Evolving On-orbit Smallsat Ecosystem

(Ronald H. Freeman, PhD, Editor-in-Chief, July 2020)

MARKET SHARE TO SUPPLY ON-ORBIT SATELLITE MARKET GROWTH

The size of the global space economy, which combines satellite services and ground equipment, government space budgets, and global navigation satellite services (GNSS) equipment, is estimated to be about $345B. There is continued, strong investment in start-up space ventures. 2016 was the highest investment year for start-up space. Average deal size increased by about 50 percent, while the number of deals, investors, and firms reporting new funding all decreased by about 30 percent. Well over 100 investors put $2.8B into 43 start-up space ventures across 49 deals. In 2017, service providers conducted a total of 90 orbital launches from sites in seven countries. Overall, the commercial launch market has not grown significantly during the past decade; instead, the market shares have changed size, with U.S. providers expanding their cut from zero percent in 2011 to 54 percent in 2017. The number of FAA AST-licensed launches, which went from a low of one in 2011 to a high of 23 in 2017, also indicates strong commercial launch service growth in the U.S.

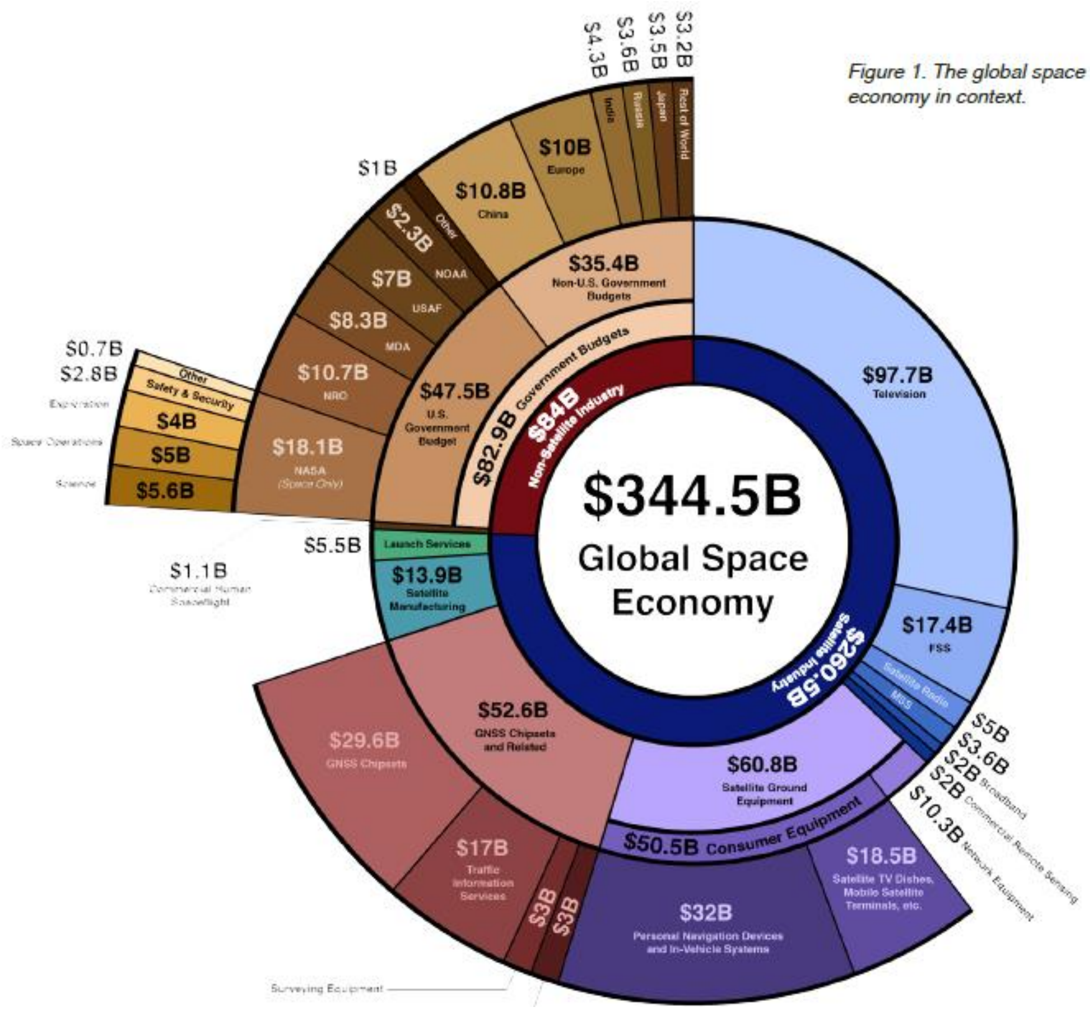
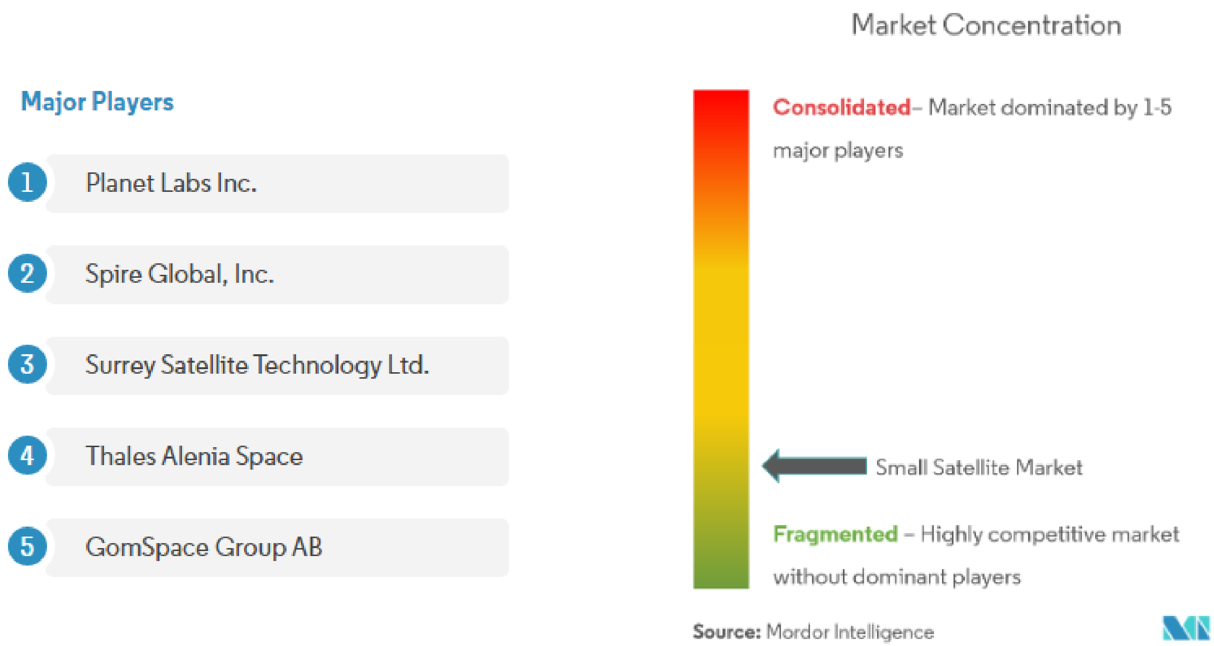


Figure 1. The global space economy in context.

About $261B (76%) was revenue generated by companies providing services like television; mobile, fixed, and broadband communications; remote sensing; satellite systems and ground equipment manufacturing and sales; and, of course, launch services. The remaining $84B (24%) constituted government space budgets ($83B) and commercial human spaceflight (almost $2B). Globally, the growth of space-related industry has outpaced world economies reaching 208 billion dollars, more than twice what it was in 2006. Failure to recognize critical space infrastructure can only delay the needed research along emerging risks and vulnerabilities along with approaches for analysis and assessment, remediation, indicators and warning systems, mitigation, and incident response, and reconstruction [1].



