"Can you imagine what students are going to do with these satellites?"
—Bob Twiggs

AEROSPACE

Game Changer

DO-IT-YOURSELF SATELLITES: APPLICATIONS FOR CITIZEN SPACE

Jake Singh

A new application of very small satellites, weighing less than one kilogram and deployable in large clusters, is likely to change the game for space exploration, operations, and citizen participation. Student and citizen scientist user groups are using flat picosatellites—cheap, simple, and deployable in large numbers and at low altitudes. ThinSats and ThumbSats show great promise in promoting science, technology, engineering, and mathematics (STEM) education and fostering high demand for space access. Additionally, successful citizen space applications of these satellites could lead to new applications across the spectrum of space actors—similar to the evolution of CubeSats from their academic origins to their current role as a recognized asset for military communications and even Mars exploration.

The use of picosatellites introduces questions and issues, including the demand for citizen science in an increasingly "democratized space." Who wants to do what with these satellites? What are other ways in which they could be used? What potential problems emerge with mass deployments? Picosatellite applications will have implications not only for citizen space but for mainstream space missions.

DIY Picosatellites: Market Readiness	
Do-it-yourself picosatellites are in the growth phase for citizen space applications. **In-Space: Maiden flights for commercial programs introduced during late 2010s**	
Strengths *Drivers that might advance DIY picosatellite use*	**Weaknesses** *Drivers that might delay DIY picosatellite use*
• Very low cost of development and launch • Lowered technical barriers to entry for citizen space missions • Easy to rapidly respond, build, and customize in large volumes • Low-risk option for technology demonstration and payload prototyping • Streamlined integration, assembly, testing, and launch process provided by commercial programs	• Regulatory concerns—picosatellites are very hard to track and massive deployments could be dangerous to other space assets • Active command and control has not been demonstrated • Small size (<1 kg) requires miniaturization of spacecraft systems, which could limit power and other mission capabilities • Perception of limited usefulness

Introduction

Picosatellites, weighing less than a kilogram and deployable in large clusters (or "swarms"), are emerging as the cheapest and easiest option for students and amateur space scientists to get a payload into orbit. Citizen space participants are now able to access commercial picosatellite hardware do-it-yourself (DIY) kits and associated services and expertise to customize their missions and place their payload into orbit. Companies like Virginia Space and ThumbSat, Inc. (no longer operating) have designed STEM education and citizen science programs that customize the design of a payload with all the other necessary space mission services—from telemetry streaming to launch vehicle selection to spacecraft testing—at very low costs. Although the satellite technology is not necessarily a breakthrough, these types of accessible user-centered space programs are unprecedented. Commercial picosatellite leaders are opening the door for a whole new demographic to participate in space. The expected success of these picosatellite programs is game changing, as successful "citizen space" applications can have a variety of technological, demographical, and regulatory implications across all space sectors.

Many of the world's important technologies are used in ways that were never imagined at their inception. In the space realm, this is especially true. Smartphone cameras, for example, exist largely because of efforts to fit cameras on small satellites.[1] When the CubeSat was invented about 20 years ago, it was not thought of as much more than a toy for graduate students. But as successful CubeSat missions began to accumulate, previously skeptical organizations began to reconsider their value. For example, as of 2019, CubeSats have traveled to Mars to serve as communication relays for surface rovers;[2] tested space elevator concepts;[3] and undergone development as next generation battlefield communication constellations for the U.S. military.[4] Successful CubeSat applications by academia led to a wide variety of new applications. It is reasonable to expect that smaller and cheaper picosatellites could also usher in new applications over time as new users develop their missions. According to an article from SpaceNews.com, inventor Hank Voss "thinks [ThinSats] will shake off the 'just a toy' stigma early cubesat proponents know so well."[5]

Who are the actors behind these picosatellite innovations? In an increasingly democratized space, we find that the innovators, leaders, and users span the full range of civil and commercial players. Users include students from university down to the middle school level, as well as citizen scientists, hobbyists, and even professional engineers at NASA JPL.[6] The innovators are not just the picosatellite inventors but also the entire value chain of electronics manufacturers, launch vehicle manufacturers, launch pad operators, and STEM education leaders in government and industry.

Table 1: Common Mass Classification Scheme for Satellites

"Small satellites" typically represent all classifications where the mass is less than 500 kg.

Classification	Mass (kg)
Large Satellite	>1000
Medium Satellite	500–1000
Minisatellite	100–500
Microsatellite	10–100
Nanosatellite	1–10
Picosatellite	0.1–1
Femtosatellite	<0.1

The "Citizen Space" Sector

Space activities can generally be thought of in three sectors: civil space, commercial space, and national security space.[7] Somewhere between civil and commercial space lies a small but growing demographic sometimes referred to as *citizen space*. Citizen space participants are not motivated by profit nor are they members of government agencies; rather, they seek to leverage the assets of commercial space (affordable launch, small satellites) for scientific purposes typically associated with civil space agencies like NASA or NOAA.[7] Academia would naturally make up much of this sector. But also entering the scene is an important new player: the citizen scientist.

