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NANOSATELLITES

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Abstract

The introduction of nanosatellites brought a revolution in space flight as it was considered until the late 90's. The development of a spacecraft capable of operating inside the space environment required long term and resource exhausting projects occupying field experts into custom design endeavors. Traditional satellite missions also require strenuous component testing and verification sessions so as to assure every segment is space qualified in order to minimize the probability of possible failures in such high risk ventures.

Nanosatellites are classified as satellites of mass below 10 kilograms. While traditional applications such as broadcasting and real-time telecommunications over large regions may not be feasible in their full extent at the moment, numerous applications exist and can be realized at a fraction of the cost of traditional satellites. Applications such as measurements in the environment of earth and space, imaging, telecommunications and technology verification can still be supported with great success. Additionally, nanosatellites are of high educational interest since students can participate in a real space mission in every phase of the project, namely system requirements phase, design phase, assembly phase, testing phase and in-orbit operations phase leading eventually into mission success.

A solid breakthrough in small satellite development was brought by the CubeSat standard in 1998. The CubeSat's fundamental form (1U) is a cube with edges of 100 millimeters and limited to 1 kilogram of total mass. Hundreds of CubeSat missions have been completed since the introduction of the standard, varying among multiple unit sizes, all the way up to 12U units. Numerous universities, corporations as well as space organizations, both civilian and military, have already engaged in CubeSat missions supporting the potential of this satellite class. In addition, a promising industry has been developed, providing commercial-off-the-shelf components compatible with the standard, minimizing both cost and development time for a nanosatellite mission.

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This article presents an overview of nanosatellites, a list of CubeSat missions launched between March 2013 and November 2014 that is indicative of the trends in nanosatellite objectives, applications and prospective stakeholders, and two high-level proposals for starting points for a future CubeSat project, that also illustrate the cost benefits from the nanosatellite class on jumpstarting a space mission.

Keywords: Satellite Communications, Nano-Cube Satellites, Wireless Communications

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1. Introduction to Nanosatellites

The breakthrough in integrated circuit electronics during the 1970's and especially in the Very Large Scale Integration (VLSI) sector provided the industry with highly complex functions in a reduced volume, compared to available solutions at that time. As a result, the overall volume of satellites could be restricted while still retaining a high level of functionality. This led to the development of smaller scale satellites in the range of microsatellites, namely satellites with a mass up to 100 kilograms.

The next great breakthrough in the field of small scale satellites was the adoption of commercial-off-the-shelf (COTS) components which accommodate the technological advancements of custom designed hardware to mass produced devices at a fraction of the cost. COTS components enabled the rapid decrease in total design and development time required for a small satellite mission.

Apart from objectives aiming at communications, earth observation and space sensing, such a small project duration enables satellites to be built for educational purposes. Project development times, now reducing to less than two years, provide young students, engineers and scientists with hands-on experience of an actual space mission.

The introduction of the CubeSat standard in 1998 by Professor Robert Twigs of Stanford University brought the first standardization for small-scale satellites. Satellites shaped as cubes with dimensions of 100x100x100 mm3 as their fundamental form, revolutionized the market of COTS components. This common standard enabled the satellite developers to select the components out of a wide variety of products in order to create a CubeSat design, avoiding spending time to develop custom devices.

1.1. CubeSat Specification Standard

The CubeSat Specification Standard was compiled in order to act as a guide for a potential CubeSat developer. The standard describes all the necessary requirements [1], [2], for a CubeSat to be accepted for deployment using a standard deployment system. Requirements include mechanical, electrical as well as operational aspects which are imposed on a candidate CubeSat design. The first deployment system for satellites of this class was the Poly Picosatellite Orbital Deployer (PPOD) originally developed by the California Polytechnic State University and Stanford University. Due to the fact that numerous deployment systems exist, each has its own requirements but quite analogous to each other.

1.1.1 Small Satellite Design Philosophy

Small satellite design in the modern era is driven by cost minimization rather than complex and expensive custom engineering. A typical trade-off between conventional cost and technical capabilities is aiming for 80 % of typical functionality for 20 % of the cost [3]. This radical cost reduction objective can be met by the use of commercial off-the-shelf (COTS) components which in turn require less development and testing resources in order to achieve satisfactory results. System level testing, rather than time consuming testing cycles at unit level, is followed so as to support the target of reducing the overall project cost to a lower level.

Class	Mass (kg)	Cost (M€)
Conventional large satellite	>1000	>130
Conventional small satellite	500-1000	30-130
Minisatellite	100-500	9-30
Microsatellite	10-100	1.3-9
Nanosatellite	1-10	0.13-1.3
Picosatellite	<1	<.13

Table 1: Classification of spacecrafts by mass and cost.

1.1.2 Small Satellite Classification

Satellites are typically classified by their mass and cost. In Table 1, [3], a comparison between different classes of spacecrafts is presented. In particular, a rough estimate for a nanosatellite mission would vary between €0.13M and €1.3M while the cost for a picosatellite mission was rated for less than €130K. The aforementioned cost includes satellite cost, launch cost as well as orbital operations costs over the spacecraft's life-time. From a mass perspective, nanosatellites are classified as spacecrafts between one and ten kilograms of mass while anything below one kilogram is rated as a picosatellite.

1.2 Applications

Small satellites in low earth orbit have many applications which in principle are considered to be of the same scope with larger GEO, MEO and LEO satellites.

