Acta Astronautica 170 (2020) 93–105

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Review article

Small satellites an overview and assessment

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ABSTRACT

The small satellite industry has seen incredible changes over the last few years. With new constellations of 1000+ satellites being proposed – the industry is primed for an explosion of growth. Governments are taking a new look at small satellites, as commercial customers use them for their flexibility, speed of development, resiliency, low cost, and tolerance of risk in cutting edge technology. A new era of small satellites has emerged augmenting larger systems and, in some cases, replacing them.

Advances in micro-electronics have enabled small spacecraft to maintain performance characteristics of modern spacecraft in unbelievably small packages. These spacecraft are inexpensive to build, test, and launch – which has enabled the production of large constellations. These constellations are being used to provide daily imagery enabling new uses in defense, agriculture, business intelligence, forestry, and disaster recovery.

Competitors are entering the small satellite market at a staggering rate providing new ideas and innovations. Small satellites will launch the world into the next space race as companies and countries look to develop new break throughs. These capabilities will connect our world in ways we cannot imagine, allowing us to provide precision support during disasters, and see our world in a new light.

1. Industry overview

A satellite is defined as "an artificial body placed in orbit around the earth, moon, or another planet in order to collect information or for communication [1]." To set the stage in which small satellites operate we must first examine the classifications of small satellites. Table 1 shows how satellites are categorized by their weight. The satellite weight classification comes from the widely accepted Sweeting publication [2]. While there are several classifications of satellites, the focus of this paper will be satellites less than 500 Kg deemed "Small Satellites".

Small satellites in the nano satellite classification can be further broken down by volume. 1U is a 1 unit cube sat with a 10 cm^3 volume and maximum mass of 1 kg [3]. This unit can be extended to a 2U cube sat of 10 cm × 10 cm x 20 cm and maximum mass of 2 kg; these classifications can be seen in Table 2. This concept was initially proposed by Robert Twiggs during the University Space Systems Symposium in November of 1999. An important note is that while a max weight is prescribed as part of the cube sat definition it is not a stringent requirement.

Utilizing data found in the Union of Concerned Scientists (UCS) satellite database, the weight distribution for satellites launched from 2006 to 2016 [4] can be generated. As seen in Fig. 1, 47% of all satellites launched were large satellites or satellites over 1000 kg. These satellites are typically high throughput communication, navigation, and earth observation satellites. Communication satellites are usually stationed in a Geosynchronous Orbit (GEO); however, the navigation and earth observation satellites can be found in various orbits. Medium sized satellites in the 500–1000 Kg range are usually a mix of Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) satellites with a variety of missions: communications, earth observation, navigation, space science, and technology development.

The small satellites launched to date are almost always placed in LEO, most of which fall into Sun-Synchronous and Non-Polar Inclined orbits as seen in Fig. 2. A Sun Synchronous orbit is the most popular for small satellites as it places the satellite in constant sunlight. This is convenient for satellites that image earth in visible wavelengths, and allows for simpler power subsystems. Additionally, LEO provides the lowest $/kg delivered to orbit.

The number of small satellite launches is typically dominated by the United States who has launched over 201 small satellites, as seen in Fig. 3. These launches include commercial, defense, scientific, and university programs. While the US makes up 40%, the rest of the list is comprised of various countries strengthening their space programs or developing them. Fig. 4, shows the number of small satellites launched each year from 2000 to 2016. During this time, small satellites have seen an increase of almost 100%–2016 alone saw the launch of 92 small satellites.

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https://doi.org/10.1016/j.actaastro.2020.01.034
Received 16 December 2019; Accepted 23 January 2020
Available online 27 January 2020

Table 1
Satellite weight classification.

Satellite Classification (N., 1992)	Mass (kg)
Large Satellite	> 1000
Medium Satellite	500 to 1000
Mini Satellite	100 to 500
Micro Satellite (Cube Sat)	10 to 100
Nano Satellite	1 to 10

Table 2
Cube satellite classification.

CubeSat Designation	Size (max)	Mass (max)
1U	10 cm × 10 cm x 10 cm	1 kg
2U	10 cm × 10 cm x 20 cm	2 kg
3U	10 cm × 10 cm x 30 cm	3 kg
6U	10 cm × 20 cm x 30 cm	6 kg

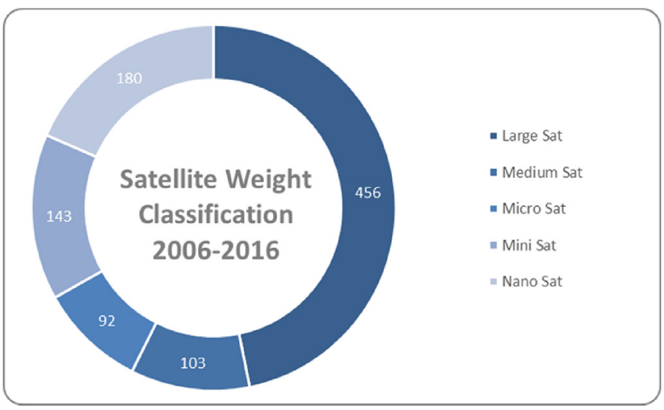

Fig. 1. Satellite weight classification (2006–2016).

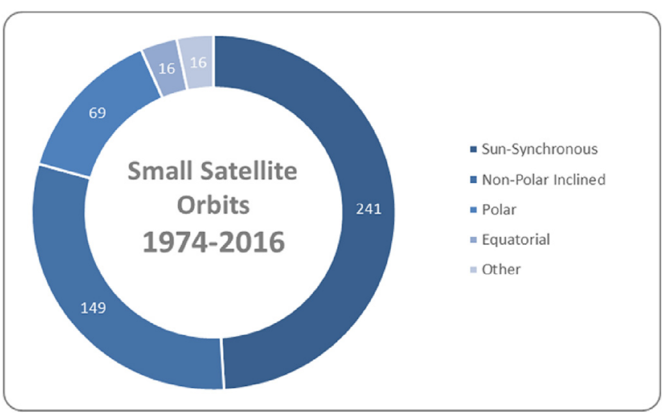

Fig. 2. Small satellite orbits.

OneWeb, previously known as WorldVu, has set their sights on a LEO constellation that will provide global broadband internet. With backers such as Google, Virgin Galactic, Arianespace, and SoftBank; OneWeb plans to launch a constellation of 648 satellites for global coverage [5–7]. SpaceX is also looking at a LEO constellation of satellites to provide continuous communication coverage of the earth. In 2015 SpaceX submitted a filing with the FCC for two 400 kg satellites to test RF characteristics and link throughput [8]. Recently, SpaceX gave the Senate Commerce Committee an update saying it is planning to launch 4425 satellites into LEO starting in 2019, with an additional 7500 at an altitude of 335 km [9,10]. With companies such as OneWeb and SpaceX predicting thousands of launches to develop global internet coverage the small satellite market seems to be exploding.

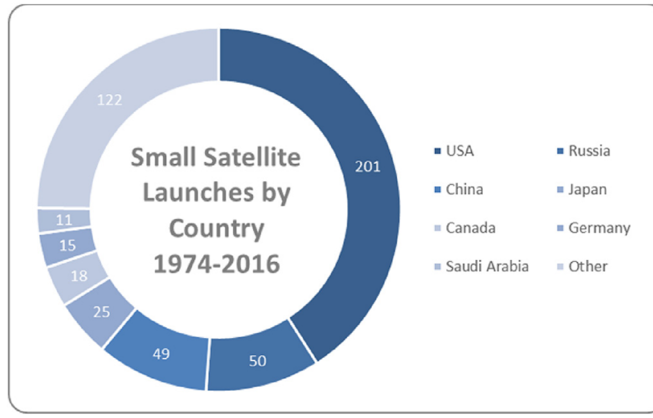

Fig. 3. Satellite launches by country.

The greatest push for small satellites is currently in communications constellations and earth observation, but small satellites have filled a variety of missions in the past. Fig. 5, shows the various uses for small satellites in previous launches. This data shows that 35% of all small satellite missions have been comprised of earth observation missions such as optical imaging, radar imaging, and earth science. Communications and technology development making up the next largest segments. Space science such as space weather make up 32 launches. The final category, other, is satellites that were dual purpose such as earth observation and communications.

Fig. 6 shows the spacecraft weight and GSD of panchromatic and multi-spectral images over several years. It can be seen that a spacecraft's weight grows as GSD decreased through various generations of spacecraft. Additionally, this chart shows that in 2016 small spacecraft, less than 500 kg, were able to achieve similar GSD to spacecraft weighing in 7 times higher. Details on these small satellites will be discussed in Recent Small Satellite Launches and Their Missions.

