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## A Brief History of Nanosatellites

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## 1.1 Introduction

The term “nanosatellite” first appeared in print in a paper by the University of Surrey in 1992 [1]. Although originally defined as a spacecraft with a mass of less than 10 kg, nanosatellites are now more narrowly defined as spacecraft with a mass between 1 and 10 kg. Solid-state electronics and primitive solar cells enabled the first active nanosatellite, Vanguard 1, launched by the USA in 1958. It carried two continuous wave (CW) transmitters that enabled monitoring of spacecraft’s internal temperatures and the total integrated electron density between the satellite and a ground station. This first nanosatellite is still in orbit but has been silent since 1964. Continued advancements in microelectronics/nanoelectronics, solar cells, microelectromechanical systems (MEMS), and computer-aided design (CAD) now enable visible imaging nanosatellites with 5 m ground resolution and nanosatellites that use global positioning system radio occultation measurements to measure ionospheric electron densities, tropospheric and stratospheric humidity levels, and temperatures. Much has happened in the intervening 60 years.

## 1.2 Historical Nanosatellite Launch Rates

Figure 1.1 shows the launch history of active nanosatellites from 1958 through 2017. Over 600 passive nanosatellites, operating basically as reflectors of radiofrequency (RF) radiation or as air drag monitors, were launched by the USA and the former Soviet Union during this period of time. These simple spacecraft did not have the typical spacecraft systems, such as power conditioning, command and control, and communications, so were therefore not included in Figure 1.1. Figure 1.1 shows historical data for active nanosatellites within the 1–10 kg mass range that were successfully launched and deployed into orbit. It includes all 1U CubeSats. The original CubeSat Specification Document mandated a mass limit of 1 kg per “U” of volume, but later versions increased the “U” mass to 1.33 kg. In addition, many early 1U CubeSats came within 10–20 g of the original 1000 g target, a mass deficiency

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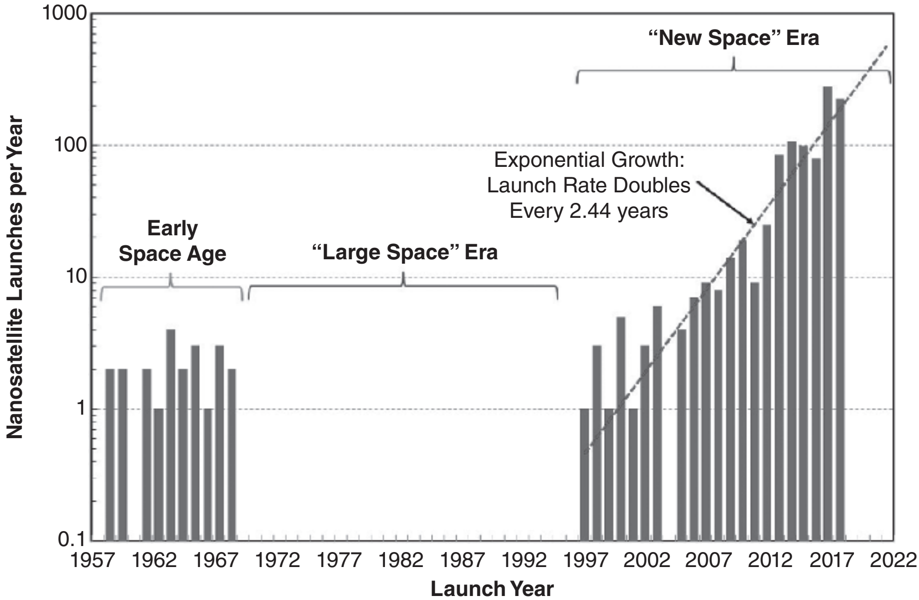


**Figure 1.1** Yearly launch rates of nanosatellites from 1958 through 2017. Source: Data compiled from [2–4]. (*See color plate section for color representation of this figure*).

of 2% or less. All "sub-U" CubeSats (e.g. PocketQubes and SunCubes) are well within the picosatellite mass range and are not included in Figure 1.1. Note that the vertical scale in Figure 1.1 is logarithmic in order to show the dramatic rise in launch rates over the past two decades. This is an "integer logarithmic" plot, because the lowest launch rate has been labeled zero rather than the mathematically correct value of 0.1 for this plot. Since spacecraft come in integer values, this should be acceptable.

Figure 1.1 shows that nanosatellites were flown during the first decade of the Space Age at a rate of about two per year, and then disappeared for almost three decades. Hundreds of passive nanosatellites were flown during these three decades, along with many 11–13 kg mass, 23 $cm^3$ "almost" nanosatellites, but no active nanosatellites. Active nanosatellites finally reappeared in 1997, with launch rates doubling every 2.44 years since then. Launch rate predictions for the next 4 years are consistent with another 4 years of similar exponential growth. This remarkable, two-decade-long exponential growth parallels Moore's law for microelectronic/nanoelectronics—the doubling of performance every 2–3 years due to a continual reduction in transistor size. Exponential growth of nanosatellite launch rates was initiated by a combination of continuing advancements in microprocessor performance, memory storage capability, microelectromechanical sensors and actuators, image sensors, the development of CubeSats, and commercial forces.

Two nanosatellites from the Technical University of Berlin, Tubsat-N and Tubsat-N1, were inexpensively launched in 1998 from a Russian submarine as a commercial service [5]. CubeSats were launched starting in 2003 on relatively inexpensive Russian Dnepr launch vehicles, also based on converted intercontinental ballistic missiles (ICBMs). Newly minted Russian capitalists were able to compete with established Western launch providers by repurposing military hardware. Continued exponential growth of nanosatellite launch rates in the 2000s was due to government and university projects, while commercial exploitation of new space markets using CubeSats has been driving exponential growth in the 2010s.

## 1.3 The First Nanosatellites

Table 1.1 shows the first nanosatellites put into orbit, or beyond, from the start of the Space Age through 1968. Note that all of these spacecraft are from the USA. The former Soviet Union started the Space Age with larger launch vehicles that enabled heavier spacecraft using heavier components and systems. The 83.6 kg mass Sputnik 1, launched on October 4, 1957, became humanity's first artificial satellite. It had a polished 58.5 cm diameter sphere with a pressurized internal volume that contained 51 kg of batteries to drive a 1 W output transmitter alternating between 20.005 and 40.002 MHz. The 3.5 kg mass transmitter

**Table 1.1** The first successfully launched nanosatellites from 1957 through 1968.

| Name | Launch date | Mass (kg) | Perigee (km) | Apogee (km) | Inclination (degrees) | Country |
|---|---|---|---|---|---|---|
| Vanguard 1 | 17 March 1958 | 1.47 | 652 | 3961 | 34.3 | USA |
| Pioneer 3 | 06 December 1958 | 5.88 | | 102 300 | | USA |
| Vanguard 2 | 17 February 1959 | 10.75 | 558 | 3321 | 32.9 | USA |
| Pioneer 4 | 03 March 1959 | 5.88 | Lunar Flyby | Lunar Flyby | | USA |
| Explorer 9 | 16 February 1961 | 7 | 636 | 2582 | 38.6 | USA |
| OSCAR 1 | 12 December 1961 | 4.5 | 235 | 415 | 81.2 | USA |
| OSCAR 2 | 6 February 1962 | 4.5 | 208 | 386 | 74.3 | USA |
| Flashing Light | 15 May 1963 | 5 | 161 | 267 | 32.5 | USA |
| ERS 9 | 19 July 1963 | 1.5 | 3662 | 3731 | 88.4 | USA |
| ERS 12 | 17 October 1963 | 2.1 | 208 | 103 830 | 36.7 | USA |
| Explorer 19 | 19 December 1963 | 7 | 589 | 2393 | 78.6 | USA |
| ERS 13 | 17 July 1964 | 2.1 | 193 | 104 400 | 36.7 | USA |
| Explorer 24 | 21 November 1964 | 9 | 334 | 1551 | 81.4 | USA |
| ERS 17 | 20 July 1965 | 5.4 | 208 | 112 184 | 35 | USA |
| ERS 16 | 9 June 1966 | 5 | 180 | 3622 | 90 | USA |
| ERS 15 | 19 August 1966 | 5 | 3669 | 3701 | 90.1 | USA |
| ERS 18 | 28 April 1967 | 9 | 8619 | 111 530 | 32.9 | USA |
| ERS 20 | 28 April 1967 | 8.6 | 8619 | 111 530 | 32.9 | USA |
| ERS 27 | 28 April 1967 | 6 | 8619 | 111 530 | 32.9 | USA |
| Explorer 39 | 8 August 1968 | 9.4 | 673 | 2533 | 80.6 | USA |
| ERS 28 | 26 September 1968 | 10 | 175 | 35 724 | 26.3 | USA |

Inclination and perigee values are given for spacecraft that completed more than one Earth orbit.
Source: Data compiled from [6–8].

used vacuum tubes and required a fan to provide temperature control [9]. Sputnik 1 was designed to produce a strong radio signal that could be received by millions of common shortwave receivers all across the planet, and to be visible in small telescopes. Sputnik 2, at 508 kg mass, was launched on November 3, 1957. It contained the backup satellite to Sputnik 1, plus an additional science instrument package, as well as a pressurized capsule that held the small dog named Laika. The Soviets launched the 1327 kg mass Sputnik 3 into orbit on April 27, 1958. The Soviets were focused on putting the first human into space, and that occurred on April 12, 1961 when Yuri Gagarin took the 4730 kg mass Vostok 1 into orbit. Whether hindered by their much heavier spacecraft design, or blessed by their massive launch capability, the former Soviet Union had little need for active nanosatellites. The United Kingdom, Canada, Italy, France, Australia, West Germany, the People's Republic of China, and Japan also lofted their own satellites into orbit through 1970 using either US or indigenous launch vehicles, but these were microsatellites (10–100 kg mass) and minisatellites (100–500 kg mass) [10].

