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COSMIC SHIFT

THE COMMERCIAL SPACE REVOLUTION

IQT IN-Q-TEL

IQT Quarterly is a publication of In-Q-Tel, Inc., the strategic investment firm that serves as a bridge between the U.S. Intelligence Community and venture-backed startup firms on the leading edge of technological innovation. *IQT Quarterly* advances the situational awareness component of the IQT mission, serving as a platform to debut, discuss, and debate issues of innovation in the areas of overlap between commercial potential and U.S. Intelligence Community needs. For comments or questions regarding IQT or this document, please visit www.iqt.org, write to iqtquarterly@iqt.org, or call 703-248-3000. The views expressed are those of the authors in their personal capacities and do not necessarily reflect the opinion of IQT, their employers, or the Government.

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ON OUR RADAR

THE NEW RACE FOR SPACE

By Ryan Lewis and Todd Stavish

President John F. Kennedy, speaking several months after John Glenn's historic flight aboard Friendship 7, famously proclaimed that, "No nation which expects to be the leader of other nations can expect to stay behind in this race for space." The origins of the modern space industry are rooted in one of the most renowned global competitions: the race for space between the United States and the former Soviet Union. Fifty years later, a new space race is underway that is being driven not by nations, but by venture-backed startups.

Throughout the 1960s and 1970s, space research and development was driven by government agencies seeking to expand their national security capabilities and prestige. In today's space race, this generation of venture-backed startups is challenging long-held industry conventions by leveraging the same techniques that drove innovation in the software market and applying them to space systems. As a result, space capabilities and services are rapidly becoming accessible for commercial and government consumers alike.

The changes currently unfolding in the market are truly unprecedented. While the space industry had its share of new commercial entrants in previous decades, never before has the industry experienced aggressive startup activity across every market segment. From providing reliable and affordable access to space to developing new analytics for remote sensory data, startups are looking to disrupt current practices by leveraging affordable platforms that allow them to innovate quickly and inexpensively. This approach allows companies to rapidly evolve their products and services at previously unimaginable price points.

The cost structure of these startups also allows them to pursue new types of business models. Unlike a majority of their predecessors, most new space startups are not looking to government agencies to serve as their sole or even primary customers. Instead, commercial industries serve as their main sources of revenue generation. While many of these consumers may be unfamiliar with space-based capabilities, the insights provided from space remote sensory data fit directly into existing big data, communications, or tracking and monitoring challenges. This comprehensive market change and rising commercial interest has not been lost on investors. For the first time, venture capital firms are playing an increasingly significant role in funding space startups. As more money enters the industry, more entrepreneurs are likely to join this new race.

It is important to consider why this innovation in the market is happening now. Startups are taking advantage of fundamental changes occurring across a variety of market sectors, including launch vehicles, hardware and software, satellites, and analytics.

Decreased Cost to Access Space

The ability to reach outer space safely has always been one of the biggest challenges in the space industry. As recent events have shown, rocket launches are still risky enterprises. Despite the inherent challenges of rocket science, recent advances in expanding affordable

For the first time, venture capital firms are playing an increasingly significant role in funding space startups. As more money enters the industry, more entrepreneurs are likely to join this new race.

access to space have made it possible for entrepreneurs and startups to put pathfinders and prototypes into orbit at a fraction of the cost. Demand for secondary rides has developed so rapidly that startups specializing in launch brokerage services have emerged to simplify the process for new companies. The U.S. government also helped ease access to space by supporting efforts like NASA's rideshare program, which provides secondary rides to university science projects.

Although the secondary launch market helped catalyze growth among aspiring small satellite startups, it cannot address the ever-increasing demand for launch services. From launch dates to desired orbits and altitudes, startups are demanding increasingly complex services to meet their needs on an already overtaxed system. A series of startups have emerged to meet this demand for timely, reliable, and affordable access to space. These innovations will be important not only for aspiring companies dedicated to small satellite launch, but also the current heavy lift providers who are looking to diversify their product lines.

Commodity Hardware and Software

The second major change to the space industry is the adoption of commodity hardware coupled with the use of agile development methods. The advantage of using commodity hardware is most widely recognized in "Moore's Law" — the observation that, over the history of computing hardware, the number of transistors in a dense integrated circuit doubles approximately every two years. This doubling effect creates massive computing power over generations. The power of generational doubling is not isolated to computing, however. For example, space startups are utilizing the rapid pace of innovation currently experienced in solar power cells, battery systems, software-defined radios, and smartphone sensors.

The exponential improvement of commodity hardware is further amplified by the use of agile development methods, in which requirements and solutions evolve through collaboration between self-organizing, cross-functional teams. This promotes adaptive planning, evolutionary development, early delivery, continuous improvement, and rapid and flexible response to change. The end result is that a single satellite design can evolve through ten generations in one or two years — taking advantage of hardware that did not exist at the inception of the design cycle.

Standardized Satellite Buses

Expanding on the original CubeSat standard developed at California Polytechnic State University and Stanford University, manufacturers have drastically simplified the process for researchers and companies alike to procure, test, and fly their own inexpensive satellites for a wide variety of missions and/or research projects. This flexibility has catalyzed numerous startup companies to develop tailored satellite services leveraging an inexpensive satellite bus. As the standard matures and companies support different elements of the supply chain, it will become easier for individuals and companies interested in CubeSats to experiment with their own satellites.

Common Analytic Engines and Services

Historically, the analysis of remote sensory data from space assets required a series of highly trained professionals to prepare, analyze, and disseminate the data to the appropriate stakeholders. While there will always be a need for highly trained professionals, the emergence of proprietary and open source analytics engines have enabled companies to sell affordable analytic products, not just raw data.

The shift from raw data to insights will have a substantial impact on the market. Companies, both incumbents and startups, now have new product lines to sell customers. Furthermore, it has given rise to a new group of startups focusing exclusively on remote sensory analytics. Thus, a major barrier to entry for most commercial companies interested in space-based remote sensing data has been removed. Companies, no longer encumbered by analytic challenges associated with raw data exploitation, focus directly on business needs by purchasing tailored analytic products.

In conclusion, the transformation occurring in the commercial space industry is undeniable, but change is not easy. In each market segment, consumers, both public and private alike, are slowly being forced to reconsider how they currently plan, buy, and use commercial space services and products. Similar to the software market, customers, including the Intelligence Community, will be increasingly challenged to decide between a series of companies, not simply one or two sole-source suppliers.

Recognizing this shift in the space market, IQT is undertaking a strategic mission initiative focused on exploring the commercial space revolution. Going beyond IQT's core investment model, this initiative seeks to provide the IC with a mechanism to rapidly understand, architect, and demonstrate the art of the possible using new capabilities from the emerging commercial space industry.

As space services become the realm of startups, not just governments, the IC and its partners must consider the implications of global commercial sales. While these market forces present both changes and challenges, it is truly an unprecedented time in the market. The new space race is on. Q

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A Look Inside: Cosmic Shift

This issue of the *IQT Quarterly* examines recent advances in space technologies. Commodity hardware and software, agile development, and small satellites are among the factors that have lowered the barriers to entry for a growing class of space-related startups who are driving the new, commercialized space race.

Peter Beck of Rocket Lab opens the issue with a discussion of the small satellite and orbital launch vehicle markets. While small satellite business has experienced significant growth in the past year, orbital launches have remained cost-prohibitive and infrequent. Rocket Lab aims to generate new launch opportunities and applications with low-cost, mass-produced small launch vehicles.

Next, Rob Call and Andrew Kalman of Pumpkin introduce the CubeSat Kit line of modular satellites. They suggest that these small spacecraft are poised to populate low-Earth orbit (LEO) in significant quantities and provide increased utility at a fraction of the cost of traditional satellites.

Rich Leshner describes Planet Labs' agile aerospace approach to building small satellites, which uses in-house processes to shorten development timelines, reduce costs, and quickly iterate for rapid performance improvements. Planet Labs aims to drastically improve traditional imagery revisit rates by launching a constellation of small satellites to image the entire Earth every day at 3-5 meter resolution.

Aaron Q. Rogers of The Johns Hopkins University Applied Physics Laboratory continues the conversation on small satellites with commentary on the capabilities and limitations of various form factors.

Next, Pavel Machalek of Spaceknow discusses how the ubiquitous satellite data provided by a dense network of small satellites will impact imagery analytics. Systems of the near future will utilize a continuous data stream and near real-time analysis to provide critical intelligence on change detection.

Paul Graziani explores a new model for space situational awareness (SSA), the detection, tracking, and characterization of space objects from a variety of sensors. Analytical Graphics, Inc. (AGI) leverages new technologies to offer persistent tracking and provide users with clear, holistic data about their satellites and the objects around them.

Beyond the focus areas presented in this issue, there is a range of innovative technologies being developed in space-related startups and academia. It is critical for the IC to address this rapidly changing market, and gain an early understanding of the opportunities and challenges presented by the new space race. Q

SPACE IS OPEN FOR BUSINESS

By Peter Beck

The small satellite industry is reaching an inflection point, with a 269 percent increase in the market in the last year. Dedicated orbital launches, on the other hand, have remained prohibitively expensive and infrequent. Rocket Lab is building the Electron launch vehicle to tie the two markets together and provide dedicated orbital launches for the current cost of a secondary rideshare.

For most people, the idea of a rocket launch brings up images from the Apollo era: monstrous booster engines, ground-shaking noise, and a behemoth of a machine slowly climbing against the grasp of Earth's gravity. This iconic image — the one that transformed us into a space-going species — captures the power and strength of rockets. But it is not the image that will make space a commercial reality.

Replace this image with the bustle of a high-speed assembly line, where rocket boosters feed off a conveyor belt connecting to pre-encapsulated payload stages, rolling out on to the launchpad one after the other. This image, by contrast, is about speed and efficiency.

Last year, the United States launched 19 dedicated orbital missions, at an average cost of $132 million per launch. Still waiting on its Model-T transformation, the way we access space has changed little in the past fifty years. Not only is the design philosophy unchanged, but the actual hardware used today was physically built decades ago.

Where Is My Internet From Space?

Satellites today are becoming smaller and lighter, using distributed networks to achieve the same performance as traditional multi-ton, multi-billion dollar assets. Constellations such as the Iridium network have paved the way for a new wave of distributed space architectures, including the highly successful Skybox Imaging and Planet Labs constellations, that have used the CubeSat standard to reduce production time and cost. Although slower to react, many government organizations are also looking to disaggregate their assets into multiple smaller payloads.

A market analysis by SpaceWorks in 2014 reported a 269 percent growth in the small satellite market since 2013. More importantly, the report revealed that the application of small satellites is moving beyond technology demonstration, with Earth observation and scientific applications overtaking technology demonstration as the leading use case for sub-50 kg satellites.

Although there are clear advantages to distributed space architectures — namely risk reduction and the ability to replace malfunctioning or outdated satellites — launching small satellites reliably, cost-effectively, and on schedule remains the biggest obstacle for the small satellite industry.

Launch Options for Small Satellites

Today, small satellites overcome the high price of launch either by piggybacking rides as secondary payloads on larger rockets, or by pooling resources and flying on cheaper non-U.S. rockets or converted ballistic missiles.

While secondary rideshare has provided a valuable avenue for technology demonstration, especially for the CubeSat class of satellites, additional dedicated launch services will be required as the industry moves from technology demonstration to commercial ventures with specific orbit and timing requirements.

