Historical Perspectives on the Evolution of Small Satellites

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Abstract

This chapter reviews the history and the evolutionary development of small satellites and of launch vehicle systems and the evolution of orbital space debris over time. It suggests that the development of space technology, space systems, and rocket launchers has occurred in response to various military, political, economic, scientific, and business mandates. This history that as now cover a period of over a half century has evolved in an almost haphazard fashion, largely

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without concern for the space environment in Earth orbit and the need to pay attention to the long-term sustainability of outer space activities. Such concerns for "sustainability" have only come into focus since the 2010s. It also notes that the concept of "smallsats" has continued to evolve and change in many ways over time.

This chapter notes how technical innovation, disruptive technologies, new commercial space opportunities, and entrepreneurial aspirations have all contributed in the past decade to fuel the newest aspects of "New Space" or "Space 2.0" and "smallsat" development. This has created new opportunities to use space systems in new and innovative ways – especially for new entrants and users from developing economies. Yet these new commercial space initiatives and especially new large-scale "smallsat" constellations have also given rise to the problems of excessive amounts of space debris in Earth orbit. There are now particular concerns about the need for space traffic control and management that arise from the fear of runaway proliferation of space debris, known as the Kessler syndrome. This "Kessler syndrome" posits that there could be a real future possibility of a growing avalanche of space debris accruing over time with new major collisions in space happening every 5–10 years. This history seeks to give a comprehensive view of the new opportunities that small satellite systems and new launch systems could bring to global economic growth and new space-based services but also to note negative developments and concerns that need to be addressed to ensure the longer-term sustainability of the space around Earth – especially LEO, MEO, and GEO orbital regions. This history thus seeks to place the development of small satellites into some context that compares their current state of technical and operational evolution in without repeating the historical notes already provided in Chap. ► "Introduction to the Small Satellite Revolution and Its Many Implications"

Keywords

Disruptive technologies · Explorer 1 · Kessler syndrome · Launch vehicles for small satellites · Miniaturization · "New Space" · Off-the-shelf components · Orbital space debris · Satellite constellations in low Earth orbit · Small satellites · "Space 2.0" · Space traffic control/space traffic management · Sustainability · Sputnik 1

1 Introduction

The history of space and small satellites dates back to the start of the space and even the age of Isaac Newton. When Newton first grasped the concept of gravitational force, he not only understood the gravitational attraction between the Earth and falling objects, but also how artificial satellites could achieve orbit. He was able to calculate what it would take, in terms of accelerative force, to achieve orbital velocity. In his book, *Principia Mathematica*, written in 1685–1686, he produced an illustration showing how a cannon ball fired with sufficient speed would be able to achieve orbit (Writing of Principia Mathematica n.d.) (Fig. 1).

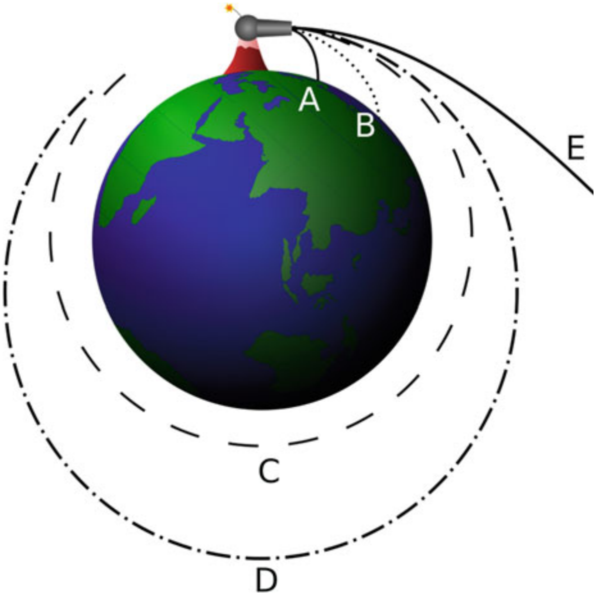

Fig. 1 Isaac Newton's conception of the launch of a satellite from *Principia Mathematica* (1686) (Recreation of Newton's concept of cannon ball launched into Earth orbit). By user: Brian Brondel – Own work, CC BY-SA 3.0. https://commons.wikimedia.org/w/index.php?curid=1657849

Thus, it could be said that the launch of a small satellite was first specifically envisioned, based on a clear conceptual knowledge of the physics involved, at the end of the seventeenth century.