Vanguard 1 was the USA's second artificial satellite, but it was also the first nanosatellite from any country to reach orbit, the first satellite with solar cells, and is now the oldest man-made object still in space. Figure 1.2 shows a photograph of a Vanguard 1 model at the Smithsonian National Air and Space Museum's Steven F. Udvar-Hazy Center, Chantilly, Virginia, USA. Like Sputnik 1, it was spherical and shiny, but it was a lot smaller at 16.5 cm in diameter. Radio output power was 10 mW at 108 MHz for the battery-powered transmitter, and 5 mW at 108.030 MHz for the solar cell-powered transmitter. These transmitters used one transistor each, not vacuum tubes, operated in a vacuum. Transistors were first demonstrated in 1947 in the USA, and offered more efficient, reliable, and compact electronics due to the elimination of the hot, glowing filaments required in vacuum tubes. Note that both Sputnik 1 and Vanguard 1, and many early spacecraft, did not contain radio receivers; they could not be controlled from the ground. Attitude control, either active or passive, was not included. Thermal control was provided by the polished outer shell, with an internal instrument capsule thermally and electrically isolated from the outer

**Figure 1.2** Photo of Vanguard 1 at the Smithsonian National Air and Space Museum's Steven F. Udvar-Hazy Center, Chantilly, Virginia. Source: Photo by author.

shell using Teflon rods. This vacuum Dewar approach effectively averages out external shell temperature extremes caused by exposure to sunlight, followed by eclipse, and return to sunlight.

The next nanosatellite put into space was Pioneer 3. This was NASA's third attempt to at least fly by the Moon, but an upper-stage malfunction prevented attainment of Earth escape velocity. It reached an altitude of 102 300 km and then. fell back to Earth, where it re-entered 38 hours after launch. Pioneer 3 was basically cone-shaped with a 58 cm high, 25 cm diameter thin fiberglass conical shell covering a squat instrument base [11]. The shell was coated in gold to provide electrical conductivity, with stripes of paint to adjust the overall thermal balance. Pioneer 3 was spin-stabilized along the long axis, so this axis had to be a principal axis with the maximum moment of inertia to maintain spin stability. Pioneer 3 had two Geiger–Müller (GM) tubes and a 0.5 kg mass transmitter producing 0.18 W at 960.05 MHz. Pioneer 3 transmitted radiation data for 25 hours before re-entry, and these data showed the existence of a second radiation belt at higher altitudes. The inner radiation belt was discovered by Explorer 1, and both radiation belts are now named after Dr. James Van Allen, professor of physics and astronomy at the University of Iowa.

Figure 1.3 shows a photo of Pioneer 4, a copy of Pioneer 3 with one GM tube replaced by a lunar photosensor and a camera, held by Dr. Wernher von Braun, John Casani, and Dr. James Van Allen. The layout of the components, particularly the outer ring of mercury batteries, provided the needed maximum moment of inertia about the spin axis for both Pioneer 3 and Pioneer 4. Pioneer 4 flew past the Moon at an altitude of 60 000 km and became the first US spacecraft to reach heliocentric orbit [12].

Vanguard 2, which flew after Pioneer 3 but before Pioneer 4, was the first weather satellite. The spherical satellite had an aluminum-coated magnesium shell with a diameter of 50.8 cm and used two internal optical telescopes to monitor the brightness of each field-of-view. The intent was to monitor cloud cover around the Earth. Each telescope scanned the Earth, and space, as the spacecraft rotated at 50 rotations per minute, and a raster scan image could be created as the satellite moved across the Earth. Unfortunately, Vanguard 2 was deployed with a significant wobble about the intended spin axis, so the

**Figure 1.3** Dr. Wernher von Braun (left), John Casani of the Jet Propulsion Laboratory (center), and Dr. James Van Allen, holding parts of the Pioneer 4 spacecraft. Source: Photo courtesy of NASA.

brightness data were hard to use. This spacecraft had a data tape recorder for recording brightness as a function of time, and a command receiver to activate playback of the tape as the spacecraft went over a ground station [13]. A 1 W output telemetry transmitter operated at 108.03 MHz, and a 10 mW, 108 MHz beacon transmitter provided a CW signal for tracking. Although both transmitters stopped working after 26 days, Vanguard 2 has been optically tracked for six decades, providing initial gravity field measurements for the Earth, and continuous atmospheric density measurements based on air drag.

The next nanosatellite launched into space was Explorer 9. It was the first satellite launched from Wallops Island, Virginia, and it was almost an order of magnitude larger than Vanguard 2. Explorers 9, 19, 24, and 39 were 3.6 m diameter balloons used for determining atmospheric density as a function of altitude. These balloons were inflated using nitrogen gas and were composed of alternating layers of aluminum foil and Mylar (polyester) film. The two hemispheres were electrically isolated so that they could function as a dipole antenna for the 15 mW output, 136 MHz tracking beacon. Power for the transmitters was supplied by solar cells and rechargeable batteries. Thermal control was supplied by the application of many white paint spots of 5.1 cm diameter to the surface. Figure 1.4 shows a photograph of Explorer 24 with a human for size comparison.

The first Orbiting Satellite Carrying Amateur Radio (OSCAR 1), a nanosatellite, was ejected into orbit in 1961. A group of amateur radio operators in Sunnyvale, California, decided to “build a continuous-wave beacon to transmit Morse code, to hook it up to batteries, place it into a metal box with an antenna coming out of the top, and have it launched into space” [14]. OSCAR 1 was the world’s first private, nongovernment spacecraft; and, unlike previous nanosatellites, this one went into orbit as a secondary payload. It was launched for free as ballast on a launch vehicle of the US Air Force, thus explaining the curved shape of the $30 \times 25 \times 12\,cm^3$ box shown in Figure 1.5, as a section cut from a thick ring. Ejection off of the primary mission “was done with a very sophisticated technique:

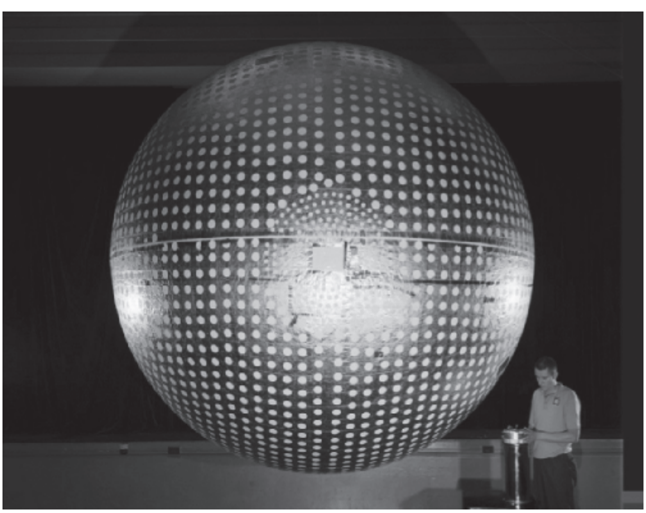

**Figure 1.4** Photo of Explorer 24. Source: Photo courtesy of NASA.

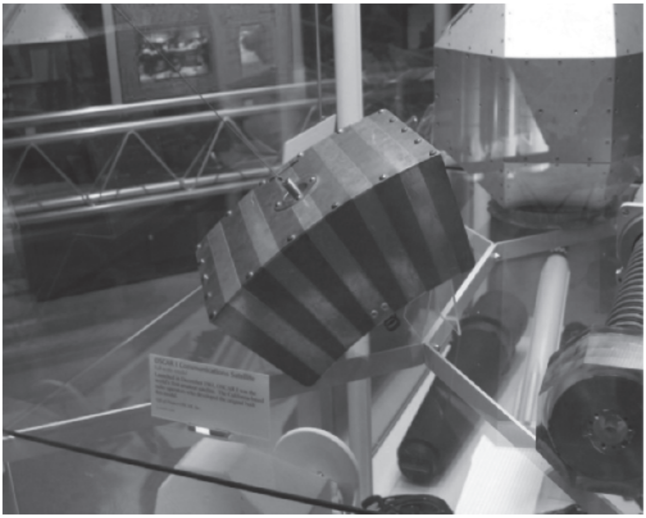

**Figure 1.5** Photograph of OSCAR 1 at the Smithsonian National Air and Space Museum's Steven F. Udvar-Hazy Center, Chantilly, Virginia. Source: Photo by author.