Source: www.mordorintelligence.com/industry-reports/small-satellite-market

Commercially launched spacecraft are typically used for the following mission types:

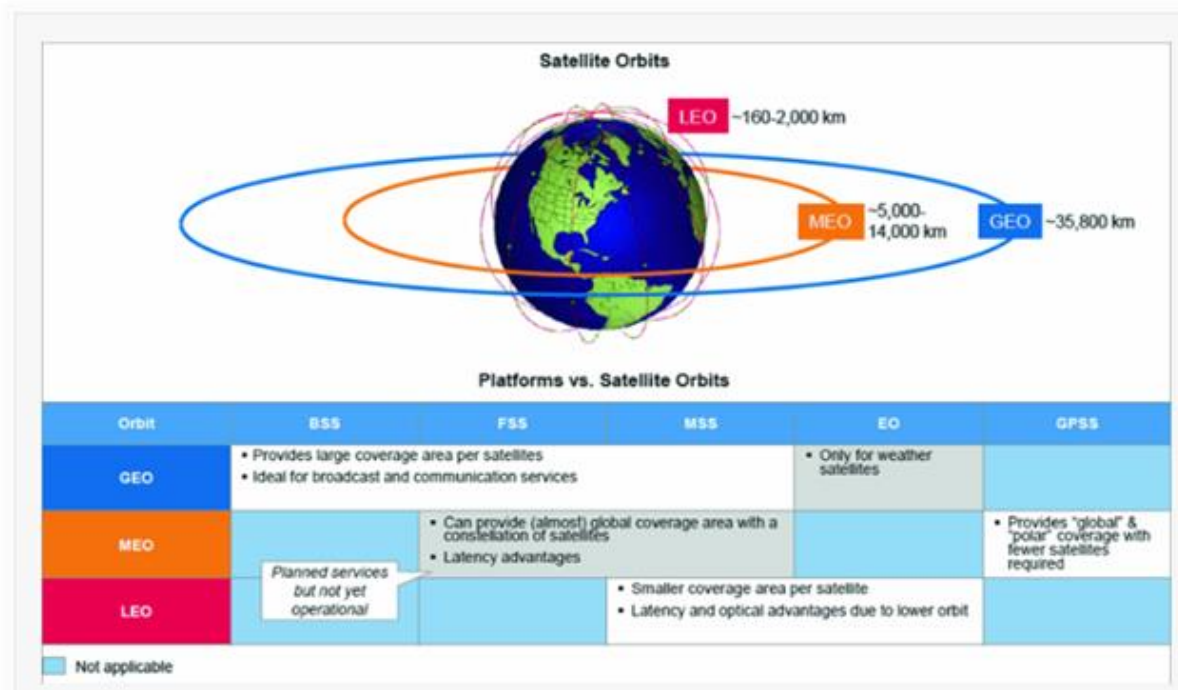
Commercial communications satellites;
Commercial remote sensing or Earth observation satellites;
Commercial crew and cargo missions, including on-orbit vehicles and platforms;

LAUNCH VEHICLE TEST AND DEMONSTRATION MISSIONS

Typically such missions involve telemetry packages or dummy payloads. In 2017, launch service providers worldwide sent 466 spacecraft on their way to orbit, though 23 failed to reach their destinations due to a launch failure. Ninety-seven percent of these spacecraft were satellites (450). Of the 450 satellites launched, 403 were launched to LEO (including SSO), 40 were launched to GEO, and 7 to medium Earth orbits (MEO). This was also a record year for CubeSats, with 290 launched (67 destined for deployment from ISS), more than any previous year since CubeSats were introduced in 2003 [2]. The commercial telecommunications segment included payloads launched to geosynchronous orbit (GSO) and non-geosynchronous orbits (NGSO). All other segments included payloads launched to NGSO, such as low Earth orbit (LEO), medium Earth orbit (MEO), elliptical (ELI) orbits, and external (EXT) trajectories beyond orbits around the Earth. The market demand for launches to GSO is projected at an average of 21.5 satellites per year.

By leveraging space infrastructure in new ways and embracing new technologies, innovative telecom solutions open up new operations strategies for spacecraft and payloads. Like terrestrial infrastructure, space infrastructure is increasingly relied upon for convenience, services, and national security/defense. As orbiting debris increases, new technologies emerge for tracking and capturing. With the sharp increase in spacecraft on the horizon, now more than ever, the shift towards an always-connected, internet-of-things mindset in space is paramount. For example, Solstar Space, a New Mexico startup, created a “Space Wide Web” whereby Solstar’s Schmitt Space Communicator, a transceiver, relayed messages in GEO orbit between spacecraft and the ground through commercial communications satellites in April and July 2018 on board Blue Origin’s New Shepard, sending the first tweets from space. Startups are beginning to leverage space infrastructure in new ways and to embrace new technologies crafting innovative telecom solutions that open up new operations strategies for spacecraft and payload [3].

As a new constellation for global satellite communication networks applying optical inter- satellite links, a double-layered low earth orbit satellite constellation with two different altitudes is proposed. In the lower layer, several hundred satellites operating as links for user terminals are arranged. The upper layer contains several tens of satellites that relay data from the lower layer satellites to other satellites or earth-based gateway stations. The satellites deployed in the lower layer can be simplified and miniaturized, because their only function is to link small earth-based terminals and they have only three inter-satellite link terminals. The satellites in the upper layer are complex and heavy, but only a small number of them are required. Orbital parameters and inter-satellite link parameters are evaluated in the constellation.



Main applications for satellite capabilities, depending on orbit

ON DEFINING CRITICAL SPACE INFRASTRUCTURE

Failure to recognize critical space infrastructure can only delay the needed research along emerging risks and vulnerabilities along with approaches for analysis and assessment, remediation, indicators and warning systems, mitigation and incident response, and reconstruction. These issues along with the interdependent nature key resources and asserts, present a fatal ground for space as a critical infrastructure. This vast space features a host of threat. Two unique threats, space debris and space weather are known to have a direct impact on terrestrial systems—some of with are critical. However, there remain unknown threats due to lack of research. The growths of satellite constellations and of start-ups developing simpler, smaller (less costly) satellites indicate defining functionalities that abound in LEO, MEO, and GEO orbits.

1. ON-ORBIT SATELLITES:

The only complex engineering system without routine maintenance, repair, and upgrade infrastructure is spacecraft. However, the emerging technologies for autonomous on-orbit servicing of satellites portend a contrasting scenario if cost-effectiveness compares favorably to the traditional lack of spacecraft re-usability. The growth of large on-orbit satellite constellations signify large trade space missions and servicing infrastructures, and conventional approaches prove limiting. First, servicing cost uncertainty is too high. Second the flexibility provided by on-orbit servicing to spacecraft has not been accounted for [4]. Like terrestrial infrastructure, space infrastructure is increasingly relied upon for convenience, services, and national security/defense. On-orbit activities conducted by a space vehicle perform up-close inspection of or result in beneficial changes to another resident space object. These activities include non-contact support, orbit modification (relocation) and maintenance, refueling and commodities replenishment, upgrade, repair, assembly, and debris mitigation. If there were an emerging trend, it is that space infrastructure is increasingly stressed while benefiting from the sources of that stress: commercially-driven services and technologies.

With on-orbit satellites, orbiting debris increases requiring new technologies for tracking and capturing. And of course, technologies for further development would be required for positioning, navigation, and timing (PNT) satellites, and missile detection satellites. This vast space features a host of threat. Two unique threats, space debris and space weather are known to have a direct impact on terrestrial systems—some of which are critical. However, there remain unknown threats due to lack of research. With the rapidly growing number of small satellites in orbit, the space industry's concern about orbital debris and interference grows. This heightens the need for comprehensive space traffic management capabilities. Commercial efforts remain key to engage diverse stakeholder groups to integrate available data that will provide a reliable space traffic management service for assessing risks with respect to orbital debris and interference. The rising number of LEO satellites is also indicative of the rising need for de-orbiting services, as sustainable space operations prioritize sharing efforts by government and commercial space players.

Additionally, smaller satellites take longer to pull down due to the drag of Earth's atmosphere. SHERPA, a ring-shaped spacecraft, has thrusters that can potentially carry smaller satellites down to a lower orbit, where the atmosphere is thicker. So, they burn faster at the end of their mission and contribute less to the problem of orbital debris. RemoveDEBRIS mission employs key Active Debris Removal (ADR) technology demonstrations to find the best way to capture the estimated 40,000 pieces of space debris that is orbiting Earth. The mission will comprise of a main satellite platform (100kg) propelled to the International Space Station by a SpaceX Falcon 9 rocket, and then deployed by NanoRacks Kaber systems into orbit. Once in orbit, a series of experiments will take place on how to capture space debris.

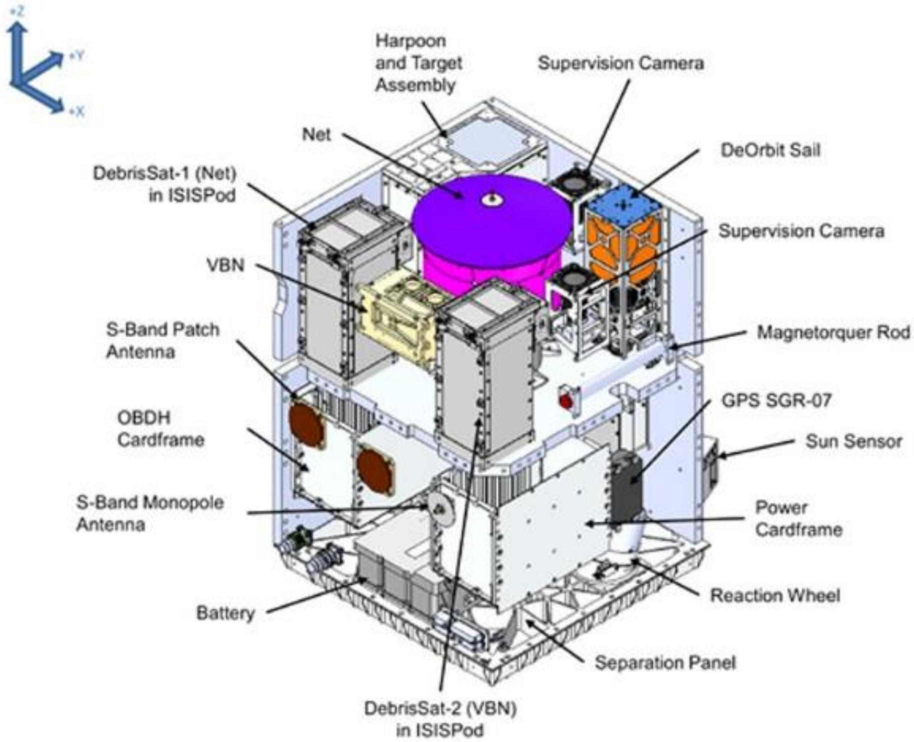


Figure. RemoveDEBRIS Platform: Side view.