2. Recent Small Satellite Launches and Their Missions

2.1. Nano Satellites

2016 saw the launch of 58 Nano Satellites in the range of 1–10 kg; 44 of which were commercial launches by Planet Labs. These Nano satellites are earth observation satellites that were launched into various LEOs; additionally, all other launches in this mass range were to LEO. Besides the earth observation satellites, many of the satellites were launched to test cutting edge technology. The Earth Observation Portal was extremely valuable in gathering the following information on Nano, Micro, and Mini Satellites.

An in depth look at the Planet Lab Dove flocks will be discussed. Great efforts have been made to ensure this data is current; however, due to Planet Labs start up approach they have been able to make several iterations in what the space industry would consider an extremely short amount of time. They claim to have made 12 full satellite iterations over 3 years.

2.1.1. Planet Labs – dove flocks 2P, 2E, 2 EP

Planet Labs is a startup, out of Sunnyvale California, interested in the acquisition of earth imagery. They have named their CubeSats Doves. Each Dove is a 3U satellite that uses non-space rated commercial off the shelf parts in its construction. A flock consists of a group of Doves that were deployed simultaneously [11]. The anticipated life for a Dove depends on its orbit. A Dove at 420 km is expected to last one year while a dove at 475 km is expected to last 2–3 years.

The Ground Sampling Distance (GSD) also changes with altitude. The GSD is a measure of imagery resolution — where a GSD of 2 m

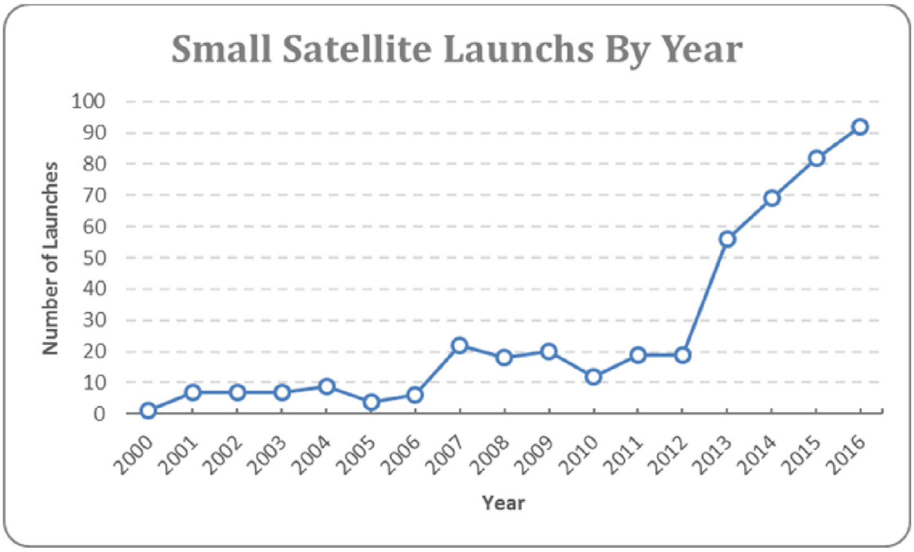

Fig. 4. Small satellite launches by year.

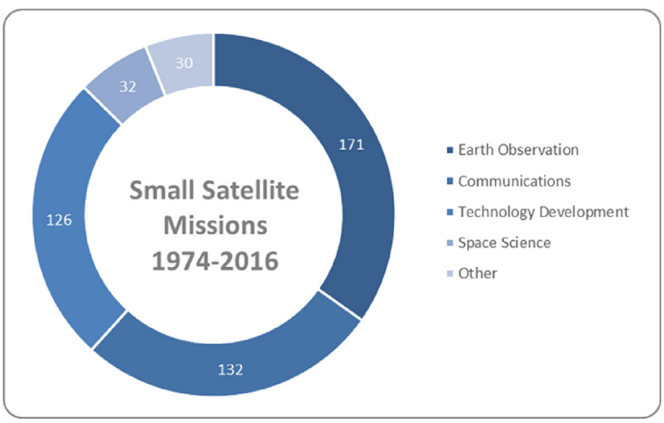

Fig. 5. Small satellite missions.

means that one pixel in the image represents 2 m on the ground or 4 m^2. A Dove at 420 km can expect a GSD of 2.7–3.2 m while a dove at 475 km will see a GSD of 3.7–4.9 m. Doves can contain various imagery sensors and optical setups. The PS0 generation consists of a 2 element Maksutov Cassegrain optical system with a 11 MP CCD sensor [11]. Similarly, the PS1 generation features the same optical system; however, it is aligned and mounted in an isolated enclosure—this isolates the optical system from the Attitude Determination and Control System (ADCS) which consists of active components such as reaction wheels which create disturbances. The final setup is the PS2 which features a 5-element optical system with wider field of view and superior image quality. Additionally, the PS2 has a 29 MP CCD sensor.

While the Doves do not contain a propulsion system they still need the ability to overcome differences in their orbits – to maintain the delicate chorography required in a continuous coverage constellation. To do this the Doves use atmospheric drag. Doves are in a low enough orbit that they can use their attitude to increase or decrease their ballistic coefficient – thus increasing and decreasing their drag [12]. Doves cannot provide any additional thrust so they are limited to controlling their drag until they are the same speed as the fastest satellite – trading

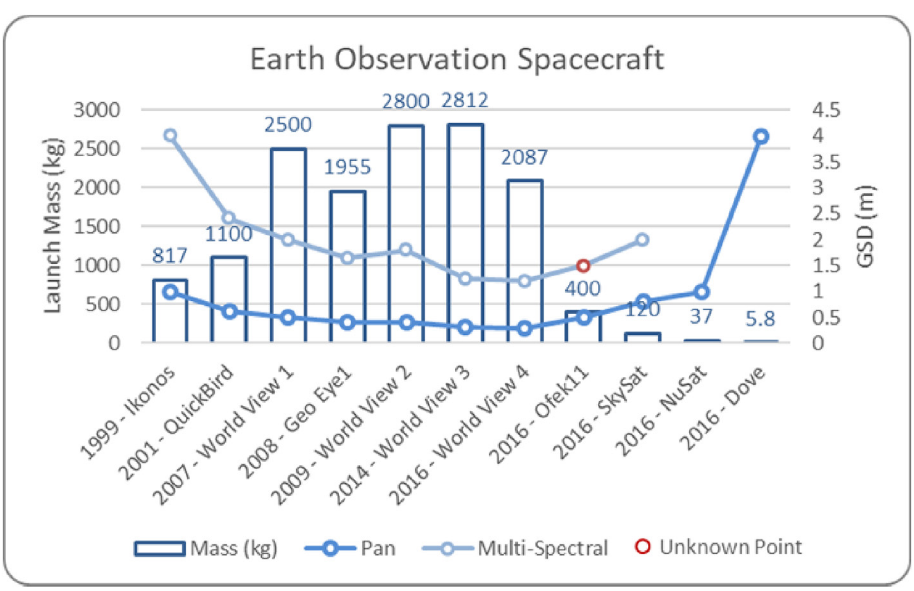

Fig. 6. Earth observation spacecraft through the years.

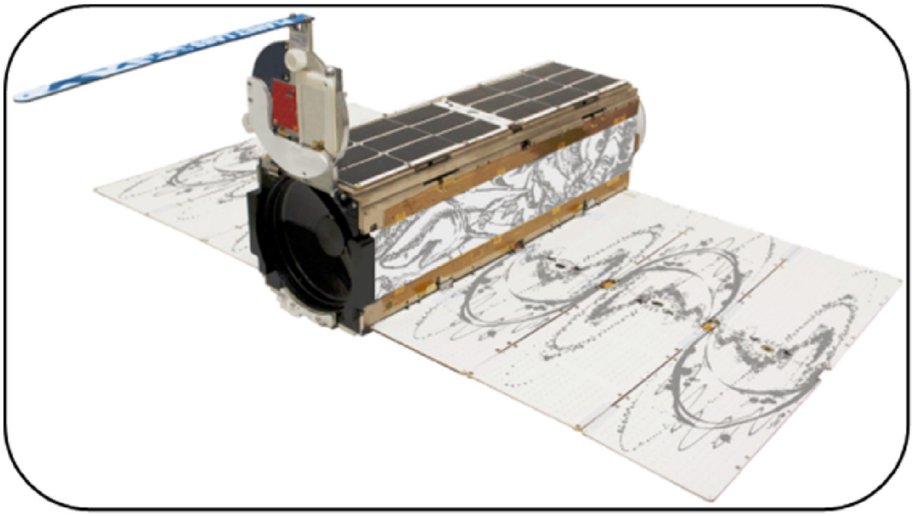

Fig. 7. Planet Lab Dove [13].

their orbit potential energy for additional speed at a lower orbit.