The Oxford dictionary defines *citizen science* as "the collection and analysis of data relating to the natural world by members of the general public, typically as part of a collaborative project with professional scientists."[8] Citizen scientists have the tools to excel—from internet resources like DIY forums and open source code projects to cheap and available electronics and instruments like quadcopters, Fitbits, and smartphone GPS. Citizen scientists have found creative ways to use these technologies to advance knowledge in a wide range of areas.

Key Market Drivers

There are four key market drivers for citizen science: (1) disruptive creativity, (2) lower cost threshold, (3) independent validation, and (4) collective wisdom of the crowd. A successful application of citizen science is typically enabled by at least one of these key market drivers. An understanding of the market provides insight into how citizen scientists may advance the space sciences.

Creative Disruption. In 1609, Galileo learned about Dutch perspective glasses and decided to build his own. Instead of looking down, he pointed his new instrument skyward and the world was never the same. As Galileo continued to study the stars, he became convinced that the Copernican (sun centered) model of the planets was correct. His ideas were considered heretical at the time, although he continued to work and write until his death in 1642.[9] This early case study highlights an important aspect of citizen space: the disruptive power of unconventional players.

Elon Musk's cherry red Tesla convertible, flying beyond Mars with a space suit mannequin, is arguably one of the most audacious creative disruptions in the space industry to date. While technically a test flight of the new Falcon Heavy launch vehicle, the February 2018 mission includes perhaps the first space demonstration for the sake of art. The mission disrupted how the public views space and future space missions. It has also engaged the imagination of the public with iconic imagery and the second most viewed YouTube live stream event ever.[10] Using public tracking data provided by NASA JPL, the world can track "Starman" as he travels through the solar system. This disruptive, creative design of a launch vehicle test mission would unlikely exist without Elon Musk and SpaceX, players that entered the space industry only 17 years ago.

Lower Cost Threshold. The CubeSat was the first citizen science satellite for space, and its success was derived primarily from the lower cost threshold that it set for users. The size and design of a basic 1U CubeSat puts the cost of construction around $50,000. Launch costs are similarly low but have been lowered further by new deployment technologies.

A lower cost threshold for launch was introduced in 2009 by NanoRacks, manufacturer of the NanoRacks CubeSat Deployer (NRCSD). The NRCSD deploys up to 48 CubeSat units at a time from the International Space Station (ISS) and provides a standard interface between spacecraft and launch vehicles. NanoRacks has launched 186 satellites from over 20 countries at costs that were previously unattainable with custom-designed hardware and launch vehicle interfaces.[11] The NRCSD makes use of standards—like a payload form factor and NASA ISS flight safety requirements—to make low-cost citizen space missions feasible in the professional civil space environment.

Independent Validation. "El Niño" is a weather pattern that affects the Pacific coast and brings high levels of flooding to the California coastline. In 2016, a California environmental group called "The Nature Conservancy" began recruiting drone hobbyists as citizen scientists to map flooding and coastal damage caused by El Niño storms. Matt Merrifield, the organization's CTO, said, "We use these projected models and they don't quite look right, but we're lacking any empirical evidence. This is essentially a way of 'ground truthing' those models. "[12] Using camera-equipped drones, these crowd-sourced citizen scientists helped develop 3D maps that allowed professional scientists to validate their flooding models.

A fundamental element to deep-space radio communication is the quartz piezoelectric resonator—a technology independently validated by the amateur radio community in the 1930s. Also known as a crystal oscillator, the technology is responsible for generating precise and stable frequencies required for high-fidelity communication. Amateur radio operators took the quartz technology (still in the research and demo phase for most of the professional science community), built their own prototypes from commercial crystal vendors, and began to establish a widely accepted standard for crystal control.

The independent validation of this technology by amateur radio operators spurred massive development of the U.S. crystal industry as well as the decision by the military to convert their radios to crystal control.[13] Perhaps as small, do-it-yourself satellites gain traction in the space sector, similar independent validation efforts by citizen scientists could emerge for space technology.

Collective Wisdom of the Crowd. NASA developed a citizen science project in 2012 called "Target Asteroids!" This project harnesses the collective efforts of amateur astronomers to characterize the population of near-Earth objects (NEOs) by crowd-sourcing scientific observations. Specifically, citizens provide data on the position, motion, rotation and light emission intensity of NEOs, which forms a knowledge base to refine theoretical models and support asteroid observation missions.[14] In May 2017, citizen scientists actually discovered a distant exoplanet. When NASA scientists publicly posted spacecraft data from the Kepler K2 mission, interested citizen scientists found an important data pattern that NASA had missed.[15] Crowd sourcing scientific data is extremely valuable and has driven not only citizen science applications in astronomy, but also in finance, software development, and journalism, among other sectors.