a $1.15 (USD) spring purchased from a local hardware store. The total out-of-pocket cost (not including donated material) was only $68 (USD)" [15]. It transmitted the message "HI" in Morse code (•••• •• ) at a rate proportional to the internal temperature using a two-transistor transmitter operating at 140 mW output at 144.98 MHz [16]. It transmitted for 3 weeks. Average spacecraft temperature was set by the tape pattern on the external magnesium surface, but it was warmer than expected at greater than 50°C after 60 orbits. OSCAR 2 was a copy of OSCAR 1, but with a lower-power transmitter (100 mW) for longer battery life, and modified surface treatments to lower the average spacecraft temperature to 15 $\pm$ 5°C. It started out in a lower orbit and was able to monitor the temperature increase as it started to re-enter.

The Flashing Light Unit listed in Table 1.1 was a subsatellite ejected by the Faith 7 Mercury capsule piloted by the US astronaut L. Gordon Cooper. It was a 15 cm diameter sphere that contained a pair of xenon strobe lights powered by batteries to test the visual acquisition and tracking of other spacecraft by astronauts [17]. Cooper was able to see the flashes one, two, and three orbits after ejection.

The remaining nanosatellites in Table 1.1 belong to the US Air Force Environmental Research Satellite (ERS) series. These spacecraft were used as technology test beds for spacecraft systems and components at medium Earth altitudes (greater than 1500 km apogee). They monitored radiation levels and radiation damage to solar cells. Due to their high perigees, ERS spacecraft were in sunlight most of the time, thus eliminating the need for batteries and battery charge regulators. Figure 1.6 shows a photograph of the 2 kg mass ERS 11 satellite on display at the Smithsonian National Air and Space Museum's Steven F. Udvar-Hazy Center in Chantilly, Virginia. This satellite is identical to the ERS 12 satellite flown in 1963. ERS 12 had an omnidirectional radiation detector to monitor electron fluxes for energies in excess of 0.5 and 5 MeV, and proton fluxes for energies between 10 and 20 MeV, and 50–100 MeV [8]. Note the large number of solar cells on each face, and the coiled

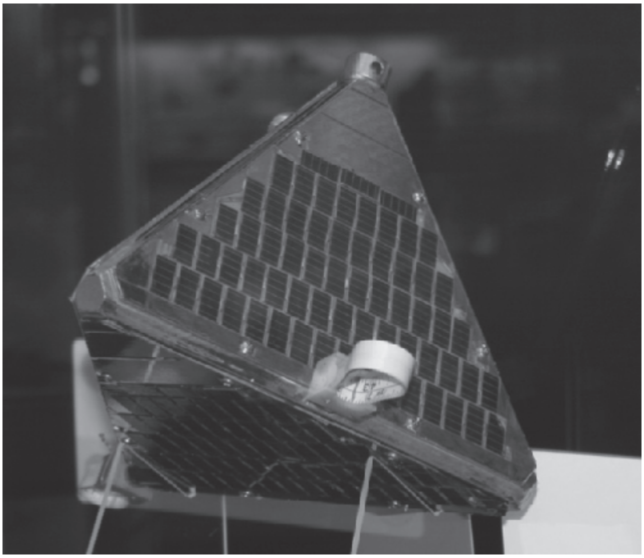

**Figure 1.6** Photo of ERS 11 at the Smithsonian National Air and Space Museum's Steven F. Udvar-Hazy Center, Chantilly, Virginia. Source: Photo by author.

"carpenter tape" antennas (bottom right and left) that form a dipole when released. All of the ERS spacecraft were launched as secondary payloads.

The Early Space Age was a time of excitement and exploration fueled by the Cold War between the USA and the former Soviet Union. Both parties were learning how to exploit the high ground of space in order to monitor each other visually and electronically, and were vying to be the first to put a human being on the Moon. The world's largest rocket, the Saturn V of the USA, was developed to win the space race to the Moon. Weather satellites and geosynchronous communications satellites improved the lives of billions of people, about 3.5 billion in 1967, and precursors of today's ubiquitous global navigational satellites were flown. Average satellite mass had increased well beyond the microsatellite and nanosatellite mass range, and active nanosatellites would disappear for almost three decades.

## 1.4 The Large Space Era

The Large Space Era started in 1968 and ended by around 1996. No active nanosatellites were launched, but microsatellites continued at an average rate of 18.9 per year. This was a period of government-funded space programs and large commercial geosynchronous communications satellites.

At the start of the Space Age, an international telephone call required a reservation because the extremely limited total bandwidth available using cables and radio waves bounced off the ionosphere [18]. Satellites offered vastly increased bandwidth over the long term, and, realizing this, the Communications Satellite Act was passed in 1962 by the United States Congress. The first paragraph of Public Law 87-624 states: "The Congress hereby declares that it is the policy of the United States to establish, in conjunction and in cooperation with other countries, as expeditiously as practical, a commercial communications satellite system, as part of an improved global communications network, which will be responsive to public needs and national objectives, which will serve the communication needs of the United States and other countries, and which will contribute to world peace and understanding" [19]. The intent of this act was to foster competition in this new area of commerce and enable nondiscriminatory access to global communications. This was a major paradigm shift, since, at least in the USA, AT&T had almost complete control of both fixed terrestrial and undersea (cable) communications. Competition fueled continuous growth both in value of services and in spacecraft size over the next 55 years.

Hughes Aircraft, based in California, developed the first geosynchronous communications satellite, Syncom 2, launched in July 1963. Hughes invested US$2 million (about US$17 million in today's values) to develop the 35.5 kg mass, spin-stabilized microsatellite prototype, but they needed additional funding to build and launch an operational version. The US Department of Defense provided additional support, and NASA launched the spacecraft. This government–industry collaboration helped start a new industry in the early 1960s, and this model still works today.

Figure 1.7 shows the almost linear growth in geosynchronous communications satellite launch mass over time for Intelsat satellites. Beginning-of-life (BOL) mass at orbit is typically about half of the launch mass because most geosynchronous satellites are injected into a geosynchronous transfer orbit and contain a thruster and significant propellant to circularize the orbit at geosynchronous altitude. The first two generations were microsatellites, but BOL mass grew to ∼800 kg during the 1970s (fourth generation), ∼1000 kg during most of the 1980s (fifth generation), and ∼2000 kg starting in 1989 (sixth generation). Satellite mass growth through 1997 exemplifies the "Large Space" era, and this trend has continued through today for more than half of the Intelsat spacecraft. A lower-mass branch started in 1997 with the eighth generation, leading to a series of half-mass satellites produced by Orbital Sciences debuting in 2007.

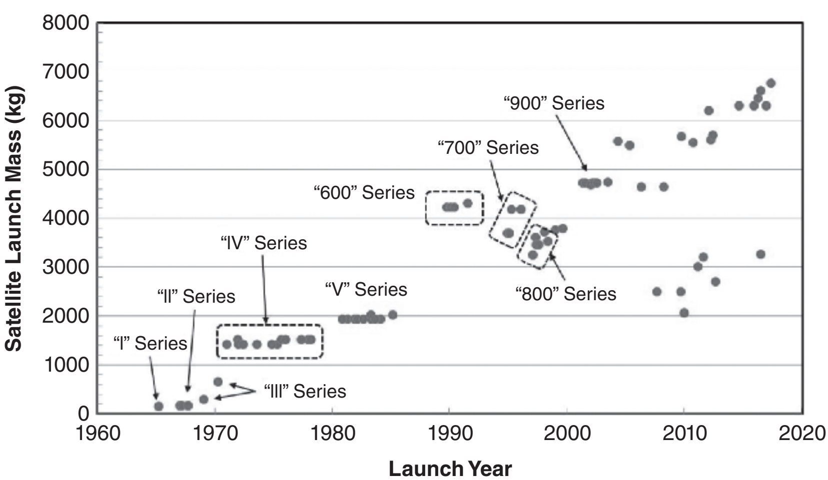


**Figure 1.7** Launch mass of the Intelsat series of geosynchronous communications satellites.

Spacecraft became ever more capable during the Large Space era, but electronic and actuator technologies were still too primitive to enable active nanosatellites. A number of “almost nanosatellites,” spacecraft with a mass slightly higher than 10 kg, were launched starting in 1990. Three 13 kg mass AMSAT “MicroSats” (PACSAT, OSCAR 17, and LUSAT), a 16 kg version called Webersat or OSCAR 18, and two ~46 kg mass microsatellites of the University of Surrey (UoSAT-OSCAR 14 and UoSAT-OSCAR 15) were put into orbit as secondary payloads with SPOT 2, an 1869 kg mass Earth observation satellite [20–26]. The cost to launch the secondary payloads was about US$1 million [27].