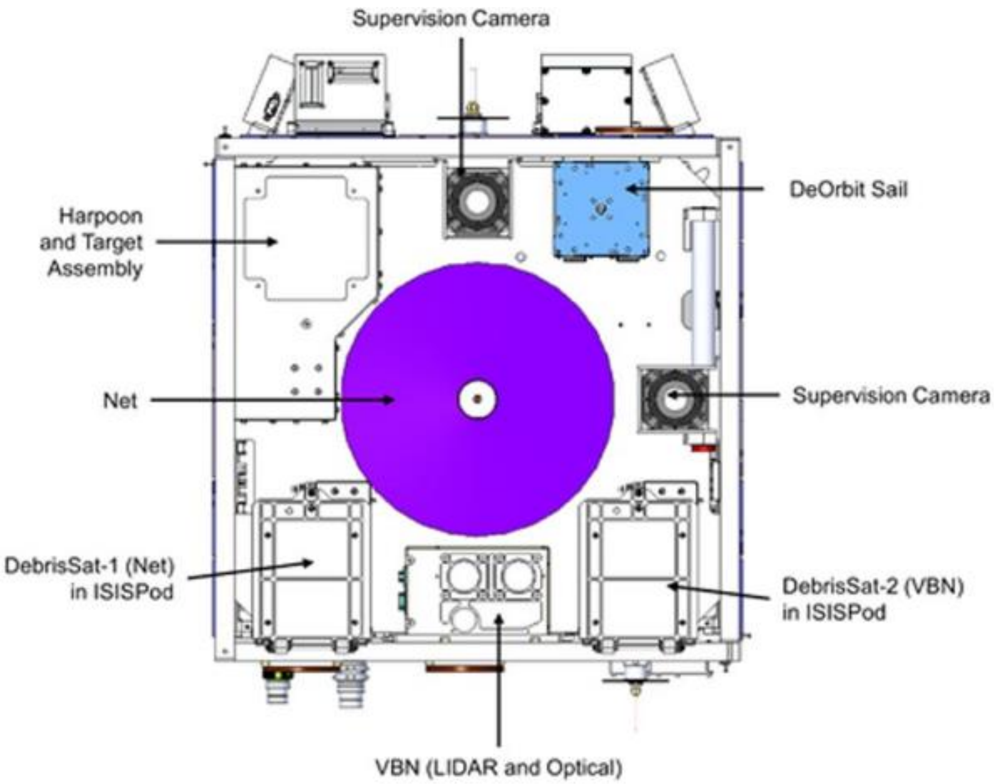


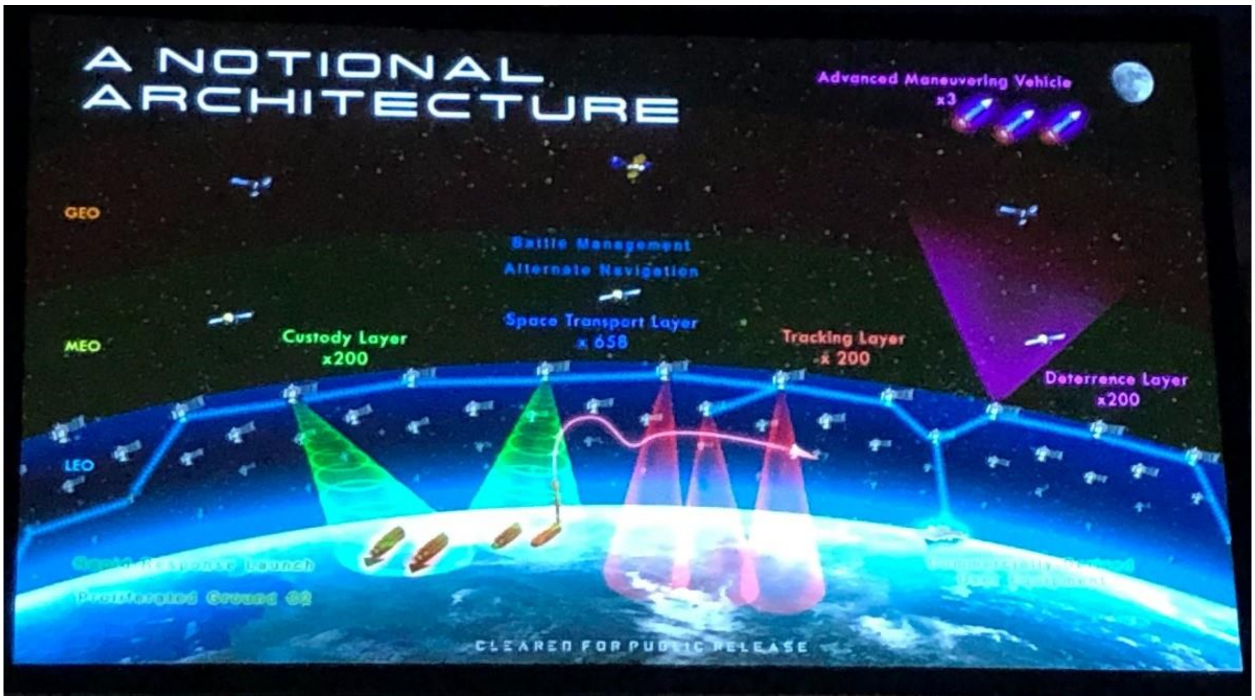
Figure. RemoveDEBRIS Platform: 3D view

The RemoveDEBRIS mission will perform four experiments, including the first harpoon capture in orbit and a net that will be used on a deployed target. Also, a vision-based navigation system that uses cameras and LiDaR technology will be tested to observe the release of CubeSats from the main spacecraft. Finally, RemoveDEBRIS craft will deploy a large sail that will drag it into the Earth's atmosphere, where it will be destroyed. The project is co-funded by the European Commission. The RemoveDEBRIS platform is provided by SSTL (Surrey Satellite Technology Ltd) and utilizes the next generation of low earth orbit spacecraft avionics systems and structural design being developed at SSTL called the X50 series. X50 architecture is based on a modular and expandable philosophy that utilizes common modules. This allows the system to be adaptable to varying mission applications and requirements. The platform is based on four side panels, a payload panel, and a separation panel. Payloads are mounted either on the payload panel within the payload volume atop the avionics bay or along the side panels as required.

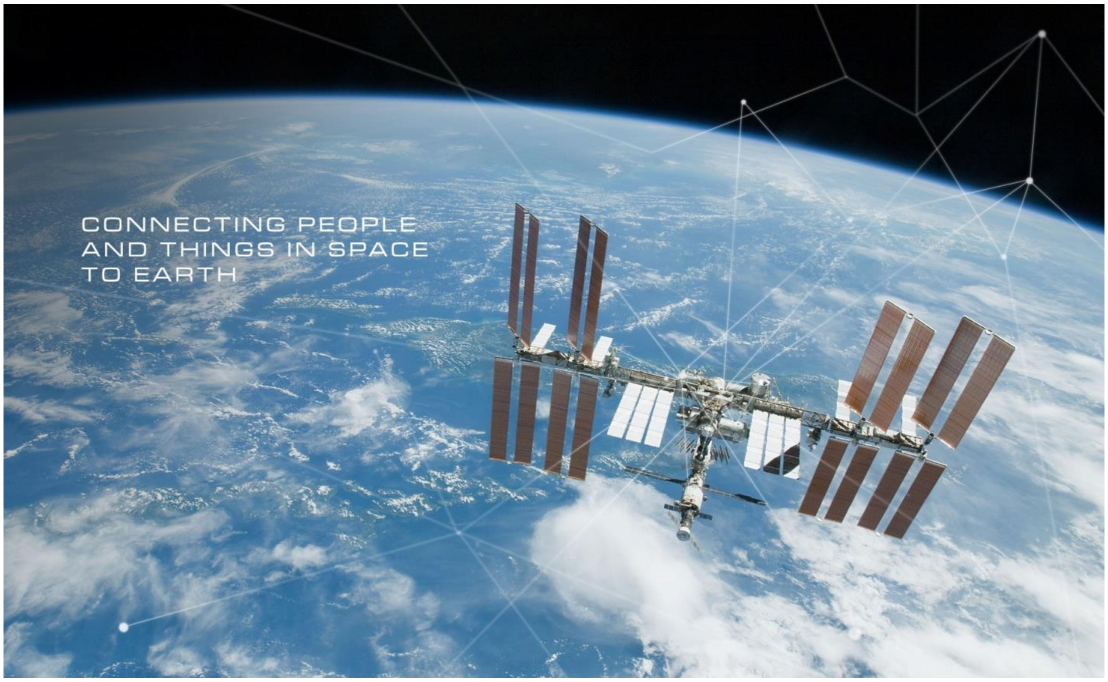
New space supply chain

"New space" supply chain is being challenged to produce component designs that can deliver unprecedented performance to vanishingly small satellite platforms — because satellite size is really the key driver of constellation cost. In fact, SpaceX initially staffed their satellite division with several dozen ex-software engineers and program managers for whom the build-test-learn-revise methods are the only way to design a system. Unlike DigitalGlobe's corporate roots in the DoD's Strategic Defense Initiative of the 1990's, the recent start-ups are rooted in Silicon Valley business tactics and have launched dramatically smaller and more affordable satellites for their constellations — deciding to sacrifice modestly on spatial resolution in order to deliver a more sustainable data product at a more affordable price point." Communications satellite constellations such as those being launched by SpaceX, OneWeb, Telesat and Amazon, haven't proven they can make money, so the Pentagon needs to build its own Low Earth Orbit (LEO) network," says DoD Research & Engineering czar Mike Griffin.