Recent market analysis predicts that 945 launches will be required for 100 kg satellites in the next five years. However, the U.S. government's use of converted intercontinental ballistic missiles (ICBMs) has severely depressed investment in new small and medium launch vehicles in recent decades. Despite a market opportunity of $4.9 billion, the number of dedicated small launch vehicles available today is zero.

Small Rockets for Small Satellites

The primary obstacles for dedicated small launch vehicles are overcoming fixed costs such as launch fees, and maintaining efficient propellant mass fractions for the small vehicle.

Several projects aiming to overcome these challenges have emerged, including DARPA's Airborne Launch Assist Space Access (ALASA) program that recently selected Boeing to develop a small satellite launch system for delivering payloads up to 45 kg into orbit for $1 million each.

Air launch, while often seen as a compelling solution to reduce thrust requirements and mitigate range costs, has so far failed to gain traction in the industry. Orbital Science's air-launched Pegasus rocket, the most successful air-launched vehicle to date, has only launched twice per year on average in its 24-year history, with expensive launch costs in excess of $35 million often cited as the reason for the lack of demand.

Rocket Lab's Electron launcher is part of the new style of small launch vehicles designed from the outset to be purpose-built for the 100 kg class of satellites. As a cryogenic liquid pump-fed carbon-composite vehicle, Electron is capable of delivering payloads up to 110 kg to sun-synchronous orbits. Launches are priced at $4.9 million, the current average cost of a rideshare.

Maintaining Efficiency in Small Launch Vehicles

Electron's technology is as simple as possible, based on the idea that simplicity is strongly correlated with reliability and low cost. To this end, several R&D programs have developed reliable and low-cost systems, including two new patented propulsion technologies.

The requirement for mass production and standardized components affects all levels of the design, from

Rocket Lab's Electron launch vehicle.

Rocket Lab's Electron launch vehicle.

individual fasteners to the standardized Rutherford engine used on both the first and second stages.

Rocket Lab's 3,000 pound thrust Rutherford engine is a turbo-pumped, liquid oxygen Rocket Propellant-1 (RP1) engine tailored to the performance and throughput requirements of the Electron launcher. Electron uses nine Rutherford engines on the first stage, for a combined liftoff thrust of 27,000-lbf, and a single Rutherford engine on the second stage. Rutherford testing is now at a mature stage, with an average of one hot fire every three days.

Extensive use of carbon composite technology enables a mass fraction of 90 percent for the propellant tank systems. While composite technology can offer significant reductions in mass, it has traditionally been incompatible with the storage of cryogenic liquids. Compared to monolithic structures, the carbon fiber/epoxy construction is more susceptible to thermal stresses that can lead to the propagation of microscopic cracks and eventually cause failure.

The issue of microcracking was resolved following an extensive R&D program, and Electron's cryogenic tanks are now qualified for flight. With a standardized tank structure, Electron's tanks are formed from a common mandrel, making them 60 percent lower cost and faster to manufacture than aluminum tanks.

Vertically Integrated Launch System

Since its foundation in 2007, Rocket Lab has delivered a range of complete rocket systems and technologies for low-cost payload deployment, including contracts with DARPA, Lockheed Martin, and Aerojet Rocketdyne. The Electron program is funded through Silicon Valley-based venture capital, transitioning to commercial operations following the first test flight in 2015.

Either by way of geographical isolation or a stubborn reaction to traditional aerospace monopolies, Rocket Lab has focused on growing in-house capabilities and now has complete vertical integration over the entire launch process. Accordingly, all major propulsion, structural, and electronic systems are designed and tested in-house.

Vertical integration of the launch process extends to Rocket Lab's purpose-built launch range currently under development in New Zealand. While New Zealand is not an ideal launch site for equatorial launches, it is highly attractive to low-Earth orbiting small satellites. The site has access to a wide range of orbits, including high inclination (up to 45 degrees) sun-synchronous.

Compared to launching from U.S. government facilities, launching from New Zealand enables a 100-fold reduction in launch range cost and frequency. Unlike the $700,000 average cost associated with U.S. Air Force bases, the fee to launch from New Zealand is a nominal $400.

With relatively negligible air traffic and the geographic advantages of an isolated island nation, the New Zealand site is a core part of Rocket Lab's strategy for achieving a target of one launch per week.

Plug and Play Encapsulation

Following the launch range limitations, the second largest obstacle to achieving high launch frequencies is the lengthy and expensive process of payload integration.

Delays in schedule to either the launch vehicle or the payload are compounded in the integration phase, with a cascading effect on subsequent launches. This is especially true for missions with specific launch windows, which can cause lengthy delays and idle assets and facilities.

Recent market analysis indicates 32 percent of delays for launching nano and microsatellites were caused by development delays. To achieve a sustained launch frequency of one per week — or in even more ambitious cases, one per day — the integration process must be independent from the booster assembly to eliminate this source of risk.

In the Electron model, payload owners have the ability to encapsulate their assets into Electron's fairing stage independently of the main booster assembly, using their own facilities and personnel. The sealed payload is transported to the launch facility where integration with the booster can occur in a matter of hours.

Electron's technology is as simple as possible, based on the idea that simplicity is strongly correlated with reliability and low cost.

Testing Rocket Lab's 3,000 pound thrust Rutherford engine.

For the launch provider, a decoupled integration process reduces duplicated resources, especially of expensive clean room environments. Most importantly, the launch provider retains control of the schedule, with minimum waste in resources and available launch slots.

The Road Forward

If there was any doubt as to the growth in the small satellite market, the level of interest in an untested launcher would go far to erase it. Electron has secured commitments for its first 30 launches to be announced in the coming months, including a payload for its maiden test flight scheduled for late 2015.

Moving forward, there will always be a market for traditional rideshares, especially for technology demonstration and R&D. Dedicated launch vehicles, with their ability to provide high frequency launch to specific orbit and timing requirements, will play an important role for commercial constellations and future applications such as remote sensing and low-latency, high-speed communication. More excitingly, like the disruptive innovation of the mass-produced automobile, mass-produced small launch vehicles will also have the potential to generate applications that cannot yet be anticipated.

Peter Beck *is the CEO and Technical Director of Rocket Lab. Since founding Rocket Lab in 2007, he has grown the company in both New Zealand and the United States into a premier institute for innovative space systems, and has led the company through numerous milestones including becoming the first private company to reach space in the southern hemisphere with the Atea-1 suborbital sounding rocket. Beck is an acclaimed scientist and engineer, having been awarded a Meritorious Medal and the Cooper Medal from the Royal Aeronautical Society, and multiple innovation, engineering, and business awards.*

The Second Decade of CubeSats: Utility Cubed

By Rob Call and Andrew E. Kalman

Can an off-the-shelf spacecraft accomplish your mission? Are non-traditional, agile, entrepreneurial companies the key to success in small satellites?

Within the space industry, CubeSats were considered novelties, even toys, when the first units were launched in 2003. Originally used to educate aerospace students, gather data for simple science missions, and beep at ham radio operators, these toaster-sized spacecraft are poised to populate low-Earth orbit (LEO) in significant quantities and provide utility at a fraction of the cost of traditional satellites.

Pumpkin's MISC 3 CubeSat.

A seminal paper at the 2008 SmallSat Conference entitled, "MISC-Miniature Imaging SpaceCraft" foresaw mass production of low-cost optical imaging satellites whose lack of high resolution would be offset by high temporal resolution.[1] In other words, the revisit rate of a number of satellites could show multiple images per day of the same area. As a step in realizing the imagined future, there are already large constellations of simple satellites operated by entrepreneurial companies.

Background

In 1999, Bob Twiggs, then the head of Stanford's Space Systems and Development Laboratory (SSDL), proposed the idea of a 10 cm x 10 cm x 10 cm satellite — known as 1U. Foreseeing an opportunity to provide a commercial off-the-shelf (COTS) space vehicle, Pumpkin, Inc. created the CubeSat Kit™ (CSK) line of modular, adaptable components which became a de facto standard. An ecosystem of CSK-compatible products formed, as startups offered additional drop-in components such as radios, power systems, and other subsystems designed for Pumpkin's CSK bus.

The original 1U cube grew to 3U as customers realized that the larger form factor permitted three-axis pointing and greater power. Pumpkin delivered twelve 3U buses to the government in 2009. Designated "Colony I," these spacecraft buses provide a standard payload interface and have been the foundation of numerous missions operated by a variety of sophisticated customers.

"The Colony I bus serves as a go-to platform for getting the job done," said Dave Williamson, CubeSat Program Office Technical Lead at NRO. "While current bus platforms promise more sophisticated performance, the Colony I has provided reliable on-orbit performance for several government payload programs including those developed by the Naval Research Laboratory (NRL), the Air Force Institute of Technology (AFIT), the Department of Homeland Security (DHS), and the U.S. Naval Academy (USNA)."

CubeSats proliferated to the point that, at times, there was a backlog awaiting launch. Pumpkin alone has delivered more than 300 CSK around the world, with many launched outside the U.S.

CubeSats are no longer sitting on shelves awaiting a ride to LEO, thanks to numerous innovations, such as the Aft Bulkhead Carrier (ABC) on the Atlas V, deployment from the International Space Station (ISS), and new launch vehicles (LVs) such as SpaceX's Falcon.[2] New deployers allow simple manifest on most LVs for sizes greater than 3U. Pumpkin's 6U bus offers more than double the payload accommodation along with higher data rates and encrypted communications.

Typical CubeSat orbits are on the low range of LEO, at an altitude of approximately 300 kilometers (LEO extends to 1,200 km). The LEO space environment is relatively benign, obscured from the sun for about half the orbit and generally below the Van Allen radiation belts. Many LEO orbits are even below the ISS.

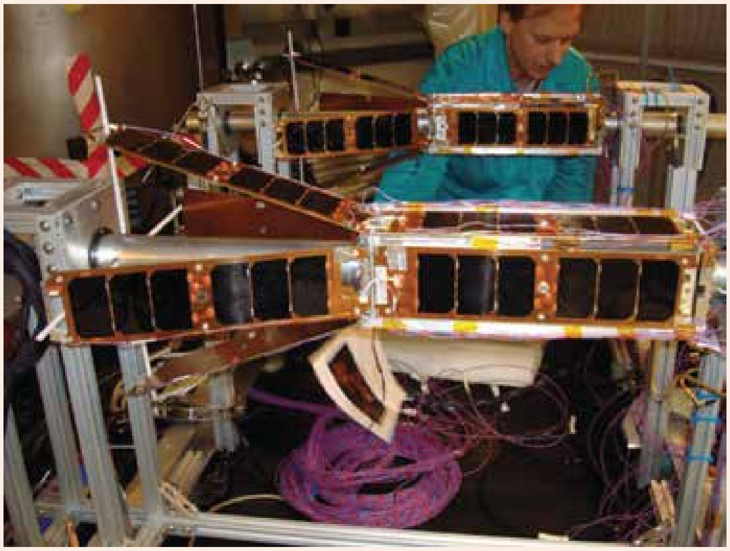
At these altitudes there is exoatmospheric drag, which is beneficial for mitigating concerns regarding space debris. Drag-induced orbital decay will cause burn-up within a few years, while the small mass ensures that virtually nothing survives reentry.