Another successful citizen science project, called Aurorasaurus, capitalizes on the ubiquity of smartphones to complement professional research on auroras and space phenomena. Founded in 2013 by NASA scientist Elizabeth MacDonald, the project uses social media like Twitter and Facebook as well as a mobile app to gather realtime reporting data from users around the world when auroras are sighted. In 2016, citizen scientists discovered a new type of aurora labeled with the acronym STEVE (Strong Thermal Emission Velocity Enhancement). The impressive discovery was welcomed by professional researchers and physicists.[16]

These are just some of many citizen science success stories, and each demonstrates at least one key driver. The common theme is that with the right technology, access to data, and know-how, the citizen can perform legitimate science without deep pockets and professional scientist resources.

A New Tool for Citizen Science

The CubeSat's success and transition into a mainstream commercial space asset has also highlighted its ongoing challenges for citizen scientists and students. ThinSat developers note that ground communication equipment, launch and operation licensing, and spacecraft systems integration and assembly are still significant challenges for CubeSat developers.[17] Recognizing the barriers and difficulties encountered by CubeSat pioneers, picosatellite technology leaders in commercial space proactively address these challenges by providing technical resources to users, internet-based telemetry streaming, and a low orbit and short lifetime that results in no debris generation. These picosatellites make use of existing standards for launch and deployment (stacking into existing 3U CubeSat deployers, space-ready avionics). They are appropriately designed for the citizen scientist by having development processes that provide technical assistance, low costs, and ground station outsourcing. As a new tool for citizen science in space, these do-it-yourself picosatellites lower the barrier to entry for space missions.

Case Studies

There are a number of emerging picosatellite projects and programs; however, the real game changers are those that can address the entire value chain (including development, launch, and ground station infrastructures) to streamline the lifecycle process—from design to orbit. These are the programs that are going to enable and encourage the new citizen scientist user described in the previous section. The case studies presented in this section focus on ThinSats and ThumbSats. This section also outlines *enabling elements*, using known ThinSat examples, that are common to these emerging picosatellite programs.

ThinSat – Key Enabling Elements

Bob Twiggs, co-inventor of the CubeSat standard, had been working on even smaller and cheaper small satellite designs to promote STEM education in space. At a small satellite conference in 2016, he made a deal with Orbital ATK (later acquired by Northrop Grumman) to secure secondary payload space for a new small satellite design. Working with private companies NearSpace Launch and Virginia Space, he finalized the ThinSat design, which can be stacked such that 21 ThinSats fit into the volume of a

3U CubeSat. To support this new picosatellite, Twiggs partnered with Virginia Space—operator of the Wallops Island, Virginia, launch pad—to create a STEM education program offering opportunities to students from middle school to university level.[17] The first ThinSat launch is expected in April 2019.

The enabling elements that characterize citizen space picosatellites as game changing are outlined below.

Path to Hosted Payloads. The ThinSat picosatellite is a part of the ThinSat Program, a STEM education program developed by Virginia Space and Twiggs Space Labs. As explained by its developers, the program's purpose is "to teach students in middle school and later grades on the iterative engineering design process, systems engineering, data collection methods and analytical processes, and atmospheric and space science".[17] The ThinSat program streamlines the process of going from an idea for an experiment into a flight-ready, hosted payload. The program has three phases: The first is primarily a teaching phase, the second is the development of an engineering model, and the third is the development of the flight-ready ThinSat. In the first phase, students learn programming basics, experiment with plug-and-play sensors, and conduct a low-altitude balloon flight of a flat sensor board. In the second phase, students design their payload and integrate it with a 3D-printed engineering model for testing and a high-altitude (36 kilometers) balloon flight. In the third and final phase, students use knowledge and data from the previous two phases to design the final ThinSat payload.[3] This three-phase model provides a full path from classroom to orbit that provides ample technical assistance along the way.

Low Orbital Altitude and Lifespan. ThinSats enter extremely low Earth orbit (ELEO) via lower cost launch vehicles such as Northrop Grumman's Antares vehicle, and typically orbit at an altitude between 200 and 250 kilometers for about five days.[17] With such low altitudes and flight durations, ThinSats are designed to burn up upon atmospheric reentry and generate no lasting debris. This orbit is beneficial because (1) no debris means less difficulty in securing the required licensing for launch and operation, (2) short-mission cycles capture a young student's shorter attention span, and (3) short-mission cycles mean rapid repeatability and low cost. Figure 1 displays a simulated graphic of two ThinSat strings in orbit to paint a physical picture of a typical flight. The simulation was created using Aerospace's Satellite Orbit and Analysis Program (SOAP).