There is a need for a national security communications substructure to any future architecture. This is why the Space Development Agency (SDA)'s second priority — after building a LEO-based missile tracking constellation aimed at low-flying hypersonic cruise missiles — is to build a data communications 'transport layer' to link satellites to shooters on the ground. SDA will orchestrate the development and fielding of the next-generation national defense space architecture. SDA's main priority is to build a proliferated communications and transport layer enmeshed network in low Earth orbit that is resilient and ungradeable. This Notional Space Architecture will have a "deterrence layer" of 200 satellites based in high LEO or low MEO equipped with optical sensors "looking out" toward the Moon to "provide real-time custody of objects" in cislunar space. They will essentially serve a space situational awareness (SSA) function for the U.S. military. Eventually, such sensor layer will provide space traffic management (STM) functions for operators in the region. It could also relay data to a minimum of three so-called "Advanced Maneuvering Vehicles (AMVs)".



Technology has been developed to "approach, grasp, manipulate, modify, repair, refuel, integrate, and build completely new platforms and spacecraft on orbit. Space activities known as "on-orbit rendezvous and proximity operations" are being explored although the lack of clear, widely accepted technical and safety standards for on-orbit activities involving commercial satellites remains an obstacle to the expansion by commercial firms, civilian governments and their military [5]. DARPA's support for on-orbit satellite services began years ago. The agency pioneered the concept of using robots in space and more recently invested hundreds of millions of dollars in a public-private partnership with Maxar Technologies' Space Systems Loral to build an autonomous vehicle for servicing satellites 22,000 miles above Earth. Maxar in June announced that Space Infrastructure Services (SIS), a new U.S. company, will commercialize sophisticated satellite servicing, including refueling. SIS awarded SSL a $228 million contract to design and build a satellite servicing spacecraft that meets DARPA's specifications. SES Networks, operating more than 50 geosynchronous satellites and 12 mid-Earth orbit satellites, will be the first commercial customer to use the SIS satellite refueling services. SES Networks provides managed connectivity services in telecommunications and Cloud computing with internet users in remote regions, air- / at sea- travelers, wind farms, mines, and for defense missions.



The sequence in which the experiments are undertaken is shown below. After launch, and deployment from the International Space Station, ISS (see the launch page), the 4 experiments are undertaken.

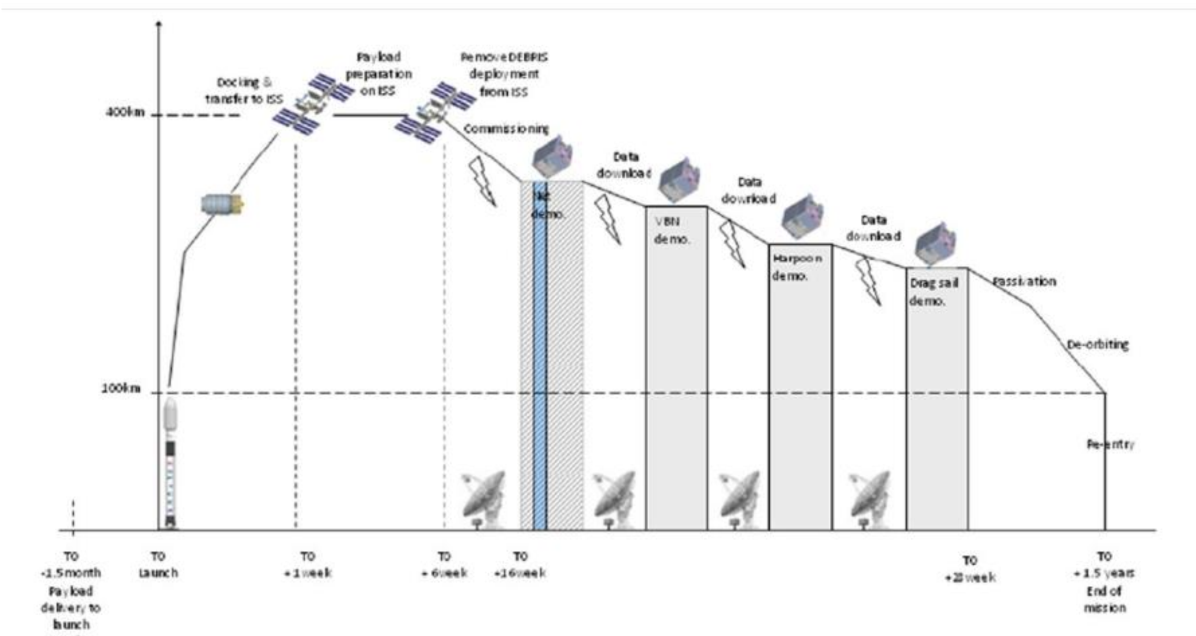


Figure. Experimental Timeline for the Mission

Technological advancements, in terms of miniaturization of electronic components, space 3D printing, advanced material technology, artificial intelligence (AI), and machine learning are likely to assist the manufacturers to overcome some of the existing growth restraints and develop advanced small satellites with multi-mission capabilities in the future [6].

Satellite refueling mission (Credit: MDA)

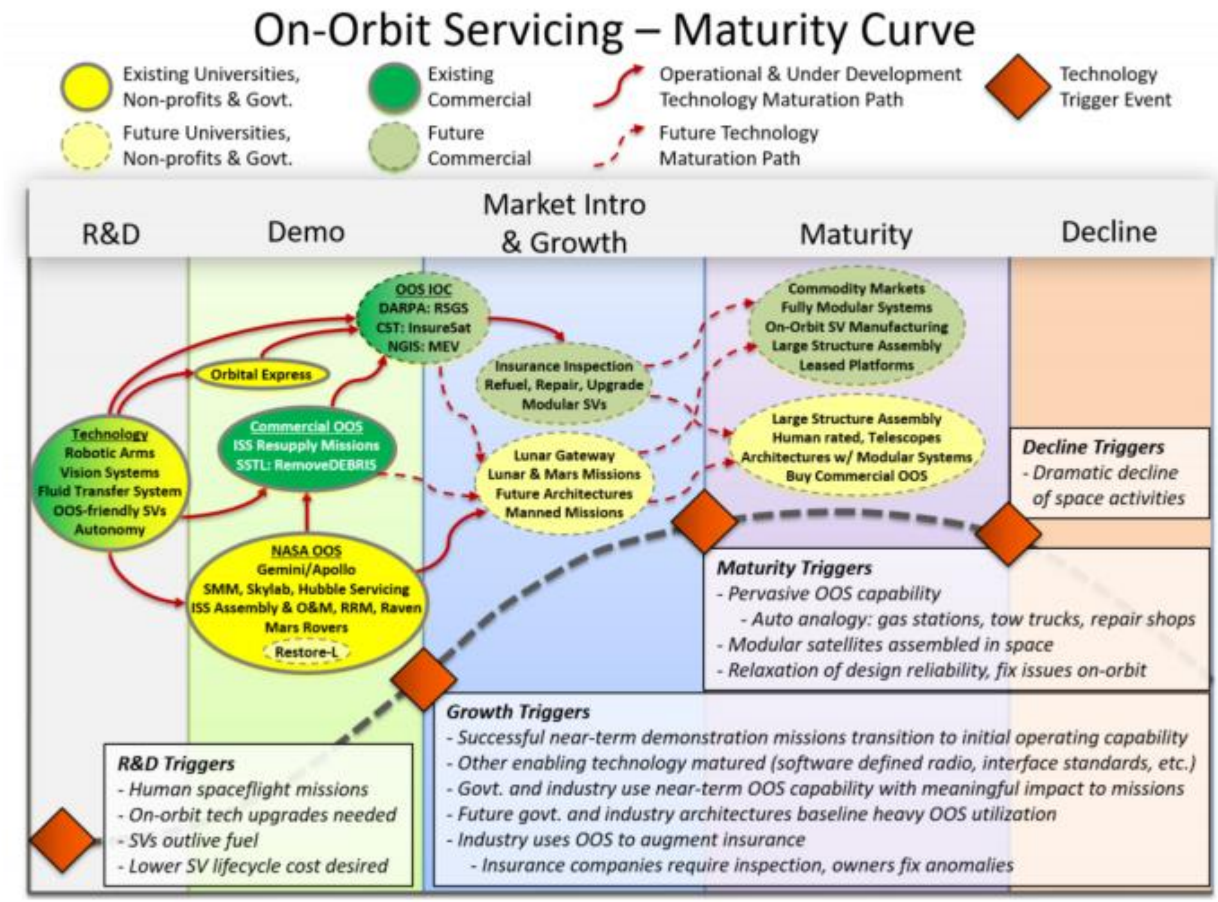
SAN FRANCISCO, June 28, 2017 (SSL MDA PR) — SSL MDA Holdings Inc., a global communications and information company, today announced important milestones in its progress to bring transformational on-orbit satellite servicing to market.