Benefits

Aside from the obvious cost advantages of reducing launch mass — and launching to lower orbits — volume production offers economies of scale and a short product lifecycle. For example, Pumpkin manufactures most components in lots of fifty, which allows for cost efficiencies, as well as a parts inventory from which to build bespoke spacecraft with lead times of only a few months.

The shortened product lifecycle allows the technology on orbit to be refreshed frequently. Since the spacecraft will be replaced in a relatively short period of time, expensive measures to eliminate any chance of failure, however remote, are not warranted. Triple redundancy, radiation hardness, and the like are not well matched to the CubeSat paradigm.

Of course, cost per node on orbit is only part of the equation. The cost savings from less complex spacecraft are offset by a larger number of nodes. This too has benefits, with enhanced economies of scale and the possibility of global coverage.



The Naval Research Laboratory launched these two Pumpkin Colony I CubeSats in 2010 as QbX1 and QbX2.[3]

A spacecraft in LEO makes one orbit in about 90 minutes, passing overhead — horizon to horizon — in about ten minutes. Only a relatively small number of CubeSats are required to ensure near constant overhead coverage.

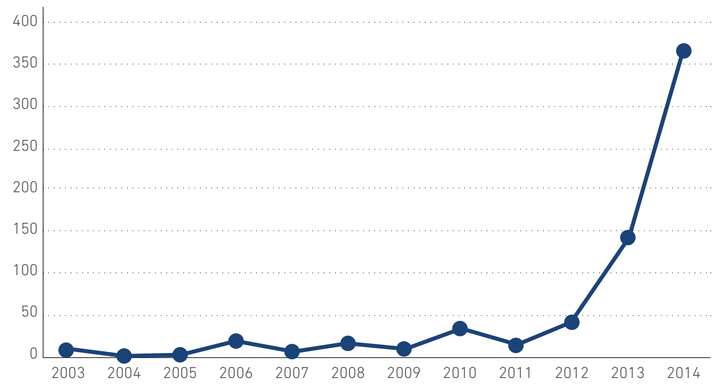
While they may be placed into strictly defined constellations, CubeSats lend themselves to more casually dispersed "clusters" or swarms of somewhat randomly dispersed nodes. This dynamic permits greater risk-taking since no single node is critical.

For Earth observation, the limited capabilities of smaller apertures can be offset through lower orbits and the attendant higher imaging resolution.

The low cross-section and low observability of a single 5 kg CubeSat offer inherent defensiveness. The sheer number of CubeSats on orbit also provides enhanced robustness.

CubeSats are simple and affordable enough that one can envision them being stockpiled, on the ground or in orbit, ready to be launched on demand.

CubeSats Deployed (Total Units)



Applications

While optical imaging was among the first applications seriously considered, and later implemented, it is not necessarily the most promising. Small, deployable antennas, or even low-drag patch antennas, are well-suited for radio applications on CubeSats.

Applications for RF payload include SIGINT; tagging and tracking; intelligence, surveillance, and reconnaissance (ISR); and space situational awareness (SSA). As an example, a recent European mission demonstrated the ease of tracking aircraft from LEO using an ADS-B receiver on a 2 kg CubeSat. Other CubeSat missions have demonstrated ship tracking via AIS. Advances in deployable structures are reaching the stage where larger CubeSats (e.g., 12U or 24U) might even be able to operate radar.

Multiple on-orbit nodes allow for determination of location via triangulation in cases where transponder data is encrypted. Various forms of stereo imaging are also possible depending on the types of sensors.

Despite the unseasonably calm space weather of the current solar cycle, disturbances still occur. A distributed network of sensors could be instrumental in mapping changes in the ionosphere in order to recalibrate communications and navigation systems.

The authors can only hypothesize as to all possible applications. In this regard, we view CubeSats as pawns on the chessboard of LEO. Moving just one step at a time, pawns are not flashy, but since you start a chess match with eight of them, you cover the width of the board without sweating the loss of any single one.

Challenges

While the benefits of tiny spacecraft are exciting and provoke creative mission concepts, there is work to be done. Generally, these challenges are not technical; very little truly new science is required. Even in terms of engineering, much of what is needed is creatively packaging existing consumer electronics into a box that can be placed in LEO.

Financing is always a challenge. While spaceflight has been the domain of well-funded governments for most of the space age, future success hinges on offering value to a broader set of consumers. Success in space means bringing value to people on Earth, whether that means navigating to your in-laws using GPS, listening to satellite radio in the car, or watching sports on satellite TV once you arrive. Government funding must pass a stricter test: "How does this benefit the national interest?"

Perhaps the greatest challenge to our community is from international competition. The CubeSat form factor opened the door to universities around the world. Countries that never had a space program have now designed, built, and launched successive iterations of increasing complexity. For much of the first decade of CubeSats, the number of launches outside the U.S. exceeded U.S. missions. A new kind of space race has begun, with lower barriers to entry, and, based on the pace of innovation abroad, it is not clear that the U.S. is ahead.

Opportunities

Inter-space links (ISLs) are one key to reaping benefits from large numbers of spacecraft. While ISLs are already in use on larger platforms, only the simplest of ISLs have been demonstrated between CubeSats. Implementing radios and antennas for ISL, in addition to standard ground station communications, is not technically difficult; however, this effort is only worthwhile when there is a sufficient number of nodes on orbit.

Once the number of nodes increases to the point where each CubeSat is generally in communication with one or more other CubeSats, the network effect comes into play. Terrestrial computing transcended this barrier with Wi-Fi-enabled laptop computers, routers, and the Internet. Now we take for granted our interconnected handheld devices. But why are our cars, TVs, and phones more savvy than what operates in space?

We see the opportunity in LEO as analogous to smartphones, which communicate globally via nearby cell towers, but also to nearby computers via Wi-Fi, or other devices via Bluetooth. The more people have these devices, the more useful they are. Now that they are nearly ubiquitous, these devices are mass produced for a surprisingly reasonable cost. We expect the same will be true in LEO as the production volume of spacecraft hardware — primarily electronics — grows. Simultaneously, spacecraft are making greater use of electronics that are already in mass production.

Autonomous operations — realistically semi-autonomous — are another promising opportunity. Current space architectures require tremendous ground support. There is a significant need for spacecraft that are able to execute a mission with less user attention. Especially as we move towards larger groups of smaller spacecraft, ground architecture must be simplified through automation. With processing power on CubeSats equal to laptop computers, the opportunity lies in developing the sort of apps used in home automation, such as smart thermostats that learn users' desired comfort settings when they are not home.

The single greatest opportunity in space will arise from harnessing the entrepreneurial spirit of Silicon Valley to find creative new applications on orbit. The NRO's Williamson believes that, "non-traditional, agile small businesses are key to responding to the dynamic partnership environment critical to the success of the small satellite market."

Small companies and startups have created much of the recent web-based and mobile technology we take for granted in our daily lives. As mission developers reach out to this community, leveraging their energy and ingenuity, we can expect this pace of innovation to extend into space.

Conclusions

Moore's Law posits that costs decrease and computing power increases as the number of transistors per chip rises. Pumpkin's Paradigm: The more tiny, smart satellite nodes in LEO, the lower the mission cost and the higher the utility.

Just as we could not have predicted in 2005 that we would be using our phones as we do today, we cannot tell you today exactly what CubeSats will be doing in 2020. Applications that do not make sense on traditional space platforms will be created and will harness distributed networks of tiny satellites. Who would have predicted a billion cell phones in use on the surface of the Earth? What is the upper limit for CubeSats in LEO? Q

Rob Call *joined Pumpkin, Inc. in 2008. He began his career as a Corporate Strategy Consultant with Bain & Company and has been instrumental in growing numerous businesses worldwide. Call earned an M.B.A. from the Wharton School at the University of Pennsylvania and a B.A. from Stanford University.*

Dr. Andrew E. Kalman *is Founder, President, and Chief Technologist of Pumpkin, Inc. Pumpkin designs and builds flight hardware for NanoSats and CubeSats including turnkey spacecraft buses. Pumpkin has delivered hardware and software for more than 20 space missions since 2004 without ever having sought external financing. Kalman is a Consulting Professor in the Aero/Astro Department at Stanford University. He is also Director of Stanford's Space and Systems Development Laboratory, where the CubeSat standard was created. Kalman earned his doctorate in Electrical Engineering at The University of Florida.*

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Planet Labs satellites. *(Photo: NASA)*

SEEING THE WHOLE EARTH, EVERY DAY: MORE THAN A THOUGHT EXPERIMENT

By Rich Leshner

It is an understatement to say that satellite development projects can cost large sums of money, and take several years to complete. Often this is unavoidable, as the performance of space systems dictates a certain level of investment, and a certain kind of diligence in management. However, the capabilities and services these systems provide are often needed before they are available, and any delays that arise only exacerbate the gap between need and availability. It has long been the goal of many in the space community to find more rapid development paths for space systems, so as to bring new capabilities to bear faster for those who need them.

Planet Labs is using an approach called agile aerospace to shorten development timelines, lower costs, and bring the information made available by space systems to users more rapidly and efficiently. It intends to launch a constellation of small spacecraft to image the whole Earth every day at 3-5 meter resolution, and make the information collected available via the Cloud, so that global change can be visible, accessible, and actionable. The constellation will be quickly manufactured and consistently refreshed, so that its space systems are operating with the latest technology. Planet Labs calls this Mission One.

How We Get There: The Space Segment

Founded in 2010, Planet Labs designs and builds small satellites via an agile aerospace approach, which seeks cost efficiencies and rapid improvements in performance. Satellite design, integration, testing, and demonstration is done in-house. By establishing processes for quality assurance and control, an entirely new industrial capacity for the rapid manufacturing of large numbers of spacecraft has been created. In just over two-and-a-half years, the company has gone through 12 complete satellite design iterations, built and prepared for launch 97 satellites, called Doves (Figure 1), and successfully launched 71 of those satellites across a total of 7 launch campaigns. The company can go from zero to more than 20 satellites built, tested, and ready for launch in only a couple of months. Planet Labs has the full in-house capability to operate these spacecraft and is building a new suite of automated tools to do so as efficiently as possible. The Doves are highly capable, with pointing and stability control; GPS, S- and X-band communications; and capacity for orbital maneuvers. They have been launched under the authority of a commercial remote sensing license, granted by NOAA, and with licenses from the FCC for spectrum utilization. Planet Labs conforms to provisions necessary to avoid contributing to orbital debris, coordinates orbital maneuvers regularly with the JSPOC, and is fully committed to being good actors, neighbors, and partners in orbit.

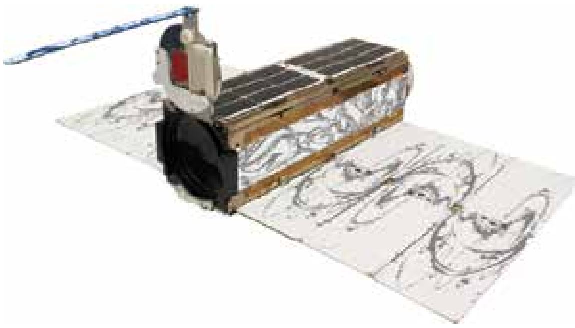

Figure 1 | The Planet Labs Dove spacecraft (3U form factor).

Figure 2 | The Planet Labs mission — small satellites creating a line-scanner of the Earth.