The AMSAT MicroSats were 23 $cm^3$, and covered with solar cells with a maximum output power of 15.7 W [28]. They used NEC V40 microprocessors, had up to 10 Mbytes of solid-state memory, and used a 15 cm long local area network to link the five electronics trays together. They operated as flying digital bulletin boards; you could upload data or have a file broadcast to all available ground stations within the satellite footprint. Figure 1.8 shows a photo of the author’s ground station that was used with these and other amateur radio satellites. A personal computer with a color cathode ray tube monitor is on the left, various radio modems occupy the shelf to the right of the monitor, three transceivers are on the shelf below them, and a 50 W power amplifier for 435 MHz operation is on the extreme bottom right of the image. Data rates ranged from 300 to 9600 bits per second.

The 23 $cm^3$ (cube) form factor pioneered by AMSAT became popular for small satellites. Table 1.2 lists launch date, mass, orbit, and country data for 31 of these satellites. Their masses range from 10 to 13 kg, and some individual satellites have a range in mass, depending on which reference you use. Seven flew during the Large Space era, the rest during the New Space era. Note that most went into sun-synchronous orbits.

The majority of spacecraft in Table 1.2 used a permanent magnet to provide passive attitude control. This created two flips per orbit, and the antennas were painted in such a way that solar pressure would cause a small rotation rate about the magnetic axis. Instead of

**Figure 1.8** Photo of author’s 1990s era amateur satellite ground station. Source: Photo by author.

**Table 1.2** Nanosatellites and "almost nanosatellites" with a 23–25 $cm^3$ design.

| Name | Launch date | Mass (kg) | Orbit (km) | Inclination (degrees) | Country |
|---|---|---|---|---|---|
| PACSAT (OSCAR 16) | 22 January 1990 | 11 | 787 × 804 | 98.72 | USA |
| Dove (OSCAR 17) | 22 January 1990 | 11 | 787 × 804 | 98.72 | USA |
| Webersat (OSCAR 18) | 22 January 1990 | 13 | 787 × 804 | 98.72 | USA |
| LUSAT (OSCAR 19) | 22 January 1990 | 11 | 787 × 804 | 98.72 | USA |
| ITAMSAT (OSCAR 26) | 26 September 1993 | 11 | 789 × 803 | 98.7 | Italy |
| EYESAT 1 (OSCAR 27) | 26 September 1993 | 11 | 792 × 805 | 98.8 | USA |
| UNAMSAT B | 5 September 1996 | 11 | 988 × 1010 | 82.9 | Mexico |
| SaudiSat 1a | 26 September 2000 | 10 | 625 × 656 | 64.56 | Saudi Arabia |
| SaudiSat 1b | 26 September 2000 | 10 | 632 × 664 | 64.55 | Saudi Arabia |
| PCSat-1 | 30 September 2001 | 10 | 790 × 800 | 67 | USA |
| LatinSat A | 19 December 2002 | 12 | 602 × 675 | 64.56 | Saudi Arabia |
| LatinSat B | 19 December 2002 | 12 | 613 × 710 | 64.56 | USA |
| SaudiSat 1c | 22 December 2002 | 10 | 633 × 690 | 64.56 | Saudi Arabia |
| OSCAR 51 | 29 June 2004 | 12 | 697 × 817 | 98.2 | USA |
| LatinSat C | 29 June 2004 | 12 | 698 × 766 | 98.26 | USA |
| LatinSat D | 29 June 2004 | 12 | 695 × 852 | 98.26 | USA |
| SaudiComsat 1 | 29 June 2004 | 12 | 701 × 749 | 98.2 | Saudi Arabia |
| SaudiComsat 2 | 29 June 2004 | 12 | 700 × 783 | 98.2 | Saudi Arabia |
| SaudiComsat 3 | 17 April 2007 | 12 | 653 × 718 | 98.1 | Saudi Arabia |
| SaudiComsat 4 | 17 April 2007 | 12 | 650 × 751 | 98.1 | Saudi Arabia |
| SaudiComsat 5 | 17 April 2007 | 12 | 652 × 729 | 98.1 | Saudi Arabia |
| SaudiComsat 6 | 17 April 2007 | 12 | 649 × 762 | 98.1 | Saudi Arabia |
| SaudiComsat 7 | 17 April 2007 | 12 | 651 × 740 | 98.1 | Saudi Arabia |
| AprizeSat 3 | 29 July 2009 | 13 | 564 × 664 | 98.3 | USA |
| AprizeSat 4 | 29 July 2009 | 13 | 605 × 763 | 98.3 | USA |
| AprizeSat 5 | 17 August 2011 | 13 | 610 × 693 | 98.4 | USA |
| AprizeSat 6 | 17 August 2011 | 13 | 627 × 694 | 98.4 | USA |
| AprizeSat 7 | 21 November 2013 | 13 | 596 × 654 | 97.6 | USA |
| AprizeSat 8 | 21 November 2013 | 13 | 597 × 669 | 97.6 | USA |
| AprizeSat 9 | 19 June 2014 | 13 | 619 × 718 | 97.8 | USA |
| AprizeSat 10 | 19 June 2014 | 13 | 620 × 737 | 97.8 | USA |

a permanent magnet, LatinSat A and LatinSat B used a ferromagnetic rod surrounded by a solenoid coil. Current pulses would set, and reset, the magnetic dipole moment of the rod in one of two antiparallel directions. This allowed these satellites to control their flip, and to thus present the best orientation to both the northern and southern hemispheres [29].

## 1.5 The New Space Era

Table 1.2 lists satellites from two nanosatellite-class “little LEO” communications constellations in the New Space era (1997 through the present); AprizeSat, which includes LatinSat A through LatinSat D; and SaudiComsat. The AprizeSat satellites provide store-and-forward, machine-to-machine (M2M) communications for applications, such as monitoring of oil and gas wells, mobile asset tracking, and environmental monitoring [30]. The seven SaudiComsat satellites are also store-and-forward M2M satellites for commercial applications. The first commercial M2M constellation used nadir-pointing Orbcomm 46 kg mass microsatellites, in 720 km altitude, 45° inclination orbits [31]. Launches of experimental satellites started in 1995, and this constellation provided near-continuous surface coverage between 60 °N and 60 °S latitudes using multiple ground stations. The AprizeSat system uses fewer, smaller satellites for applications that do not require continuous connectivity, but can do so over the entire planet. One specific application is the monitoring of automatic identification system (AIS) data packets transmitted by maritime vessels. These packets contain ship-identifier plus global positioning system (GPS)–based position and heading data. AIS is extremely helpful in monitoring ship traffic near coastlines and rivers, and satellite-based AIS extends this monitoring to the open oceans. AprizeSat 3 and AprizeSat 4, together, recorded 460 000 AIS transmissions from 22 000 ships each day in 2010 [32].

The first nanosatellite ejected into space in the New Space era was Sputnik 40 in 1997. Four one-third-scale Sputnik 1 spacecraft were built by Aéro-Club de France, AMSAT, and Rosaviakosmos to commemorate the 40th anniversary of the historic launch [33]. They were 23 cm in diameter, 4 kg in mass, and transmitted at 145 MHz amateur radio band [34]. They had no vacuum tubes or pressure vessels. The first was hand-deployed from the Mir space station on October 5, 1997; the second was never deployed; the third (Sputnik 41) was hand-deployed on November 10, 1998; and the fourth (Sputnik 99) was hand-deployed on April 2, 1999. The last one was turned off before deployment due to a radio licensing issue; it was going to transmit advertising for Swatch, the Swiss watchmaker, using amateur radio frequencies. New Space had some birthing issues.

Tubsat-N (8.5 kg mass) and Tubsat-N1 (3 kg mass) were launched in July 1998 from a K-407 Novomoskovsk Russian submarine from the Barents Sea. These store-and-forward communications nanosatellites became the first submarine-launched satellites. Tubsat-N had a charge-coupled device (CCD) star sensor and a reaction wheel as experiments, plus active magnetic attitude control using a magnetometer and two coils [35]. Active attitude control, a necessity for most interesting satellite missions, was being miniaturized for nanosatellites. Energy storage was supplied by decades-old nickel–cadmium battery technology.