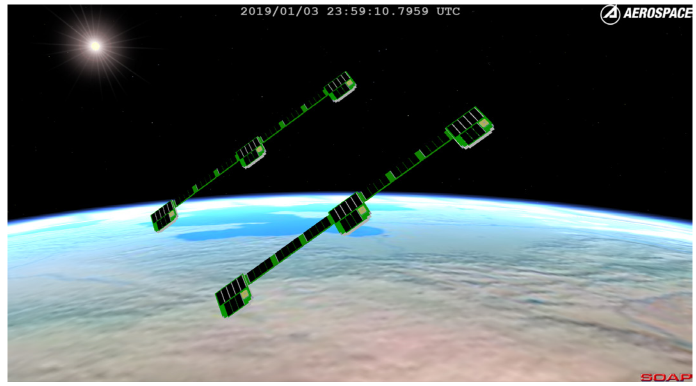

Figure 1: SOAP simulation of two ThinSat strings, connected by flexible solar panel ribbons, in ELEO. Models are not to scale.

Compact and Flexible Configurations. One ThinSat is about the size and shape of a slice of bread, measuring 111 by 114 millimeters with a thickness of 12.5 millimeters. A typical ThinSat weighs about 280 grams. Standard avionics include an accelerometer, gyroscope, magnetometer, and sensors for temperature, voltage, current, light, and radiation. One-half of the satellite is dedicated to housing the users' payload, allowing a volume of approximately 107 by 52 by 10 millimeters. The other half houses the electrical power system, battery, microprocessor, and radio. ThinSat clusters are deployed as secondary payloads on commercial resupply missions to the international space station. They are designed such that 21 units can be packed into standardized 3U CubeSat deployers (seven ThinSats per 1U CubeSat volume). ThinSat cluster configurations can vary depending on mission specifications, but a typical configuration will involve six "daughter ships" and one "mothership," all tethered together as a "string" with either fanfolds or nitinol wire. This modular design allows the satellites to have a compact configuration during launch and physical connection to the mothership during flight. The mothership configuration includes a camera and GPS.[17]

Internet-based Telemetry Streaming. Radio communication is achieved using the GlobalStar satellite network.[17] ThinSat radios transmit data to low Earth orbit (LEO) satellites in the GlobalStar constellation, which then downlink telemetry to the internet. Users can then view their telemetry data in realtime as well as other educational resources in a secure online portal called the

"Space Data Dashboard." This internet-based telemetry streaming avoids the need for a cost-prohibitive ground station installation and the technical knowledge to operate a ground station.

Plug-and-Play Avionics. ThinSat avionics are developed by XinaBox Inc. The company manufactures sensor chips with standard sizes and connectors, allowing for the combination of any set of sensors and instant communication between all chips. This plug-and-play nature allows students to focus on *using* the sensors rather than manufacturing, assembling, testing, or calibrating. The first phase of the program includes curriculum for working with the XinaBox chips and interpreting sensor data, making for a smooth learning process for even the most inexperienced students. The payloads that students develop for the second and third phases are typically based on XinaBox or Twiggs Space Lab products, although they can be completely customized if desired.[17]

Customer Interface. In addition to the chips included in the Phase I kits, users can purchase other chips and accessories directly from the XinaBox website and can purchase additional avionics products from Twiggs Space Lab as well. These commercial supplier sites, combined with the Space Data Dashboard, provide an accessible customer interface for all mission stages—from development to flight.

Open-Source Software. The CPU chip is programmed using Arduino, a popular open-source coding platform based on the C++ language. Arduino has a vast network of libraries, online support, developers, and code projects. This network is helpful not only for learning Arduino programming, but also for sharing data and successful projects with the rest of the developer community.

ThinSat users have thus far spanned schools throughout the mid-Atlantic United States and shown excitement for the program. "In the past I was used to having to coordinate, micro manage, etc. These kids have taken the ball and run," said Mark Lepsch, mentor of a Charlottesville, Virginia, high school team.[18] Other STEM organizations are adopting ThinSat programs of their own and are evolving to help students accomplish more. Students of Destination SPACE, an educational program based in Asheville, North Carolina, "conduct their own research, have the opportunity to compete for scholarships, and attend high level STEM conferences," according to founder DeWayne Cecil. The first ThinSat launch, originally scheduled for November 2018, was rescheduled for April 2019 as a result of an aborted Soyuz launch a month prior.

ThumbSat Startup and Regulatory Challenges

ThumbSat Inc. was a startup with a vision and product similar to that of the ThinSat developers. The company emerged in 2015 with the goal of designing an affordable, customizable picosatellite and developing the technology, launch planning, and ground station infrastructure to greatly simplify the process for the user. "Before you even think about your experiment on a CubeSat, you have to buy a kit, put it together, apply for licenses to launch and transmit from space, find a launch and get together plenty of funding to do it. If you choose the ThumbSat route, all you have to think about is the experiment, and we can help you a lot with that too," says ThumbSat inventor Shaun Whitehead.[19] Unfortunately, FCC licensing difficulties delayed the company's progress, and maiden flights planned for 2016 were canceled. The ThumbSat technology, however, shows promise.