Even with its achievements to date, Planet Labs is still in development mode. Of the 71 satellites launched, more than two dozen remain in operation, and another dozen await deployment from the ISS. Planet Labs had 26 satellites on the Antares launch vehicle that was lost on October 28, 2014 and this 26-satellite flock (a large group of satellites) contained a mix of 16 unique technology demonstrations. This mix exemplifies agile aerospace: building and testing on the ground, which feeds into building and testing in space, which in turn feeds further continuous cycles of ground and on-orbit building and testing. Take what you learn, lock in the next build, manufacture a flock, and get it launched. This approach allowed Planet Labs to quickly build two replacement spacecraft for launch on the upcoming SpaceX cargo mission to the ISS.

The purpose of this continuous build and test approach is to finalize an operational satellite design intended for deployment into orbit by 2016, thus making Mission One a reality. Ideally, Planet Labs will place 100 or more satellites into sun-synchronous orbit to collect imagery of the Earth. The Doves will point on nadir, taking a snapshot of the Earth roughly once per second — thus creating an effective line scanner of the globe (Figure 2). With this many satellites in orbit, the company expects this monitoring mission to yield a new picture of every place on Earth every day.

How We Get There: The Data Segment

Getting satellites in orbit, and then getting the data downloaded, is the backbone of Mission One, but it is not the endpoint. The next step is creating a global mosaic, refreshed rapidly from imagery collected every day. This mosaic will be a seamless, uniform view of the Earth from space, with consistent look angle and shadowing. Stated somewhat differently — Planet Labs intends to create a foundational, global base map, updated frequently, with a stack of imagery that gets deeper the longer the company is in operation.

Making this mosaic from raw satellite imagery, and assuring ourselves that it will be refreshed rapidly, involves creating new techniques for georectification, color correction, and other processes in order to be sure that what's being viewed is what and where Planet Labs says it is on the planet. The company wants to do as much of this as possible open source, and it already is (you can find Planet Labs on GitHub). In addition to mosaics, individual images, or scenes, will be available via an online platform. An application programming interface (API) is being built to interact with that platform as well as a graphical user interface to create a new look and feel for both sophisticated and new users of geospatial data. And, to be ready for Mission One and the challenge of moving terabytes of data per day, it's all being done in the Cloud.

Everywhere, Every Day — Implications and Opportunities

Planet Labs' approach to Earth imaging is notably different than all existing Earth observing missions — whether for science or more directed surveillance and reconnaissance needs. Landsat, for example, takes images in the same consistent, down-looking mode, but it does not have the same refresh rate. Satellites used by the defense and intelligence communities, both commercially and government owned and operated, have greater spatial resolution and collectively cover more of the spectrum. They operate in a tasking mode based on priorities and needs of the end users of that imagery. They are highly capable, as they need to be, so

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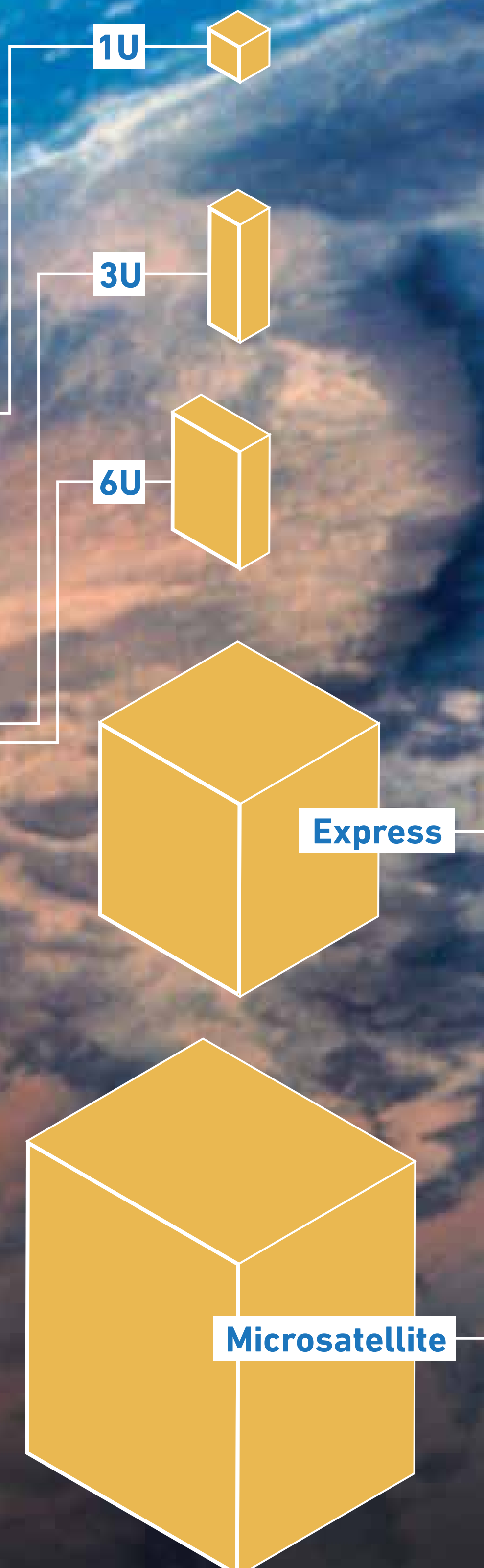
A COSMIC SHIFT

By Aaron Q. Rogers

Small satellites are driving a commercial space revolution

A combination of technological innovation, market forces, and on-orbit success are exponentially building momentum for small satellites to execute a broad range of compelling civil, national security, and commercial mission applications. While the use of this class of spacecraft was historically focused on experimentation, a major change is upon the community with a host of commercially-focused endeavors that are proffering disruptive services, lowering costs for space-sourced analytic products, and dramatically increasing spatial and temporal understanding of the Earth. The form factors of the satellites being employed span the smallest 1U (one unit) CubeSat to microsatellites approaching 200 kg.



10 cm x 10 cm x 10 cm
1 - 1.5 kg

Representing the fundamental canonical unit of a CubeSat space vehicle, the 1U form factor has historically represented a meaningful and accessible/affordable constraint to university programs seeking to bridge engineering principles with hands-on experience. While diminishing in present day usage — as the cost and space access barriers to developing larger, more capable designs decrease — the global community has been very effective in producing 1U CubeSats with highly integrated packaging, conducting simple purpose experiments benefited by multi-point measurement (e.g., radiation dosimetry), and standing up grassroots federated ground networks for command and control.

10 cm x 10 cm x 34 cm
4 - 5.5 kg

Moving from classroom learning projects to expectations of utility, early developers recognized that volume was the most constraining resource. The first "triple" CubeSat, QuakeSat, was launched in 2003 to provide a space-based monitoring capability for seismic activity. This form factor takes advantage of the entire contiguous volume within a CubeSat deployer to permit a larger space vehicle design that is capable of incorporating all the functionality typically found in much larger systems. While physics still constrains the limits of packaging and performance, significant operational capability and utility has been demonstrated within this class of small satellite. Among leading examples, Planet Labs provides global imagery with unprecedented spatial cadence achieved through a continuously refreshed constellation of more than 100 small satellites launched to date. Similarly, privately-financed Planetary Resources Corporation is building 3U CubeSats to validate enabling components of its asteroid prospecting architecture.

10 cm x 22.5 cm x 34 cm
8 - 12 kg

With more than double the volume of 3U and several deployers expected to be flight-qualified in 2015, 6U is emerging as the preferred standard for nanosatellite missions — particularly by those who have already tackled the tough engineering and packaging challenges of 3U and smaller form factors. The additional size translates to an increased ability to utilize commercial off-the-shelf (COTS) technologies and advanced components, as well as significant accommodation provisions for one or more payloads — or small propulsion systems. As a consequence, 6U systems are now being developed with the intent to serve as on-orbit testbeds for prototype sensors and instruments, pathfinders for larger systems, and even endeavor into new space domains as part of lunar and interplanetary missions.

47 cm x 47 cm x 56 cm*

25 - 75 kg

Postured as an intermediary space vehicle solution between 3U/6U CubeSats and microsatellites, Express-class systems are envisioned to both dramatically extend accommodation provisions to payloads (e.g., volume, mass, and power) and more optimally utilize the abundant residual capacity of launch vehicles for secondary rideshare to orbit. The larger form factor also enables greater use of mature COTS technologies, as well as mission-enabling elements like propulsion — critical for orbital maneuvers such as phasing constellations. Presently, several government organizations and national laboratories like The Johns Hopkins University Applied Physics Laboratory are exploring concepts for missions in this class, including those supporting technology risk reduction, disruption-tolerant communications networks, and both terrestrial and space weather applications.

60 cm x 71 cm x 91 cm*

100 - 181 kg

Crossing a critical threshold of highly-integrated engineering design, small microsatellites are the most directly positioned to address large-scale, high-performance mission applications by way of constellation architectures. Representing the antithesis of monolithic, exquisite systems, companies like Skybox Imaging and OmniEarth are deploying globally distributed remote sensing platforms with comparatively modest, state-of-the-industry engineering sensor solutions, but with the unique ability to aggregate, assimilate, and exploit large data sets derived from full-motion video and hyperspectral data. Other endeavors, such as WorldVu, are seeking to bring Wi-Fi to areas of the globe without Internet access. In all of these efforts, large-scale production manufacturing and advanced analytical methods are underpinning the value proposition.

*Express-class and microsatellite dimensions are approximate, and may vary based on specific launch conditions.

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Photo: The Johns Hopkins University Applied Physics Laboratory designed and built two Pathfinder 3U CubeSats for the Multimission Bus Demonstration (MBD)/Vector program, which launched in November 2013.

Figure 3 | Images from Hubei Provence, China show changes in infrastructure development over one year.

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they can collect imagery of areas of interest at different viewing angles as one way of providing persistence. However, there are opportunity costs to tasking — namely, what you gain in persistent coverage in one area, you lose in opportunities for any coverage across several areas.

Planet Labs is taking a new approach to the idea of persistence. As described previously, Planet Labs aims to image every place on Earth, every day. This is a new kind of global monitoring mission, with imagery updated daily at 3-5 meter resolution. What is traded in spatial resolution is gained in temporal resolution. What is traded in persistent imaging of a certain kind in limited numbers of targeted areas is gained in persistent and consistent imaging of a new kind in all areas.

The benefits of this persistent global base map can best be illustrated by two pairs of images. Consider first the images of road and bridge construction in Hubei Province in China (Figure 3). The image on the left is from Landsat, taken in August 2013. On the right is an image from a Planet Labs satellite taken in July 2014 — almost a year later. One can see differences in the finished bridge, paved roads, and an entirely new vein of construction parallel to the river.

Second, and more interestingly, consider a pair of images from Itumbiara, Brazil, an area of agriculture activity (Figure 4). The image on the left was collected by Landsat on August 8, 2014. The image on the right was collected by Planet Labs on August 9, 2014 — the following day. One can easily discern the fire that is new on August 9, as well as areas that appear to have been tilled that day, after earlier burns (visible below the active fire).

On scales that range from one day to one year, there is obviously a great deal of power in terms of what can be learned when information is updated daily. Deep stacks of information over the course of long periods can be used for forensic analysis in the event of a catastrophe in some previously unmonitored area: perhaps something can be found to serve as a predictor or catalyst of future events. Seasonal variations can be tracked in real time and compared to years past as a way of looking for irregularities. Updated information based on changes observed in real time can inform a variety of time-sensitive decisions in business, civil government, or military operations. In slightly less time-sensitive situations, information derived from moderate resolution monitoring can be used to cue high-resolution assets to conduct more detailed collections before decisions are made. These notions are inherently speculative — because they have to be. A data set like this has never existed.