And the very first satellite launches by the USSR with Sputnik 1 and by the USA with Explorer 1 were both small satellite launches. It has been noted by Space Traffic Control advocate Stuart Eves that the very first launch in October of 1957 of Sputnik 1 put not only a small satellite into orbit but the first space debris objects as well. Eves notes that the ejected nose cone, the upper stage of the R-7 rocket stage, and even the Sputnik 1 satellite itself that stopped transmitting after several days of operation all become the first three debris objects in Earth orbit (Eves & Space Traffic Control 2019). Today the many debris objects in Earth orbit, with over 40% of them in low Earth orbit (LEO), have led to rising concern that space debris could eventually deny humans safe access to space.

From the very first days of the space age in the late 1950s and late 1960s, the efforts were to find new ways to make practical use of space systems that extended beyond the earliest use of space as rockets as military instruments to deliver bombs and destruction during times of wars. The creation of civilian space agencies such as NASA thus began to develop satellite applications such as for telecommunications and broadcasting, for remote sensing, Earth observation, meteorology, navigation, precise timing, and so on. In other cases space systems developed for military purposes such as the GPS were adapted to perform a wide range of practical purposes such as aircraft safety, self-driving cars, and mapping. The space agencies and the largest commercial activity, namely, satellite communications, followed a pattern of "bigger and better" spacecraft with more power, wider radio-frequency spectrum allocations; this pattern was shown in Fig. 3.

In the 1970s and 1980s, there were a number of initiatives undertaken first by amateur radio operator technicians and engineers and then by projects initiated by the Surrey Space Centre with regard to non-real-time data relay and machine-to-machine relay and lower-resolution remote sensing activities involving small satellites. These few “off the beaten path” activities were, at the time, not considered “mainline” undertakings. The main space businesses with the large streams of revenues were involved either with major governmental and military projects or commercial satellite activities that were engaged in designing, building, and launching larger and larger satellites.

In the late 1980s and 1990s, however, there began to be a number of new ideas percolating in the industry about what satellites could do in terms of mobile communications satellite services. Most of these new concepts involved the idea of deploying low Earth orbit (LEO) constellations. Most of these new initiatives concentrated on how to deploy lower latency satellite services and using very small handheld user terminals that could provide narrowband data and voice services. There was a lot of thought about how to use more effectively efficient digital compression techniques and application-specific integrated circuits to achieve user transceivers that could be used for personal communications.

2 Evolution of New Small Satellite Systems in Low Earth Orbit for Telecommunications Services

Perhaps the most significant of these new initiatives was the Iridium Satellite network, which was spearheaded by Motorola. The concept that was advanced envisioned a 66 satellite LEO constellation with spares that would utilize phased array antennas on the satellites, inter-satellite links, and new ground antennas that could be made smaller and more efficient using digital processing and application-specific integrated circuit (ASIC) firmware.

This innovative “smallsat” LEO system sought to break the mold of relying on advancement through deploying larger and larger satellites in GEO orbits. This effort to design a system with smaller satellites in low Earth orbit was spearheaded by Motorola and network of partners that Motorola recruited from around the world. Motorola already had a great deal of experience with handheld radio units for cellular radio communications services and high-quality, mass production of consumer products, but a limited amount of satellite experience. It formed a global partnership to design, manufacture, and launch this LEO constellation. Along the way it recruited knowledgeable people from the global Intelsat community and sought a number of commercial participants from the Intelsat network to join in the partnership. It came up with a very innovative design that used 3 phased array antennas to create some 48 reasonably high-powered spot beams. See Fig. 2 (Gupta and Swearingen 2016).

The design was fairly sophisticated for a small satellite and included the ability to create four inter-satellite links to connect to the two satellites to before and after it in the North-South orbit as well as the two satellites to the East and West in the constellation. Despite the sophistication of the design with the phased array antennas and the inter-satellite links, the goal was set to produce these satellites on a rapid production line. And by the end of the production, the Iridium satellites were being produced in a 4.5-day sequence. This was in contrast to the production of large GEO satellites on an 18–24 month or even longer production cycle. Although these satellites were first conceived to have a 7-year lifetime, many of these satellites operated in the range of 15–18 years (see Fig. 2).