Not only do Doves need to control their attitude to control their speed, but they also need to maintain proper orientation of the spacecraft and camera relative to earth. This is achieved using star trackers and magnetometers for orientation determination, and magnetic torquers and reaction wheels for attitude adjustments.

Communications is achieved over several frequencies. Space to earth transmission of telemetry data and compressed jpeg's is over the high-speed X-band link (8133 and 8200 MHz) [13]. Command and control data is delivered over S-Band (2056 MHz). There is also a backup Telemetry Tracking and Control downlink and uplink at 401.3 MHz and 450.0 MHz respectively.

Power is stored in 8 Lithium-ion cells providing 20Ah of capacity. These cells are charged by deployable Triangular Advanced Solar Cells (TASC). The solar panels are spring-loaded and deployed via burn wires. A Dove with deployed solar panels can be seen in Fig. 7. Additionally, this figure also shows the novel deployment mechanism of the communications antennas. This deployment mechanism protects the optics from foreign object debris (FOD) during launch, but once deployed allows the optical payload and communication payload to point towards earth. Additionally, it does not take any real-estate from the solar arrays which wrap around the body during launch.

2.1.2. Prometheus

Prometheus 2.1 and 2.2 were launched in 2016 as secondary payloads to the WorldView4 launch in a sun synchronous orbit at an altitude of 500 km. Constructed and operated by Los Alamos National Laboratory (LANL), these two satellites were created for technology demonstrations. The Prometheus series was constructed to demonstrate the ability to rapidly build a low-cost satellite as well as demonstrate tactically important communications features such as encryption and communications in highly contested environments. Prometheus 2.1 and 2.2 are an update to the Block 1 satellites and consist of larger solar arrays, a GPS sensor, a star field sensor, and an updated design of the deployable helix antenna [14]. The Block 2 satellite with deployed helix antenna and solar panels can be seen in Fig. 8. One of the major updates to Block 2 was the ability to host a payload. Prometheus being a 1.5U satellite, allows for a 1.5U payload to be added extending the satellite to 3U. 3U is significant in that it is the most common size of CubeSat dispensers.

Prometheus was designed with modularity in mind. Fig. 9 shows the Prometheus structure and modularity. The top stack in Prometheus contains the analog processing system and deployable antenna. This system is responsible for both transmitting/receiving communications, and contains the necessary digital converters. The modularity of this system allows Prometheus to change carrier frequencies for future missions by simply swapping this module. There are two antennas on the spacecraft that are individually fed by two software defined radios. The first is a helical high gain directional antenna, and the other is a low gain isotropic crossed dipole antenna.

The next module in the stack is the software defined radio module. This module is fully reprogrammable on-orbit, allowing for LANL to make updates extending the life of the spacecraft. The data rate is automatically adjusted based on the signal strength allowing for low rate communications in challenged environments. Prometheus being designed for weak signals has optimized the SDR for low signal to noise ratios.

Attitude is determined using models of the earth's magnetic field, sun sensors, a gyro, and in the case of Block 2 the newly added star field sensor. This system calculates the satellites attitude and feeds this information to the control system which commands the reaction wheels and three orthogonal torque rods. The attitude determination and control system module can be seen in Fig. 10.

In terms of manufacturing, Block 2 leverages lessons learned from Block 1. Block 2 utilized connectors and flex circuits wherever possible – greatly reducing the touch labor of soldering connectors. Metal structural components were manufactured using high speed machining. All plastic components were 3D printed utilizing fused deposition modeling (FDM) and a low out gassing material.

2.1.3. AAUSAT-4

Aalborg University CubeSat 4 is a cube sat developed by a student team with an Automated Identification System (AIS) receiver. This system is used by sea vessels to send and receive messages at 162 Mhz containing identification, position, course, and speed information [15]. This system is typically used locally, but a satellite could conceivably detect these signals and relay them to a ground station for wider distribution.

AAUSAT-4 is a 1U CubeSat with an aluminum structure containing printed circuit boards. It utilizes body mounted solar panels which store power in a 2.2Ah Li-Ion battery. The ADCS utilizes magnetic torquers to achieve 3-axis stabilization from data received from a three-axis gyro and magnetometer. The CubeSat utilizes a UHF radio at 437.425 Mhz to downlink data it has gathered from sea vessels [16].

2.1.4. AeroCube 8C & 8D

Over the last 18 years the Aerospace Corporation has developed and launched several small satellites for technology development. The most

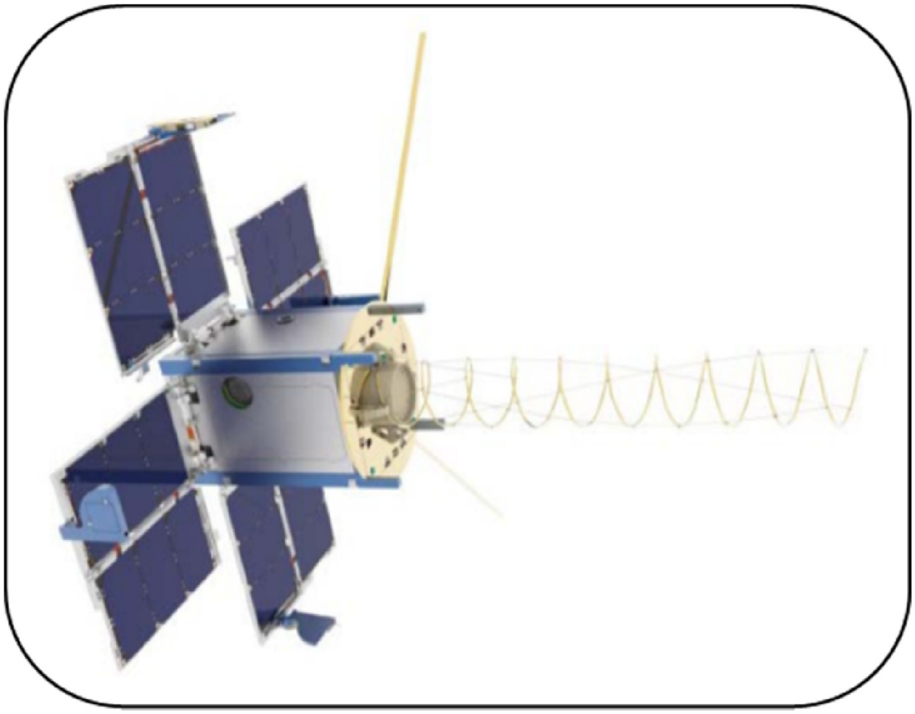

Fig. 8. Prometheus block 2 with deployed antenna [14].

recent launches include AeroCube 8C and 8D. These two spacecraft are demonstrating scalable ion-electrospray thrusters, as well as measuring the IV curves for 4-junction IMM solar cells and 5-junction SBT cells. Additionally, these spacecraft are exploring Carbon Nanotubes (CNT) harnesses and evaluating CNT radiation-shielding material [17].

Due to the extremely limited mass and volume of CubeSats, typical mono-propellant and bi-propellant thrust systems are out of reach. Electrospray thrusters accelerate charged particles through an electric field. These thrusters are capable of high efficiencies; however, suffer from low total thrust. This makes them ideal for thrust over long periods of time, but incapable of instantaneous high thrust maneuvers.

Multi-junction solar cells are cells made with several semiconductor materials. The various materials respond to different wavelengths of light. This allows the overall panel to absorb a larger rage of wavelengths and thus improves the efficiency of the panel. Lab tests currently show 4 junction cells to be capable of 46% efficient [18].