2. ON-ORBIT SERVICING:

Globally, the growth of space-related industry has outpaced world economies reaching 208 billion dollars, almost twice what it was in 2006. Failure to recognize critical space infrastructure can only delay the needed research along emerging risks and vulnerabilities along with approaches for analysis and assessment, remediation, indicators and warning systems, mitigation, and incident response, and reconstruction [7]. A new generation of cooperative spacecraft designed specifically for on-orbit servicing (OOS) could upgrade their own hardware every few years—a need that has been identified by the commercial, civil, and military satellite sectors. This would end the current paradigm of relying on satellites with decades-old hardware and technology, then having to launch replacements to modernize them. OOS refers to on-orbit activities conducted by a space vehicle that performs up-close inspection of, or results in intentional and beneficial changes to, another resident space object (RSO). These activities include non-contact support, orbit modification (relocation) and maintenance, refueling and commodities replenishment, upgrade, repair, assembly, and debris mitigation [8].

MARKET DRIVERS: ON-ORBIT SERVICING IMPACTS ON THE COST OF SPACE ACTIVITIES, SPACECRAFT DESIGN, AND SPACE ARCHITECTURE

While OOS is still in its infancy, the potential market implications, even in the near term, are enormous.



The anticipated maturity curve and technology maturation path of OOS.

A. NASA's efforts to explore space have been the driving factor for OOS development to date. Their human spaceflight lunar missions and space stations have required significant amounts of RPO and servicing activities on a consistent basis to be successful. Recent interest by commercial companies has resulted in additional development efforts to extend existing satellite lifetimes and provide more flexibility to satellite owners and operators in designing their satellite architectures and developing their business plans.

B. Commercial resupply missions to the ISS are also included in this category due to the consistent need to perform RPO. In the next few years, many civil and commercial missions will demonstrate robotic OOS and begin to offer commercial services to enhance existing satellites. If these missions are successful, the space industry will likely see a rapid growth of OOS capabilities resulting in reduced operating cost—which includes servicer use in satellite insurance contracts to mitigate or repair failures in lieu of replacing spacecraft.

C. Maturity triggers will signal when the OOS technology has moved into a mature phase within the space market. Satellites will no longer be launched with a lifetime of fuel; they will be refueled throughout their lifetimes. Satellites will be designed modularly so that components or even payloads may be added post-launch. Reliability requirements may be relaxed, resulting in a lower development and assembly, integration, and test cost due to the reliance of on-orbit repairability.

D. OOS capabilities may start becoming obsolete. Even small, cheap satellites can benefit from some degree of OOS. So, it is unlikely that new technologies or architectures will result in a greatly decreased use of OOS, though the types of servicing being performed will likely evolve over time. Only a dramatic decline of space activities would negate the need for OOS.

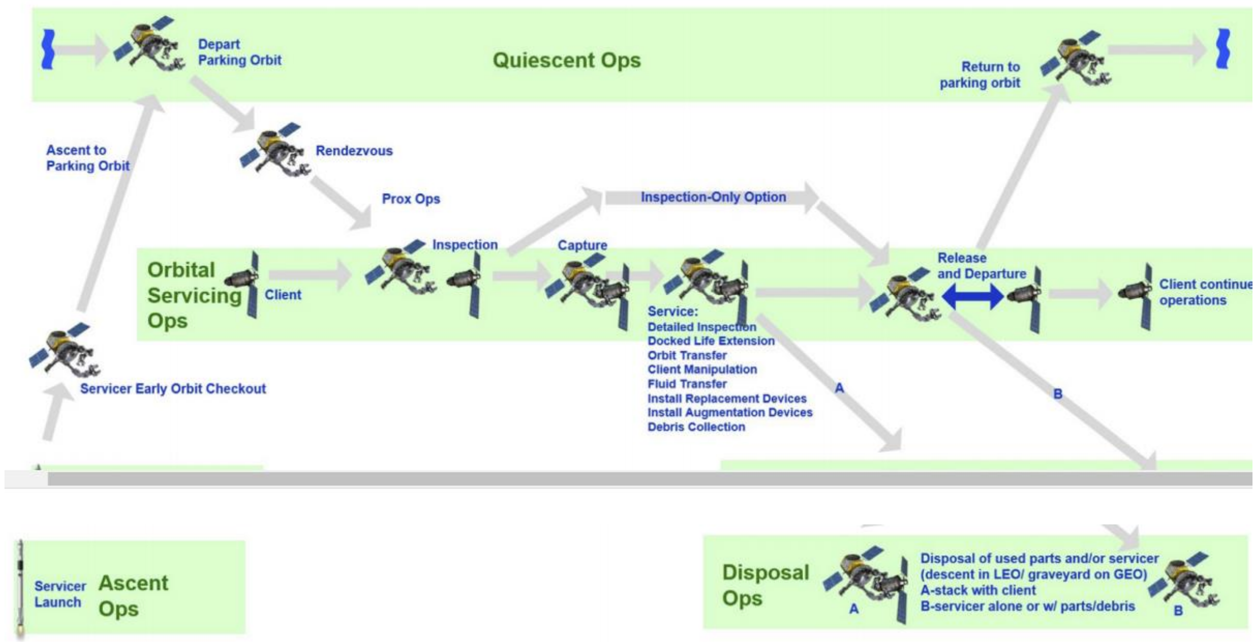


Figure. CONFERS OOS OV-1

Figure CONFERS OOS OV-1 describes a top level set of elements where each executes a specific orbital-related action, along the way to a servicing event. Starting with this OV-1 (operational view-1), the next step de-constructs each element into finer functions and attributes, suitable for quantitative metrics. One attribute of Pre-Service Preparations can be identified as Minimum Fuel Remaining at Client Orbit. This translates to the following: In order to depart the parking orbit, the Servicer must perform pre-service preparations, which in quantitative terms means it must evaluate the amount of propellant the maneuver will take to ensure sufficient propellant will remain at the end of the maneuver to perform the desired servicing operations.

If near-term OOS demonstrators suffer failures, either technical or programmatic, the market may shy away from OOS, at least until more successful demonstrations occur. A delay in the adoption of OOS will require greater investments. However, OOS is widely viewed as the most viable path forward for expanding space activities beyond their present limitations. Near-term failures will only be a temporary setback for progressing toward a mature OOS market. It is also possible that future space architectures may heavily emphasize small, cheap, “disposable” spacecraft, such as those currently being explored by the large LEO constellations proposed by OneWeb, SpaceX, and many others [9]. Even DARPA is weighing whether a large LEO constellation may make sense for DOD applications [10]. In these architectures, the role for OOS is diminished, but commercial companies remain convinced of a viable OOS market with large LEO constellations. For instance, Altius Space Machines' BullDog™ concept is a deorbiter for failed satellites in LEO [11].

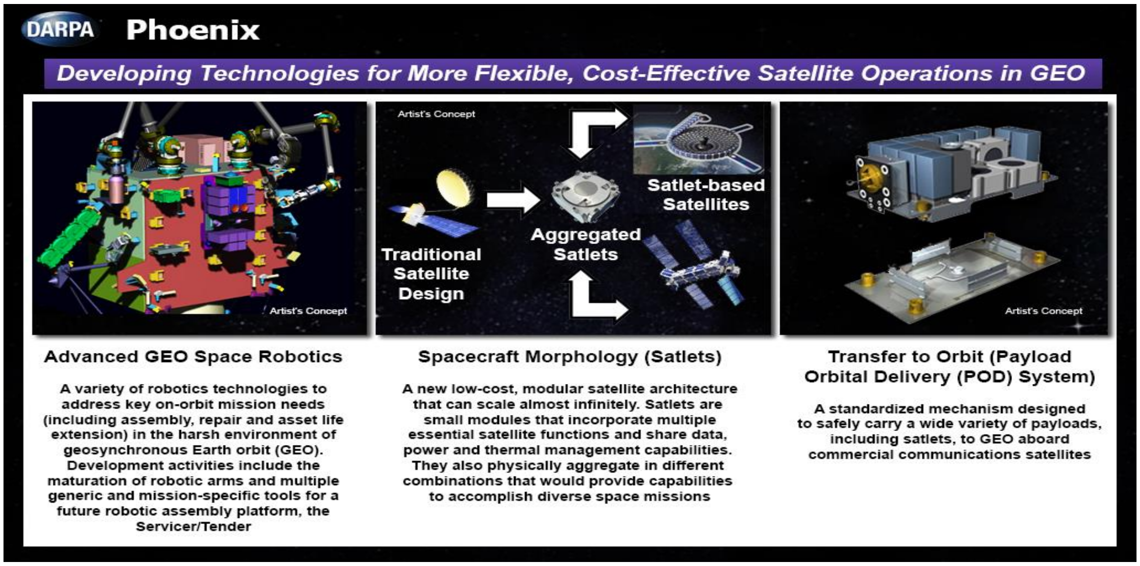
3. MODULAR DESIGNS FOR ON-ORBIT SERVICING SATELLITES