The following paragraphs present the most prevalent applications of nanosatellites.

1.2.1 Small satellites for communications

Nanosatellites may be considered as low cost and effective solutions for providing communication services to earth stations and networks. The majority of nanosatellites implement communication channels over the VHF (144 to 148 MHz) and UHF (420 to 450 MHz) bands assigned to radio amateur use. Additionally, many nanosatellites utilize parts of the spectrum in the S, C, X and L bands aiming at higher communication rates. Applications include conventional message based communications, radio repeaters, Automatic Identification System (AIS) receivers for ship tracking, Automatic Packet Reporting System (APRS) receivers as well as store-and-forward transceivers for remote areas where conventional communications systems are not yet available.

1.2.2 Small satellites for space science

Various applications focused on small-scale space science objectives are also included in many projects implemented with nanosatellites. Small-scale satellite objectives include photometric observations, x-ray measurements, earth's magnetic field measurements, space radiation measurements, biology experiments in microgravity as well as investigation of the ionospheric disturbances. Additionally, nanosatellites provide a hands-on experience to students for the complete process of developing a space mission.

1.2.3 Small satellites for technology verification

Small scale satellites also include applications in verifying novel technologies in the space environment. Providing a proof-of-concept before the development of large-scale products for a fraction of the cost, defines a strong alternative to full scale experimentation. Examples of these applications include novel propulsion and attitude control systems, de-orbiters, multipurpose custom IC designs, radar calibration, constellation flights, tracking space debris, solar wind sails and space tethers as well as new technologies in solar power harvesting and power storage.

1.2.4 Small satellites for Space and Earth observation

Space and earth observation are missions that small-scale satellites are capable of accomplishing. Apart from observing space debris, as stated within the previous section, numerous measurements can be carried out via a low earth orbit small scale satellite. Imaging missions through low cost satellites is a promising application [4] that many satellites in orbit are currently carrying out. Weather observation, forest fire observation, sea shore observation, photometric observation and space environment sensing are some of the applications regarding space and earth observation.

1.3 Nanosatellite Subsystems

The system of a small-scale satellite is an interconnected architecture which includes numerous subsystems depending on the desired application. The core subsystems that are present for the majority of small-scale satellites are the following:

- On-Board Data Handling (OBDH)
- Structural (STR)
- Attitude Determination and Orbit Control (ADC)
- Electrical Power (EPS)

- Communications (COMM)

The following sections present the main functions performed by each subsystem.

1.3.1 On-Board Data Handling

This is considered the main subsystem of a small-scale satellite. A processing core is the heart of the system along with accompanying on-board RAM and additional flash storage. Additional ADC and DAC controllers are used to convert analogue signals received from on-board sensors to digital signals to be processed and forwarded to the communications subsystem. The OBDH offers bus interfaces so as to interconnect to the other subsystems included in the satellite's design. The most prevalent bus interfaces offered by modern OBDH subsystems are the I2C [5] bus, the CAN [6] bus and the SPI [7] bus. Serial interfaces include UART and GPIO. More advanced OBDH systems conform with the SpaceWire [8] protocol for inter-satellite communications.

The main tasks of an OBDH subsystem [9] are:

- Provide adequate data storage and processing.
- Implement telemetry and telecommand protocols.
- Monitor spacecraft health and act as a watchdog.
- Act as a master for the implementation of interconnecting buses.
- Control remaining subsystems and payload.
- Perform housekeeping and time distribution around the spacecraft.

1.3.2 Structural

The mechanical subsystem must be able to provide a rigid structural foundation where every other subsystem of the satellite will be eventually accommodated into. The design of a nanosatellite structure aiming at low cost solutions allows for a modular satellite architecture where individual subsystems utilize the available internal space in its entirety. Conforming to standards such as the CubeSat [1] specification supports mass production and reduces manufacturing costs. Additionally, the structure design shall be able to provide easy access to the satellite's interfaces during development and integration prior to the system's launch.

Regarding the CubeSat specification in particular, specific mechanical restrictions are introduced. Multiple satellite sizes are compatible to the CubeSat standard. The fundamental size for a cubesatellite is 1U. A satellite conforming to the 1U CubeSat standard shall be confined in a cube with 100 mm long sides, though protruding standoffs shall be also present on each side of the launch axis. Larger sizes are also present, namely 1.5U, 2U and 3U. The sides perpendicular to the launch axis shall remain 10 mm by 10 mm at all times while the sides parallel to the launch axis may have increased lengths, depending on the required satellite volume. Mass restrictions apply as well. CubeSat's conforming to the 1U volume standard are restricted to 1.33 kg of cumulative mass while 1.5U, 2U and 3U volume satellites are constrained to 2, 2.66 and 4 kilograms of mass, respectively.

Materials used for forming a structure must balance high strength, mass minimization, machinability ease and cost. The most prevalent materials used for manufacturing nanosatellite structures are stainless steel, titanium, 6061 or 7075 aluminum as well as various composite materials. The CubeSat specification standard sets additional requirements for the materials used for structure manufacturing. Allowed materials include 7075, 6061, 5005 and 5051 aluminum only.

Another key aspect for the nanosatellite design is space management. Although the available space may be utilized on demand through custom design, a proposed specification is usually applied for the case of CubeSats. The PC/104 specification defines the dimensions of internal electronic systems boards as well as interface connector placement, the maximum height of the components on the board and the maximum thickness of the board. Following this specification allows for a uniform placement architecture as well as compatibility between different manufacturers for on-board subsystems.