The year 2000 was a major milestone for nanosatellites. On January 27, 2000, an Orbital Sciences Minotaur rocket, a refurbished ICBM, put JAWSAT into orbit. JAWSAT released the 22 kg Optical Calibration Sphere Experiment (OCSE, a 3.5 m diameter balloon), the 52 kg FalconSat 1 from the US Air Force Academy, the 5.9 kg ASUSat 1, and the 25 kg mass Orbiting Picosatellite Automated Launcher (OPAL). ASUSat 1 was cylindrical, with a diameter of 32 cm and a height of 25 cm. It was gravity-gradient stabilized using a 2 m long boom with a 125 g tip mass and contained a pair of 496 × 365 pixel cameras with a 0.5 km/pixel ground resolution, and a GPS receiver [36].

The Stanford-built OPAL microsatellite ejected three picosatellites from Santa Clara University (the 0.2 kg JAK, the 0.5 kg Thelma, and the 0.5 kg Louise), a 0.23 kg amateur radio picosatellite called StenSat, and two 0.25 kg Aerospace Corporation PicoSats [37]. Only the Aerospace PicoSats appeared to be functional. The Aerospace Corporation in El Segundo, California, helped broker a deal with the US Defense Advanced Research Projects Agency (DARPA) and the US Air Force Office of Scientific Research (AFOSR) during a US Air Force Research Laboratory (AFRL) meeting in Albuquerque, New Mexico, in 1998 to support US-built nanosatellites and to redesign the OPAL mission [38, 39]. This support was initiated by Prof. Twiggs' head-snapping comment: "I built a microsatellite (OPAL) for 50 thousand dollars!" OPAL was previously funded by the NASA's Jet Propulsion Laboratory to eject spinning picosatellies, but nonspinning spacecraft would be easier. The Aerospace Corporation assisted Stanford in developing a simplified containerized ejection mechanism for OPAL, and supplied two picosatellites for on-orbit ejection. The OPAL ejection mechanism later led to Prof. Twiggs' invention of CubeSats.

The next nanosatellites in 2000 were SaudiSat 1a and SaudiSat 1b, SNAP-1, and Munin. SNAP-1 was built by Surrey Satellite Technology Limited (SSTL) in the United Kingdom. The 6.5 kg mass satellite was designed to test technologies needed for a satellite inspection mission, and thus had three-axis attitude control, a GPS receiver, a butane warm gas thruster, four video cameras with 350 × 288 pixel resolution, and an ultra high frequency (UHF) intersatellite link to exchange data with the target spacecraft, the Tsinghua-1 microsatellite [40]. At the time, it was the most advanced nanosatellite ever launched. SNAP-1 and Tsinghua-1 were attached to a Nadezhda, a Russian navigation satellite, launched on June 28, 2000 into a 683 × 706 km, 98.13° inclination orbit. SNAP-1 and Tsinghua-1 were subsequently released by the Nadezhda and started to separate from each other. Spacecraft checkout and software fixes to remedy an anomalous spacecraft dipole moment resulted in the first thruster firing on August 15, 2000. By this time, the dispersion in initial deployment vectors and differential drag caused SNAP-1 to have a 2 km lower semi-major axis than Tsinghua-1. The 3.5 m/s delta-V from the butane thruster was insufficient to match orbits, with correct phasing, to rendezvous with Tsinghua-1. Flight results showed a lower demonstrated delta-V, most likely caused by liquid, rather than gaseous, butane ejection during initial thruster firings [41]. Ullage (empty space in the propellant tank) was increased for future thrusters, along with the addition of a sponge to keep liquid away from the nozzle.

Munin was a $21 \times 21 \times 22\ cm^3$ nanosatellite with a mass of 6 kg. It carried a miniaturized electrostatic dual-top-hat spherical analyzer, a device to measure ion and electron energy distributions with energies up to 18 keV per charge, and a 340 × 240 pixel CCD imager to image the aurora in visible light [42]. It was a space weather satellite and Europe's first scientific nanosatellite. It made the technological leap to lithium-ion batteries for significantly decreased battery mass per unit stored energy, but it relied on a mere 2 Mbytes of random-access memory for data storage, and passive magnetic stabilization.

The year 2001 saw one nanosatellite put into orbit, PCSat-1. Figure 1.9 shows a photograph of the 10 kg mass PCSat-1 satellite on display at the Smithsonian National Air and Space Museum's Steven F. Udvar-Hazy Center in Chantilly, Virginia. A panel, which normally holds a 144 MHz monopole antenna, has been removed to show the internal compartments. Note the simple yellow carpenter tape antennas for use at 435 MHz. This satellite received and logged amateur radio X.25 data packets [43].

The Aerospace Corporation, under funding by DARPA, created two 0.8 kg mass, $10 \times 10 \times 12.5\,\text{cm}^3$ MEMS-Enabled PicoSatellite Inspector (MEPSI) nanosatellites that were deployed by the US Space Shuttle Endeavour on December 2, 2002, using the Aerospace Picosatellite Orbital Deployer (A-POD) [44]. They were connected by a 15 m long tether. The A-POD was designed for a man-rated launch system and flew one year before the first CubeSat Polytechnic Picosatellite Orbital Deployer (P-POD), the workhorse CubeSat deployer. The other nanosatellite launched during 2002 was the 10 kg mass SaudiSat 1c. The year 2003 marked the start of an unprecedented revolution in small satellite evolution and deployment: the CubeSat era. Pumpkin, Inc. in San Francisco started delivering CubeSat kits that could be ordered online. The founder, Dr. Andrew Kalman, was an expert in embedded microcomputer systems, and had happened to meet Prof. Twiggs at Stanford in 1998. Kalman helped Twiggs create the CubeSat specifications,

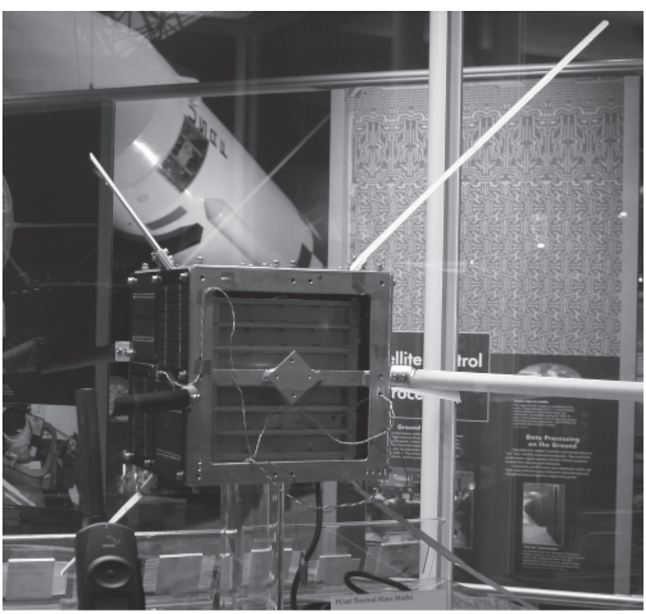

**Figure 1.9** Photograph of the PCSat-1 satellite on display at the Smithsonian National Air and Space Museum's Steven F. Udvar-Hazy Center in Chantilly, Virginia. Source: Photo by the author.

and fostered the idea of using inexpensive, state-of-the-art, commercial off-the-shelf (COTS) electronics instead of expensive, tested, high-quality electronics that could be a generation or two behind current mass-market designs [45].

Five 1U CubeSats were launched on June 30, 2003: CanX-1 (Canadian Advanced Nanospace eXperiment from the University of Toronto), AAU-CubeSat (Aalborg University in Denmark), DTUSat-1 (Danmarks Tekniske Universitet Satellite), XI-IV (X-factor Investigator, University of Tokyo), and CUTE 1 (CUbical TITech Engineering Satellite from the Tokyo Institute of Technology), each about 1 kg in mass, were deployed into an ~820 km altitude, sun-synchronous orbit. CanX-1 had active magnetic stabilization, a Complementary Metal–Oxide–Semiconductor (CMOS) horizon and star tracker experiment, and a GPS receiver [46]. AAU-CubeSat had three-axis magnetic coil stabilization and a 1280 × 1024 pixel color camera with a depth of 24 bits per color pixel. Ground resolution was about 150 m, but only basic housekeeping data were downloaded due to a significant reduction in battery capacity [47]. DTUSat-1 was dead on arrival [48]. The XI-IV CubeSat used passive magnetic stabilization and had a 640 × 480 color CMOS camera as a payload [49]. CUTE 1 was unstabilized, but contained a CMOS image sensor as a sun sensor. QuakeSat 1, a 3U CubeSat of 4.5 kg mass, was launched with the previous 5 1U CubeSats. It was built in collaboration between Stanford and QuakeFinder of Palo Alto, California [50]. QuakeFinder's goal was to save human lives by developing earthquake monitoring systems. QuakeSat 1 monitored extremely low frequency (ELF) electromagnetic fields that were predicted to occur before major earthquakes. It monitored the magnetic component of these fields and used on-board magnets for passive magnetic stabilization. This first CubeSat launch put six university-class CubeSats into orbit using P-PODs mounted on the upper stage of an inexpensive Russian Rockot RS launch vehicle. Launch cost was about US$40 000 per "U" of volume. After 15 years, CUTE 1 (aka CubeSat-OSCAR 55) and XI 4 (aka CubeSat-OSCAR 57) are still active [51]. This is an amazing tribute to Japanese engineering, especially when one considers the radiation environment at ~820 km altitude. No other nanosatellites were launched that year, and no nanosatellites were launched in 2004.