The implications and opportunities for the U.S. government based on this kind of data and information flow are potentially far-reaching. One example is a fairly straightforward, though difficult policy question: how easily can the government transform itself into a commercial customer of geospatial data and information — not defining requirements for industry, but learning how to flexibly leverage, as any other consumer, whatever is offered in the market? If Planet Labs is successful, and if others like Skybox Imaging are as well, how can the U.S. government leverage that success and direct resources to ever more exquisite capabilities or truly unique user needs?

Planet Labs' model for putting information online — a model the industry in general is moving to — means

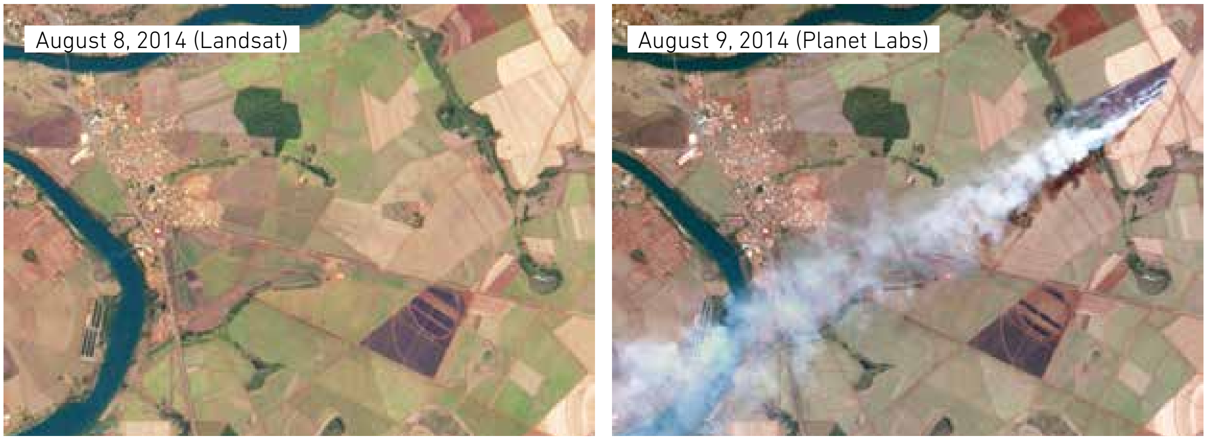

Figure 4 | Images from Itumbiara, Brazil show changes in land cover and usage over one day.

that at some point soon everyone will be looking at the same things at the same time, in real time. Information asymmetries between different groups are likely to shrink. As Planet Labs collects deeper stacks of data and as a community of commercial users, humanitarian users, and developers forms around these data, all while the community moves toward more open source practices, those asymmetries will only shrink further, at increasing speed. What new generation of practices will evolve as this happens? What will become of current efforts in crowdsourced intelligence, for example? What new standards of behavior will emerge when a global data set is available for viewing, exploitation, and analysis by global users? Again, one can speculate over those instances when the potential for shared global awareness is of obvious benefit, such as supporting humanitarian crises of various kinds. And one can equally speculate as to those instances when such shared awareness may challenge existing government practices or be a source of concern. Planet Labs is confident that the advantages for all U.S. government interests outweigh the potential risks, as increased transparency based on information easily available to everyone leads to more direct and honest dialogue and better-informed decisions. All of this will support Planet Labs' goal of making global change visible, accessible, and actionable.

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Fast Data: Satellite Imaging Analytics in the Era of CubeSats

By Pavel Machalek

As the analyst sits down at his desk, the system offers an automatically prioritized and automatically generated list of reports obtained from satellite imagery on yesterday's most significant change events globally: a collection of 15 new trucks at a North Korean nuclear testing site; a 5 percent increase in the size of a Syrian refugee camp in Jordan; an increase in the deforested area in the middle of the Amazon jungle; and an automatically reported increase in the fracking output of the North Dakota shale fields. The morning review further presents the analyst with an uptick in maritime activity in the Gulf of Aden and concludes with a report on Russian troop movements in East Ukraine as well newly detected training camps in the deserts of Mali that need further human review. All of this data is analyzed and reported automatically in text, speech, and video formats.

Availability and Cost of Satellite Imagery

Imagine a world in which the intelligence analyst has real-time access to the imaging power of hundreds of CubeSats from dozens of providers from many different countries, combined with real-time feeds from low-resolution environmental monitoring satellites like the Landsat series.[1] The deluge of imagery is no longer analyzed in a semi-manual basis by downloading imagery to the analyst's desktop, but instead freely flows from satellite or space station mounted imaging platforms, through downlink, to the satellite imaging company, and to the analyst within seconds or minutes of acquisition. Algorithms detect change in the imagery while the satellite is still overhead and issue real-time alerts to the analyst for further review.

We are rapidly approaching a world of complete saturation with low- and medium-resolution satellite imagery. Low-Earth orbit (LEO) will be full of tiny CubeSats which are always imaging, always on. No tasking requests need to be taken. Just like Twitter analyzes up to hundreds of thousands of tweets per second, it is possible to foresee a not-too-distant future where every second there will be thousands or tens of thousands of images of the Earth taken all day, every day.[2] What can be done with all that imagery? In other words, the problem is not so much big data as it is Fast Data, because the imagery has to be processed immediately as it is created, either on orbit or in-flight following a downlink. Consequently, reports and alerts need to be generated automatically without human input. Event alerts need to be issued, prompting further human review.

An unprecedented increase in the availability of medium-resolution (~5 meter ground sample distance [GSD]) and high-resolution (~1 meter GSD) satellite imagery from a variety of new CubeSat companies has led to a quiet revolution in the commercial satellite imagery market. The cost of acquiring and processing this flood of imagery is decreasing exponentially. Within a few years, Earth's entire surface will be scanned every day by constellations of U.S. and foreign imaging satellites. We envision a future where satellite data gets analyzed either on-board the space-based platform or analyzed immediately following a downlink by adopting the real-time data processing frameworks (e.g., Storm and Spark) used by leading Silicon Valley companies. Intelligence about any location on Earth from satellite imagery will be automatically analyzed by sophisticated image recognition and feature extraction algorithms, and will be available within seconds or minutes after acquisition of the imagery. How will all this satellite data be processed? What new insights can be gained by combining and analyzing massive amounts of high, medium, and low-resolution satellite data?

Making Big Data Fast

The goal of a Fast Data imagery analytics system is to derive specific intelligence on any location on Earth within seconds. In order to allow near real-time imagery analytics, we need near real-time access to high, medium, and low-resolution satellite data (see the example in Figure 1 of an area near Rome, Italy obtained through the Spaceknow satellite interface that links many imagery providers). Spaceknow has built a system that allows real-time, simultaneous fetching of satellite data from multiple providers, fast image analytics, and feature extraction of objects and locations of interest. Within 20-30 seconds (including the time to fetch the imagery), any location on Earth with available satellite imagery can have an automated, human-readable analysis. Of course, near real-time, location specific intelligence presupposes we know where to look and what to look for. What if the location of interest was unknown and one wanted to scan the entire Earth every day for generic change and issue automated alerts to the analysts?

To find an arbitrary location on Earth where a change has occurred since the previous image was taken, perhaps yesterday, the analytics would need to be done in streaming mode. There is a lot of excitement about processing the vast amounts of data generated by imaging satellites, social media data, and open geospatial data. Big data analytics usually involves batch processing massive amounts of information within the MapReduce framework, where discrete batches are analyzed at once.[3] The problem is that there

High-Resolution Image: GSD ~ 0.5 meters
(Photo: DigitalGlobe)

Medium-Resolution Image: GSD ~ 5 meters
(Photo: UrtheCast)

Low-Resolution Image: GSD ~ 30 meters
(Photo: USGS Landsat 8)

Figure 1 | High, medium, and low-resolution imagery obtained through an automated web interface for a select industrial location just south of Rome, Italy.

is an inherent time delay in this process, and thus it is not well-suited to continuous streams of ever-flowing data like tweets or large amounts of satellite imagery.

A more fitting framework for Fast Data analytics is that of streaming, where data naturally flows through the system without stopping and gets analyzed in memory.[4] Real-time data processing frameworks like Storm and Spark (used by leading Silicon Valley companies such as Twitter and Groupon) would allow for near real-time analysis of hundreds of thousands or millions of medium and low-resolution images per day.[5, 6] Such a streaming analytics system would be able to send human analysts alerts of different priority and urgency with minimum latency.

Such a real-time generic change detection system is not too far away. The current generation of low and medium-resolution imaging satellites can image on a weekly or biweekly basis, and hence the alerts can now be issued about once per week (depending on cloud cover). Once all the planned CubeSat constellations are deployed and hundreds of thousands of images float freely, daily or even sub-daily alert frequency can be achieved. We envision such a scenario happening within the next 36 months.

Combining Geospatial and Imagery Data

Let's illustrate the combination of low-resolution satellite imagery (approximately 30 meters GSD) along with publicly and commercially available geo data using a specific example: measuring the manufacturing output of the entire People's Republic of China and replicating the HSBC Purchasing Managers' Index, which is widely regarded as the most reliable metric of Chinese manufacturing (Figures 2 and 3).[7]

Spaceknow has analyzed satellite imagery for more than 6,000 industrial facilities from across China and extracted spectral information that in aggregate correlates with manufacturing output. Spaceknow analyzed more than 2.2 billion individual satellite observation points for this report, corresponding to an area of 0.5 million square kilometers spanning the last 14 years. This is possible because the provider of the low-resolution data set makes the satellite imagery immediately available through a real-time interface that allows us to request and receive 14 years of satellite data for every manufacturing facility within a few seconds. In other words, the data is stored "live" in a geo database by the satellite operator and the data user only requests small areas of interest.

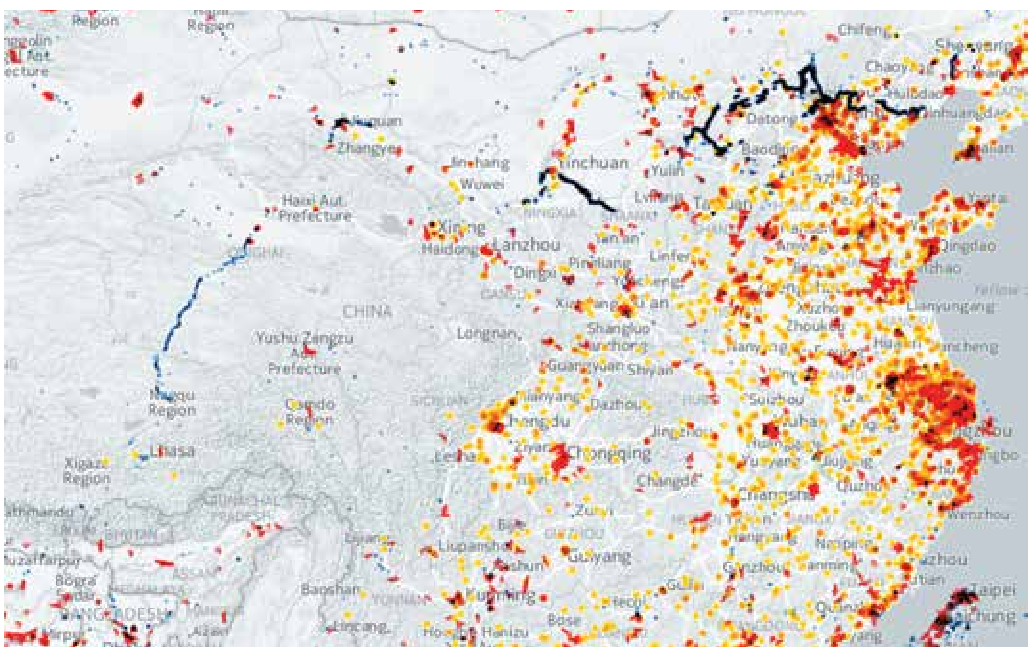

Figure 2 | Locations of manufacturing facilities in China used in the analysis.