Finally, due to the fact that throughout the space bus launch and until the satellite parts with the deployer, all systems shall remain inactive, a safety measure is introduced. Separation switches are integrated into the standoffs so as for the satellite systems to start functioning upon separation from the deployer. Additional springs may be used, integrated as well into the standoffs in order to provide additional force at the moment of separation.

1.3.3 Attitude Determination and Control

Although the attitude determination and control subsystem (ADCS) is not present in every nanosatellite, it is considered a fundamental part of a modern nanosatellite. The ADCS handles the increased requirements for accurate pointing or attitude determination throughout projects with objectives aiming at high quality imaging or high rate communications. ADCS systems integrate multiple sensors (magnetometers, star trackers, cameras, GPS modules) as well as multiple actuators (magnetorquers, miniature reaction wheels, permanent magnets). This subsystem's objective is twofold; to provide data concerning the spacecraft's position and orientation with respect to the earth, as well as to provide the appropriate torque in order to alter the satellite's orientation.

1.3.4 Electrical Power Management and Storage

The Electrical Power Subystem (EPS) provides the necessary electrical power to the satellite's subsystems. The EPS shall provide regulated power in multiple voltage levels so as to fulfill different requirements between the on-board subsystems.

Additionally, the EPS manages the power harvested by the solar cells, battery charging and discharging cycles as well as provides over-current and over-voltage protection. Modern electrical power systems are compatible to the PC/104 standard and provide telemetry and telecommand functions via standard communication buses. Power storage via on-board batteries ensure continuous operations during eclipses. The energy source for the satellite system is the solar panels mounted on its sides. Solar cells provide power from solar energy. Cells are combined into solar panels mounted on the outer surface of the satellite. Both fixed and deployed solar panels subsystems are considered as solutions depending on the power requirements and the volume of the designed nanosatellite.

1.3.5 Communications

The communications subsystem is an irreplaceable component of a nanosatellite. The communications subsystem shall provide the link to the ground stations. Telemetry and telecommand as well as payload data are transmitted and received through the communications subsystem using on-board antennas [10]. The communications transceiver used in a cubesatellite system [11] operates within the UHF, VHF and/or S bands for the majority of the satellites launched. Cases of communications systems operating within the C, X and Ka bands exist mostly on systems incorporating experimental communications subsystems.

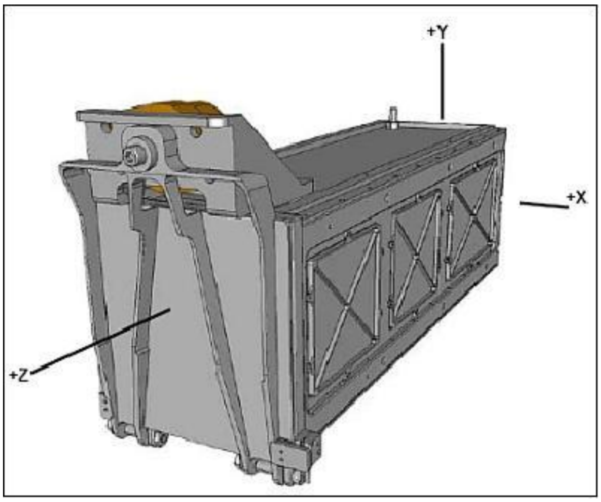

Figure 1: Illustration of the P-POD structure of the Mk III model (image credit: CalPoly).

1.4 Deployment Systems

Currently, a number of different deployment opportunities for nanosatellites exist. This variety of deployment systems increases the opportunity for a nanosatellite launch due to the fact that every deployment system is associated to an autonomous institute or organization which in turn has access to different launch missions. Some of the most established deployment systems are mentioned in the following paragraphs.

1.4.1 Poly Picosatellite Orbital Deployer (PPOD)

The Poly Picosatellite Orbital Deployer (PPOD) [12] (Figure 1) is the first deployment system that was ever provided for the deployment of nanosatellites into space. The PPOD was developed by California Polytechnic State University and Stanford University and is capable of launching up to a 3U CubeSat.

1.4.2 JAXA - Picosatellite Orbital Deployer (JPOD)

The deployer (Figure 2) developed by the Japan Aerospace eXploration Agency is the JPOD.

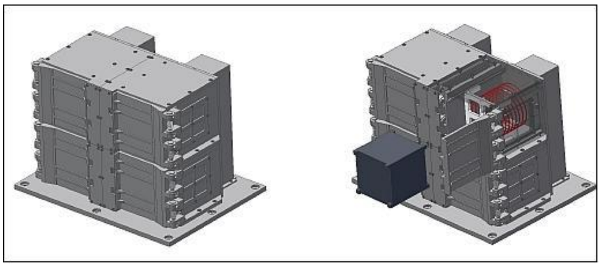

Figure 2: Illustration of the J-POD system (image credit: JAXA).

1.4.3 Tokyo Picosatellite Orbital Deployer (TPOD)

Tokyo Picosatellite Orbital Deployer (TPOD) (Figure 3) from Tokyo University is also used for the deployment of CubeSat compatible nanosatellites. The TPOD is capable of carrying up to three cubesatellites simultaneously.