As the success of OOS materializes, satellite designs will begin to incorporate cooperative servicing features such as standard quick-disconnect refueling valves; machine vision-friendly fiducials; grapple fixtures; and common structural, power, data, and fluid interfaces. Spacecraft currently being acquired are already studying serviceability features, and by the end of the 2020s, it is likely that all large satellite acquisitions will require cooperative designs for servicing. While designing for full serviceability means a change in current satellite design practices, it has been shown that modular designs are cost-neutral compared to traditional highly integrated designs when considering more than a single satellite purchase [12]. The increased cost of modular system design is largely offset during the assembly, test, and integration phases of the acquisition cycle. Modular designs tend to increase satellite dry mass compared to highly optimized designs, but those weight penalties can be recovered from OOS utility. Small satellites would also gain significantly from on-orbit assembly. Currently, one of the biggest drivers in satellite design is survival of the launch environment. Being launched on a rocket involves significant accelerations, vibrations, and mechanical shocks. An integrated system must be built to survive these environmental factors, but these environments are only present for a few minutes of a satellite's multi-year lifetime. If a satellite is broken down into modules, packaged individually, and assembled on-orbit, the structural design would be greatly simplified.

4. ON-ORBIT MANUFACTURING

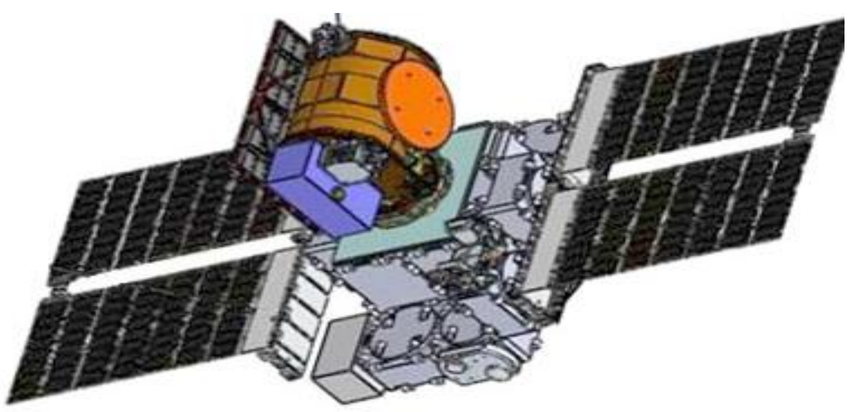
3D printing, a disruptive technology, has the ability to add capabilities to small and large satellites. A 2019 SmarTech space report on 3D printing forecasts positive growth in the market, finding that the value of additive manufactured parts – not the machines or software – was estimated to grow to $4.7 billion by 2027. In 2019, the global market for these parts reached nearly $1 billion which was dramatically higher than the estimated market for 3D printer machines, services and software, expected to top $872 million by 2027. SWISSto12 is one the first companies to use additive manufacturing to print Radio Frequency (RF) antennas. Relativity Space, a Los Angeles-based company developing 3D printers for rockets and eventually other aerospace applications, is on track to put Terran1, the world's first fully printed rocket into orbit next year. 3D printing parts instead of conventional manufacturing show that agile and organic designs can reduce the assembled part count, which reduces weight and time off systems going into orbit. Aerojet Rocketdyne began its metal additive manufacturing journey 12 years ago, aiming to reduce part count and improve performance. Virtually all product lines utilizes the technology, from flight-proven legacy engines like the RS-25 to the new lower-cost Bantam engine family [13].

In addition to assembly, the space industry is looking toward on-orbit manufacturing as having enormous potential for utility much closer to home. For example, companies like Made In Space, Inc. are exploring the manufacturing of materials in space for terrestrial applications [14]. Eventually, 3D-printing techniques will become sophisticated enough to print electronics or even an entire spacecraft. A satellite manufactured on-orbit would look significantly different from one manufactured on the ground. The former could take advantage of materials that cannot be exposed to air and avoid structural limitations of being built in a standard gravity environment. Their respective virtual configuration appears in limitless sizes and shapes. Even satellites built terrestrially in a modular fashion and assembled on-orbit would look significantly different from those manufactured and built entirely on orbit. Large truss structures and apertures that can be printed on-orbit are currently being explored for demonstrations [15].



5. ON-ORBIT SATELLITE MANUFACTURING, ROUTINE MAINTENANCE & TROUBLEHOOTING, AND REPAIR, REPLACE OR UPGRADE CAPABILITIES

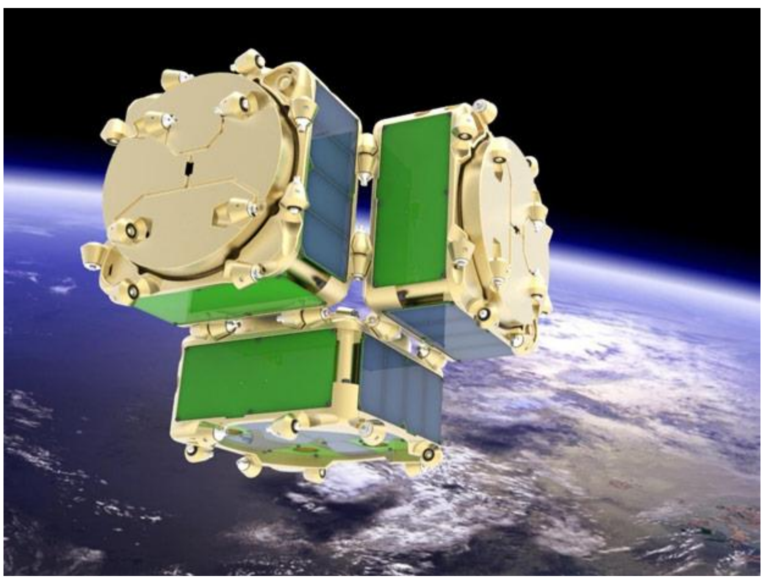
Space activities known as "on-orbit rendezvous and proximity operations (RPO)" will enable a broad class of robotically enabled missions at GEO and help satellites for the first time, to have the flexibility, accessibility and resilience that designers of terrestrial systems take for granted. DARPA's Phoenix program revives old satellites by mining them for parts and constructing a new satellite around them. The first DARPA Phoenix spacecraft, called eXCITe constructed by Los Alamitos, CA- based NovaWurks, was built from a set of identical smaller parts "satlets". HiSats, or Hyper-Integrated Satlets, measures 20 x 20 x 10 centimeters..Each satlet is effectively a self-contained spacecraft, with its own computer, power, communications capabilities, and propulsion, and are designed to be combined together.
eXCITe (**e**Xperiment for Cellular Integration Technologies) contains between 10 and 20 satlets.



eXCITe (with SeeMe on top) *[DARPA]*

The NanoRacks-NovaWurks SIMPL-Microsat applies terrestrial WiFi (Wireless Fidelity) technology and hardware to inter-satlet communications utilizing multiple node mesh network architecture. Each HISat can accommodate external payloads using an interface adaptor. HISats provide an app-based, open-source approach to core resource-sharing cellular software that provides for simple user-created applications to coordinate their requisite payload and mission needs. Developing an orbiting satellite construction and recycling operation indicates a paradigmatic shift from monolithically-built spacecraft towards something far more modular and manipulating. The photo of NovaWurks HiSat below shows the HiSat's side solar cells; edge connectors, and rotatable carousel [16].

The first DARPA Phoenix spacecraft won't be an orbiting satellite factory. Instead it will be an already completed spacecraft, called eXCITe, built from smaller parts. Constructed by NovaWurks, based in Los Alamitos, Calif., the spacecraft will be made out of a set of identical "satlets," which the company dubs HiSats, for Hyper-Integrated Satlets. Each measures about 20 by 20 by 10 centimeters. Each satlet is effectively a self-contained spacecraft, with its own computer, power, communications, and propulsion. But Talbot Jaeger, NovaWurks founder and chief technologist, says "they're designed to be combined together." He likens them to liver cells. Each one might be capable of performing the basic filtration functions of the liver, but they're only really effective in aggregate. He did note that at least one vital piece of the spacecraft, the antenna, which is by necessity fairly large, would have to be launched as a payload that's attached to the satlets.