The first nanosatellite of 2005 was TNS 0, a 4.5 kg mass, 25 cm long, 17 cm diameter cylinder with no solar cells, that contained a pair of Globalstar modems, batteries, and a timer [52, 53]. It was developed by the Russian Scientific Institute of Space Device Engineering (RSIDE)987+ and hand-deployed from the International Space Station (ISS) to test the use of the Globalstar network for continuous command and control and download of telemetry. UWE-1 (University of Würzburg's experimental satellite 1), XI-V (University of Tokyo), and nCube-2 (Norway) were of 1 kg mass, 1U CubeSats that flew in October 2005 on the second CubeSat mission, using a Kosmos-3M launch vehicle. UWE-1 was designed to test the use of established Internet protocols such as TCP, UDP, STCP, and HTML in a space environment [54]. It used passive magnetic stabilization, a micro-Linux operating system, and completed its mission within a few weeks [55]. The XI-V CubeSat was a backup to XI-IV, but included a few upgrades, such as thin-film copper–indium–gallium–selenide (CIGS) solar cells on one face and improvements in the camera control software. nCube-2 was designed to monitor maritime AIS transmissions using active magnetic stabilization and a gravity-gradient boom. Unfortunately, no signals were received, and it was believed that it never deployed from the host spacecraft. The year 2005 also saw the founding of Clyde Space in Glasgow, Scotland, to provide CubeSats, CubeSat systems, and nanosatellite systems to universities, commercial companies, and government organizations.

The year 2006 had an international mix of two "official" CubeSat launches, plus three CubeSat-like launches. The first one put the CUTE 1.7 + APD (aka OSCAR 56) CubeSat into orbit using a Japanese M-5 launch vehicle. This 3.6 kg mass, 2U CubeSat was built by the Tokyo Institute of Technology and was ejected using their own CubeSat deployer. Although it was 2U in size, it did not conform to the established CubeSat design specifications. The next flight in July used a Russian Dnepr launch vehicle. Unfortunately, it had a launch failure, resulting in the complete loss of 14 CubeSats. The third flight in September used a Japanese M-5 launch vehicle to put the $12 \times 12 \times 12\,\text{cm}^3$, 2.7 kg mass, satellite HITSAT-1 (aka OSCAR 59) of Hokkaido Institute of Technology into orbit using a custom deployer. A CubeSat launch in December used a US Minotaur 1 launch vehicle to put the 3U CubeSat Genesat-1 into orbit. GeneSat-1, shown partially assembled in Figure 1.10, was built by the NASA's Ames Research Center and multiple universities to perform genetic experiments on *E. coli* bacteria growing in microgravity and shielded ~400 km altitude radiation environment. Note the silver "tuna can" on the top side. This volume was made available by cutting a hole in the pusher plate that separates the deployment spring from the CubeSat. The tuna can fit inside the helical deployment spring.

Four additional nanosatellites were put into orbit in December on the US space shuttle Discovery. MEPSI 2A and MEPSI 2B, built by The Aerospace Corporation, were

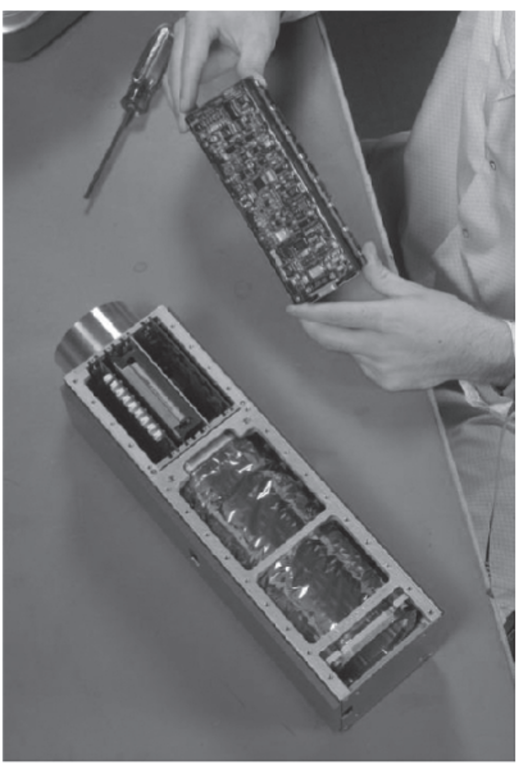

**Figure 1.10** Photo of a partially assembled GeneSat-1. Source: Photo courtesy of NASA.

$10 \times 10 \times 12.5\,\mathrm{cm}^3$ nanosatellites connected by a 15 m long tether. The "target" had six $640 \times 480$ pixel color cameras pointing out the +X, −X, +Y, −Y, +Z, and −Z faces, while the "inspector" had three reaction wheels, two cameras, and an additively manufactured 5-thruster cold gas propulsion system. We believe that this was the first additively manufactured part in any satellite. The other nanosatellites on this mission were RAFT 1 and MARScom built by the US Naval Academy in Annapolis, Virginia. These were $12.5\,\mathrm{cm}^3$ deployed by an expanded-volume A-POD.

The year 2006 also saw Innovative Solutions in Space (ISIS), based in the Netherlands, open the online CubeSat shop (www.cubesatshop.com), a "one-stop webshop for CubeSats and nanosats." ISIS was a spin-off from the Delfi-C3 nanosatellite project from Delft University of Technology [56]. GomSpace, originally based in Aalborg, Denmark, followed in 2007 as another supplier of CubeSats, CubeSat systems, and services [57]. CubeSats were slowly evolving from university experiments to scientific and commercial platforms, and at least four commercial companies were selling products to the growing market on the internet.

The year 2007 saw eight nanosatellites put into orbit. Seven CubeSats (CP 3, CP 4, CAPE-1, Libertad 1, AeroCube 2, CSTB 1, and MAST) were put into orbit using P-PODs on a Dnepr launch vehicle in April. The CP series CubeSats were built by the California Polytechnic State University, San Luis Obispo, California, CAPE-1 was built by the University of Louisiana at Lafayette, Libertad 1 was built by the Sergio Arboleda University in Columbia, AeroCube 2 was built by The Aerospace Corporation in El Segundo, California, CSTB 1 was built by the Boeing Corporation in Huntington Beach, and MAST was built by Tethers Unlimited and Stanford University [58, 59]. The 2.5 kg mass, $15 \times 15 \times 15\,\mathrm{cm}^3$ ZDPS 1 nanosatellite, designed and built by Zhejiang University, China to demonstrate small satellite technologies, was launched as a secondary payload on a Chinese CZ-2D launch vehicle on May 26. Most of these nanosatellites were designed and built in California, but South America and China were now entering the field.

The next decade of the "New Space" era saw spectacular growth in nanosatellite launch rates. Nanosatellites were launched at yearly rates of 8 in 2008, 14 in 2009, 19 in 2010, 9 in 2011, 25 in 2012, and 85 in 2013. Four years later in 2017, the yearly nanosatellite launch rate hit an amazing 293 spacecraft. Table 1.3 shows the launches of microsatellites, non-CubeSat nanosatellites, and CubeSats during 2017. Note that the last launch on November 28, 2017 was a failure. The most popular CubeSat size in 2017 was a 3U, and the next most popular size was 2U. What drove this growth? Increasing global CubeSat launch capacity, increased government funding of CubeSats at national laboratories and universities, and commercial companies trying to provide store-and-forward communications and new Earth observation capabilities using CubeSats fueled this growth.

