufacturing is the single largest change to the space industry supply chain. This approach is being used by both long-established and start-up companies. Long-established companies are integrating additive manufacturing into their existing production lines as an augmented capability, while some start-up companies have included additive manufacturing as the primary means of manufacturing subsystems. A good example is Rocket Lab, which builds its Rutherford engine using electron beam welding of metal powders, a form of additive manufacturing. Virtually the entire engine is built in this manner.[37] Blue Origin employs a similar type of additive manufacturing to produce pumps for its BE-4 engine.[38]

While start-up space companies are keen to use additive manufacturing as a major part of production, long-established companies have considerable resources that can be dedicated to improving the technology. Interestingly, one subsystem manufacturer indicated that long-established companies are leading the way on additive manufacturing, with engineers publishing more papers on the subject than those from start-up space companies. This is due to several factors, including start-ups safeguarding intellectual property and long-established companies having greater access to funding to support research.



Tier 3: Assemblies

Assemblies are typically manufactured by dedicated Tier 3 manufacturers, but are also built by prime contractors and subsystem suppliers. There are a large number of Tier 3 assemblies, from batteries and fuel cells to accelerometers and gyroscopes. Examples of Tier 3 suppliers are EnerSys, which supplies batteries for satellites, and Barber-Nichols, which manufactures liquid rocket engine turbopumps.

The Number of Tier 3 Suppliers has Increased Substantially, Particularly in Support of Small Satellite Manufacturing

Many new assembly manufacturers have emerged in recent years, most to serve the growing demand for CubeSats and other very small satellites (typically those at or below 600 kilograms in mass). In contrast, start-up launch vehicle manufacturers, particularly those developing very small launch vehicles (those with a capacity to low Earth orbit at or below 500 kilograms) tend to develop assemblies like propulsion, structures, and payload fairings internally, while relying on long-established Tier 3 suppliers for power, payload adapters, and GNC.

Companies like York Space Systems, Clyde Space (United Kingdom), Blue Canyon Technologies, and Innovative Solutions in Space (Netherlands) offer assemblies, subsystems, and complete satellite systems for customers using an online ordering process. Other companies, like Pumpkin, Inc. offer entire CubeSat kits that can then be integrated with payload packages developed separately. Most of these companies were established after 2003 to address the small but growing demand for CubeSats developed under university programs. With the advent of commercial applications for CubeSats, especially by companies pursuing large constellations, business increased substantially and inspired establishment of more competitors.

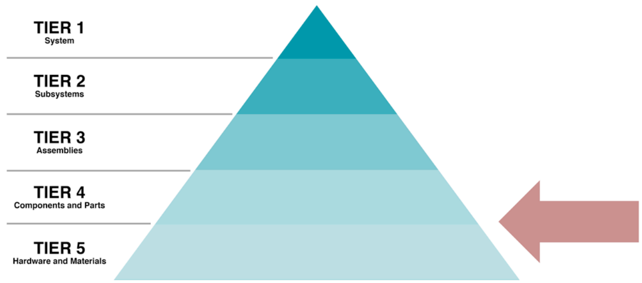
A potential benefit of this increase in demand for very small satellites by universities, governments, and commercial operators is greater innovation. Costs for assemblies, and indeed complete satellite systems, are low enough to attract more operators across all sectors, and this in turn increases the number of innovations for the satellite industry as a whole.

Start-up Prime Contractors Purchase License from Assembly Manufacturers in Vertical Integration Strategy

Like long-established prime contractors, start-up prime contractors have reached out to third-tier suppliers to design and build assemblies for subsystems. In some cases, a start-up company will purchase the license to manufacture assemblies as part of a strategy to add control to its supply chain.

Rapid Prototyping has Helped Reduce Design Costs

Rapid prototyping is a method of quickly producing hardware for evaluation and testing at the assembly level and below. Designs are drafted and improved upon using engineering software. The results are then fed to printers that produce working versions of prototype hardware. This approach is much faster and less expensive than delivering specifications and requirements to a machine shop, where prototypes would typically be made. Combined with software designed to manage product flow and rapidly integrate design changes, rapid prototyping saves time and money.