The NanoRacks Kaber Mission-1, along with the SIMPL -Microsat of NovaWurks, is the on-orbit assembly and LEO (Low Earth Orbit) deployment demonstration of the NovaWurks HISat (Hyper-Integrated Satlet) system. The research utilizes a cargo vehicle flight to the ISS with six HISats and supporting payloads manifested. To demonstrate their packaging efficiency in the pressurized area of the ISS cargo vehicle the HISats are packaged individually. The disassembled cargo vehicle configuration enables a demonstration of the ease of on-orbit HISat assembly into a microsatellite, also known as a PAC **(**Package of Aggregated Cells).

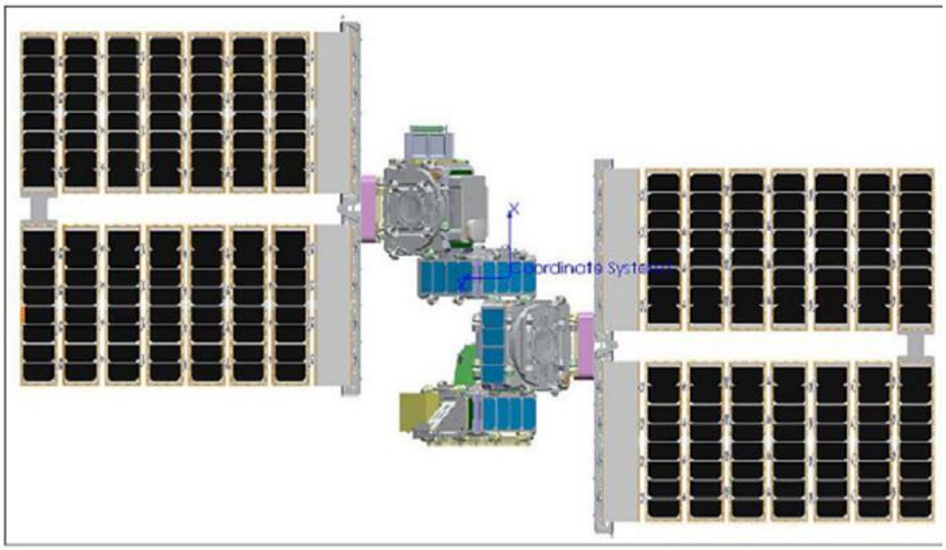
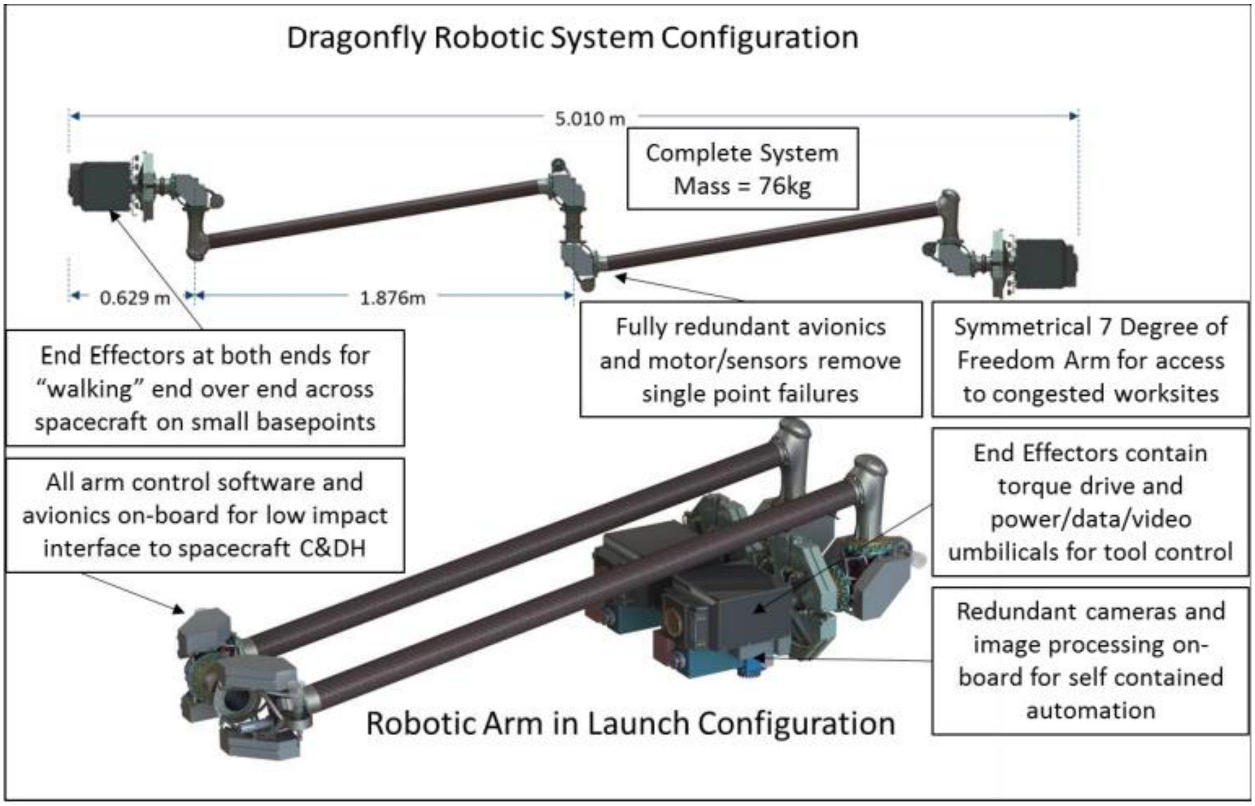


Figure. NanoRacks-NovaWurks-SIMPL-Microsat post-ISS deployment configuration, solar rays deployed.

6. DRAGONFLY ROBOTIC SYSTEM

A lightweight robotic system with a dexterous 3.5-meter arm that's able to clamp down, carry items or operate controls -- from either end of the "limb" -- Dragonfly can install delicate satellite antenna, yet also assemble satellites too massive to be launched to space in their final flight-ready state. These disassembled satellites may be stowed more efficiently or even launched in pieces via multiple flights, enabling mission planners to maximize cargo space and reduce mass. That shift would dramatically reduce launch costs and lead to less expensive, higher-performing satellites. Dragonfly is one of three NASA tipping point projects seeking cutting-edge solutions under the umbrella of the Technology Demonstration Mission (TDM) program's In-space Robotic Manufacturing and Assembly portfolio.



In-space assembly opens a range of new opportunities for satellite architectures and operations. Large structures such as platforms and apertures are no longer confined by the volume limitations of the rocket fairing. Sensitive instruments may be launched in a soft environment, removing the need to survive traditional launch vibration environments, and then installed on-orbit and refreshed at a cadence appropriate to the mission need. The in-space logistics paradigm can be transformed to match terrestrial models. In–space storage of ready-to-use components on robotic platforms enables *on demand* assembly and dispensing of assets on a timeline that is independent of launch schedule. This operational freedom improves the responsiveness and resilience of services provided by orbiting assets. Restore-L Servicer, for example, is a robotically enabled multi-purpose (and refuelable) Servicer whose in-orbit transport, assembly, and logistics are limitless [18].

7. SOURCING AND REPURPOSING REPLACEMENT SATELLITE COMPONENTS FROM GEO GRAVEYARD

"The Recycler" is a mission proposed to source replacements for failed components in GEO satellites by extracting functioning components from non-operational spacecraft in the GEO graveyard. The mission demonstrates a method of analyzing in-space re-purposing missions such as the Recycler, using real satellite data to provide a strong platform for accurate performance estimates. An inventory of 1107 satellites in the extended GEO region is presented, and a review into past GEO satellite anomalies is conducted to show that solar arrays would be in the greatest demand for re-purposing. This inventory is used as an input to a selection algorithm and trajectory simulation to show that the Recycler spacecraft could harvest components for 67 client satellites with its allotted fuel budget. This capacity directly meets the levels of customer demand estimated from the GEO satellite anomaly data, placing the Recycler as a strong contender in a future second-hand satellite-component industry. Propellant mass is found to be a greater restriction on the Recycler mission than its 15-year lifetime — a problem which could be solved by on-orbit refueling [19].

Demand for On-Orbit Servicing, Assembly, and Manufacturing

Demand and subsequent investment in on-orbit servicing, assembly, and manufacturing (OSAM) is influenced by developments in upstream and downstream fields (e.g., communications, earth observation, space exploration, data analytics, private launch market, etc.). Developments in interconnected markets continue to impact the feasibility of OSAM and the nature of its implementation for small satellites. If, for example, a booming market demand develops for applications in satellite constellation but launch costs are not lowered, then investments toward technology drivers will continue to grow since on-orbit assembly and manufacturing represents an affordable alternative for replacement satellite launches. OSAM, therefore, represents an emergent area of space activity for which value may be generated and ordered to a value-chain. Unassembled satellite components and raw materials are able to be packaged into launch vehicles more efficiently than completed spacecraft, reducing the total number of launches required to implement a constellation. Once materials have reached orbit, OSAM platforms act as orbital "factories," carrying out rapid production and deployment. Dead satellites are quickly replenished by spares made in the factories and stored in an orbital warehouse, without need to wait for a launch window to put a replacement into orbit. The cheaper, streamlined implementation process offered by on-orbit assembly and manufacturing dramatically increases the viability of large constellations. In this scenario, multiple persistent platforms in LEO and GEO are being used by governments and the private sector for on-orbit OSAM. However, as large satellites become cost-competitive and hosted-payload platforms become the norm, the satellite industry will then have the flexibility to design, build, and deploy satellites best suited for a given application. Compared with traditional satellites, smallsats typically have shorter development cycles, smaller development teams, and consequently, lower cost, both for the development and for their launches. CubeSats have the additional benefit of a standardized form-factor and containerization, enabling mass production and easier launch vehicle integration, which can further lower cost. Lower-cost satellites' expendability, faster refresh, and simultaneous deployment in large numbers—facilitate lower costs, spatially or temporally, in distributed data collection. Moreover, they afford greater risk-taking, experimentation, and creation of new applications, not feasible with larger satellites. Consequently, smallsats are making inroads in almost every area of space—communication, remote sensing, and technology demonstration.