The second initiative that followed closely on the heels of Iridium was the Globalstar mobile satellite communications system. In this case the plan was to deploy some 50 small satellites in a LEO constellation covering the Earth between 70° North and 70° South since they saw little market from seals and polar bears. Globalstar also envisioned voice and data satellite communications to handheld units from small satellites in LEO orbit. The INMARSAT network for maritime and aeronautical mobile communications and operated a series of GEO-based satellites also moved to spin off a new venture known as the ICO (or International Circular Orbit). This new venture began to plan and deploy a constellation of 15–18 satellites in MEO orbits. Finally the Orbital Sciences Corporation proposed a constellation of quite small satellites for store and forward data links and machine-to-machine communications (Ibid.).

These various initiatives began to introduce a number of highly innovative technologies. These were, among other aspects, (i) in the design of small satellites and their antenna systems; (ii) in the systems for management and operation of global constellations of satellites in low orbit to avoid collision and to control deorbit activities; (iii) in the design of handheld user units as well as smaller-scale mobile and portable units for military or defense-related use; (iv) in the use of inter-satellite links; and (v) in global billing systems and country access codes that these systems used. The market studies and strategic business plans for these systems were a different matter. In 1998 not long after these systems were

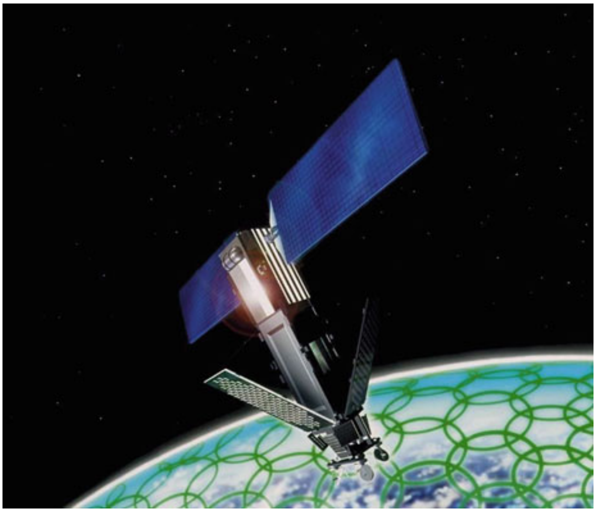

Fig. 2 Iridium satellite in low Earth orbit with spot beam patterns shown below. (Graphics courtesy of Iridium)

deployed Iridium and Globalstar systems declared bankruptcy. The ICO system declared bankruptcy without ever deploying any spacecraft. The Orbcom system which was a much lower-cost system with a smaller capital investment continued to operate longer, but it too was forced to declare bankruptcy as well.

The technologies for these LEO constellations had some issues with link margins especially when handheld units were expected to operate from inside of an automobile or other vehicle. Yet, all three systems (i.e., Iridium, Globalstar, and Orbcom) worked technically despite some initial bugs and improved in the performance over time. Both the small satellite constellations and the ever-improving ground systems and user handsets and user terminals all demonstrated that such systems could provide satellite services directly to end users. Clearly there were problems inside of cities with high rises, in forests, and inside of buildings and cars, but these were problems that second-generation systems with higher power could solve.

The Iridium system provided useful new information about how to operate large-scale constellations and new ways to replace operating spacecraft with technical difficulties with replacement satellites. Iridium engineers developed a clever way to deploy 66 instead of 77 satellites in their constellation by adjusting their orbital elevations and also how to replace efficiently failed satellites with spares on a single launch.

First they raised their orbit slightly to a new deployment altitude of 781 km. At this height they found that they could eliminate 11 satellites from their constellation. The original plan was to have 77 satellites (Note: The atomic number of Iridium is 77) that would be deployed in seven different planes populated by 11 satellites each. With the higher altitude, they were able to go to 6 planes of 11 satellites each and thus reduce the constellation number to 66 satellites (Op cit, Stuart Eves p. 10).

The other lesson learned, in terms of efficient deployment, was to discover a way to populate the Iridium constellation with replacement satellites in two different planes with a single launch which would be carrying multiple satellites. In this particular case, they launched the replacement satellites into an altitude of only 666 km instead of 781 km. They then quickly boosted satellites with onboard thrusters into the correct plane where replacements were needed. They then waited until the remaining satellites meant for replacement of satellites in the adjacent plane to drift into the proper plane position at the lower altitude and they then boosted them up into the proper location 115 km above (Op cit, Stuart Eves p. 10).

The technical problems were challenging. Clearly there were problems of satellite design and performance. And there was an even greater need for improved ground systems design for user transceivers. There were in need of the technology that would come decades later in the form of electronic beam forming and tracking systems that can replace more expensive physical tracking systems that require dishes to physically track satellites as the move across the sky. Technical challenges were addressed and mainly solved over time. It was the market, charging tariffs, and financial failures of all these systems, however, that created the real shock waves, bankruptcies, and crises in financial markets.