Tiers 4 and 5: Components, Parts, Hardware, and Materials

Components and parts are typically manufactured by a large number of dedicated Tier 4 suppliers. At this level in the supply chain, suppliers provide parts to a variety of industries and focus on providing high technology products. In most cases, the space industry represents one among many clients. There are a large number of Tier 4 components and parts used in the space industry, including complex propellant mixtures like ammonium perchlorate for solid motors, hydraulic components, optical encoders, and traveling wave tubes. An example of a Tier 4 supplier is Moog, which a large number of components and parts for propulsion and flight control assemblies.

Suppliers of hardware and materials represent the bedrock of the U.S. space industry supply chain. A huge selection of hardware, from screws and fastener to couplers and ball bearings, are provided by a wide variety of companies throughout the United States. In addition, raw materials like gases, liquids, metals, plastics, and resins are provided by an equally large number of companies. At this level in the supply chain, the space industry can represent a small part of the customer base of a particular company. The DoC "Deep Dive" survey revealed that 1,603 companies, or about 75 percent of those supplying parts to the space industry, have a relatively low exposure in terms of sales.[39] For example, The Timken Company is a major supplier of ball bearings for a large number of customers across many industries, with customers in the space industry representing a relatively small part.

Higher Quality Electronics from Other Industries Feeding Space Industry Supply Chain

During the past decade, the introduction of miniaturized high quality electronics used in consumer electronics and MEMS has meant that a new source of components and parts has become available to start-up space companies seeking low-cost options when building satellites and launch vehicles. This is especially true with companies manufacturing CubeSats or components for CubeSats. The increasing capability that microelectronics has contributed to CubeSat manufacturing has made the small satellite form factor a popular option for start-up companies seeking low-cost options for satellite technology demonstration missions. These technologies have also supported work being conducted for precision landing of reusable systems, such as those developed by start-ups SpaceX, Moon Express, Astrobotic Technologies, and Masten Space System, among others.

Higher Prices in Metals, Composites, and Resins

Increasing prices in certain elements, in particular beryllium and titanium, have been reported. Beryllium product sales in the aerospace, automotive electronics, ceramics, computers, and telecommunications markets have been growing steadily, and this increasing demand has led to increasing prices. Demand for titanium and composites have also been increasing substantially in recent years, a trend driven mostly by the airplane manufacturing sector.

Cost increases have also been reported for resins and plastics supporting uses in the aerospace and automotive industries, where growing demand continues.

Implications for NASA

During the past decade, NASA has increasingly sought to leverage and support the capabilities of a robust commercial space sector. NASA has adapted its acquisition mechanisms to engage more effectively with commercial firms, especially for the commercial crew and cargo systems being developed by Boeing, Orbital ATK, Sierra Nevada Corporation, and SpaceX. The agency has also encouraged development of CubeSat technologies and the development of low-cost, very small launch vehicles.[40]

Three key supply chain trends, advanced IT solutions, COTS products, and additive manufacturing, have the potential to reduce costs for NASA. Increasingly available COTS products enable NASA and its contractors to tap high-quality, high-volume parts developed for other industries (in particular, miniaturized electronics for mobile devices) requiring reliable, sophisticated components. NASA has also observed that additive manufacturing is likely to be a game changer. **The capability to produce parts and tools through rapid prototyping for evaluation and testing, followed by the production of operational hardware via additive manufacturing, all supported by easy to obtain and use IT solutions, means that virtually any organization or individual with the means can produce parts.** As additive manufacturing techniques improve and become less expensive, it is likely that the effect on lower tier suppliers will be significant in the coming decades. For NASA to achieve full benefit from both of these trends, it needs to ensure cost-effective mechanisms for meeting reliability and quality standards.

About Bryce Space and Technology

Bryce Space and Technology is an analytic consulting firm serving government and commercial clients. Bryce provides unique, integrated expertise on the space economy.