Carbon Nanotubes have been explored as a method of protecting harnesses and other electronic equipment from electromagnetic

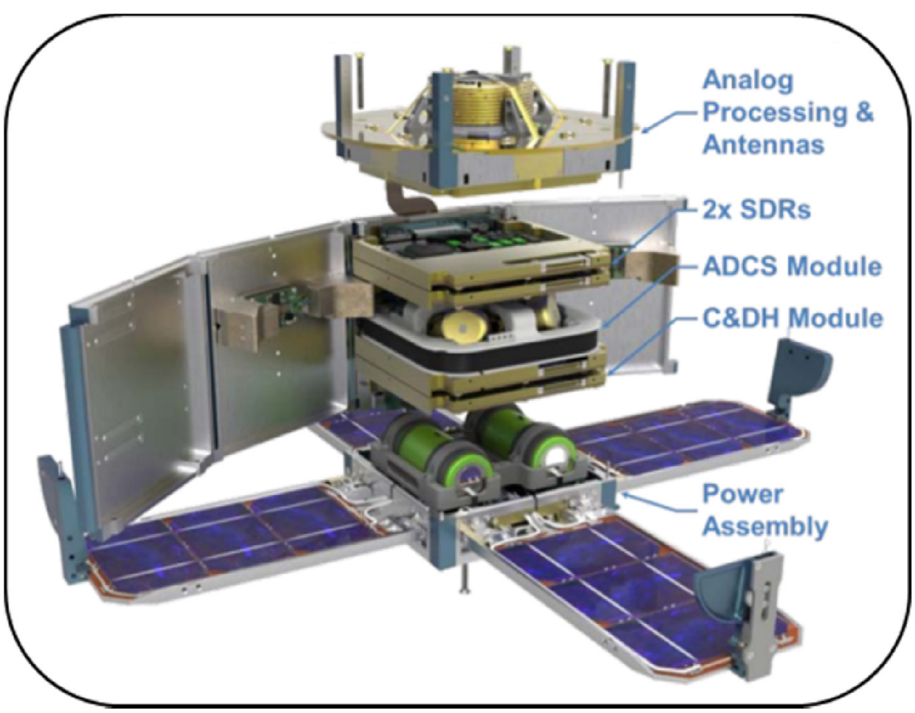

Fig. 9. Prometheus block 1 structure [14].

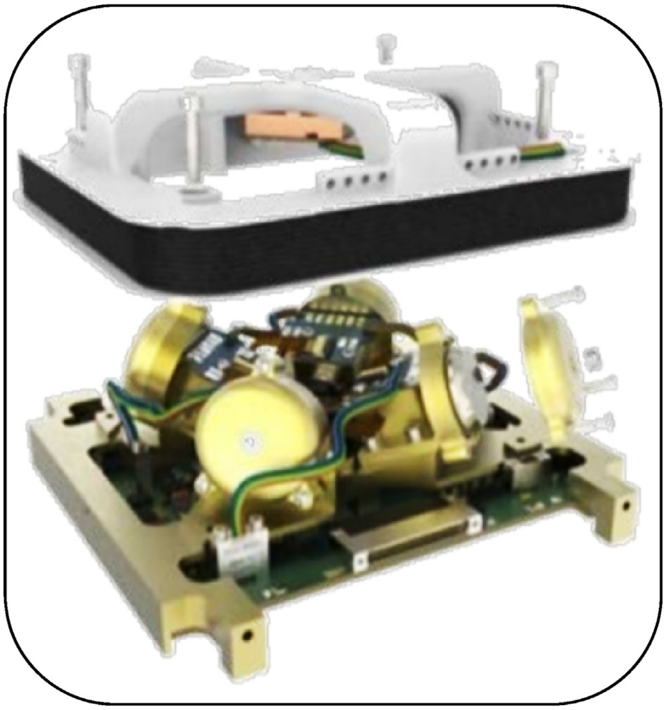

Fig. 10. Prometheus block 1 ADCS [14].

interference. Additionally, CNTs show promising characteristics of protecting crew and equipment from the harmful effects of radiation. Single-wall CNT coated with an electrically conducting polymer have been seen to dissipate some incoming radiation [19].

2.1.5. SAMSAT-218D

SAMSAT-218D is a technology demonstration CubeSat developed by Samara State Aerospace University in Russia. It was developed to examine the potential use of aerodynamic stabilization. This 3U CubeSat consisted of body-mounted solar panels and communicates in the amateur VHF and UHF bands at 145 and 435 MHZ. Fig. 11 shows the internals of SAMSAT-218D. The top two decks, in the picture, consist of 8 batteries. The wires coming from the top deck most likely are connected to the solar panels mounted on the body – not shown. Interestingly, the other two decks are PCB boards that utilize through pin headers and are connected to the next panel with male to male header pins. The structure utilizes spacers to separate the different decks. It is unclear if a single bolt traverses the entire assembly or if the spacers thread into each other.

2.1.6. Swayam

Swayam is a university 1U cube sat developed by students at the College of Engineering Pune in India. This technology demonstration satellite consisted of a small communication payload which records a transmission and repeat it to another area on earth. Swayam utilized a Passive Magnetic Attitude Control (PMAC) system which uses permanent magnets and hysteresis rods to stabilize the spacecraft. This approach needs no power unlike magnetic torque rods and reaction wheels, but is less accurate. With this method permanent magnets are mounted to the nadir and/or zenith decks which create the greatest moment to alight the satellite with earth's magnetic field. Hysteresis rods are ferromagnetic rods which adjust their atomic dipoles to align with a magnetic field – in this case earth's magnetic field. This creates a damping effect on the satellites pointing response, as these rods take time to adjust their magnetic fields to that of earths. This slows or eliminates the oscillation that would occur at the energy minimum.

2.1.7. Ravan

RAVAN, seen in Fig. 12, is a technology demonstration 3U CubeSat developed by Johns Hopkins Applied Physics Laboratory. This satellite will measure Earth's radiation. It uses a small radiometer developed at L-1 Standards and Technology that detects radiation from ultraviolet to far infrared. This sensor utilizes a field of vertical carbon nanotubes that act as the light absorbers.

2.1.8. CELTEE 1

CubeSat Enhanced Locator Transponder Evaluation Experiment 1 is an Air Force Research Lab CubeSat developed to test the M42 Techs Enhanced Location Transponder. This transponder allows tracking and orbit determination of satellites. This mission will only last 3–6 months in the 500 km orbit it is launched into. The satellite can be seen in Fig. 13, the body appears to be made of machine metal – most likely aluminum, and hosts 2 ceramic panel antennas. No solar panels are immediately visible, but may not be necessary for the short mission

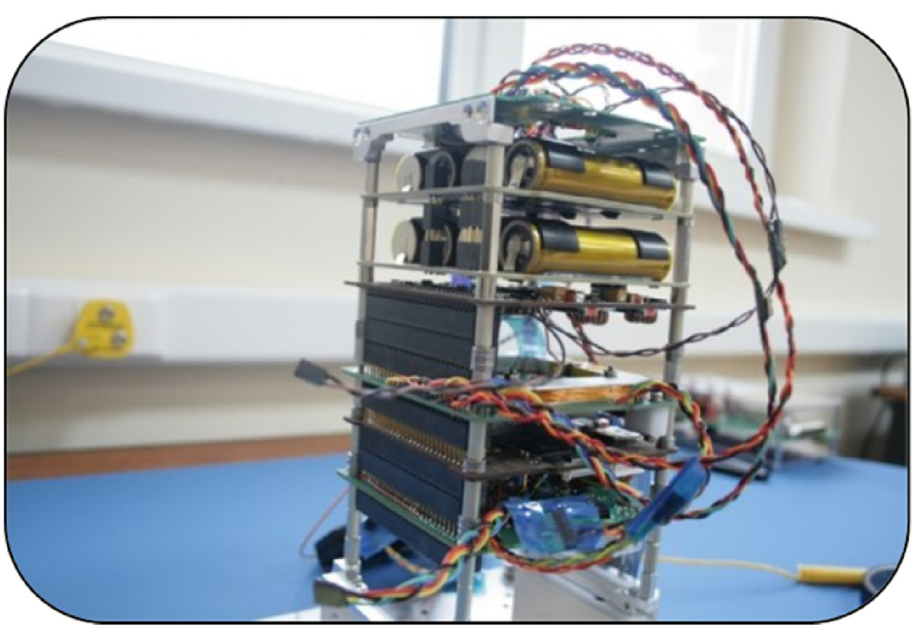

Fig. 11. SAMSAT-218D internal picture [20].

Fig. 12. RAVAN [21].

Fig. 13. CELTEE [22].

duration.

2.1.9. PISAT

PISAT is an earth observation satellite built by the Research and Innovation Laboratory of the Institute of Technology in Bangalore India. It will capture images of earth using a CMOS multispectral camera with a GSD of ~80 m. The spacecraft can be seen in Fig. 14, the image shows body mounted solar panels, and a machined metal body. Additionally, the lens of the camera is seen protruding from the center of one of the body panels. It is flanked by two white panels which may be ceramic antennas, but are oddly mounted with a single screw.