And the problems were not limited to mobile satellite services. Further problems for small satellites deployed in constellations came from the Teledesic system proposed around this time. This was the ahead of its time proposal for a so-called MegaLEO system. This proposal advanced the idea of a LEO constellation capable of providing broadband digital services for fixed satellite services via a huge constellation (about a 1000 satellites). The fact that this Teledesic system, backed by billionaires Bill Gates and Craig McCaw, also experienced bankruptcy further discouraged the idea of providing commercial satellite services from small satellite constellations deployed in LEO orbit. As noted in the introductory chapter, this string of bankruptcies took its toll on smallsat constellation concepts. The idea of moving from GEO-based systems to LEO constellations using "smallsats" for communications services was abandoned for years to come.

Although the idea of new entrants providing LEO-based services from "smallsat" in a LEO constellation essentially went on pause, the idea of LEO constellations never went entirely away. Several things served to change the landscape. The Iridium, Globalstar, and Orbcom satellites were bought out of bankruptcy and the reorganized businesses found a way to achieve profitability. Part of this success was based on the low cost of acquiring the satellites from the bankrupt organizations, and part was due to market development. Second-generation satellites for these systems have all now been deployed, and financial viability has been established for all these networks. Ground user systems have greatly improved. Further systems for use on aircraft and marine systems have improved and market demand has increased. Twenty years allows time for many improvements.

Also, most significantly the concept of cubesats was born, and their design, fabrication, and testing for in-flight operation have rippled through universities in the USA and around the world. This development process has found technicians, engineers, and scientists engaged in intensive studies focused on miniaturization of virtually all of the components that were involved in creating and manufacturing truly small operational satellites. This process has led to the development of miniature remote sensing devices. We have seen the creation of exceeding tiny digital processors and digital communications systems. The performance of satellites and especially user terminals has been enabled by all sorts of specialized software, small star and sun sensors, improved and miniaturized stabilization systems, small thrusters, innovative small solar array systems, tiny batteries, small antenna systems, and more. Many of these miniaturized systems were thus invented and successfully deployed for university student experiments, but can today be utilized in commercial systems. New systems such as passive deorbit systems using inflated balloon systems can deploy at end of life to create atmospheric drag. We have seen creative deployable and slide-out body structures and antenna extension systems. These innovative designs have allowed very small cubesats to become highly functional and efficient as antenna and solar arrays deploy and the body structure doubles in space-based configurations.

Many of the experimenters have not only created compact but highly functional new and creative cubesat designs, but they have also found that they could use much lower-cost off-the-shelf components in these satellites. The end result is that an amazing capability could be fitted within these small satellites that were only $10 \times 10 \times 10$ cm in size (or about four in cubes). Even when they have been scaled up to a three-unit cubesat (i.e., $10 \times 10 \times 30$ cm), they are still quite small in mass, and their functionality is increasingly amazing. Of course the savings come not only from having smaller satellites and units that use lower-cost off-the-shelf components. The biggest cost savings is on launch costs. Planet that deployed 88 three-unit cubesats they call "Doves" (i.e., their solar arrays evoke the image of a bird's wings) in a single launch on an Indian PSLV accomplished this entire deployment for a cost less than a third the cost of major communications satellite launch.

Instead of satellites that came from space agency designers, large aerospace companies and military agencies, we saw the emergence of small satellites created with an entirely new mindset. These cubesats created by young innovators and entrepreneurs became the starting point from which to question conventional thought about how big a satellite had to be to accomplish its various missions.

From this starting point, we even saw the invention of ultra-small femtosats, picosats, and nanosats that could accomplish many tasks once thought to require very large satellites that took years to design, manufacture, and test which were ten times, a hundred times, or even larger in size.

This new mindset some have called "Silicon Valley" meets the aerospace industry, or Space 2.0, or just "New Space." Regardless of what one calls this new mindset, it has become the motive power that has given rise to a host of new commercial "smallsat" ventures. This in turn has also helped to fuel a new commercial effort to create new more cost-efficient launch systems as well.

There were engineering students and budding entrepreneurs who jumped at the chance to design and build very small satellites that could engage in commercial remote sensing, data relay, automatic identification services, and even communications services by building and launching constellations of these smallsats.