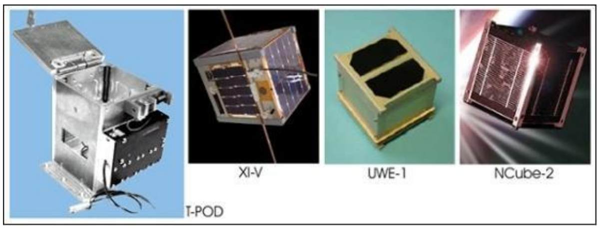

Figure 3: Illustration of the T-POD and the CubeSats (image credit: TU Wien).

1.4.4 CUTE Separation System (CSS)

A proprietary deployment system (Figure 4) by the Tokyo Institute of Technology, for the deployment of their cube and nanosatellites.

Figure 4: View of the CSS as flown on the CUTE-1.7+APD mission (image credit: TITech).

1.4.5 Naval Postgraduate School Cubesat Launcher (NPSCuL)

The NPSCuL (Figure 5) is a deployment mechanism designed to accommodate multiple individual PPODs (Section 1.4.1). Up to eight PPODs may be mounted onto the NPSCuL raising the number of the CubeSats to be launched to a total of 24U. The launcher was designed and developed by the students of the Naval Postgraduate School based in Monterey, California, U.S.A..

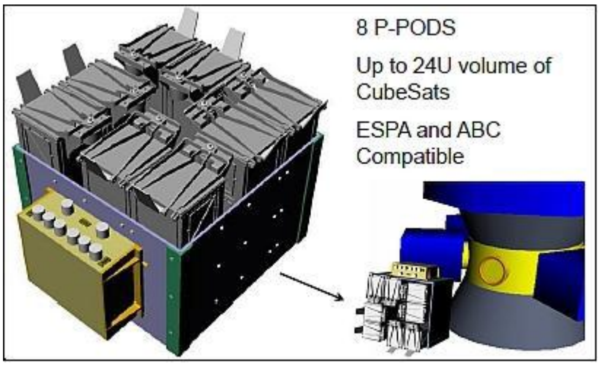

Figure 5: Conceptual view of the NPSCuL-Lite configuration (image credit: NPS).

1.4.6 eXperimental Push Out Deployer (XPOD)

Another custom deployment mechanism (Figure 6) was developed by the joint venture of the University of Toronto Institute for Aerospace Studies and the Space Flight Laboratory. Up to 10 3U CubeSats can be accommodated in this deployer while arbitrary dimensions may still be launched after adjustments in the deployer's configuration.

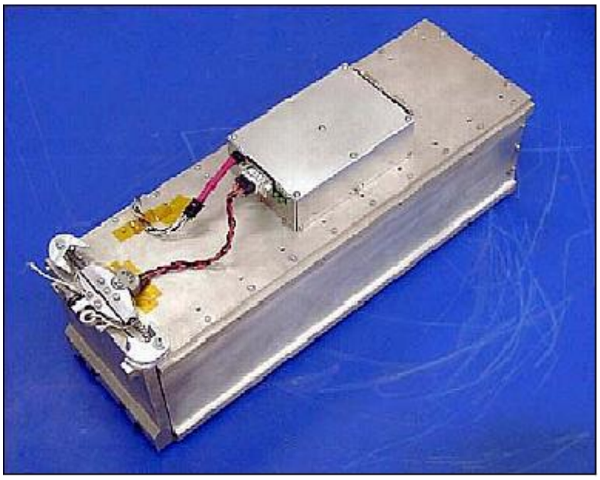

Figure 6: Illustration of the XPOD system (image credit: UTIAS/SFL).

1.4.7 Single Picosatellite Launcher(SPL)

Capable to deploy up to a 1U CubeSat or a 1.5 kg picosatellite, SPL (Figure 7) was a deployment system developed in Berlin, Germany, by Astro und Feinwerktechnik GmbH.

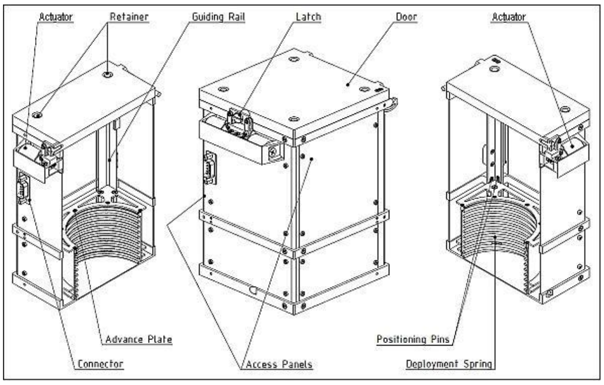

Figure 7: Schematic views of the SPL system configuration (image credit: AFW).

1.4.8 JEM Small Satellite Orbital Deployer (JSSOD)

The J-SSOD deployment mechanism (Figure 8) is capable of accommodating up to six 1U Cubesats in two containers. Thus, the maximum volume for a CubeSat to be transported in the J-SSOD shall be 3U. The JEM Small Satellite Orbital Deployer was developed by JAPAN Aerospace eXploration Agency to provide nanosatellite launch via the International Space Station.