Analyzing more than 6,000 industrial areas for a major country like China required a little over an hour on a laptop, which includes fetching the raw data over the Internet and analysis. What is significant is the access pattern to the satellite data rather than the complexity of the data or its inherent size. Spaceknow only requested imagery for the small area of the facility being analyzed and did not request any other pixels that fall outside of the boundary of the industrial facility.

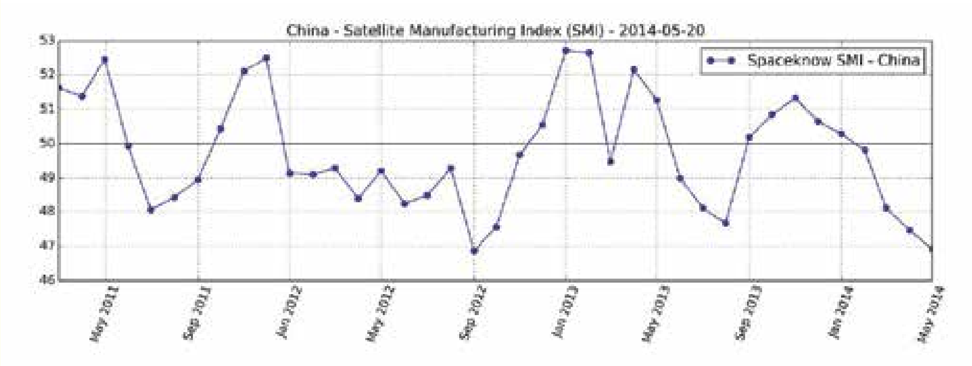

Figure 3 | Satellite Manufacturing Index (SMI) for China from 2011 to May 2014 obtained using low-resolution imaging data. SMI values above 50 show increasing manufacturing output in China, and SMI values below 50 designate decreasing manufacturing output.

All the data used in this example are unclassified, come from public or commercial sources, and are readily available. The methodology and examples developed can be readily extended to other countries very quickly. Within the next 6-18 months it will be possible to image and analyze vast amounts of industrial facilities across continents using medium (approximately 5 meters GSD) and high-resolution imagery (sub-meter GSD) to achieve highly accurate industrial intelligence on entire countries and continents at once.

Future Trends in Agile Satellite Imagery Analytics

We introduced two key concepts in this article: ubiquitous satellite imagery data provided by a dense network of CubeSats and the ability to analyze all such data in near real-time to derive time-critical intelligence for generalized change detection. Instead of downloading satellite imagery data onto desktops and analyzing it with GIS software, the satellite imagery analytics systems of the present and near future will utilize a continuous stream of data, pre-analyzed on the space platform, downlinked, analyzed in real time, and delivered to the analyst or end user within seconds or minutes of acquisition.

The satellite imagery analytics framework of the future will depend on large amounts of automatically analyzed imagery data, near real-time processing, and electro-optical imagery combined with commercially available high-throughput synthetic aperture radar (SAR) data, geo data, and social data.[8] A combination of streaming satellite imagery, frequently updated open source geo data, and real-time social data will provide a highly complex and rich data set about our breathing, living, ever-changing planet.

Dr. Pavel Machalek *is a Co-Founder of Spaceknow, Inc., a VC-funded satellite imagery analytics company based in San Francisco. Previously, Machalek was Head of Remote Sensing at the Climate Corporation, which was acquired by Monsanto Company for more than $1 billion. Throughout his career, he worked with numerous NASA observatories like Spitzer, Hubble, and Kepler Space Telescopes as Principal Investigator searching for planets in our galaxy and characterizing their atmospheres. Machalek holds a Ph.D. in Physics and Astronomy from Johns Hopkins University.*

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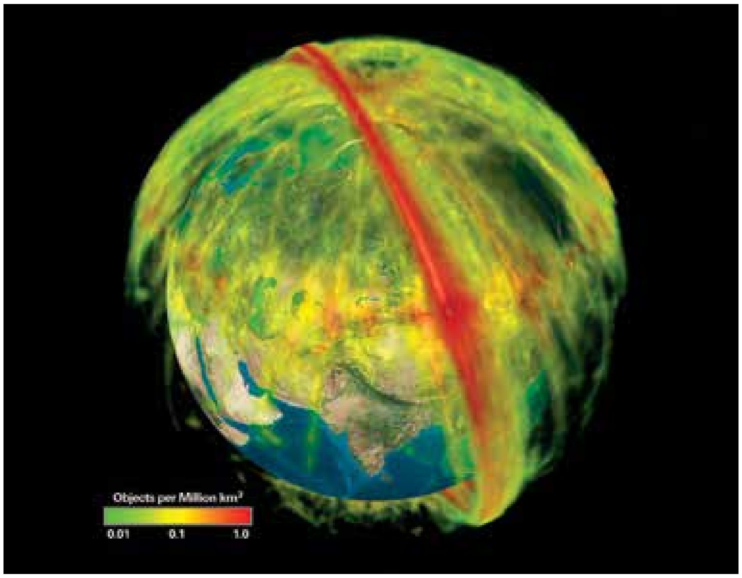


AGI's probability density cloud illustrates the crowdedness of space.

A New Model for Space Situational Awareness

By Paul Graziani

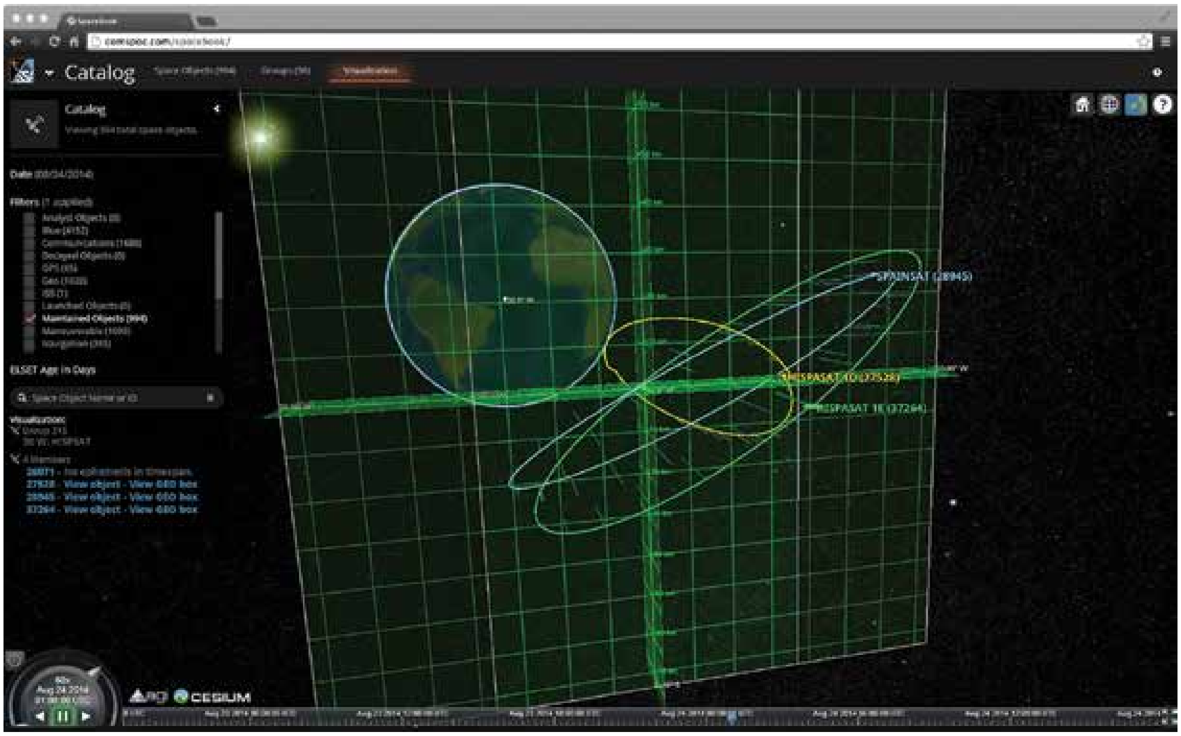
Space is a complex ecosystem populated by growing numbers of multi-national commercial and military satellite networks and sensors that are critical to the daily functioning of large-scale industries, ranging from banking and transportation to science, energy, and national security. According to *The Space Report 2014*, the global space economy grew by 4 percent in 2013 — establishing a new record of $314.17 billion — with the majority of that growth fueled by commercial space products, services, infrastructure, and support industries. While commercial activities are dominating the space market, customers everywhere are "demanding, and receiving, greater control over the way they interact with space products and services."[1]

Government spending on space may be declining worldwide, but no one can dispute our burgeoning dependence on space services for commercial and military applications such as communications, navigation, timing, and intelligence. The number of space objects is increasing; satellite size is decreasing; the number of capabilities resident on each satellite is growing; multiple-payload launches are dramatically increasing the number of objects placed into orbit at one time; and the number of space-faring nations continues to rise. That space is congested, contested, and competitive is a common refrain, but space is also becoming a serious warfighting domain, according to U.S. Air Force leaders. Protecting this critical global commons is an emerging and increasingly urgent element of American national security strategy. As Lt. Gen. John "Jay" Raymond, Commander of the 14th Air Force Space Command, said in a May 2014 speech, "A day without space would be a bad day. It would be a really bad day."[2]

Raymond is not alone among military and civilian leaders in touting the importance of space situational awareness (SSA) — the detection, tracking, and characterization of man-made and natural space objects from a variety of sensors in space and on the ground. Coupled with data processing and integration, SSA data can provide advanced warning and prediction of threats to an operational satellite. The 2007 Chinese anti-satellite weapon test and the 2009 Iridium and Cosmos satellite collisions highlight the persistent threat posed by space debris, both intentionally and unintentionally generated. Ensuring the efficient and safe operation of this fragile space-based ecosystem is of the utmost strategic and economic importance. Accurate and timely SSA data is needed for day-to-day satellite operations as well as the deft maneuvering of satellites to avoid debris. Operators require real-time information on the position of their satellite, its course, what other objects are around their assets, and whether their satellite needs to maneuver to bypass other threatening objects. This is no trivial issue. With objects in low-Earth orbit (LEO) traveling at more than 17,500 miles per hour, any impact is devastating and the corresponding debris field seriously compounds the resultant SSA challenge. As a result, SSA can also be expensive, time-consuming, and manpower intensive — all of which means that SSA is ripe for the application of a new business model.

What Is ComSpOC?