Undertakings in the "New Space" arena had many sources of inspiration. One such inspiration was the Ansari XPrize. This created the challenge to develop commercially a space plane that could fly with crew of two on a suborbital flight into space and back and then do it again within 8 days. Only if all of these conditions were met would the new space plane developer be entitled to collect a $10 million challenge award. This feat was rather miraculously accomplished in 2004. This remarkable achievement created a huge impetus toward private new space ventures. The key aspect of this challenge was not only that the Burt Rutan and Paul Allen succeeded and actually won the prize in 2004 but that dozens of teams were formed around the world. These various private venture entrepreneurs sought to prove that they could create the new technology to make this happen.

There are now many ventures that have blossomed from efforts to create new and lower-cost launch vehicles, new small satellite ventures for remote sensing, or new ventures for satellite communications and networking services, especially in the underserved areas of the world.

3 The Rebirth of Small Satellites for Telecommunications Services

There is a remarkable man named Greg Wyler who, perhaps more than any other, has given impetus to the current boom in LEO constellations for telecommunications and networking services. He began a quest some two decades ago to provide domestic telecommunications services in Africa. He looked at various models that would deploy fiber-optic cable systems and found that none of these business models would work financially. He finally had his “aha” moment when he looked at the idea of using satellites to cover not just one country, but to create a satellite system that would cover the entire equatorial region of the world as had been first proposed by Brazil in their “string of pearls” satellite along the equator. Wyler decided that as a first step he and his partners would create a medium Earth orbit (MEO) constellation called O3b. This system would be named O3b for the Other Three Billion people in the equatorial region of the world that had limited access to telecommunications, educational services, health care, potable water, and nutrition. He was able to recruit a number of partners such as SES of Luxembourg that operated one of the world’s largest GEO networks, Google, Liberty Global (the cable television and Internet service provider that was started by John Malone) HSBC bank, and a number of other backers for this $1.3 billion venture. It began with 4 satellites in its MEO constellation and then grew to 8, 12, and then 16 satellites to provide broadband services with greatly improved latency over GEO satellites. This network was sold to SES that now owns the entire network.

But Greg Wyler had a much more ambitious second act in mind. He left his position at Google and along with Brian Holtz and David Bettinger to start WorldVu in 2014. They created a company with about 30 employees to design and build a large constellation of small satellites that would blanket the world with around 900 satellites to provide low latency broadband services. This number has now been scaled back to about 600 satellites (Henry 2018).

In January 2015 it was renamed OneWeb and key investors started to come into the $3 billion smallsat system. As now planned it is to begin as a 648 network, but plans to expand over time.

There were many innovations here that one can attribute to Weyler and his partners. One of these was that one of the larger investors in the project was AirBus that was selected as the contractor to build this network of 110 kg small satellites. Another large investor was Arianespace which was contracted for the launch of many of the satellites. Thus the companies that provided a significant amount of the financing for this MegaLEO system were also the contractors for building the satellites and launching many of the satellites (https://www.oneweb.world/) (see Fig. 3).

One of the concerns that was discussed with Weyler on the occasion of his being awarded the Arthur C. Clarke Innovator Award was the problem of safe operation of this large network, avoidance of interference with GEO satellites and ground

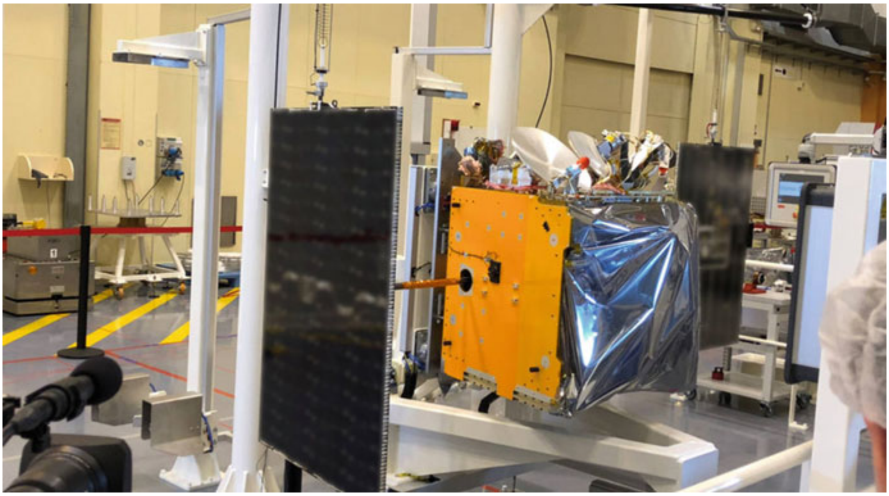

Fig. 3 One of the 110 kg. OneWeb satellites in production in Toulouse, France. (Graphic courtesy of AirBus)

systems, and disposal of the OneWeb satellites at end of life. The altruistic Weyler admitted concerns about avoiding interference and noted that the 25-year period for disposal of satellites at the end of life was inadequate and that this was in 2016 before the spate of additional large-scale systems were proposed for launch (Talk with Greg Wyler in Washington, D.C., n.d.).