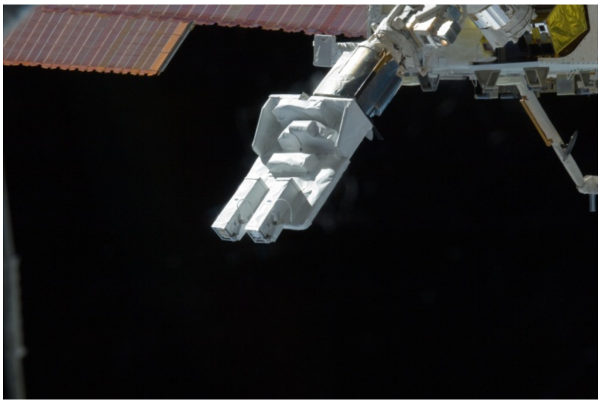

Figure 8: The J-SSOD attached to the International Space Station.

1.4.9 Nanoracks Cubesat Deployer (NRCSD)

The Nanoracks Cubesat Deployer (Figure 9) was developed in Houston, Texas, U.S.A. by NanoRacks LLC. The deployer's design aimed at a deployment system for deploying CubeSats from the International Space Station. The NRCSD is capable of deploying sixteen individual 1U CubeSats from two separate containers.

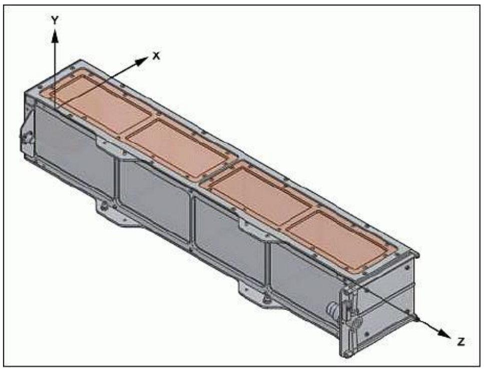

Figure 9: Illustration of the NRCSD (image credit: NanoRacks).

2. Modern CubeSats

This section presents a subset of the nanosatellites launched between March 2013 and November 2014. Nanosatellites were chosen based on their application and volume as well as their implementation platform. Nanosatellites of volumes up to 3U complying to the CubeSat standard, are considered. Additionally, the nanosatellites presented here are selected so that their applications satisfy educational, research or technology demonstration objectives.

Two hundred and ten different microsatellites were launched between March 2013 and November 2014. Universities, technology institutes as well as corporations participate in the design and development of individual satellite ventures with many applications. A subset of the applications includes earth and space observation, telecommunications, technology demonstration, APRS relays, weather observation and imaging. A subset of the previous launches is comprised of the CubeSats launched within the same period. Additionally, Cube-Sats that contribute to a satellite fleet were not considered as individual cases. CubeSat fleets from identical satellites contribute as single spacecrafts to the survey (see [13-14] and the references therein).

2.1 STRAnD 1

The STRAnD-1 3U satellite is a product of the cooperation of Surrey Satellite Technology Limited (SSTL) and University of Surrey Space Center (USSC). This satellite was built in order to demonstrate new technologies on attitude control actuators and imaging. Notably, the satellite has been the first ever to include a cellular phone in order to be used in space.

2.2 AAUSat 3.

The AAUSat 3 1U satellite was designed and built in the Department of Electronic Systems Aalborg University, Denmark. It was built entirely in-house by university students and faculty. No Cubesat kit components were used and its main mission was to be deployed along with two AIS receivers.

2.3 Dove 2

The Dove 2 3U satellite was developed by Planetlabs (previously Cosmologia Inc.) for technology demonstration purposes.

2.4 BeeSat 3

The Beesat 3 1U satellite was built by Techniche Universität Berlin (TUB) with the primary goal of technology demonstration as well as student training on a real satellite mission. Moreover, as a secondary objective, BeeSat 3 uses the HiSPiCO S-Band transmitter developed by the TUB and IQ Wireless as well as an earth imaging payload.

2.5 BeeSat 2

The BeeSat 2 is also a project of the TUB. The main objective of the BeeSat 2 satellite is technology verification of a custom design attitude control system.

2.6 SOMP

The SOMP 1U satellite is a project of the STARD research group at Technische Universität Dresden (TUD). The main objectives of this satellite are technology verification and demonstration as well as the deployment of scientific experiments into space.

2.7 OSSI 1

The OSSI 1 1U satellite was developed solely by the Open Source Satellite Initiative comprised by Hojun Song at the time this thesis was written. The main objective was to develop an open source cubesat by only one individual. The satellite offers a novel optical beacon based on LED lights.

2.8 TurkSat 3USat

The TurkSat-3USat 3U satellite was developed by the ITU. The main objective of this satellite is to support voice communications.

2.9 ESTCube-1

The ESTCube-1 1U satellite was developed by the cubesat project student team of the University of Tartu based in Estonia. The main objective of the satellite is testing a ten-meter tether, part of the electric solar wind sail which constitutes another project of the university. Moreover, the satellite shall harvest measurements of the force produced by the sail and take a picture of it.

2.10ArduSat

The ArduSat 1U satellite was an initiative for the reinforcement of an open-source development platform in space. Most of the team members were alumni of the

International Space University, where they met and started considering such an endeavor. The satellite offers a wide variety of sensors in its payload, interconnected via an Arduino platform component board.

2.11PhoneSat 2

The PhoneSat 2.0b 1U satellite was developed by NASA/ARC as a part of its Small Spacecraft Technology program. The main objective of this satellite was to demonstrate the use of COTS smartphones in the space environment.