The ThumbSat picosatellite comes in various sizes and designs per user needs, but all designs typically feature a flat, square circuit board of about 50 by 50 millimeters. Standard equipment includes GPS, radio transmitter, microcontroller, battery, and camera. The user payload can be at most 48 by 48 by 30 millimeters with a mass up to 25 grams.[19] Users can plan their mission and launch as well as view mission data through the ThumbSat website. Similar to the ThinSat, ThumbSats downlink telemetry by using existing satellite constellations as relays to ground stations across the globe.

ThumbSat, Inc. originally partnered with the New Zealand startup Rocket Labs to provide low-cost and frequent flights. In 2017, ThumbSat made an agreement with the California-based CubeCab to launch 1,000 satellites.[20] Using either of these two microlaunch providers, a ThumbSat launch is expected to cost about $20,000. The ThumbSat is designed for LEO (about 250 kilometers higher that a ThinSat's orbit) and has a lifetime of about two weeks, concluding its lifecycle by burning up in the atmosphere and generating no lasting debris.[19] Facing persistent regulatory challenges, ThumbSat, Inc. was denied an FCC experimental license in both December

2016 and June 2017; for the latter, the FCC cited concerns over trajectory uncertainty, ground command capability, and communication abilities.[21] Since then, founder Shaun Whitehead has been working with students at Teesside University in England on a project that hopes to bring a ThumbSat into orbit via a small student-built rocket.[22]

The ThumbSat satellite demonstrates many of the enabling elements outlined in the ThinSat case study, including path to hosted payload, compact and flexible configurations, internet-based telemetry streaming; customer interface, and low-profile orbit. Although not explicit in the program description, open-source software and plug-and-play avionics are likely to be components of successful ThumbSat applications. Combined with emerging commercial launch opportunities and regulatory resolutions, the ThumbSat could enable the growth of the citizen space scientist market. As the "father of ThumbSat" considers what the future holds, Whitehead notes, "Look at all of the amazing hardware add-ons and apps that have been created for smart phones. Nobody predicted that. I think we will see a revolution in space science. Space will no longer be elitist."[19]

Additional Picosatellite Examples

Thinsats and Thumbsats are certainly not the only do-it-yourself options for those seeking affordable space missions. The TubeSat is a satellite kit manufactured by Interorbital Systems. A successful launch occurred in December 2016 after Tancredo Middle School students in Brazil assembled Tancredo Sat-1, which carried an audio recording device and a probe to study plasma bubble formation in the ionosphere. The satellite was deployed from the ISS on January 19, 2017. Like CubeSats, TubeSats can be assembled in varying unit sizes such as 1U, 2U, 3U, etc. Weighing 0.75 kilograms, a 1U TubeSat falls into the picosatellite classification and has an $8000 price tag for academic use. Users can take advantage of an Arduino processor and a variety of standard and custom hardware for their missions. TubeSats have self-decaying polar orbits in LEO (310 km).[23] TubeSat appears to be finding success without spending much on advertising, and Interorbital Systems currently has more than 45 planned TubeSat launches on its launch manifest.[24]

The precursor to the ThinSat was another smaller-than-a-CubeSat design called a PocketQube. The PocketQube was Bob Twiggs' next small satellite solution after the increased demand for CubeSats drove up launch costs significantly. PocketQubes are one-eighth the size of a 1U CubeSat. They are also cube-shaped, but have 5-centimeter dimensions and are typically 250 kilograms or less. Several of these satellites were launched in November 2013.[25] While this smaller design further reduces launch costs, PocketQubes did not gain popularity like CubeSats did. Additionally, they proved to be difficult to assemble for students and sometimes incompatible with traditional CubeSat deployers. As a result of these difficulties, the ThinSat concept was conceived by Twiggs' friend Hank Voss, president of NearSpace Launch.[26] PocketQubes are still used as low-cost picosatellite options, and Alba Orbital is an active developer of new PocketQube deployer systems.[27]