OneWeb, however, set off an avalanche of other "smallsat" constellations that were to follow. Some of the constellations, just for telecommunications and networking services, that were to follow are listed below (see Table 1).

4 The Evolution of "Smallsat Ventures" for Remote Sensing, Tracking, and Weather Monitoring

The many new ventures use "smallsats" to provide commercial services in such areas as remote sensing, vehicular and ship tracking, and automatic identification services (AIS) and began to blossom starting around 2010. Many of these started from university-based cubesat.

The Planet Labs Remote Sensing System: This is a story that started quite close to home in that the author of this particular article was teaching at the International Space University (ISU) at its Space Studies Program held at NASA Ames in the Summer of 2009. In partnership with my colleague Dr. Scott Madry, we were co-chairing the Space Applications Department. One of the 20 or so "students" in the department was a very bright and compelling young man named Will Marshall who was also working as an intern at NASA Ames at the time as well as being an ISU participant.

During these NASA Ames sessions, Scott Madry gave a number of enthusiastic talks and demonstrations related to "smallsat" and their utility to a growing list of

Table 1 Some of the "smallsat" constellations for networking (Chart by J. Pelton all rights reserved)

Country	Constellation	Number of sats	Radio-frequency bands
Canada	CANPOL-2	72	LEO and highly elliptical Earth orbit in VHF-, UHF-, X-, and Ka-bands
Canada	Telesat constellation	117 sats plus spares	LEO in Ka-band
Canada	COMSTELLATION	Nearly 800 satellites	LEO in Ka-band
Canada	Kepler	15 to start and 120 in time	LEO in Ku-band
France	Thales Group's MCSat	Between 800 and 4000 in time	LEO, MEO, and highly elliptical Earth orbit in Ku- and Ka-bands
Liechtenstein	3ECOM-1	264	Ku- and Ka-bands
Norway	ASK-1	10	Highly elliptical Earth orbit in X-, Ku-, and Ka-bands
Norway	STEAM	4257	Ku- and Ka-bands
UK	UK / L5 (OneWeb) (Has now declared bankruptcy)	600–750 and increased number in time	Ku- and Ka-bands
USA	Boeing	1396–2956	V-band in 1200 km orbit
USA	SpaceX	Up to 4000	Ku- and Ka-band
USA	SpaceX	7500 plus	V-band
USA	USA/Leosat (Has now declared bankruptcy)	80 to start	Ka-band

remote sensing applications. He stressed how miniaturization and new small-scale components were making very capable new "smallsats" possible for remote sensing activities. Will Marshall took his ISU learning experience to heart. With his clever young colleagues he went on to organize right there in Silicon Valley a new enterprise called Planet Labs. These enterprising entrepreneurs designed three-unit cubesats that they called "Doves." They managed to find backers in the fertile startup soil of Silicon Valley and their new enterprise took root in the skies.

They began deploying and improving with each one of their successive batches better and better "seeing eye" birds. This enterprise continued to grow and prosper until it truly took wing in 2017. They made arrangements to have 88 of their Doves to be launched on an Indian PSLV rocket that placed 2 regular-sized satellites plus a record total of 104 cubesats into low Earth orbit (LEO) as of mid-February 2017 (Indian PSLV Rocket set for Record-Breaking Launch with 104 Satellites, Space-flight 2017).

The also made an epic arrangement with Google that sold the title of the high-resolution Skybox satellites to Planet Labs in a deal whereby Planet Labs also changed their name to simply "Planet." Part of the sales agreement involved their signing a long-term contract to provide data to Google on a long-term basis (Kaplan 2017).