Bryce's expertise includes market analytics, technology readiness, cyber security, policy and economics, and strategy. Many authoritative data sets characterizing the space industry and sub-segments were originated by our analysts. We understand the interplay of national security, civil, and commercial space programs, capabilities, and markets.

Carissa Christensen, CEO

Carissa Bryce Christensen is the founder and CEO of Bryce Space and Technology. She previously co-founded The Tauri Group, LLC and was a minority partner in CenTauri Solutions, LLC (acquired by CSC in 2010).

Ms. Christensen is an internationally recognized expert in commercial space. For over two decades she has engaged the leading edge of the space industry with innovative analysis of space systems and advanced technology. She led the creation of widely used financial and economic indicators now considered global metrics for the commercial space and satellite sectors.

A frequent speaker and author on space and satellite trends, Carissa serves as a strategic advisor to government and commercial clients, and has been an expert witness and testified before Congress on market dynamics. She is also an active investor in technology-focused startups and advises several companies she has helped seed. She serves on the board of QxBranch, an early stage quantum computing software firm in which she is a partner.

Ms. Christensen holds a Master of Public Policy degree from Harvard University's Kennedy School of Government, where she specialized in science and technology policy. She also completed the General Course in Government at the London School of Economics and was a Douglass Scholar at Rutgers University.

Ms. Christensen is an Associate Fellow of the American Institute of Aeronautics and Astronautics.

Phil Smith, Program Manager

Mr. Smith has worked in the space industry for 18 years, building on a technical foundation of graduate-level education and military experience. His background includes space industry analysis, nuclear weapons technology, industrial hygiene, clinical laboratory studies, policy analysis, market forecasting, and aerospace history.

He is a program manager senior space industry analyst with Bryce Space and Technology, primarily supporting the Federal Aviation Administration's (FAA) Office of Commercial Space Transportation (AST), NASA's Office of the Chief Technologist and Space Technology Mission Directorate, the Satellite Industry Association (SIA), and various commercial clients.

Previously, worked with the Secure World Foundation (SWF), a non-profit organization dedicated to the peaceful uses of outer space through the rule of law, Futron Corporation, and SAIC. Mr. Smith also served in the U.S. Air Force as a nuclear missile maintenance specialist and in the U.S. Air Force Reserve as a bioenvironmental engineering technician.

In addition to conducting research, analyzing the results, drafting written materials, and presenting, Mr. Smith is an accomplished fine artist and illustrator and has volunteered as a tour guide at the Smithsonian National Air and Space Museum since 2003.

Anton Dolgopolov, Senior Analyst

Mr. Dolgopolov is a senior aerospace engineer and analyst with more than 20 years of leadership experience in the international space industry. Anton is the lead analyst characterizing international satellite data for the FAA AST, and he regularly consults with private satellite firms on market analysis and strategy. He is also a primary analyst for the annual State of the Satellite Industry report for SIA. Anton assisted with the development of a satellite and launch forecast model and analyzed satellite hardware trends. Anton holds a master's degree from the Johns Hopkins School of Advanced International Studies (SAIS).

Travis Doom, Technology Analyst

Mr. Doom is an experienced analyst and researcher for multiple government and commercial clients. He supports technology portfolio management for NASA and aerospace manufacturers. His work has been incorporated into NASA resources, such as NASA's TechPort database and the NASA Strategic Technology Investment Plan. His work also includes a project developing an interdisciplinary taxonomy for a large technology licensing database. He has in-depth knowledge of the history, theory, and practice of science and technology policy, and a sophisticated understanding of research and development. Mr. Doom has worked for a highly ranked science policy think-tank, where he conducted a long-term study of DoD's innovation system. Mr. Doom is an engineering graduate of Arizona State University in Tempe, Arizona.