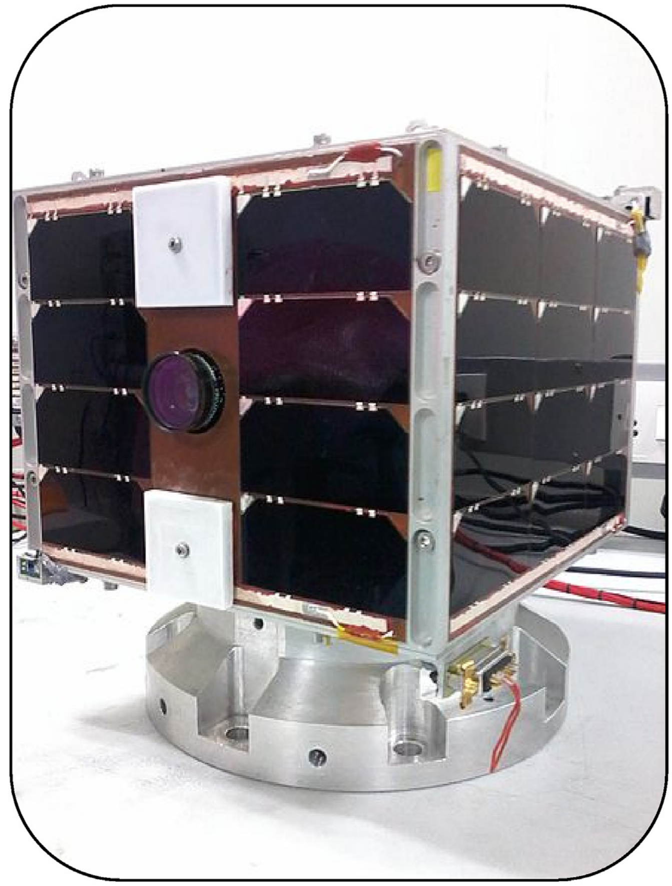

Fig. 14. PISAT [23].

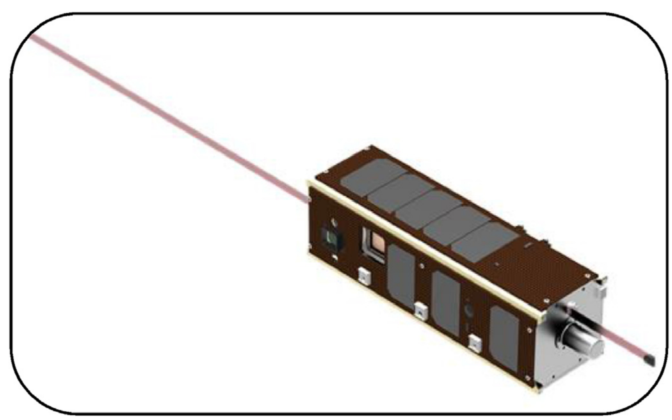

Fig. 15. AISat-1N deployed copper–beryllium tape antenna [24].

2.1.10. AISat-1N

AISat-1N is an Algerian 3U CubeSat, hosting 3 UK payloads. This CubeSat utilizes a UHF Downlink, at 437.646 MHz, to allow for any amateur radio enthusiast to receive data from the satellite and upload it to the designers. The designers choose to heavily utilize commercial off the shelf components to keep costs as low as possible. The spacecraft utilized a Copper–Beryllium tape form antenna – seen in Fig. 15.

The first payload is a deployable boom mechanism. It is a 1.5 m rolled composite which deploys a lightweight magnetic sensor and a radiation sensing field effect transistor. The second payload is an imaging payload which consists of a Sapphire CMOS sensor. The third and final payload is a thin film solar cell. This is an ultra-thin flexible glass cover that acts as both the substrate and radiation protection for the solar cell. The payload measures the current and voltage response of the

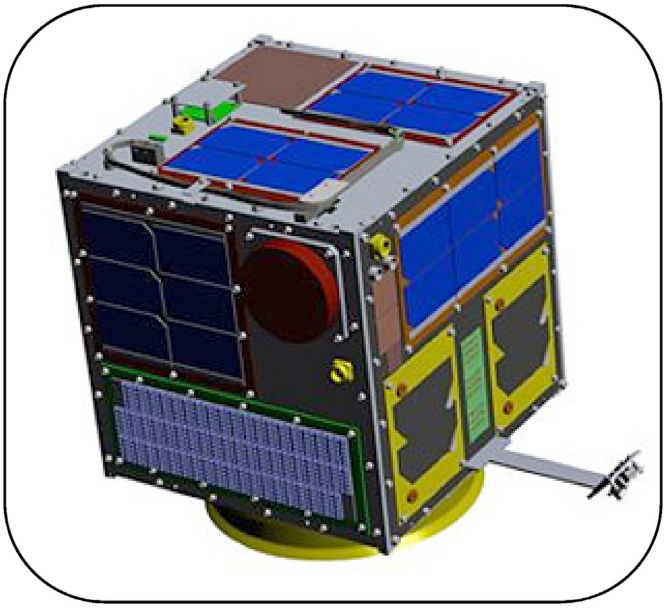

Fig. 16. Horyu 4 arc event generator and investigation satellite [25].

solar cell.

2.1.11. Horyu-4

Horyu 4 is a Japanese technology development satellite weighing approximately 10 kg – seen in Fig. 16. This satellite had four missions: acquire on orbit data of discharge occurring on high voltage solar arrays, obtain images of arcing, advance knowledge of spacecraft charging, and contribute to reliability improvement of present and future space high power systems. The power control and distribution system was designed utilizing commercial off the shelf (COTS) components which in turn charge Nickel Metal Hydride (Ni-MH) batteries. Power is captured via 34 triple junction solar cells.

The Attitude Determination and Control System also utilize a large number of COTS parts. HORYU4 has six sun sensors, one mounted on each side of the cube, a GPS receiver with two antennas, two 3-axis gyros sensors, and four permanent magnets and a hysteresis damper. Horyu4 contains a number of communications frequencies. The spacecraft can transmit in both the S-band (2400.3 MHz) as well as in UHF (437.375 MHz). Receiving is accomplished through either VHF (145 MHz) or L-band (1200 MHz).

2.1.12. CanX-7

CanX-7 is a Canadian, defense funded, satellite that is exploring the effects of drag with a modular storable sail – seen in Fig. 17. If successful, this sail could one day be used to de-orbit small satellites. Large satellites typically use their propulsion system to deorbit the satellite, but since CubeSat's do not usually have propulsion systems this is not an option. Additionally, current methods require redundant attitude control systems to ensure functionality – both requiring higher, cost, mass, and volume. Passive mechanically deployed sails provide a simple and reliable method to deorbit small satellites. This system utilizes mechanically stored energy in springs to deploy the sails. The sails then create the drag necessary – assuming a LEO orbit – to slow the satellite until it loses altitude and burns up in the atmosphere. The analysis leveraged the Satellite Tool Kit (STK) lifetime analysis, shows the 4 m^2 sails can deorbit the 3.75 Kg satellite in 5.3–10 years from an altitude of 800 km [26].

CanX-7 is a 3U cube sat utilizing body mounted triple junction solar panels. These supply power to the 4.8 Ah battery. It uses a 3-axis magnetometer and three magnetic torque rods for attitude determination and control. Uplink utilizes the UHF band via four canted monopole antennas that are deployed after release, with downlink taking place on the S-band via two patch antennas [27].

2.2. Micro Satellites

Micro Satellites are satellites that weigh between 10 and 100 Kg 19 Micro Satellites were launched in 2016. 8 of these launches were of the Cyclone Global Navigation Satellite System (CYGNSS). All of these launches were into a LEO, and many of the payloads were earth observation payloads.

2.2.1. GHGSat-D

GHGSAT-D is a 15 kg spacecraft created by GHGSat designed to monitor greenhouse gasses. This is accomplished through a hyperspectral short-wave infrared (SWIR) imaging sensor. An additional sensor augments this data by measuring clouds and aerosols. The satellite bus was designed and developed by the University of Toronto, Institute for Aerospace Studies/Space Flight Laboratory. The bus utilizes magnetic torque rods and reaction wheels for attitude control, and receives attitude data from a star-tracker. Three 26 W-Hr Li-Ion batteries powered by the body mounted solar panels. In total the bus is 20 × 30 × 42 cm.

2.2.2. CYGNSS FM1-8

CYGNSS is a NASA Earth System Science Pathfinder program, designed to improve weather predictions. CYGNSS stands for Cyclone Global Navigation Satellite System and consists of 8 LEO spacecraft. These spacecraft measure the roughness of the ocean surface from which local wind speed can be determined. The roughness of the ocean is measured by receiving the GPS signal reflected off of the ocean and comparing it to the signal received directly from the GPS spacecraft.

Each spacecraft is composed of a milled Aluminum structure supporting the 25 kg spacecraft. The trapezoidal shape of the spacecraft allows 8 spacecraft to mount to a single core supporting all vehicles during launch – seen in Fig. 18. The hinge deployed solar panels supply power to the spacecraft at 38.3 W. The spacecraft is 3 axis controlled utilizing horizon sensors, magnetometers, momentum wheels, and torque rods. The spacecraft is capable of 4 Mbps downlink via a software defined radio.