The large number of 2U CubeSats launched in 2017 was an anomaly driven by the QB50 project. QB50 was approved in January 2012 by the European Commission as a multisatellite network to study lower thermospheric physics. Forty 2U CubeSats were to be deployed to fill a complete orbit, plus 10 2U/3U CubeSats for "science and technology demonstration" [60]. Twenty eight were deployed by the ISS in May 2017, and eight more were deployed by an Indian Polar Small Launch Vehicle in June 2017 [61]. These CubeSats were built by universities in Europe, the USA, Australia, South Africa, etc., and typically carried one of the

**Table 1.3** Launches of small satellites during 2017.

| Date | Country | Micro | Nano | 1U | 1.5U | 2U | 3U | 3.5U | 5U | 6U | 12U | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 January | China | 1 | | | | 2 | | | | | | 3 |
| 15 February | India | | 2 | 1 | | 1 | 99 | | | | | 103 |
| 2 March | China | 1 | | | | | | | | | | 1 |
| 18 April | USA | | | 1 | | 29 | 6 | | 1 | 1 | | 38 |
| 20 April | China | | | | | | 1 | | | | | 1 |
| 3 June | USA | | | 5 | | | | | | | | 5 |
| 14 June | Russia | 1 | 1 | | | | 2 | | | | | 4 |
| 15 June | China | 1 | | | | | | | | | | 1 |
| 23 June | India | 3 | 1 | 3 | | 4 | 18 | | | 1 | | 30 |
| 23 June | Russia | | 1 | | | | | | | | | 1 |
| 14 July | Russia | 4 | | 1 | | | 59 | | | 7 | | 71 |
| 14 August | USA | 1 | | | | | 1 | | | 2 | | 4 |
| 26 August | USA | | 1 | | 2 | | | | | | | 3 |
| 31 October | USA | | | | | | 4 | | | | | 4 |
| 12 November | USA | | | 1 | 2 | 1 | 10 | 1 | | 1 | | 16 |
| 14 November | China | 1 | | | | | | | | | | 1 |
| 18 November | USA | | | 3 | | | 2 | | | | | 5 |
| 21 November | China | 3 | | | | | | | | | | 3 |
| 28 November* | Russia | 3 | 1 | | | | 12 | | | 2 | | 18 |
| Total | | 19 | 7 | 15 | 4 | 37 | 214 | 1 | 1 | 14 | | 312 |

*Entries with an asterisk denote a launch failure.

three space science instruments: an ion-neutral mass spectrometer, a flux-Φ-probe (flux of atomic oxygen), or a multineedle Langmuir probe [62]. QB50 created two distributed space weather measurement systems.

### 1.5.1 Technology Development

Small satellites in any size class go through a series of system, subsystem, and component technology development stages. Smaller satellites need more miniaturization and become possible at later dates in time as technologies mature. Fortunately, ever-smaller transistors have enabled the doubling of integrated circuit density roughly every 2 years [63]. This trend, called Moore's law, has proven true since 1965 for microprocessors, memory, and other electronic circuits. Consider the Intel 4004 4 bit microprocessor introduced in 1971, with 3200 transistors on a 12 $mm^2$ die, fabricated with 10 000 nm minimum feature size, that processed instructions at an average rate of 60 kHz [64]. Today's 32-core, AMD EPYC 64 bit processor was introduced in 2017 and fabricated using 14 mm minimum feature size, has 19.2 billion transistors on a 768 $mm^2$ die and processes instructions at 2.2 GHz, per

**Table 1.4** Data downlink rates for CubeSats in 2014.

| Downlink data rate | Number |
|---|---|
| <9600 bps (Morse code, 400 baud, 1200 baud, etc.) | 85 |
| 9600 bps | 36 |
| 9600 to <1 Mbps | 16 |
| 1 Mbps and greater | 7 |

Total number of CubeSat transmitters for this dataset was 144.

core [65]. In terms of processing efficiency adjusted for 32 bit operations, the 4004 operated at ~6000 instructions per second per Watt, while EPYC (a high-end server microprocessor) operates at 390 million instructions per second per Watt. Simpler microcontrollers with a smaller memory addressing space and simpler input/output circuits easily exceed several billion instructions per second per Watt. Note that typical spacecraft command and control operations require about 1 million instructions per second, while image processing, autonomous navigation, etc. may require processing speeds in excess of 100 million instructions per second. Even 1/4U CubeSats can now support these processing functions on their limited power budget.

Semiconductor memory has also followed Moore's law. PACSAT, launched in 1990, had 10.25 megabytes of memory, with 8 megabytes used by the store-and-forward payload [66]. Today, we can use 256 gigabyte flash RAM cards to put 1 terabyte or more into a 1/4U or larger spacecraft. Generating 1 TB of data is easy; a high-definition HD video stream at 1920 × 1080 pixel resolution, 24 bit pixel depth, at 30 frames per second would generate 1.6 TB of data per day using 10× data compression. Getting this data rate down to the ground from LEO is hard. If one assumes four ten-minute passes per day for a single ground station, the spacecraft would need a 540 million bit per second download rate. Table 1.4 shows data download rates for CubeSats in 2014 [67]. Less than 5% of the transmitters had a data download rate greater than one million bits per second (bps), and the majority used data rates less than 9600 bits per second. Out of 172 total CubeSat transmitters, 112 used the amateur radio 435 MHz UHF band, but only four used X-band where data rates of 100+ million bps (Mbps) are possible.

Use of X-band downlinks has significantly increased since 2014, driven primarily by commercial Earth imaging CubeSats from Planet Labs. Their latest 2 W output, 8150 MHz transmitter has demonstrated 220 Mbps at X-band [68]. More bandwidth is available at higher frequencies, such as Ku, K, and Ka bands, and ultimately, optical. Future nanosatellites will need these increased bandwidths. The 3U Integrated Solar Array and Reflectarray Antenna (ISARA) CubeSat recently demonstrated a Ka band antenna, with greater than 33 dB gain, patterned on the backside of deployed three-panel solar array that would enable 100+ Mbps communications for LEO CubeSats [69]. Figure 1.11 shows a larger, X-band version of the reflectarray used on the two Mars Cube One (MarCO) 6U CubeSats currently heading for a flyby of Mars to support the InSight Mars lander of NASA's Jet Propulsion Laboratory [70]. These are the first interplanetary CubeSats.

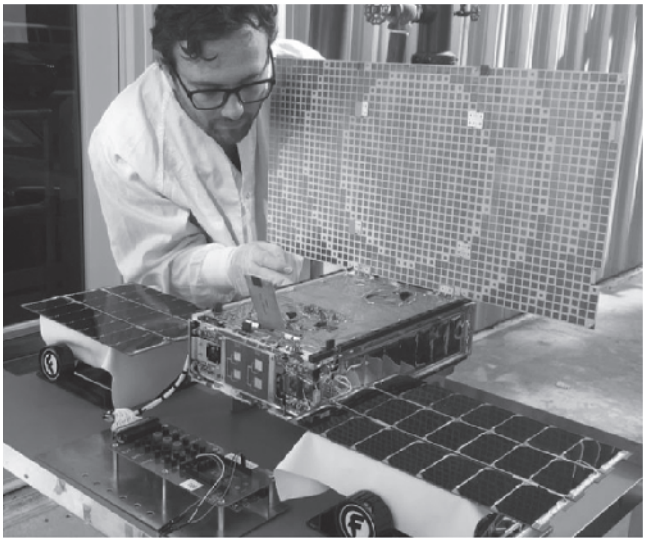

**Figure 1.11** Photograph of one of the 12U MarCo CubeSats heading to Mars. Source: Photo courtesy of NASA.

Due to much higher frequencies, optical communication offers downlink rates in the 1–10 Gbps range, even on nanosatellites. Figure 1.12 shows a photograph of AeroCube-OCSD-B CubeSat put into orbit in late 2017. This effort, like ISARA, was funded by NASA's Small Satellite Technology Program. Two almost identical 1.5U CubeSats were launched to test proximity operations using a steam thruster. Each CubeSat also carries a 2 W output, 1064 nm fiber laser capable of producing a 500 Mbps data rate using on/off modulation. The laser is hard-mounted to the CubeSat body, and the on-board attitude control system provides tracking of an optical ground station during a pass [71]. One of the CubeSats recently demonstrated an optical downlink at 200 Mbps to a 40 cm diameter receive telescope, with 400 Mbps expected by mid-2019. Gigabit per second data rates can be achieved on future CubeSats by using larger-diameter ground stations, and/or narrower angular beam widths.

Obtaining accurate geo-registration of Earth images at several meter ground resolution or pointing a 0.05° full-width-half maximum (FWHM) laser beam at a specific ground station requires a three-axis attitude control system with one or more star trackers and at least three reaction wheels. Star trackers were readily available in the early 2000s as 10 cm size and larger modules for normal size spacecraft and microsatellites. A prototype using "new" active pixel sensor technology, ubiquitous today in cellphones and most cameras, was a 6 $cm^3$ with a 10 cm diameter and 14 cm long sunshade [72]. It had a total mass of about 1 kg, consumed 5 W of power, and used a $1024 \times 1024$ array of 15 μm square pixels, a 24.5° square field-of-view, and saw stars down to 5th magnitude. The AeroCube-OCSD CubeSats use a $742 \times 480$ image sensor with 6 μm pixels for each of two star trackers [73]. They are about 2.5 cm on a side, excluding an appropriately scaled sun shade, and would easily fit in a 1/2U CubeSat. Many similar-size designs are available today from a number of vendors, some of which could fit in a ¼U CubeSat.