Endnotes

[1] The following questions were provided in the survey: 1) Have you noticed a change in your supply chain during the past 10 years in terms of cost? 2) Have you noticed a change in your supply chain during the past 10 years in terms of quality? 3) Have you noticed a change in your supply chain during the past 10 years in terms of delivery speed? 4) Have you observed any shifts in the regional and/or national distribution of your supply chain during the past 10 years? 5) Assuming there have been changes in your supply chain during the past 10 years, do you generally assess the changes as positive or negative? Why? 6) What manufacturing technologies and approaches to product development have significantly altered your supply chain during the past 10 years, if at all? 7) Any additional remarks about the U.S. space industry supply chain and how it has changed or may change?

[2] Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration.

[3] See "Start-Up Space 2017: Update on Investment in Commercial Space Ventures," report by Bryce Space and Technology, 2017 (https://brycetech.com/downloads/Bryce_Start_Up_Space_2017.pdf).

[4] Ibid, page i.

[5] Ibid.

[6] Botwin, Brad and Christopher Nelson, "U.S. Space Industry 'Deep Dive,' A Collaboration Between the DoC and the USAF, NASA, and NRO, Final Dataset Findings," May 2013 (https://www.bis.doc.gov/index.php/forms-documents/technology-evaluation/769-final-dataset-overview/file).

[7] Specifically, "The Lower Tiers of the Space Transportation Industrial Base," OTA-BP-ISS-161 (August 1995).

[8] Bromberg, Joan Lisa (1999). *NASA and the Space Industry*. The Johns Hopkins University Press. See also J.D. Hunley's *Preludes to U.S. Space-Launch Vehicle Technology: Goddard Rockets to Minuteman III* (2008) and *U.S. Space Launch-Vehicle Technology: Viking to Space Shuttle* (2008).

[9] Stanzione, Kaydon Al (1989). "Engineering". *Encyclopædia Britannica*. 18 (15 ed.). Chicago. pp. 563–563.

[10] Boshuizen, Christopher, J. Mason, P. Klupar, and S. Spanhake (2014). "Results from the Planet Labs Flock Constellation," 28th Annual AIAA/USU Conference on Small Satellites. pp. 2. CubeSats also feature microelectromechnical systems (MEMS) because of their high reliability and low power consumption.

[11] Susan Helper et al (2009). *The US Auto Supply Chain at a Crossroads: Implications of an Industry in Transformation*. Study performed by Case Western Reserve University under a grant awarded by the U.S. Department of Labor's Employment and Training Administration.

[12] Orbital ATK's Combined Heritage: Pioneering New Spacecraft Technologies (https://www.orbitalatk.com/news-room/insideOA/Ultraflex/default.aspx).

[13] Based on interviews conducted with CubeSat manufacturers in 2014, a 1U CubeSat costs about $100,000 to build. The bulk of the cost is related to payload design and manufacture, but may also include customized buses.

[14] Bryce Space and Technology proprietary Spaceflight Database.

[15] Helvajian, Henry and Janson, Siegfried W. eds. (2008). *Small Satellites: Past, Present, and Future*.

Aerospace Press.

[16] Cole, Sally. "Small satellites increasingly tapping COTS components." *Military Embedded Systems*. June 8, 2015. 600 kilograms is based on payload mass class categorization provided by the Federal Aviation Administration's (FAA) Office of Commercial Space Transportation: Femto 0.01 – 0.1 kg (0.02 – 0.2 lb), Pico 0.09 – 1 kg (0.19 – 2 lb), Nano 1.1 – 10 kg (3 – 22 lb), Micro 11 – 200 kg (23 – 441 lb), and Mini 201 – 600 kg (442 – 1,323 lb).

[17] Boshuizen, C. et al (2014). "Results from the Planet Labs Flock Constellation." pp. 4.

[18] Plait, Phil. "Kickstart your way to an experiment on a satellite!" *Discover*. June 15, 2012.

[19] https://www.raspberrypi.org/blog/compute-module-cubesats/ (accessed June 25, 2017).