2.2.3. NuSat 1-2

NuSat 1 and 2 are commercial Earth observation satellites manufactured by Satellogic. Each satellite is 37 kg and 40 cm × 43 cm x 75 cm. The satellites image earth in both the visible and infrared spectrum providing a GSD of 1 m. These spacecraft sit in a 500 km sun synchronous orbit.

2.2.4. BlackSky pathfinder 1

BlackSky Pathfinder 1 and 2 are experimental spacecraft used to prove the design before the buildup of the 60-satellite constellation. BlackSky global hopes this constellation of satellites will be able to provide temporal resolution of a few hours. These spacecraft will be launched into a 450 km orbit and provide multi-spectral imagery of 1 m GSD. This is accomplished using the SpaceView 24 imaging telescope from the Harris Corporation. This telescope was specifically designed with small satellites in mind and weighs less than 10 kg; bringing the BlackSky Pathfinder spacecraft to ~44 kg.

2.2.5. Spark 1-2

Spark 1 and 2 are earth observation satellites built by the China Academy of Sciences' Shanghai Small Satellite Center. These satellites are capable of providing 50 m GSD visible and near infrared images. Each satellite weighs 43 kg and is launched in a 700 km orbit.

2.2.6. ChubuSat 2–3 (Kinshachi 2–3)

ChubuSat 2 and 3 are satellites built by Nagoya University and

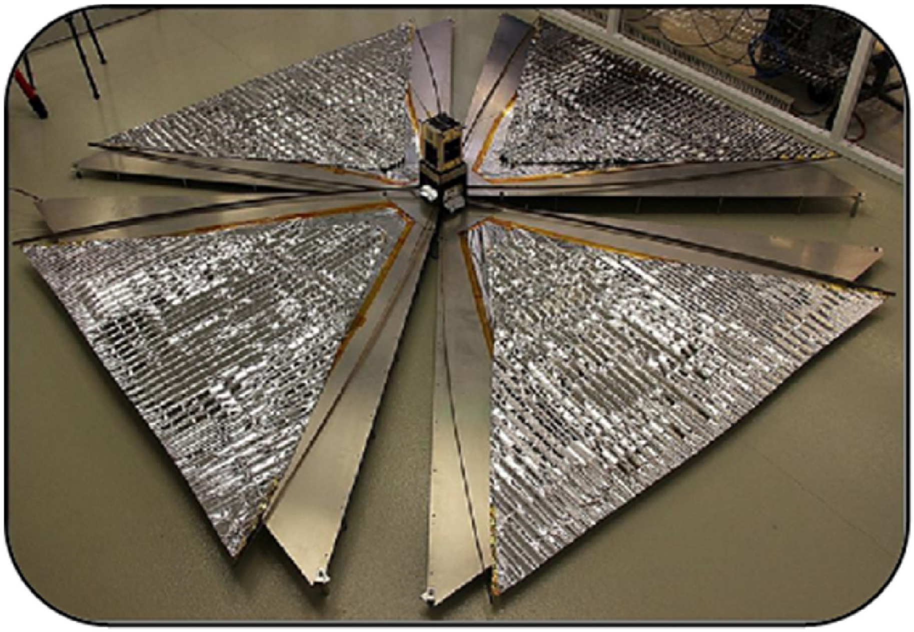

Fig. 17. CanX-7 sails deployed [28].

Fig. 18. CYGNSS deployment Configuration [29].

Daido University. These satellites weight approximately 50 kg and are launched into a 559 km orbit. ChubuSat 2 observes radiation from the sun and earth and photographs earth and space debris. ChubuSat 3 is built upon a similar bus, but collects Automatic Identification System (AIS) signals from maritime ships, as well as taking pictures of the earth and space debris.

2.2.7. M3MSat (maritime monitoring and messaging MicroSatellite)

M3MSat is a Canadian technology demonstration satellite created by the Canadian Space Agency, COM DEV, and the Department of National Defense. The satellite is built to monitor maritime traffic of Canada's 243,772 km coast line. This is accomplished using the Automated Identification System (AIS) which ships carry to assist in locating other nearby ships.

The spacecraft is 80 kg and measures 80 cm × 60 cm x 60 cm – as seen in Fig. 19. It supports a 40 W payload at 26v and communicates telemetry via s-band at 4kbps uplink and 6.26 mbps downlink. The payload data is downlinked using a high-speed C-Band transmitter at 20 Mbps. Power is collected using 6, triple junction body mounted solar panels. Power storage is managed by a single Li-ion battery capable of storing 17.4 Ah. The spacecraft is 3-axis stabilized using reaction wheels and magnetic torque rods. Attitude is determined using 3-axis magnetometers, two 3-axis microelectromechanical systems (MEMS) gyros, and six 2-axis sun sensors.

2.3. Mini Satellites

Mini Satellites range from 100 to 500 kg – in 2016 15 of these satellites were launched. 11 of these launches were optical imaging satellites launched into a sun synchronous LEO. This class of satellite appears to be the sweet spot for optical imaging satellites capable of hosting the necessary bus equipment and the specialized optical equipment for high resolution imagery. Additionally, many satellites in this range host propulsion equipment for orbit maintenance – extending the life of many of these assets.

2.3.1. AlSat-1B

AlSat 1B is the result of a partnership between Algerian Space Agency and Surrey Satellite Technology Ltd. It is an earth observation satellite built on the Surrey SSTL-100 platform. The payload consists of a 24 m GSD multispectral imager and a 12 m GSD panchromatic camera. The launch mass was 103 kg, and the spacecraft was launched into a 700 km sun synchronous orbit from Sriharikota India.

The Surrey SSTL-100 is a common satellite bus built to accept a payload with a standard interface – priced at $11 M. It is designed for a 5-year mission lifetime and is available 18 months after purchase. It is capable of supporting a 15 kg payload mass, with 24 W of power – 48 W

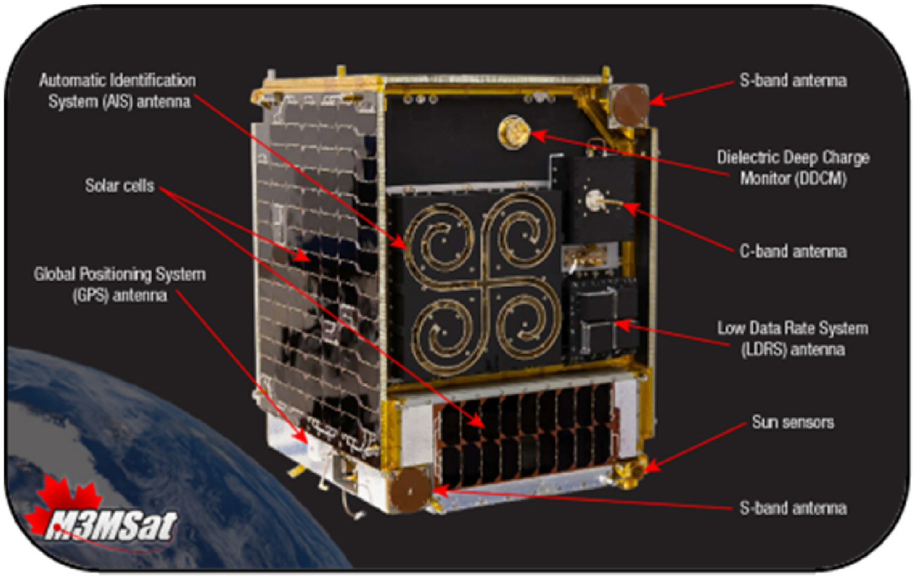

Fig. 19. M3MSat [30].

peak. The bus dry mass is 83 kg and consist of an 80 mbps X-Band downlink for data. The spacecraft is 3-axis stabilized using reaction wheels and magnetorquers. A 14Ah Li-ion battery provides energy storage at 28–33 V. Electrical energy is generated with body mounted solar panels. The satellite also has a propulsion system capable of generating a velocity of 20 m/s using liquified butane gas. The spacecraft thermal control system is primarily passive; however, uses heaters in critical locations. Telemetry tracking and control is accomplished using S-Band.

2.3.2. AlSat-2B

AlSat-2B is also built by the Algerian Space Agency, but this time in partnership with EADS Astrium a subsidiary of the European Aeronautic Defense and Space Company (EADS). Unlike AlSat-2A, AlSat-2B was built at Algeria's Satellite Development Center in country. This satellite is 116 kg with dimensions of 60 cm × 60 cm x 130 cm. This spacecraft carried the New AstroSat Optical Modular Instrument (NAOMI). NAOMI is an earth imaging sensor capable of 2.5 m GSD panchromatic images, or 10 m GSD multispectral images. These images are used for cartography, agriculture management, natural resource management including forestry; water; mineral's; and oil, as well as natural disaster management.