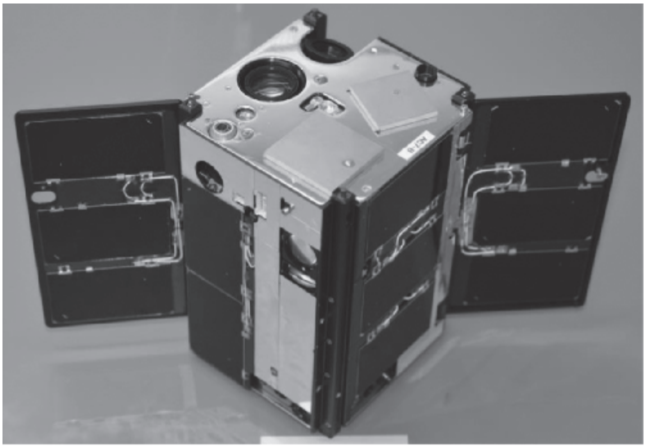


**Figure 1.12** Photograph of AeroCube-OCSD-B with deployed wings.

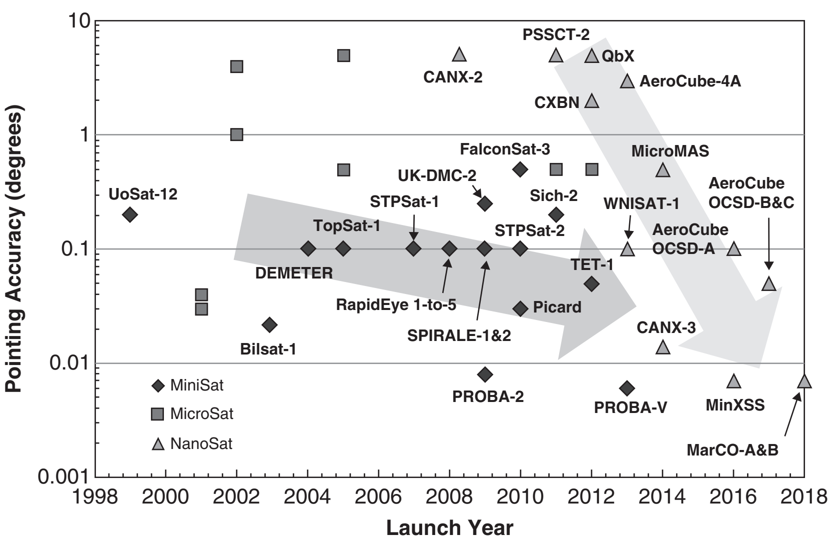


**Figure 1.13** Evolution of small satellite pointing accuracy over the last 20 years. (*See color plate section for color representation of this figure*).

The development of cm-scale star trackers and cm-scale reaction wheels enabled nanosatellites with three-axis pointing accuracies typically associated with light minisatellites in the 100–200 kg mass range. Figure 1.13 shows the evolution of pointing accuracy for 100–200 kg mass minisatellites, microsatellites, and nanosatellites as a function of launch year. These data are primarily from reference [74] with extra satellite data added using the European Space Agency's (ESA) eoPortal website. Note the gradual increase in minisatellite pointing accuracy (pink arrow trendline) since 2002 and the rapid increase in pointing accuracy for nanosatellites (green arrow trendline) during the last 6 years.

This was driven by the perceived potential market and the ability to design, build, test, fly, and repeat on a 1-year timescale, as opposed to the traditional 7-year timescale for large satellites, and the 2 year to 3-year timescale for minisatellites.

### 1.5.2 Commercial Nanosatellites and Constellations

Table 1.2 has eight AprizeSat satellites plus four LatinSat satellites that formed the 12-satellite AprizeSat constellation for low data rate store-and-forward communications using 13 kg mass "almost" nanosatellites. WNISAT-1 was a pioneer commercial nanosatellite with a 10 kg mass and 27 $cm^3$ shape launched in November 2013 with a visible red, green, blue color camera and a near infrared camera. It was designed for commercial monitoring of northern sea routes [75]. It had a spatial resolution of 500 m per pixel, a three-axis pointing accuracy of 0.1°, and was funded by Weathernews, Inc., of Tokyo, Japan.

Explosive commercial nanosatellite development started with the launch of two 3U imaging CubeSats in April 2013 called Dove 1 and Dove 2 by Planet Labs of San Francisco, California. They carried Maksutov–Cassegrain telescopes of 9 cm diameter with an 11 megapixel RGB + near infrared imager at the focus to image the Earth at 3–5 m resolution [76]. The next generation used a five-element optical system coupled to a 29 megapixel imager. Planet's goal is to image the Earth daily at 3–5 m resolution. By the end of August 2013, Planet Labs had raised more than US$13 million in venture capital funding [77]. By April 2015, they had raised an additional US$118 million [78]. By June 2018, 324 Dove imaging satellites, all 3U CubeSats, had been launched.

Table 1.5 lists commercial CubeSat constellations with at least two functional spacecraft on orbit, as of February 2019 [92]. Spire Global currently has the second largest nanosatellite constellation, also using 3U CubeSats. The first experimental CubeSats, ArduSat-1 and ArduSat-X, were launched in 2013 [93]. The experimental ArduSat-2 followed in February 2014, and the Lemur 1 prototype was launched in June 2014. The Lemur 2 series was launched starting in September 2015. These 3U CubeSats have GPS radio occultation receivers to measure atmospheric temperature, pressure, and humidity profiles, AIS receivers to monitor ship locations, and automatic dependent surveillance broadcast receivers for tracking aircrafts.

Astro Digital has launched five of ten "Landmapper-BC" 6U CubeSats, starting in July 2017. Each CubeSat has separate red, green, and near-infrared cameras that match the Landsat 8 Earth observation satellite of US National Oceanic and Atmospheric Administration (NOAA) [94]. Ground resolution is 22 m, and 1.2 TB per day, per satellite, of data are downloaded at Ka band.

The first two companies listed in Table 1.5 are headquartered in San Francisco, California, while the third is headquartered in nearby Santa Clara, California. The fourth is headquartered in London, The United Kingdom. Sky and Space Global (SAS) is planning a 200-nanosatellite constellation of 3U CubeSats to provide voice, data, and global messaging for near-equatorial regions [95]. Three pathfinder CubeSats, the Red, Green, and Blue Diamonds, were launched in June 2017. Note that the last five entries in Table 1.5 are for space connectivity to the Internet of Things (IoT). This is a recent development which could add over 300 new nanosatellites to LEO.

**Table 1.5** Commercial CubeSat constellations with at least two functional spacecraft on orbit as of February 2019.

| Organization | Number launched | Target number | Form factor | Funding (million US$) | Purpose | Ref. |
|---|---|---|---|---|---|---|
| Planet Labs | 355 | >150 | 3U | 183 | Daily Earth imaging at 5 m resolution | [79] |
| Spire | 103 | >150 | 3U | 150 | Maritime tracking, GPS radio occultation data, aircraft tracking | [80] |
| Astro Digital | 6 | 25 | 6U/16U | > 16.7 | Earth imaging at 22 m resolution, four bands | [81] |
| Sky and Space Global | 3 | 200 | 3U | 11.5 | Mobile communications in the tropics | [82] |
| GeoOptics | 7 | TBD | 6U | 5.15 | GPS radio occultation data | [83] |
| Helios Wire | 2 | 28 | 16U | 4 | Store-and-forward communications, IoT | [84] |
| Swarm Technologies | 7 | 8 | 1U/4U | 28 | Store-and-forward communications, IoT | [85, 86] |
| Kepler Communications | 2 | 140 | 3U, 6U | 21 | Store-and-forward communications, Ka band | [87] |
| Hiber Global | 2 | 48 | 6U | 14.5 | Store-and-forward communications, IoT | [88, 89] |
| Fleet Space | 4 | 100 | 1.5U, 3U, 12U | 5 | Store-and-forward communications, IoT | [90, 91] |

## 1.6 Summary

The first nanosatellites were launched near the start of the Space Age between 1958 and 1968. These were experimental spacecraft designed to test new technologies and to provide environmental data for low Earth orbit and beyond. Small satellites were launched from 1968 through 1996, but none of these were active satellites within the 1–10 kg mass range. Miniaturization technologies continued to evolve during this period, and eventually enabled active nanosatellites starting in 1997. CubeSats were invented during the next few years and started flying in 2003. The ability to fly a satellite for US$50 000–300 000 enabled universities and small companies to fly their own spacecraft. The availability of 10 or more launch opportunities per year created a design, build, test, and fly cycle of about 1 year for CubeSats, which spurred rapid development of key spacecraft technologies, such as imaging systems and accurate three-axis attitude control. These developments stimulated venture capital and other funding sources to create "New Space" businesses based on CubeSats. Nanosatellite launch rates have grown exponentially since 1997, similar to Moore's law, with a doubling time of 2.44 years. Based on current plans for new nanosatellite constellations, this exponential growth could continue for at least another 5 years.

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