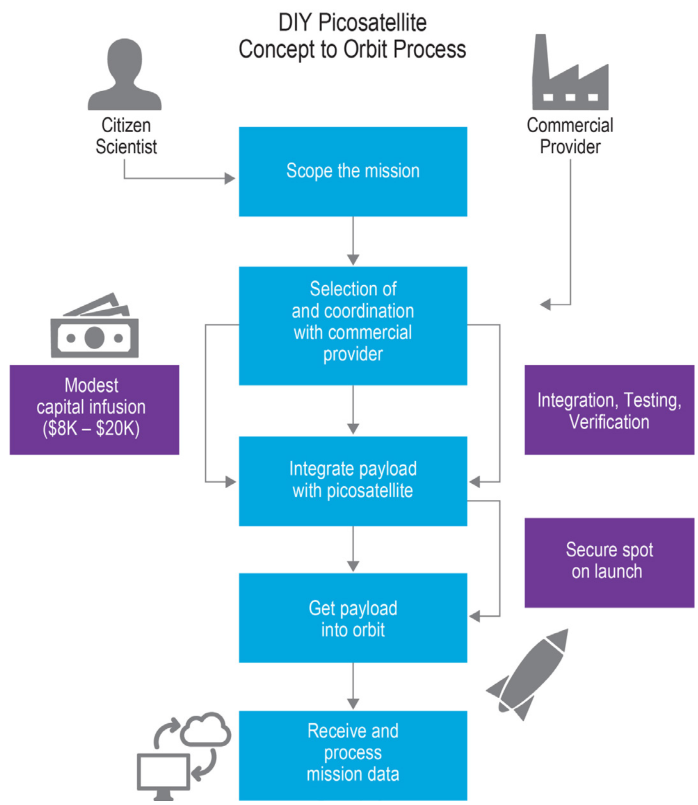

Figure 2: The concept-to-orbit process of DIY picosatellites. A typical process of executing a space mission can take years after conception. The DIY route aims to take months or even weeks.

Implications

As these picosatellite programs find continued success, demand may increase, and deployments may become more frequent. Increased use of these picosatellites will have implications for (1) picosatellite users, (2) advancement of space technology, and (3) existing space policy needs.

Picosatellite Users

It is clear that picosatellite programs will open the door to new citizen scientist space participants. They are already expanding existing academic participation by introducing students at lower grade levels and with less experience and fewer skills. With such low costs and the ability to launch upwards of 80 satellites per launch, picosatellites could become an option for developing countries looking to establish space programs. More than 80 countries have launched and operated a satellite,[28] and this number could increase significantly as picosatellites proliferate within the space community.

Strong opportunities for STEM education in the U.S. are essential for developing the next generation of leaders in science and engineering fields. American STEM jobs are projected to grow 13 percent between 2017 and 2027, and our universities are expected to produce only 29 percent of the necessary STEM-degree graduates to fill that demand.[29] The advent of picosatellite-based educational opportunities in the U.S. and elsewhere could lead to a strong new generation of space leaders, who can cite flying their own space experiments in middle school as an early motivator to pursue a career in the industry. For emerging international players in the space industry, adoption of similar do-it-yourself satellite programs could be very valuable in recruiting young engineers for their space industrial base.

Technology

Citizen science applications of picosatellites can have two types of technological impacts: (1) advancement of novel space technologies and (2) new technological applications of picosatellites themselves. An example of the first is a new type of supercapacitor riding onboard a ThinSat to achieve its first space flight.[17] An example of the second is a hypothetical scenario in which a flat satellite swarm, ejected by a larger spacecraft into a new orbit, tests and measures atmospheric properties before the large spacecraft considers a maneuver.

Picosatellite deployments can accelerate the research and development phase of a new space technology and act as in-space testbeds for new technologies. For example, ThinSat developers advocate that their low cost, short lead time, and high volume of launches can allow organizations to quickly achieve technical readiness levels with low risk of a delayed mission.[17] With cheap and abundant opportunities to get a new payload in flight, space technology developers may be quicker to test and refine new technologies that could benefit all space sectors.

Picosatellite clusters themselves may prove to be valuable for civil or commercial mission operations. A cluster, compared to a single spacecraft with integrated systems, offers safety in numbers (or "disaggregation"). For example, if an impact from an unexpected debris object causes a critical failure in the CPU of a large spacecraft, a whole mission may be compromised. By contrast, if an unexpected debris object took out just one picosatellite in a swarm, the remaining units could hypothetically finish the mission while missing only one asset or instrument. An area of ongoing research is in relative navigation technologies, which could help small satellite clusters fly together in formation. Stanford University expects breakthroughs in astronomy and astrophysics, planetary science, and space exploration as a result of satellite formation flying. Use of a picosatellite as a sort of deployable sensor, for example, would be very valuable for a planetary exploration mission. Similar to what MarCO did for Insight in the recent Mars landing, a large spread of deployable picosatellites could multiply NASA's data gathering ability during entry, descent, and landing.[30] Perhaps picosatellites could make for an effective demonstration or application of this new technology.

Regulation

Two regulatory issues are associated with the deployment of picosatellites: orbital debris mitigation and small satellite tracking. Orbital debris mitigation seeks to reduce the generation of orbital debris and any danger it imposes on existing space assets. Small satellite tracking is typically a practice of government agencies and is essential to space situational awareness and national security. Experts agree that the hardest satellites to track are those between 1 and 10 kilograms[31]—weighing typically 1 kilogram or less, picosatellites are proportionately smaller and likely harder to track.