The spacecraft is built on the AstroSat-100 platform based on the Myriade platform developed by the French space agency CNES – seen in Fig. 20. This bus can support a 50 kg payload and providing 50 W of power. The spacecraft is 3-axis stabilized utilizing 3 sun sensors, a star tracker, a magnetometer and an Inertial Measurement Unit (IRU). Attitude can be adjusted using the 4 reaction wheels and magnetorquers. Additionally, this system contains a hydrazine propulsion system capable of providing a delta V of 70 m/s. Power storage is provided by a single Li-ion battery with 15Ah of capacity. Power is generated by a two-panel deployable solar array. Telemetry is communicated on an S-Band transmitter/receiver capable of 20kbps, while payload data is downlinked on X-band at 60 mbps.

2.3.3. SkySat 3-7

The SkySat's are earth observation satellites built by Space Systems Loral (SSL) for Skybox – Skybox was purchased by Google in June 2014 and renamed to Terra Bella. Google later sold Terra Bella to Planet Labs in which it owns an equity stake. SkySat-3 was the second generation of the SkySat's and added propulsion and better reaction wheels.

SkySat-3 has a mass of 120 kg with dimensions of 60 cm × 60 cm x 95 cm – seen in Fig. 21. While detailed design information isn't available for SkySat-3, quite a bit is known about the first generation SkySat 1 & 2. The X-Band downlink is capable of 470 Mbps with TT&C managed by S-Band. The spacecraft uses 120 W of power which is collected by body mounted solar panels. Onboard data storage for images and videos is 768 Gb. SkySat 3 added high performance green propulsion (HPGP), consisting of four 1 N thrusters.

The payload is capable of capturing panchromatic images at .9 m GSD panchromatic and 2 m multispectral. These images are generated using a Ritchey-Chretien Cassegrain telescope with 5.5 mega pixel CMOS sensors. Three overlapping sensors capture high frame rate 2D images. The top half of the sensor captures panchromatic images, the bottom half of the sensor is divided into 4 areas covered with red, blue green, and near infrared filters – seen in Fig. 22.

2.3.4. LAPAN A3

LAPAN is an earth observation satellite created by the National Institute of Aeronautics and Space of Indonesia and Bogor Agricultural University. This satellite is responsible for monitoring and providing data on Indonesia. The spacecraft sits in a sun-synchronous orbit, and carries a medium resolution multispectral imager and digital camera. The multispectral imager is augmented by a 300 mm lens capable of 19 m GSD. The digital camera is amplified by a 1000 mm lens producing 5 m GSD images. Additionally, the spacecraft features an Automatic Identification System (AIS) receiver which is capable of receiving AIS data from maritime vessels. This data includes, position, movement details, as well as crew information.

These capabilities are packed into a 115 kg spacecraft with dimensions of 50 cm × 57.4 cm x 42.4 cm. Power generation is managed by GaAs body mounted solar arrays, which feed into 3 Li-ion batteries of 15 V and 6.1Ah. Attitude determination and control consists of 3 reaction wheels and laser gyros, 2 star sensors, 3 magnetic coils, a sun sensor, and a 3-axis magnetometer. TT&C is managed on the UHF frequency with a transmitter of 3.5 W. X-Band frequency with 6 W max RF output, and S-Band 3.5 W max RF output.

2.3.5. BIROS (bispectral Infrared Optical System)

The BIROS spacecraft is part of the FireBird constellation which primary mission is to detect High Temperature Events such as forest fires. BIROS has also been equipped with an Optical Space Infrared Downlink System (OSIRIS). OSIRIS is meant to demonstrate high speed datalinks, up to 10 gbps, for small satellites. OSIRIS for BIROS is

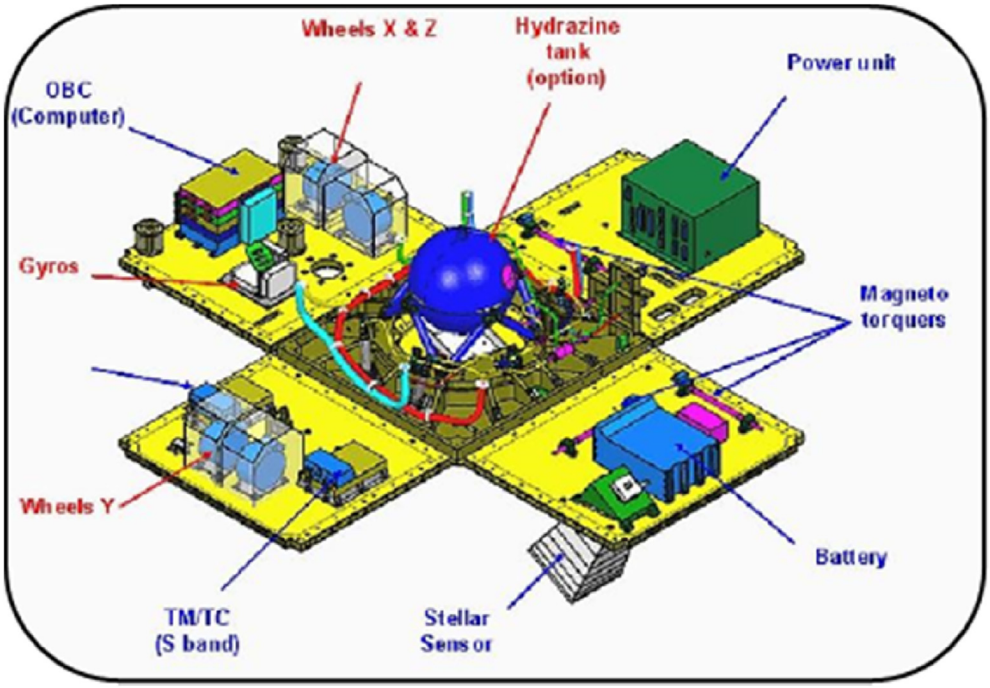

Fig. 20. AstroSat-100 BUS CAD rendering [31].

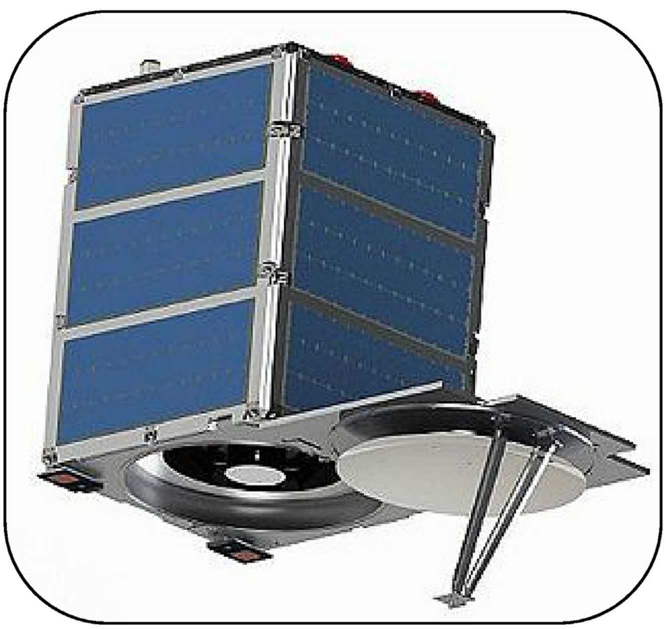

Fig. 21. SkyBox CAD rendering [32].

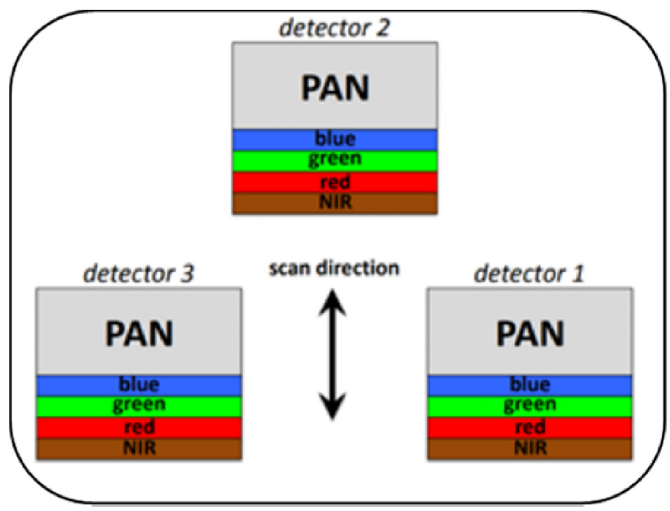

Fig. 22. SkyBox Imaging Sensor [33].

developed for 1gbps and relies on the spacecraft pointing controls to point the instrument and tracking the receiver on earth. The final mission hosted by BIROS is an Autonomous Vision Approach Navigation and Target Identification (AVANTI). AVANTI uses low cost passive sensors such as optical and infrared cameras to track an object and perform autonomous maneuvers to rendezvous with the object. After BIROS achieves stable orbit and successful check out it will release the BEESAT-4 1U CubeSat it holds – via a spring mechanism. Once BEESAT-4 reaches a distance of 5 km–10 km the experiment will begin. GPS data from both BEESAT and BIROS will augment ground radar data to prove accurate tracking using the camera equipment of BIROS.