Analytical Graphics, Inc. (AGI) unveiled the Commercial Space Operations Center (ComSpOC) in March 2014 as a subscription-based service that provides persistent



ComSpOC provides SpaceBook with tracking and deconfliction of complex geostationary formation flying (i.e., clusters) to improve operations and flight safety.

day and night tracking of space objects in Earth orbit for commercial satellite owners and operators as well as government space operations centers. ComSpOC leverages commercial off-the-shelf (COTS) software to process data and generates a wider and more fulsome range of SSA products. These products are then delivered through the SpaceBook portal, a service-oriented architecture (SOA)-based data and analysis subscription service that provides a page for every resident space object (RSO) containing all available information.

While the total number changes almost weekly, ComSpOC in its infancy is already tracking more than 3,000 RSOs, and this total will only increase as the concept matures and successfully transitions through the crawl, walk, and run phases of real world operations. AGI's focus on adding data and sensor partners will spur rapid growth in the number of space objects it can track in the near future. ComSpOC subscribers have access to all the information the system gathers. AGI and its partners have developed ComSpOC as a service that will give customers a more in-depth and accurate conjunction assessment — information about where a satellite is in reference to other space objects and debris — helping satellite operators eliminate maneuvers based on false positives and extending the lives of their satellites by conserving precious fuel. This already vexing problem for satellite operators will become more problematic as more objects of decreasing size are tracked.

The ComSpOC concept was galvanized by Deputy Assistant Secretary of Defense for Space Policy Doug Loverro, who in a 2013 speech, challenged commercial industry to step up and offer its best ideas to help transform military space in an era of austerity. AGI envisions ComSpOC being initially used by commercial satellite owners and operators, then expanding that resource to serve allied and friendly governments before the concept would be adopted by a variety of U.S. government agencies. Traditionally, SSA has been dominated by the U.S. government, which alone possessed the data, facilities, manpower, time, and resources to conduct SSA, primarily for national security purposes. The DoD tracks about 23,000 space objects, with about 1,100 of that total composed of active on-orbit satellites. However, the creation of ComSpOC provides new options for the focus and scope of government SSA efforts, which over time can be shifted to other higher-priority efforts. This theme is echoed in the U.S. National Space Policy of 2010, which urges the use of all sources of SSA information — derived from commercial, civil, and national security assets — to preserve the space environment and the responsible use of space.[3]

Significant changes in technology, sensors, and software are the critical enablers that have opened the SSA world to commercial competition — a marketplace that was unthinkable when the current SSA regime was established more than half a century ago. These technologies are all available today and widely understood.

Another difference in the ComSpOC model is the openness of the concept. The space community has long been a difficult environment for new companies and new ideas to penetrate. The barriers to entry to the U.S. space acquisition system have been high since only a few entities, the majority being elements of the U.S. government, exercised virtually complete control over access to space and the information coming from and related to that domain. The ComSpOC approach is to erect a "big tent" to allow other partners to play. If other companies or potential partners have different sensors or alternative data processing techniques, for example, they can be readily integrated into the overall concept. AGI is intent on opening this segment of the space marketplace to more players, users, and customers.

How Does ComSpOC Work?

This leap in affordable, accessible, and more accurate SSA tools — the core of ComSpOC — is a result of the emergence of new sensors, processing techniques, technologies, and ConOps. The space operations facility works by fusing satellite-tracking measurements from a continually growing global network of commercial sensors owned and operated by AGI's partners.

New sensors: ComSpOC's early successes and recognized potential are results of the system's partners providing optical sensors and radar data. ComSpOC is currently using 28 optical sensors, which will continue to grow in number and location over time, and one radar site. Current partners include ExoAnalytic Solutions and the Las Cumbres Observatory Global Telescope Network, which provide optical sensors; and SRI International, which provides data from RF radars and the Allen Telescope Array. The goal is to foster an open community and adopt a data standard that allows all contributors to benefit from the cumulative input and output of tracked information.

ComSpOC works by seamlessly integrating a variety of data derived from the uncooperative tracking of satellites, meaning that the system is not directly communicating with these satellite networks to ascertain their exact locations. Using this commercially-supported network of sensors, ComSpOC is currently tracking 75 percent of all geosynchronous satellites in orbit and 100 percent of those covering the continental U.S. ComSpOC generates High Definition Ephemeris (HiDEph) and other highly accurate SSA data products for resident space object characterization.

New processing: Tracking, processing, and development of the SpaceBook is accomplished through the adroit use of a unique mix of sensors, advanced algorithms, and leading-edge information processing software. The AGI software that powers ComSpOC, and performs the bulk of the track and information processing, is the same capability found in the Air Force's Joint Space Operations Center (JSpOC) Mission System (JMS) effort. AGI's industry partners also play critical roles in enabling ComSpOC's full range of capabilities, but more partners are needed to ensure a more robust system.

In ComSpOC's brief existence, AGI and its partners have already successfully tracked a space launch from geosynchronous transfer orbit (GTO) all the way to geosynchronous orbit (GEO), proven near real-time maneuver characterization and continuous custody for active GEOs with RF data, and performed closed-loop tracking — using its own assets to observe and reference tracked satellites — with optical sites. AGI has narrowed the variances in actual tracking to mere meters of difference versus kilometers of variance for other types of SSA systems currently in use elsewhere. ComSpOC is already tracking objects and processing data today that alternative solutions are still years away from achieving.

New technologies: Unlike existing government SSA networks and space operations centers, ComSpOC is designed to deliver its data and analysis through a robust HTML portal. SpaceBook allows subscribers to access data on orbits, maneuvers, conjunctions, health, status, event, and trending information of all tracked objects. SpaceBook gives subscribers a clear picture of their satellites and the objects and satellites around them, including event timelines and histories; RSO metadata such as position, status, and trending information; real-time messaging and alerts; and 4-D visualization tools. The data products in SpaceBook offer a one-stop shop for satellite operators to monitor patterns of life and receive deviation notification in order to plan for or monitor on-orbit maneuvers for active satellites and dormant space objects. The combined power of the data sources and processing software represents a major leap forward for commercial satellite operators.

New ConOps: ComSpOC operates in a different mode — highly automated and integrated — than current systems because it aims to accurately track and analyze more than 200,000 RSOs. Further demanding automation, the responsiveness required for today's dynamic space environment mandates very short timelines only achievable with end-to-end, machine-to-machine processing that only involves humans by exception. Sophisticated integration (e.g., centralized processes that know exactly what a specific sensor tasked at a specific time can do to improve the understanding of an orbit) further drives the efficiencies needed. The complexities of operating a system to track this many RSOs with this many sensors of several different phenomenologies is enormous, but necessary if this level of SSA is to be achieved.

Challenges and Opportunities

The advent of highly accurate and reliable commercial SSA solutions represents a cultural change not unlike that which the U.S. government successfully faced in the early 1990s, when the closed world of satellite imagery was first opened to commercial providers. Initially, there was stiff resistance within the Pentagon and other government agencies to putting high-resolution satellite imagery into the commercial marketplace, but market forces and the speed at which industry can adapt to take advantage of rapid technological advances have created a wealth of new commercial products that serve national security needs and have fueled a variety of lucrative consumer applications. Initial reservations were assuaged over time as government and commercial firms worked to remedy legal or classification obstacles that arose and each became more accustomed to the positive changes stemming from the commercialization of space imagery. AGI believes a similar approach can prevail with SSA.

The availability of enhanced commercial capabilities for what should ultimately become routine SSA monitoring and tracking frees up the government, as well as foreign partners, to apply scarce resources to more critical and higher fidelity tasks in overall space surveillance and command and control. In socializing his new Better Buying Power 3.0 philosophy, Under Secretary of Defense for Acquisition, Technology, and Logistics Frank Kendall is evolving his broad-based effort to improve DoD acquisition through a shift in emphasis on achieving dominant capabilities via innovation and technical excellence. Kendall's plan urges the DoD to remove barriers to using commercial technology, particularly where "commercial technologies with military utility are advancing at a faster pace by far than comparable military unique technologies."[4] ComSpOC fits squarely within this evolving Pentagon strategy.

AGI was able to bring ComSpOC to market in two months from its conception. There are few military capabilities, if any, that have been fielded on that kind of accelerated timeline, and even less with the agility to incorporate additional partners and still-emerging advanced tools and capabilities as they become available. This concept fits neatly into the classic "good idea" theory of innovation championed by noted author Steven Johnson.[5] Johnson's works emphasize connecting good ideas versus protecting them as the key to successful innovation and change. Good ideas are emboldened in environments that allow concepts to flourish, recombine with other ideas, and push the boundaries of innovation ahead. With the advent of ComSpOC, we are on the leading edge of a new approach to SSA. Let the innovation ensue. Q

Paul Graziani *is the Chief Executive Officer and Co-Founder of Analytical Graphics, Inc. (AGI), the producer of commercial off-the-shelf (COTS) analysis software for land, sea, air, space, and cyberspace. Graziani and two colleagues launched AGI in his living room in 1989, and today the company's flagship product, STK, is used in more than 40,000 worldwide installations by aerospace, defense, and intelligence professionals. Graziani started his career at General Electric Space Division in 1980, where he held a number of software and engineering roles.*

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TECH CORNER

To supplement the ***IQT Quarterly***'s focus on technology trends, *Tech Corner* provides a practitioner's point of view of a current challenge in the field and insight into an effective response.

ELECTRIC PROPELLANTS INTO SPACE AND BEYOND

A technology overview from IQT portfolio company DSSP

On September 23, 2014, two days after launch, the SpaceX Dragon capsule docked with the International Space Station (ISS), and began unloading cargo as part of its commercial Crew Resupply Mission (CRS-4). This cargo included SpinSat, a new spherical spacecraft developed by the Naval Research Laboratory (NRL) in partnership with DSSP. This marked the first space flight for DSSP's microthruster system and the first time NASA has ever allowed an energetic material inside the ISS (Figure 1). In the previous year, DSSP and NRL successfully met all of NASA's safety requirements to get this entirely new breed of propulsion system aboard the ISS. The Electric Solid Propellant (ESP) used in the DSSP micropropulsion system is environmentally friendly and completely safe from accidental ignition by flame, spark, and impact, and can be easily shipped as a DOT Class 1.4S explosive. After being safely stowed on-board the ISS in September 2014, SpinSat was deployed into orbit on November 28, 2014.

Similar in appearance to earlier ANDE-2 satellites launched from the space shuttle in 2009, SpinSat brings significant advances to the science of propulsion. SpinSat represents a game-changing technology capable of providing safe, non-toxic, insensitive munitions compliant, energetic (but non-pyrotechnic) solid thruster technology that is electrically controlled (multi-use and throttleable). The technology has applications to mission enabling technology for DoD

Figure 1 | *(Left)* The Dragon capsule unloads the SpinSat container, marking the first time an energetic material (rocket propellant) has ever been allowed inside the ISS. *(Right)* The SpinSat satellite before its release from the Cyclops deployer outside the International Space Station. *(Photo: NASA)*

and the Intelligence Community, providing presently unavailable capabilities that are vital to intermediate and long-term missions. These thrusters should also play a vital role in the academic and commercial sectors. The commercial sector has tremendous potential to benefit from this technology that is a prime candidate for the rapidly expanding nano-satellite constellation missions and is safe enough for deployment from the ISS.