A picosatellite's contribution to the orbital debris problem depends on its orbiting lifetime and altitude. ThinSats, for example, should not pose a significant debris concern. With altitudes in ELEO, they already avoid the trajectories of nearly all orbiting spacecraft and burn up upon atmospheric reentry. However, picosatellites finding applications in higher orbiting altitudes, such as the ThumbSat, should expect increased concern from regulatory agencies. Current picosatellite designs lack maneuverability and have very short operational lifetimes, so failure to burn up in the atmosphere as planned leads to debris with a high risk of collision. Space policy experts generally agree that "national and international debris mitigation guidelines should be strengthened for all satellites regardless of size or altitude."[31]

The proliferation of picosatellites will call into question existing small satellite tracking practices and abilities. Especially if operational lifetimes become factors of months rather than weeks, deployment opportunities could be limited unless a new solution for tracking emerges. Additionally, it is reasonable to expect that improving picosatellite capabilities could someday lead to threatening applications. In the context of asymmetric warfare, a picosatellite could be a dangerous and attainable asset that is difficult to track in orbit. The low barrier to entry for use may parallel that of cybersecurity attacks or improvised explosive devices (IEDs). National security concerns associated with the proliferation of picosatellites are thus not completely out of the picture.

A new era in which anyone can launch their own spacecraft may have similar regulatory repercussions to the advent of other democratizing technologies such as amateur radio or social media. The Center for Space Policy and Strategy recognizes the significance of the small satellite revolution, noting that "we have likely only scratched the surface of what this technology is capable of accomplishing." It is therefore important to carefully regulate this new technology in a balanced way to encourage innovation and avoid overregulation."[31]

Game Changer Lifecycle: Market and Technology Triggers

As shown in Figure 3, various market and technology triggers will advance picosatellites capabilities and spur new picosatellite applications. Currently, DIY picosatellites are still in "demo phase," although with

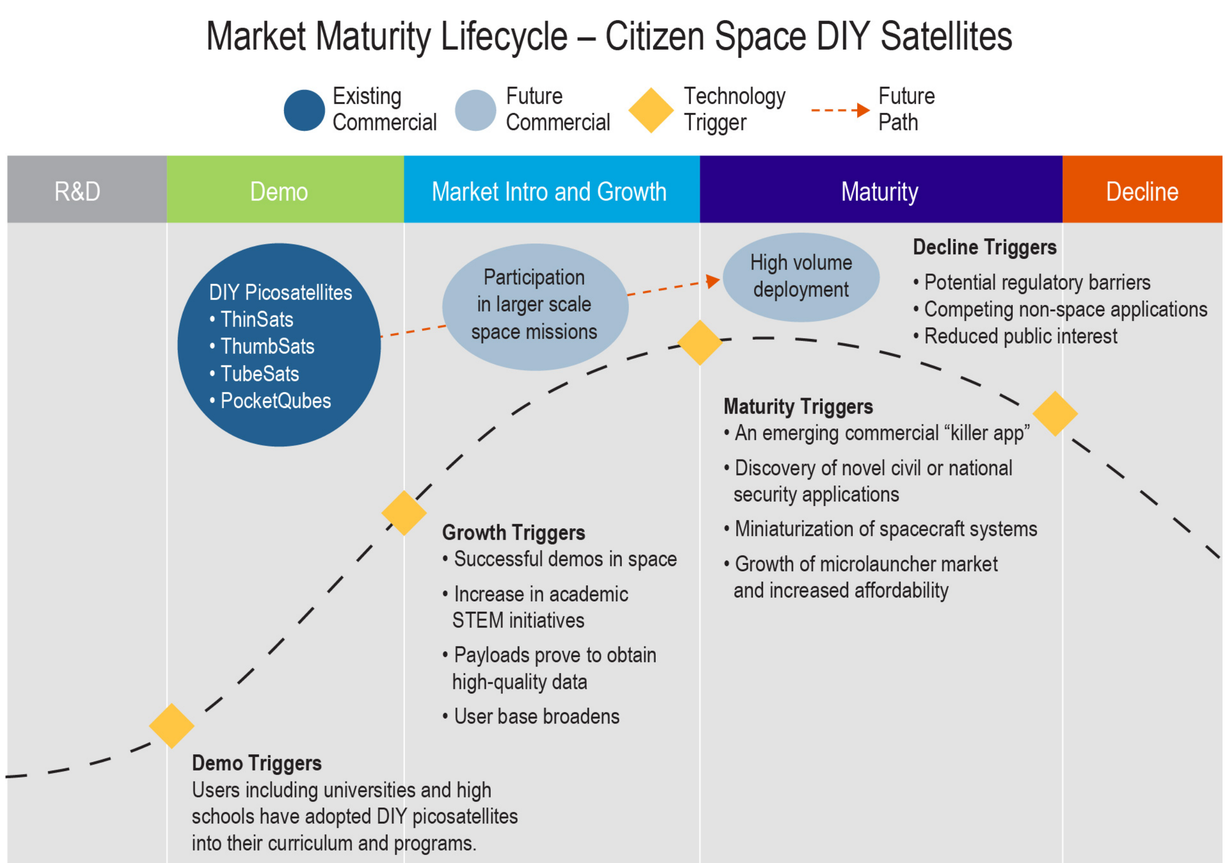

Figure 3: Anticipated maturity curve and technology maturation path of DIY picosatellites over time.

further success, funding, and adoption by a broader user base, it is expected that they will soon mature toward rapid growth.