Amazingly the "Planet" enterprise was started in the garage of the well-known "rainbow mansion" in Silicon Valley, and their Doves are fabricated in what the

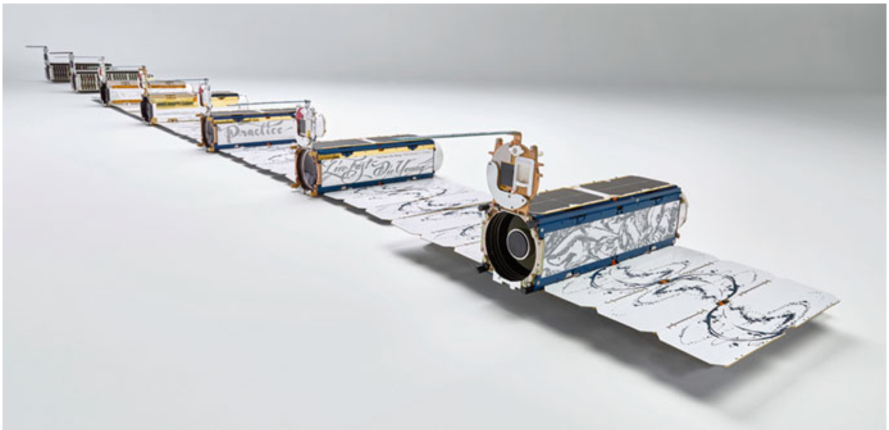

Fig. 4 Several of the Dove cubesat ready for launch (note the individualized art on each satellite). (Graphic courtesy of Planet)

young entrepreneurs call their "Clean Enough Room" in their headquarters, now in San Francisco. This amazing young startup company is now operating in close partnership with one of the world most valuable corporations, Google. It now manages a fleet of hundreds of "Dove" three-unit cubesat plus the entire Skybox/ Terra Bella system that Google has sold to Planet as well as several satellites acquired from a German supplier. The part of the story involving remote sensing and "smallsat" startup leading to Skybox and Terra Bella comes next (see Fig. 4).

The Skybox Imaging Company launched in 2011: Another example of rather remarkable startup magic is the case of the four students from Stanford University's School of Engineering that had the idea that they could design 100 kg small satellites which were only 30 × 30 × 30 cm cubes – about the size of a mini-refrigerator using off-the-shelf components. They submitted the concept for a class project and then decided to make it happen. Their concept was that these "SkySats" could provide high-resolution submeter resolution imaging for the commercial remote sensing market. They managed to convinced several venture capital firms that this was a viable business plan and raised some US$91 million by April 2012 which was sufficient capital to create and start launching this imaging system. The Skybox Imaging startup managed to raise a total of US$91 million of private capital from Khosla Ventures, Bessemer Venture Partners, Canaan Partners, and Norwest Venture Partners to develop and launch the SkySat constellation (SkySat n.d.). Their concept was to not use any expensive "flight-qualified" hardware and instead rely upon commercial electronic and automotive parts, as well as open-source software, including image processing routines developed in the medical industry.

This led to the first launch of SkySat-1 on a Russian Dnepr rocket on Dec. 11, 2013, from Yansy, Russia. This first of the series proved that high-resolution imaging (less than 1 meter) from these "smallsats" was possible and this led to the next launch of a SkySat-2 via a Soyuz 2/Fregat Russian rocket on July 8, 2014. A contract was awarded to SSL to 13 more SkySats according to a refined SkySat-C design. The first four of this series that were built under contract by SSL and then launched on an Indian PSLV (Polar Satellite Launch Vehicle) by the Indian Space Research Organization. The SSL contract covered the building of 13 of the SkySat C design that provides a much higher resolution than the Dove cubesat units. The fully deployed system envisions a network of 25 SkySats to be deployed to create a high-resolution system with frequent global updating capability.

As all of this technical and operational progress was being made, the business and financial arrangements were also rapidly evolving as well. In 2016 the Skybox Imaging Company was sold to Google for a reported price of $500 million. In 2017 Google rebranded the satellite imaging company Terra Bella and then proceeded to sell this system to Planet Labs for a financial arrangement that was indicated to be something like $300 million, but with a long-term service contract to provide imaging data to Google at an advantageous price (Google's Skybox Imaging has new name, business model 2016). This case study underlines the "Silicon Valley" effect that seems to permeate the "New Space" revolution with all of the actors in this case, namely, Planet Labs, Skybox Imaging/Terra Bella, and Google all firmly based in the Stanford, San Jose, Mountain View, and San Francisco area. Today Planet Labs and Terra Bella have morphed together to become just Planet, and they acquire remote sensing of the entire globe every day, including the first video movies from space (see Fig. 5).