The BIROS spacecraft is built on the Astro and Feinwerktechnik Adlershof GmbH bus. TET bus also known as Technology Test Vehicle (TET) can be seen in Fig. 23. The TET-X is the second generation of the TET-1 bus containing an upgraded power subsystem, transmitters, and OnBoard Computer. The TET-X weighs 70 kg with dimensions of 67 cm × 58 cm x 88 cm. It is capable of supporting a 50 kg payload at 46 cm × 46 cm x 42.8 cm at 160 W per 20 min. Power is collected via 2 deployed solar panels and a single body mounted panel. This satellite contains multiple redundancies in the AD&CS: two start trackers, two IMUs, two magnetometers, two course sun sensors, four reaction weeks, magnetic torque rods, and two GPS receivers. Additionally, this bus can be fitted with the Microjet propulsion system developed by Aerospace Innovation GmbH (AIG). This Nitrogen based system is capable of producing 67 mN per thruster in Resistorjet mode, or 118 mN per thruster in Cold Gas mode.

2.3.6. XPNav-1

XPNav-1 is an X-ray Pulsar Navigation Satellite built by the China Academy of Space Technology. Similar to a star tracker that relies on

Fig. 23. TET CAD rendering [34].

known constellations of visible stars to determine spacecraft attitude and position, X-Ray signals emitted by pulsars can be used to determine a spacecraft's location in deep space. XPNav-1 will detect X-ray signals from nearby pulsars and create a pulsar navigation database. This spacecraft weighs 270 kg and flies in a 500 km orbit, but technical details are limited.

2.3.7. Ofek-11

Ofek-11 is a reconnaissance satellite built by Israel Aerospace Industries for the Israeli Ministry of Defense – it can be seen in Fig. 24. It features an Elbit Systems Jupiter high resolution imaging system capable of .5 m GSD at 600 km. This system contains panchromatic and optional multi-spectral capabilities, and weighs 120 kg. The Jupiter imaging system is supported by the OptSat-3000 or Optical Satellite-3000 – seen in Fig. 24. The light satellite (400 kg) and compact size give the satellite a low inertia and thus it is highly agile allowing it to capture many images in a single orbit.

While detail of OptSat-3000 are sparse, it is based on the IMPS II Bus. The IMPS II bus consumed 250 W from the 30Ah battery or triple junction solar cells capable of producing 800 W at the end of life [35]. The ADCS system is comprised of two sun sensors, two magnetometers, a MEMS gyro, GPS receiver, and two star trackers, four reaction wheels, two three axis magnetic-torquers, and optional thrusters. The satellite could be outfitted with either electric, chemical, or hybrid propulsion: two hydrazine thrusters (25 N), hall effect thruster .1 N. Communications is accomplished through a highspeed X-Band downlink at 750 mbps and telemetry was transmitted via S-Band at 2.5–12.5kbps.

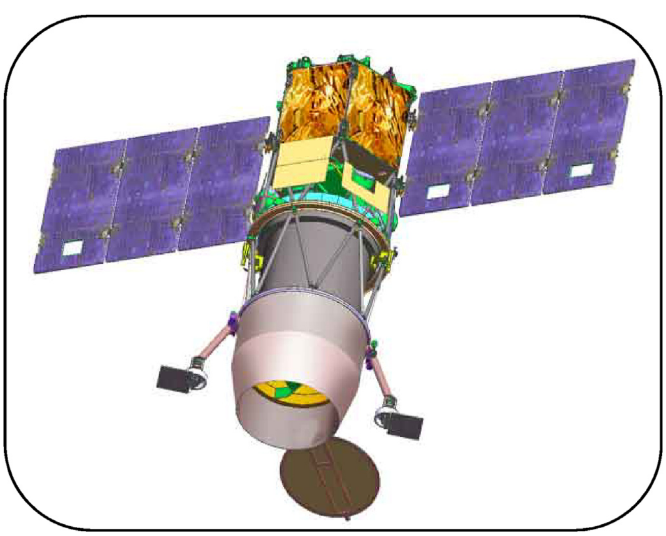

Fig. 24. OptSat-3000 CAD rendering [36].

2.3.8. MICROSCOPE

MICROSCOPE is an acronym for MICRO-Satellite à traînée Compensée pour l'Observation du Principe d'Equivalence. Which roughly translates to Compensated Micro-Satellite for observing the principle of equivalence. This satellite is a partnership between CNES, SARM laboratory (university of Bremen), and PTB (physikalisch-Technische Bundesanstalt), Observatoire de la Côte d'Azur (OCA), and Office National d'Etudes et de Recherches Aérospatiales (ONERA). MICROSCOPE's will test the equivalence principle – where objects in a vacuum fall at the same speed. To test this, the spacecraft will maintain two masses motionless inside electrostatic accelerometers. If equivalent forces are required to keep the masses static the principle will be confirmed. MICROSCOPE is a 300 kg satellite using the CNES's Myriade bus, but contains cold-gas thrusters to compensate in for small trajectory perturbations. This bus was discussed in more detail in the AlSat-2B section.

2.3.9. ERG

ERG is the short name for Exploration of Energization and Radiation in Geospace. ERG was created by the Japanese to study the formation of the radiation belts associated with magnetic storms [37]. The spacecraft will host 4 major sensors: Plasma and Particle Experiment (PPE), Plasma Wave and Electric Field (PWE), Measurement of Geomagnetic Field (MGF), Software-Wave Particle Interaction Analyzer (S-WPIA). PPE consists of four sensors: LEP-e, MEP-e, HEP-e and XEP-e which are used to measure low energy electrons, medium energy electrons, high energy electrons, and extremely high energy electrons. PWE measures electric fields from DC to 10 MHz and magnetic fields from a few Hz to 20 kHz using two pairs of wire dipole antennas. MFG will measure ambient magnetic fields and Magnetohydrodynamic pulsations. S-WPIA will measure wave-particle interactions using data from MEP, HEP, and PPE.

ERG is based on the Small Space Science Platform for Rapid Investigation and Test (SPRINT). It weighs approximately 355 kg wet, and in the launch configuration takes up 1.5 m × 1.5 m x 2.7 m. The four solar array panels generate over 700 W and charge a 35Ah Li-ion battery. The spacecraft is spin stabilized with rate initially measured by a MEMS gyro – spin axis is estimated on the ground using Spin-type Sun Aspect Sensor, Geomagnetic Aspect Sensor, and Small Star Scanner. 4 hydrazine thrusters producing 4 N place the satellite into the highly elliptical orbit.

2.3.10. ScatSat-1

ScatSat-1 is an Indian Space Research Organization (ISRO) spacecraft designed to collect global ocean wind vector data. This data is used heavily in global weather forecasting models. Surface wind data is collected by transmitting a pulse of Ku energy and measuring the reflected energy. Using measurements from various azimuth angles a geophysical model calculates the relationship between backscatter and wind speed and direction.

SCATSAT-1 is a 371 kg spacecraft based on the Indian Mini Satellite bus. The common bus allowed this spacecraft to be built for 60% of the cost and one third the time by utilizing spare components from previous builds [38]. Two deployable solar arrays generate 750 W for the 28 Ah Li-ion battery. AD&CS is managed by reaction wheels, magnetic torquers, and hydrazine thrusters. Communications is accomplished using S-Band for TT&C and X-Band payload data at 105 Mbps.

2.3.11. PeruSat-1

PeruSat-1 is an earth observation satellite built for Peru by Airbus. This spacecraft weighs 430 kg and was designed with a 10-year life span. It provides Peru with .7 m GSD panchromatic resolution, and 2 m GSD multispectral capabilities in RGB and near infrared. PeruSat is built upon the Astrobus-S platform; a smaller simpler version of the AstroBus-500. Astrobus-S takes advantage of the smaller Myriade bus, but offers greater mass and power budgets for the payload.

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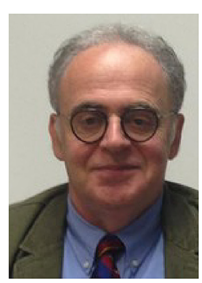

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