2.12Firefly

The Firefly 3U satellite was developed by NASA/GSFC, USRA of Columbia, MD; Siena College of Loudonville, NY; University of Maryland Eastern Shore, Princess Anne, MD; and the Hawk Institute for Space Sciences, in Pocomoke City, MD. The satellite's main objective is the study of certain phenomena that take place into the Earth's atmosphere.

2.13Hoʻoponopono

The Hoʻoponopono 3U satellite was a joint development of the University of Hawaii, Honolulu, HI, USA and the AFOSR. Hoʻoponopono corresponds to "to make it right" in the Hawaiian language. The main objective was the further development of an existing radar calibration service.

2.14ChargerSat 1.2

The ChargerSat 1.2 1U satellite was developed by the University of Alabama in Huntsville. The satellite's main objectives were to improve communications for small scale satellite operations, demonstrate passive nadir axis stabilization and improve solar power harvesting.

2.15COPPER (SLU 01)

The COPPER 1U satellite was developed in the Space Systems Research Lab of the Saint Louis University. The main objectives of this mission are firstly to test the abilities of a commercially available infrared imaging apparatus to take images of Earth's oceans and atmosphere and secondly to investigate the radiation effects on electronics in the space environment.

2.16DragonSat 1

The DragonSat 1 1U satellite was a joint development of Drexel Space Systems Lab at Drexel University and the US Naval Academy. The main objectives of the satellite include imaging of the northern and southern lights, observation of the radiation dissipation during solar events and technology demonstration of a boom deployment mechanism.

2.17KySat 2

The KySat-2 1U satellite was developed by the Space Systems Laboratory at the University of Kentucky. The main purpose of this satellite is educational. KySat 2 will demonstrate developments of the University of Kentucky in the field of small spacecraft technology including power, communications and hardware.

2.18NPS-SCAT

The NPS-SCAT 1U satellite was developed by the Naval Postgraduate School located in Monterey, CA, USA. The main objective of this mission was to develop a platform for testing solar cells while at the same time providing the students with the opportunity to gain knowledge on small satellites.

2.19Trailblazer 1

The Trailblazer 1 1U satellite was designed and built by the University of New Mexico (UNM) located in Albuquerque, NM, USA. The satellite's main objective was for the UNM to develop an AFRL (Air Force Research Laboratory). Additionally, the research of PnP capabilities, concerning the architecture of the individual subsystems and their interfaces was also considered as a secondary objective.

2.20SwampSat

The SwampSat 1U satellite was developed by the Department of Mechanical & Aerospace Engineering at the University of Florida. The main objective of this satellite was to advance and demonstrate the capabilities of control moment gyroscopes.

2.21Vermont Lunar Cubesat

The Vermont Lunar CubeSat 1U satellite, led by Vermont Technical College with parts of the project done by Norwich University, University of Vermont faculty and students and St. Michael's College students. It is supported by Vermont Space Grant Consortium. The main objective of the satellite is the development of a self-propelled CubeSat able to drive autonomously of lunar orbit.

2.22Delfi - n3xt

The Delfi - n3xt 3U satellite, was developed by the Delft University of Technology. The main objectives of the satellite were education and technology demonstration. Three experimental components were added as payload to the cubesatellite, including a micropropulsion system, a multifunctional particle spectrometer and a scientific radiation experiment on solar cells. Additionally, a high efficiency modular communications platform provided for qualification by ISISpace.

2.23CINEMA - TRIO

The CINEMA - TRIO 3U satellite was a joint development from collaborating institutions with a main objective to provide critical space weather measurements. Institutions that were part of this collaboration were the University of California, Berkeley/Space Sciences Laboratory, the Imperial College London, the Kyung Hee University and the NASA Ames Research Center.

2.24OPTOS

The OPTOS 3U satellite was a project by the Spanish Space Agency in Madrid. The main objective of this satellite was to demonstrate new technologies in spacecraft development. The project presents a distributed OBDH subsystem as well as an optical wireless communication system.

2.25GOMX - 1

The GOMX - 1 2U satellite was a project led by Aalborg University based in Denmark. GOMSpace and DSE Airport Solutions of Aalborg were also collaborators in this development. The main objective of this satellite was to demonstrate the interaction between nanosatellite platforms and the ADS-B technology.

2.26FUNCube-1

The FUNCube - 1 1U satellite is a project organized entirely by AMSAT-UK and AMSAT-NL volunteers. The objective in this satellite project was to design, build and launch a nanosatellite in order to enthuse, excite and educate students in the field of science, technology, engineering and mathematics.

2.27HiNCube

The HiNCube 1U satellite was a project of the Narvik University College located in Norway. The main objective of this satellite was the development of a nanosatellite platform to be used for future scientific missions. The aforementioned satellite was built to take pictures of the earth and provide students with experience in a large multidisciplinary project.

2.28ZACube-1

The ZACube 1 1U satellite was a project developed by the French South African Institute of Technology. The main objective of this satellite was to develop a means to characterize the Earth’s ionosphere and calibrate the auroral radar installation, property of the South African National Space Agency based in Antarctica.

2.29iCube-1

The ICube-1 1U satellite was a project of the Institute of Space Technology located in Islamabad, Pakistan. The main objective of this satellite was to provide a platform for conducting scientific experiments on various fields including microgravity, biology, nanotechnology and space dynamics.