Technology Triggers

Miniaturization of Satellite Systems and Instruments. In August 2018, The Aerospace Corporation's AeroCube CubeSats demonstrated an unprecedented 100 megabit/second laser communication for satellites of CubeSat size. In addition to the innovative use of free-space laser communication, this achievement was possible partly because of a star-tracking attitude control system with an accuracy of 0.025 degrees. In the past, these two types of spacecraft systems would have only achieved such performance on a much larger spacecraft.[32] There is reason to believe miniaturization trends will continue and eventually reach the picosatellite scale, which will allow existing space actors to consider picosatellites for new applications.

Active Command and Control Capability. Active command and control (i.e., ground station operators beaming commands up to a spacecraft) is a key component of nearly all space missions. DIY picosatellites typically have no active command and control capability; rather, they are typically programmed to operate their payload and send telemetry back home via relay satellites like the GlobalStar network. Demonstration of active command and control on a picosatellite would create possibilities for new applications.

Cost-Reducing Launch Vehicle Technology. The high cost of a rocket launch is often a barrier to entry in all space sectors. The Antares rocket, which brings ThinSats into orbit, costs about $475 million to build and about another $80 million to launch.[33][34] The final cost is proportional to the "touches" required on the vehicle during manufacturing—a touch being anything from the worker welding together fairing pieces to the drive from the integration facility to the launch pad. Any technological advancement that reduces touches or the vehicle's launch costs will reduce the launch cost for a small satellite, potentially making picosatellite missions more feasible. Examples of these technological triggers include the implementation of 3D-printed engine components and reusable rocket stages. Additionally, alternative launch schemes like the Rockoon, where a high-altitude balloon launches a rocket from the upper atmosphere, are gaining popularity and could become viable options for low-cost launches in the near future.

Market Triggers

Growth of Microlauncher Industry. There are currently many more small satellite developers than launch providers. Additionally, most satellites on the pico or nano scale are forced to "piggyback" as secondary payloads on heavy launchers such as Antares or Falcon 9. As a result, they must compete for launch opportunities, suffer long periods between launch windows, and even risk being placed into the incorrect orbit. Microlaunchers (or "small launch vehicles") are launch vehicles specifically designed to carry small satellites. Emerging microlaunch providers such as Rocket Lab, Firefly Aerospace, CubeCab, and Vector Launch will directly affect the small satellite industry, allowing for more flexible, precise, and cost-effective options to get into orbit.[35] As the microlaunch industry continues to grow in 2019, so will the small satellite market and opportunities for picosatellite launches and applications.

STEM Education Initiatives. Virginia Space's contribution to the ThinSat program was driven by its corporate goal to foster STEM education in Virginia. The corporate goal is mirrored by state legislation that is being enabled to support STEM education support. Similar initiatives by government and industry leaders could lead to more applications of low-cost picosatellites.

Conclusion

Citizen space applications of picosatellites are already demonstrating a profound democratizing effect on space activity. With increased participation and new demographics of space actors, the possibility for technological advancement and unforeseen uses of picosatellites increases exponentially. The CubeSat revolution we have witnessed over the past 20 years has proven that compounding success from one user group can break stigma and prompt innovative applications across the entire realm. As engineers continue to think smaller and smarter, the same type of revolution could easily happen on the pico scale. And as game changers in the growth phase, citizen space picosatellites could enter the spotlight sooner than we think.

Four key drivers will allow citizen science to thrive during the 21st century. The drivers are (1) creative disruption,

(2) lower cost threshold, (3) independent validation, and (4) collective wisdom of the crowd. Picosatellite programs like the ThinSat and ThumbSat have the infrastructure and design to let citizen scientists make real contributions in space. Additionally, these two case studies demonstrate all or most of the seven enabling elements that can be expected of emerging picosatellites: path to hosted payload, compact and flexible configurations, internet-based telemetry streaming, plug-and-play avionics, customer interface, open-source software, and low orbital profile. More competitors to these programs will emerge as the commercial sector awaits new launch vehicles, launch providers, and spacecraft manufacturers. The implications of citizen space picosatellite applications are numerous, but key impacts are in student interest in STEM, technological demonstration, and the revisiting of small satellite tracking practices.

In 1977, Digital Equipment Corp. CEO Ken Olsen claimed, “there is no reason anyone would want a computer in their home.”[36] It is likely that today, many would wonder why anyone would want a personal satellite. While the demand for do-it-yourself satellites will likely never reach that of a personal computer, Olsen’s quote is a reminder that technological disruption is often quite unpredictable.

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