The Spire Small Satellite Constellation that started in 2012: The Spire "smallsat" venture is another university-spawned venture. This new system has now deployed several "smallsat" prototypes for a cubesat constellation system that is intended to provide a variety of global tracking, data analytics, and weather monitoring services. It has under contract from the US National Oceanic and Atmospheric Administration (NOAA) launched an experimental smallsat for trial testing of meteorological monitoring and weather tracking services. This startup company has successfully demonstrated a range of new services can be provided by commercial cubesat systems, including automatic identification services, vehicular and ship tracking, data analytics, and even weather tracking. It was founded in 2012 and too started in an unexpected way with its initial capitalization came from a social media campaign (Foust 2016).

Spire was founded initially to develop and launch an experimental cubesat named ArduSat. This company got its money to do this as a crowd-funded project. This first cubesat was named Ardusat and in the rapid construction and launch environment that was typical of many cubesat projects was first launched on August 3, 2013. Thus one of the features that makes this commercial smallsat venture rather unique at the time was that it was made financially possible via a Kickstarter solicitation on the Internet. This initial funding of just over $100,000 led to a round of funding from venture capitalist. This "seed round" had participation by Emerge, Grishin Robotics, Shasta Ventures, Beamonte Investments, and the largest investment coming from Lemnos Labs. In late July 2014, Spire announced an additional $25M "Series A" funding from several venture capital firms that included RRE Ventures, Mitsui & Co., Global Investment, Qihoo 360 Technology, and Moose Capital.

Fig. 5 Planet SkySat 72 cm image of downtown San Francisco, California. (Image courtesy of Planet)

Emerge continued to invest in this second round as well. Spire announced on June 30, 2015, a $40 M traunch in "Series B" capital investments headed by Promus Ventures with participation from Bessemer Venture Partners and Jump Capital and then in November, 2017, yet another round of financing at $70 M through a "Series C" offering, and it also opened a European office in Luxembourg. This lightning fast series of financing sequences and its ability to build its initial series of small cubesats contract for their launch and get them into orbit signified that this was a whole new animal in the aerospace field that did almost everything differently.

The company's first three ArduSat satellites that were the first test cubesat systems have now been released from the Spire operational satellite constellation in order for it to focus on educational experiments in space for activities that can be carried out for as low as $125 per experiment.

On January 21, 2018, two Lemur-2 CubeSats were launched as part of the payload of a Rocket Lab Electron. These two the experimental prototypes represented the test version of an ultimate small satellite multi-sensor constellation of 125 spacecraft that can perform weather measurements as well as tracking and AIS applications. Spire intends to manufacture and operate this Lemur constellation itself and obtain launch via contract from several suppliers including Arianespace.

The satellites are multi-sensor. Data types such as Automatic Identification System (AIS) service are used for tracking ships, and weather payloads measure temperature, pressure, and precipitation. AIS data is meant for use in illegal fishing, trade monitoring, maritime domain awareness, insurance, asset tracking, search and rescue, and piracy (Spire: Space to Cloud Data & Analytics n.d.).

5 Conclusion

The world of small satellites might seem to many as if this is a totally new phenomenon that has exploded almost overnight. In fact this is a development that started with engineers building the tiny Oscar 1 for amateur radio some 40 years ago. The first low Earth orbit (LEO) satellites for mobile communications and data relay, i.e., Iridium, Globalstar, and Orbcom, were small satellites as well as the Surrey satellites designed and build at what is now Surrey Satellite Technology Ltd. Clearly there has been a lot of innovation and outside the box thinking that has fueled today's small satellite industries and systems as well as all the experimentation and testing of concepts that has come with all of the cubesats and even smaller satellites that are now a part of the so-called "smallsat" world.

Every new idea and development stands on the shoulders of earlier inventors, scholars, philosophers, writers, science fiction visionaries, and free thinkers. The world of smallsat innovation is no different, even though it truly has had a fresh crop of very innovative thinkers that has fueled change in the space industry in the past decade. And the revolutionary thinking has far from run its course. The articles that follow show just how remarkable the innovations now known as "Space 2.0"or "New Space" have been in just the past decade. The ability to do more with less and to find new and innovative ways to launch small satellites into space at even lesser cost is changing the world of space and expanding the range of space ventures in truly remarkable ways.

6 Cross-References

► Historical Perspectives on the Evolution of Small Satellites
► Introduction to the Small Satellite Revolution and Its Many Implications
► Network Control Systems for Large-Scale Constellations
► Overview of Cubesat Technology
► Overview of Commercial Small Satellite Systems in the "New Space" Age
► The Smallest Classes of Small Satellites Including Femtosats, Picosats, Nanosats, and CubeSats

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