A Dual-Mode Propulsion System for Spacecraft

There are two different propulsion systems on the SpinSat that use the same thruster and same ESP formulation that will fire in either a chemical mode or electric mode. In chemical mode, the ESP is burned with minimal electrical power to release the stored chemical energy, so higher thrust levels can be generated by burning more propellant. In electric mode, much higher amounts of electric power are used to ignite and ionize, providing much higher performance with much lower thrust. In electric mode, the combustion and ionization of the ESP causes electromagnetic Lorentz acceleration. The difference between chemical and electric mode burning can be clearly seen by a purple glow discharge of the plasma formation compared to the typical yellow-orange of chemical combustion (Figure 2).

Figure 2 | Identical DSSP microthrusters burning in chemical mode *(left)* and electric mode *(right)*, exhibiting characteristic purple "glow discharge" from plasma formation.

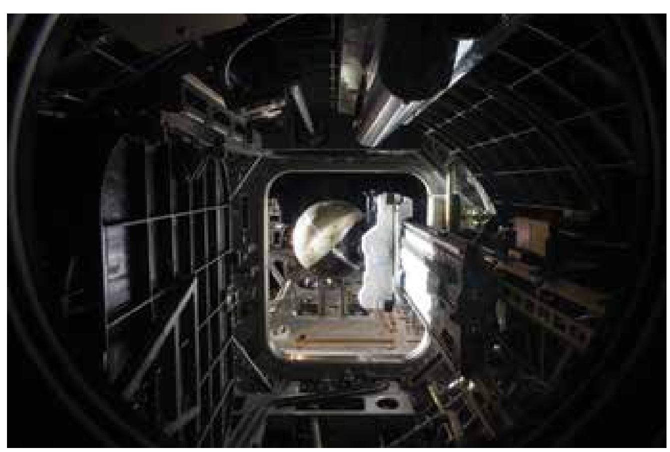
On the SpinSat, the chemical and electric mode thrusters are separate systems, each powered by a different control board. DSSP is working to combine these burning modes into a single system in the near future. This will provide satellite operators with low-thrust, high-performance electric mode propulsion for drag makeup and precision movement, or high-thrust, lower-performance chemical mode for object avoidance or other highly agile maneuvers. Scaling to orbital insertion engines, chemical mode burning would transit a spacecraft through the damaging radiation belts quickly, but could then be switched to low-thrust, high-performance electric mode burning for drag makeup or additional orbit raising.

The SpinSat Mission for NRL

There are three primary goals of the SpinSat mission. The first goal is to characterize the performance of the ESP thrusters on orbit. The SpinSat spacecraft is a 22"-diameter aluminum sphere, with the ESP thrusters physically arranged on the exterior of the satellite to provide two basic maneuvers: spin-up (de-spin) and translational thrust. For the spin-up maneuver, pairs of thrusters will be co-aligned 180 degrees apart, and provide a tangential component force on the exterior; for de-spin, a second pair of thrusters will provide the opposite force. For the translational thrust maneuver, thrusters will be oriented perpendicular to the exterior of the satellite to provide force in the normal direction. Another set of thrusters placed at the opposite pole will provide normal force in the opposite direction.

The second goal of the experiment is to provide a test object for space object characterization. SpinSat is a unique object for this purpose, providing an excellent test object for ground and space-based surveillance systems.

The third goal of the mission is to provide a calibrated drag experiment at higher solar activity than the ANDERR and ANDE2 missions to monitor total neutral atmospheric density. The spacecraft itself acts as the primary sensor for the final experiment goal; with a well-determined and characterized ballistic coefficient, the routine collection of radar tracking



SpinSat leaving the ISS airlock in November 2014.

Andy Nicholas *(left)* and Ted Finne *(right)* at NRL prepare for the September launch of SpinSat. "It's a multifold mission," says Nicholas, "but the primary mission is demonstration of a new thruster technology." *(Photo: The U.S. Naval Research Laboratory/Jamie Hartman)*

and satellite laser ranging data will provide a high-resolution atmospheric drag data set used to derive thermospheric density.

ESPs — Not Just for Spacecraft

ESPs are a novel platform technology that have found broad applications to both military and commercial users. For the military, ESPs represent a safer, environmentally friendly technology with higher performance than most conventional solid propellants. The Missile Defense Agency is examining ESPs as a shipboard-safe propellant for Aegis-based interceptors. DARPA is having DSSP develop ESPs into an electrothermal-chemical (ETC) gun propellant as

Figure 3 | *(Left)* a single eSquib can be fired hundreds of times before it needs to be replaced. *(Right)* DSSP's prototype pyro-guitar uses three eSquibs to provide added dazzle to any live performance.

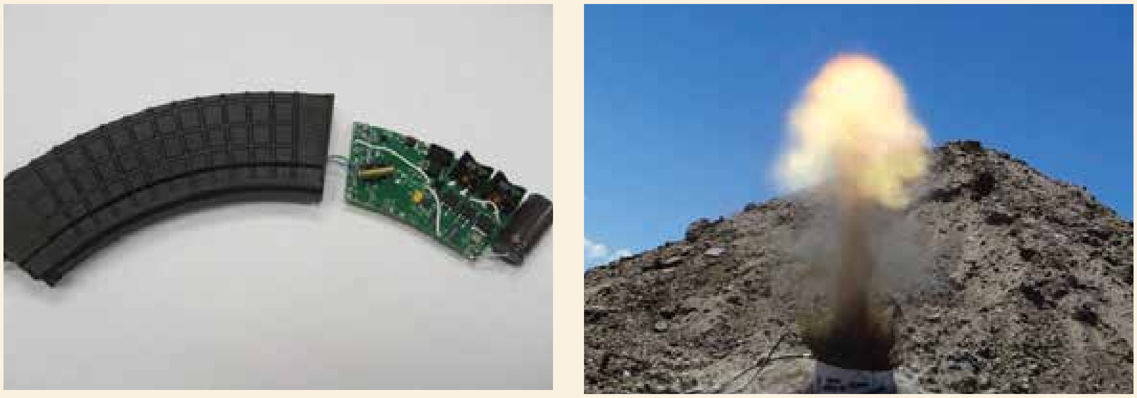


Figure 4 | *(Left)* Electronics to fire eSquibs can fit into standard magazines and will eliminate the need to collect the shell cartridges after training exercises, allowing troops more time to train or rest. *(Right)* ESPs are also being designed into environmentally safe IED and 81 mm mortar round trainers to replace environmentally hazardous PETN based explosives.

an alternative to hypersonic railguns. The Air Force has recently funded DSSP to develop variable effects munitions, where a bomb's yield can be turned up or down depending on the target, thereby minimizing collateral damage.

DSSP has also been working in the energy field as part of Shell's GameChanger program to develop a pumpable liquid electric propellant (LEP) for water-free natural gas fracking. The concept is called "energy at a distance" and involves pumping the LEP deep into the natural gas source rock, far from the drill hole, and then igniting electrically in a controlled manner to fracture the rock, enhancing gas recovery. Planning is now underway for an in-ground demonstration in the near future. There are many other applications for hydrocarbon recovery where controllable, on-demand gas generation is used, such as in down-hole gas guns, well packers, and down-hole pipe cutting.

The DoD Hollywood Connection

In September, the Nevada State Fire Marshal licensed DSSP to manufacture and commercially supply its eSquib product into the special effects industry (Figure 3). In Hollywood, squibs are used to simulate muzzle flashes, bullet hits, and electrical sparks. Unlike conventional single-fire squibs used today for Hollywood special effects, DSSP's eSquibs are environmentally friendly and can be fired hundreds of times. This means big cost savings to film producers, since cast and crew do not have to leave the set for the squibs to be reset after an unsatisfactory take. The multi-fire eSquibs will also allow for pre-takes that will allow actors to preview complex pyrotechnic effects prior to filming and immediate retakes as needed. For the actors and crew, eSquibs don't contain any heavy metals or produce any smelly combustion gases on stage. For live design (e.g., concerts, raves, festivals, theme parks, and ultra-clubs), eSquibs provide digital control and hundreds of firings with minimal fire hazard. DSSP is currently designing eSquibs into shoes, gloves, and guitars for various performers (Figure 3).

These same eSquibs are also potential replacements for standard .223 caliber training rounds (blanks) used for warfighter total immersion training. In this training, whole villages are recreated and foreign language speaking role players are used to create the complete in-country experience for the warfighter prior to deployment. High-intensity Hollywood special effects are used to prepare both our human and K-9 warfighters for the intensity of a real battle and have been instrumental in reducing causalities. However, because these training exercises are routinely conducted at the same locations, environmental contamination is an ongoing concern. Pentaerythritol tetranitrate (PETN) and lead-based primers are of particular concern on military bases. After training, troops must spend additional time collecting spent blank cartridges to prevent contamination. A single

SpinSat represents a game-changing technology capable of providing safe, non-toxic, insensitive munitions compliant, energetic solid thruster technology that is electrically controlled.

eSquib costs less and can simulate hundreds of .223 caliber rounds without wasting valuable training time picking up spent training rounds. The firing electronics can be fitted into standard magazines, with only minimal modification of the rifle required (Figure 4). For larger simulations, DSSP is developing environmentally friendly IED and 81 mm mortar simulators using ESPs (Figure 4), which should eliminate much of the need for PETN in training exercises.

DSSP's technology represents not just a new milestone for space propulsion, but many other down-to–earth, game-changing applications.

***DSSP**, an IQT portfolio company, manufactures low-hazard electrically controlled solid propellants. To learn more, visit www.dsspropulsion.com.*

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IN THE NEWS

The *IQT Quarterly* examines trends and advances in technology, often influenced by market, industry, and regulatory factors. The commercial space industry is no exception. As these snapshots illustrate, commercial space has experienced significant developments in recent years.

Market Activity

2013 and 2014 saw notable investments from firms not traditionally involved with aerospace. In October 2013, Khosla Ventures led a Series A funding round for launch provider Rocket Lab, paving the way for a new generation of dedicated small satellite launch vehicles.[1]

In 2014, Google acquired Titan Aerospace and Skybox Imaging, sending a strong signal that Google aims to merge its terrestrial presence with airborne and space layers to potentially enhance a range of services.[2, 3]

Across the Industry

The actions of many companies have also signaled an expansion of the satellite constellation model, a traditional force multiplier for adding capability and resilience. Channel Islands-based WorldVu emerged in recent months as a contender to provide global high-speed Internet access using a constellation of satellites.[4]

In October, we saw a more sobering example of the power of constellations — 26 Planet Labs Dove satellites were destroyed during the Antares launch failure. The company, however, shrugged off the loss, indicating its model of a low-cost constellation is capable of absorbing what might otherwise be a catastrophic setback.[5]

On the analytics front, satellite data has pushed into many new sectors. During the recent Ebola outbreak in West Africa, the International Charter for Space and Major Disasters was invoked to help study and contain the outbreak, using satellites developed by U.K.-based Surrey.[6]

Similarly, advocacy groups Oceana and SkyTruth in November released their prototype Global Fishing Watch system, designed to merge commercial AIS data with Google's mapping tools to help fight illicit fishing on a global scale.[7]

Regulatory Developments

Two of the most notable recent regulatory developments are the revisions to Category XV of the U.S. Munitions List (USML) and changes to existing resolution constraints, allowing commercial distribution of imagery with better than 0.5 meter resolution. Both moves are likely to expand the global market.[8]

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