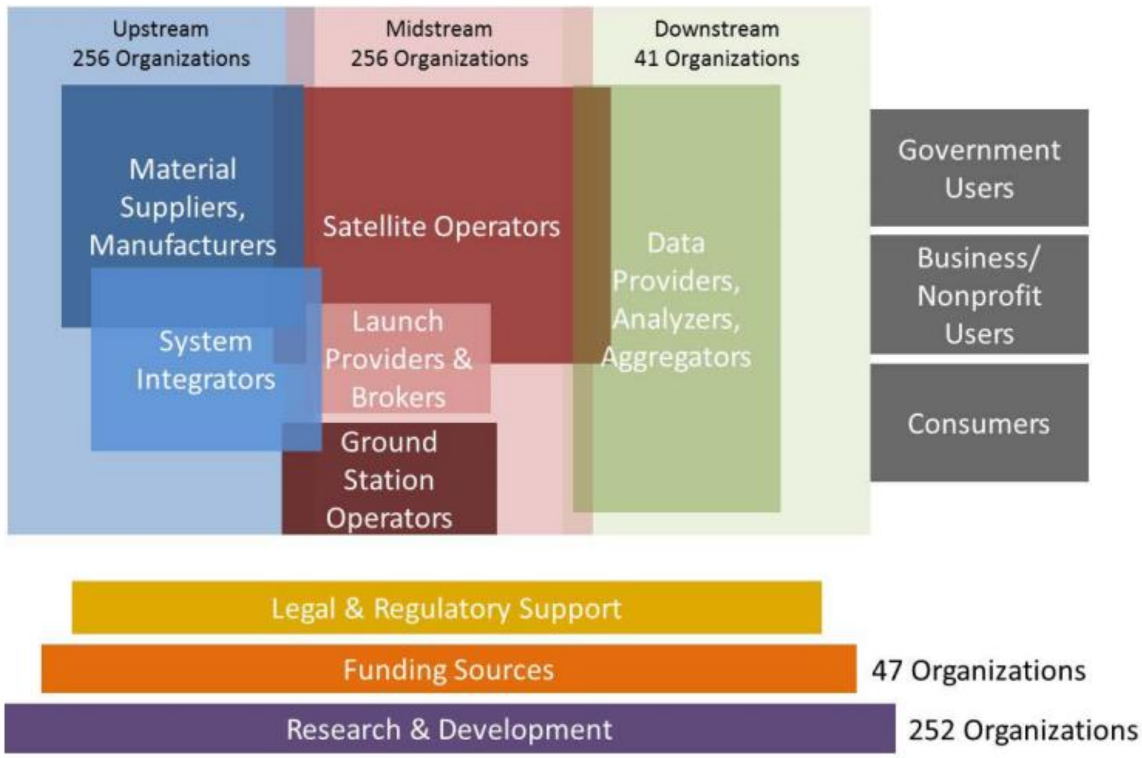
Examining the Smallsat Value Chain

Science and Technology Policy Institute (STPI) researchers conducted interviews with almost 70 individuals engaged in the small satellite industry, developing a database of over 650 organizations in the smallsat sector. The sample could be modeled a smallsat ecosystem, divided into three categories: value chain, users and consumers, and foundational actors. The value chain includes three segments: upstream actors and institutions engaged in manufacturing and system integration of smallsats; midstream organizations that operate and launch small satellites;

and downstream actors and organizations that analyze and package data streams into useful insights and business intelligence [20]. To realize a new dynamic space infrastructure, both the Servicer and Platform must have the ability to:

- Reliably perform operations in space without humans present to get the job done even when things don't work out as imagined
- Reliably perform without a large ground support crew to get the job done affordably

These two operational realities require an architecture that permits ingenuity and resourcefulness when unanticipated situations arise, and automation that, on a day-to-day basis, is trusted and easy to supervise.



Now, re-imagine six HISats and supporting payloads on-board ISS, ready to be re-assembled into a microsatellite (or PAC) and deployed into a chosen orbit to operate as designed. Or, the first 3d-printed Terran 1 rocket, additively manufactured from ISS and ready to be deployed into a chosen orbit to operate as designed. When their lifetimes terminate and they are ready for either de-orbiting, there is Altius Space Machines' BullDog™. Or, for sourcing replacements for failed components in GEO satellites, the Recycler may extract functioning components from non-operational spacecraft in the GEO graveyard. The shift away from aggregated, highly centralized and long-life satellite architectures encourages more distributed satellite constellations with shorter life spans to encourage more frequent technology upgrades. Creative cost-sharing and infrastructure financing are proving as important to overall program success as the traditional earned-value-management obligations to cost, schedule, and risk. Today's mega-satellite-constellation industry is learning that affordability and resiliency is deeply rooted in a healthy and agile supply chain.

Whereas the value chain of satellite industry commonly illustrates a satellite ecosystem both terrestrial and on-orbit, smallsat startups are increasingly populating all the orbits with satellites of varied functionalities. Tomorrow's on-orbit may very well represent an on-orbit satellite ecosystem for which a value-chain may be ascribed. The current paradigm favors optimization and its consequence, inflexibility, in part because satellites are out of reach. If satellites are no longer out of reach, they become evolvable, refreshable and dynamic assets that can respond to changing market and mission demands. Similar to terrestrial infrastructures, the new dynamic space infrastructure includes agents of action, hubs and supply chains to sustain the system.

A dynamic space ecosystem shows servicers, drones, and machine-ended platforms that maintain and sustain a refreshable, distributed capability.

REFERENCES

[1] *Why satellites matter: The relevance of commercial satellites in the 21st century – a perspective 2012-2020*. Booz & Company.

[2] *The annual compendium of commercial space transportation: 2018 Federal Aviation Administration.*

[3] Werner, D. (March 24, 2020). "NASA to hand off spacecraft communications to industry". *Space News*,

[4] Saleh, J., Lamassoure, E., & Hastings, D. (2002). Space systems flexibility provided by on-orbit servicing: Part 1. *Journal of Spacecraft and Rockets, 39*(4)

[5] Erwin, S. (November 17, 2017**).** On-orbit satellite servicing: The next big thing in space? *Space News*.

[6] Glover, R. (2020). Small satellite market - Growth, trends, and forecast (2020 - 2025) *Research and Markets.*

[7] Pötscher, F., & Lefort, T. (2020). *Why satellites matter The relevance of commercial satellites in the 21st century–a perspective 2012-2020*. Booz and Company.

[8] Davis, J., Mayberry, J., & Penn, J. (2019). *On-Orbit Servicing: Inspection, Repair, Refuel, Upgrade, and Assembly Of Satellites in Space.*

[9] Henry, C, (March 2018). LEO and MEO broadband constellations mega source of consternation." *SpaceNews*,

[10] Thomas, P. (February 2019). *Blackjack*. Retrieved from www.darpa.mil

[11] Davis, J., Mayberry, J. & Penn, J. (2019). On-orbit servicing: inspection, repair, refuel, upgrade, and assembly of satellites in Space.

[12] Rossetti, D., Keer, B., Paneck, J., Reed, B., Cepollina, F., & Ritter, R. (2015). Spacecraft modularity for serviceable spacecraft, 2015 AIAA SPACE Forum, September 2015.

[13] Wainscott-Sargent, A. (April, 2020), From prototyping to production: 3D printing for space comes into its own. *Via Space*

[14] Parke, S. (March 2, 2020). *Satellite Parts 3D Printed On ISS Deployed in Functioning Satellite* Retrieved from www.madeinspace.us

[15] Nikishchenko, I. (2020). Retrieved from www.launcherspace.com

[16] Courtland, R.(December 2014).DARPA Prepares to Launch "Satlets". *Spectrum*, IEEE

[18] Lymer, J. (April 8, 2019). NASA's Dragonfly Program: Commercialized robotics - enabling a new generation of evolvable, resilient assets in orbit 35th Space Symposium, Colorado Springs, Colorado

[19] SpaceNews Staff (February 26, 2020). *Space industry predictions for 2020*.

[20] Campbell, D. (October 17, 2017). *The Dawning Of A New Space Supply Chain—How Can The U.S. Military Cash In?*