2.30HumSat-D

The HumSat-D 1U satellite was developed by an open international collaboration of organizations developing nanosatellites. The HumSat project is endorsed by the UN Program on Space Applications called BSTI (Basic Space Technology Initiative) which was started in 2009. The overall objective of the HumSat constellation is to provide messaging services through small user terminals on the basis of the store-and-forward concept.

2.31PUCP-Sat 1

The PUCP-Sat 1 1U satellite was a project developed by the Institute of Radioastronomy of the Pontifical Catholic University of Peru. The main objective of the satellite, apart from providing a multidisciplinary project for teaching purposes, was to deploy a smaller picosatellite.

2.32First-MOVE

The First-MOVE 1U satellite was a project developed by the Technical University of Munich. The satellite, as its name suggests, is the first of many to come, sharing the MOVE satellite platform. The main objective of this first spacecraft was to test space rated solar cells provided by EADS Astrium, in extreme conditions.

2.33UWE-3

The UWE 3 1U satellite was a project developed by the University of Wuerzburg. The main objective of the satellite was to demonstrate the use of a real-time miniature attitude determination and control subsystem. Additionally, the UWE-3 spacecraft was also an advancement on the objective of developing a modular and highly flexible platform for cube satellites.

2.34Firebird A,B

The Firebird A, B 1.5 U satellites were a joint program developed by the Montana State University and the University of New Hampshire. The objective of the Firebird satellite is twofold. The research objective focuses mainly on space weather observation and the educational objective focuses on the design and the development of a spacecraft and the induced knowledge transfer to the students.

2.35IPEX

The IPEX 1U satellite was a project developed by the Jet Propulsion Laboratory and the Goddard Space Flight Center of NASA and the California Polytechnic State University at San Luis Obispo. The main objectives of this project were to demonstrate the operations of autonomous instrument processing, downlink operations and ground station operations.

2.36M-Cubed

The M-Cubed 1U satellite was a project run by the University of Michigan. The main objective of this satellite was to demonstrate the highest resolution color imagery to date of Earth’s surface with at least 60% land mass and a maximum of 20% cloud coverage from a single CubeSat platform.

2.37Lituanica Sat - 1

The Lituanica Sat - 1 1U satellite was a project developed by the Vilnius University of Lithuania and is the first small satellite project developed in the country. The main objectives of the satellite were primarily technology demonstration using COTS components and secondly the testing of low-cost silicon-based solar cells to be use to power future nanosatellites.

2.38SkyCube

The SkyCube 1U satellite was a project developed by the Southern Stars, a U.S. corporation with long history in space software design. The main objective of this satellite was technology demonstration and earth imaging.

2.39ALL-STAR THEIA

The ALL-STAR THEIA 3U satellite was developed in a project run by the University of Colorado at Boulder and Lockheed Martin. The main objective of this satellite was to create a reproducible modular bus capable enough to be used for a variety of small research and technology-based payloads.

2.40DTUSat 2

The DTUSat 2 1U satellite was a project developed by the Technical University of Denmark. The main objective of the satellite was to develop a space-borne radio-tracking system capable of locating small birds on intercontinental migration routes.

2.41Duchifat 1

The Duchifat 1 1U satellite was a project developed by the Space Laboratory of the Herzliya Science Center in Israel. The main objectives of this satellite were firstly to provide an educational platform for the students of the university and secondly to provide real-time information via the amateur bands using the APRS protocol.

2.42CanX-4 & 5

The CanX-4 & 5 dual-nanosatellite system, developed by the Space Flight Laboratory of the University of Toronto, Institute for Aerospace Studies in Toronto, Canada. The main objective of this dual launch was to prove that satellite formation flying can be achieved in this scale offering submeter tracking error accuracy.

2.43UKube-1

The UKube 1 3U satellite was a project developed by the United Kingdom Space Agency. Various companies were also part of the development. The main objectives of this satellite were to demonstrate UK space technology and also provide industry and university hands-on training in spacecraft development.

2.44MicroMAS

The MicroMAS 3U satellite was a joint development of MIT/LL (Massachusetts Institute of Technology/Lincoln Laboratory), MIT/SSL (Space Systems Laboratory) and the University of Massachusetts at Amherst. The main objective of this satellite was to fulfill the need for low-cost, mission-flexible and rapidly deployable spaceborne sensors. The nanosatellite hosted a passive microwave spectrometer.

3. Discussion

This 1U CubeSat assembly is considered as a viable proposal for a satellite capable to communicate with earth stations over radio-amateur bands. The proposed 1U CubeSat draws its main components from the CubeSatKit component pool. The structure, comprised out of the chassis walls and top and bottom plates as well as the system’s motherboard and pluggable processing module are parts of the CubeSatKit solution offered by Pumpkin Inc. Bundled with the CubeSatKit are many additional components. Development board, Salvo Pro software, power supply units, programming/debugging adapters as well as various tools and mounting hardware are also included within the Kit.

This design was driven by a minimal cost incentive while at the same time maintaining a fully operational telecommunications CubeSat. The processing core of the CubeSat system is a Pluggable Processor Module A3 mounted on a Motherboard provided by Pumpkin Inc. The Electrical Power System selected was a third generation ClydeSpace EPS. A 10 Whr integrated battery provides the necessary energy storage for the cubesatellite to remain functional during eclipses. The energy is harvested from six solar panels provided by ClydeSpace. Four side panels and 2 base panels are parts of the proposed system. Altogether, the solar panels yield 10.74 Watts of electrical power at a surrounding temperature of 80°C.