[20] Debes, Joshua, R. Harrington, R. Cobb, and J. Black. "Small satellites increasingly tapping COTS components." 25th Annual AIAA/USU Conference on Small Satellites.

[21] LaBel, Kenneth and Michael Sampson. "The NASA Electronic Parts and Packaging (NEPP) Program: Overview and Update FY15 and Beyond." Presentation to Space Parts Working Group (SPWG), April 28-29, 2015.

[22] Christopher R. Boshuizen et al (2014). "Results from the Planet Labs Flock Constellation." 28th Annual AIAA/USU Conference on Small Satellites.

[23] History of the ORS Office (http://www.kirtland.af.mil/Portals/52/documents/AFD-150701-026.pdf?ver=2016-06-28-112742-690).

[24] Seedhouse, Erik (2014). *Suborbital: Industry at the Edge of Space*. Springer. pp. 59.

[25] As of October 31, 2017.

[26] Winick, Erin. "Additive Manufacturing in the Aerospace Industry." *Engineering.com*. January 31, 2017. (http://www.engineering.com/AdvancedManufacturing/ArticleID/14218/Additive-Manufacturing-in-the-Aerospace-Industry.aspx).

[27] "Rocket Lab Reveals First Battery-Powered Rocket for Commercial Launches to Space." Rocket Lab News. May 31, 2015. (https://www.rocketlabusa.com/latest/rocket-lab-reveals-first-battery-powered-rocket-for-commercial-launches-to-space/).

[28] "The Future of Exploration Starts With 3-D Printing." NASA Press Release. March 19, 2013. (https://www.nasa.gov/exploration/systems/sls/j2x/3d_print.html).

[29] "A 50 percent reduction in mass and schedule accomplished by SSL's additive manufacturing." *Satnews Daily*. March 9, 2017. (http://www.satnews.com/story.php?number=152398837).

[30] Werner, Debra. "3D printing saving satellite builders time and money." *Space News*. March 8, 2017.

[31] "Additive Manufacturing and a New Revolution in Design Engineering." Lockheed Martin Feature Article. May 27, 2014. (http://www.lockheedmartin.com/us/news/features/2014/additive-manufacturing.html).

[32] "Closing Tech Gaps Can Fortify Advanced Manufacturing and Save $100 Billion Annually, NIST Studies Say." NIST News. November 17, 2016.

[33] Boshuizen, C. et al (2014). "Results from the Planet Labs Flock Constellation." pp. 6.

[34] Larsen, Wiley and James Wertz eds. (1999). *Space Mission Analysis and Design (3 ed.)*. Microcosm Press. pp. 353-518.

[35] Swarts, Phillip. "Loser of ULA's Vulcan engine downselect will likely lose Air Force funding." *Space News*. May 25, 2017.

[36] Foust, Jeff. "XCOR lays off employees to focus on engine development." *Space News*. May 31, 2016.

[37] Gebhardt, Chris. "Rocket Lab's Electron conducts inaugural flight from New Zealand." *NASASpaceflight.com*. May 24, 2017.

[38] Saunders, Sarah. "Blue Origin's Liquid-Fueled BE-4 Rocket Engine Utilizes Additive Manufacturing to Make Boost Pump Components." *3DPrint.com*. February 2, 2017.

[39] Botwin, B. et al, "U.S. Space Industry 'Deep Dive,' A Collaboration Between the DoC and the USAF, NASA, and NRO, Final Dataset Findings," May 2013. pp. 26. (https://www.bis.doc.gov/index.php/forms-documents/technology-evaluation/769-final-dataset-overview/file)

[40] CubeSat Launch Initiative (https://www.nasa.gov/directorates/heo/home/CubeSats_initiative).

THE SOLAR SYSTEM.
Liquid hydrogen
Liquid oxygen
Crew
Carbon dioxide and miasma absorbers
1903
The 1914 rocket
The 1915 rocket
Oct
Nov
Dec
2007
Feb
Mar
Apr
May
Jun
Jul
Aug
Volume 1,214,700
Splits
Dividends
1D
5D
1M