The communications subsystem is a Helium 100 [13] radio transceiver provided by Astrodev. The proposed CubeSat shall communicate over the UHF band for transmission and over the VHF for reception. The conjunction of the aforementioned transceiver and the ANT430 antenna deployment system provided by GOMSpace fulfill the requirements for a complete communications payload subsystem. Additional components shall also be used for the interconnection of individual subsystems as well as for the system’s overall structural rigidity.

The following table (Table 2) includes all the aforementioned componets considered as parts for the 1U cubesatellite proposed in this section. In addition, each componet’s price along with the mass in grams.

	Individual Components	Provider	Mass (g)	Cost (USD)
Structure	CubeSat Kit Skeletonized Chassis Walls Assembly	Pumpkin Inc.	71	7,500
	CubeSat Kit Base Plate	Pumpkin Inc.	50	
	CubeSat Kit Cover Plate	Pumpkin Inc.	37	
On-Board Computer	CubeSat Kit MotherBoard	Pumpkin Inc.	67	
	CubeSat Kit Pluggable Processor Module A3	Pumpkin Inc.	11	
Electrical Power System	Third Generation EPS & Integrated Battery	ClydeSpace	169	7,500
Solar Panels	4 Side Solar Panels	ClydeSpace	168	11,300
	Top & Bottom Solar Panels	ClydeSpace	84	5,700
Communications System	Helium 100 Radio Transceiver	Astrodev	78	4,900
	ANT430 Antenna Deployment System	GOMSpace	30	5,300
Additional Components	Solar Panel Connecting Harness	ClydeSpace		850
	Rod & Spacer Kit	Pumpkin Inc.		200
	Midplane Standoff Kit	Pumpkin Inc.	10	200
	Solar Panel Clips for 1.6mm thick solar panels	Pumpkin Inc.	4	450
Total			779	43,900

Table 2: Commercial off-the-shelf components as a proposal for a 1U CubeSat.

An alternative to the 1U design proposal mentioned in the previous section is presented within this section. This 2U CubeSat shall provide an RF communications channel for the ground stations as well as digital photographs using the onboard camera. Additionally, attitude control shall be also among the features of the satellite so as to increase the satellite's overall stability as well as on-demand attitude control requirements.

The on-board computer subsystem is comprised of a Nanomind A712D provided by GOMSpace. The core of the system is a powerful ARM7 microprocessor. FreeRTOS as well as a custom driver library is included. Moreover, an Integrated Development Environment based on Eclipse aids to a faster development cycle. An ISISpace 2U structure was selected for the chassis of the CubeSat. ISIS-space provides fully compatible structures to GOMSpace subsystems. In addition, the NanoPower Pack for a 2U CubeSat handles the requirements regarding energy harvesting and power management within the satellite. This bundle in particular includes a NanoPower P31u electrical power subsystem, ten NanoPower solar panels (seven NanoPower P110 and three NanoPower P110U solar panels) as well as additional flight preparation and interstage panels and a harness kit for the interconnection of the solar panels to the electrical power subsystem.

Space communications are supported through a NanoCom U482C module, operating in the UHF amateur band. A compatible antenna deployment system, namely the ANT430 was selected as the satellite's antenna system.

As an addition to the satellite's payload, an onboard space camera subsystem was included so as to provide high quality imaging features to the system's capabilities. The NanoCam C1U space qualified camera defines a system which is considered fully compatible to the CubeSat standard, regarding sizing and on-board communications. The NanoCam offers a 3.15 megapixel CMOS sensor and an on-board processor dedicated to image processing and compression. An integrated 32 MB RAM as well as a 2 GB solid state storage provide temporary storage for captured images. The on-board interconnection to the system's OBC is made through I^2C or SPI, both fully compatible to the CubeSat Space Protocol. At a mass of 166 grams and physical dimensions of 96 mm X 90 mm X 58 mm, the NanoCam shall be considered as a good compromise to the system's overall volume. The price for a NanoCam C1U is $ 11.500.

Lastly, as an additional measure for attitude control accuracy, a magnetorquer board provided by ISISpace is also part of the system. A fully CubeSat compatible board acts as a three-axis magnetorquer. On-board communication is made over I^2C bus protocol via a standard PC/104 interface.

	Individual Components	Provider	Mass (g)	Cost (EUR)
Structure	2U CubeSat Structure	ISISpace B.V.	390	2950
On-Board Computer	Nanomind A712D	GOMSpace	55	4750
Electrical Power System Pack	Nanopower Pack 2U	GOMSpace		22000
	Nanopower P31u EPS	GOMSpace	200	
	7 Nanopower P110 Solar Panels	GOMSpace	420	
	3 Nanopower P110U Solar Panels	GOMSpace	180	
	Flight Preparation and Interstage Panels			
	Solar Panel Connecting Harness			
Communications System	Nanocom U482C	GOMSpace	75	8000
	ANT430 Antenna Deployment System	GOMSpace	30	5500
Additional Components	Nanocam C1U Camera	GOMSpace	166	11500
	Magnetorquer Board	ISISpace B.V.	196	8000
Total			1762	62700

Table 3: Commercial off-the-shelf components as a proposal for a 2U CubeSat.

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