Nanosat / Cubesat constellation concepts

Alexandru Catalin Munteanu

Luleå University of Technology
Master Thesis, Continuation Courses
Space Science and Technology
Department of Space Science, Kiruna
CRANFIELD UNIVERSITY

SCHOOL OF ENGINEERING
Astronautics and Space Engineering

MSc THESIS

Academic Year 2008 – 2009

ALEXANDRU CATALIN MUNTEANU

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Supervisor: Dr. Stephen Hobbs

June 2009

This thesis is submitted in partial fulfillment of the requirements for the degree of Master of Science

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ABSTRACT

This thesis was produced at Cranfield University, with support from EADS Astrium who introduced the base requirements for the study. The subject to be researched was the possibility of using Cubesats for producing viable Earth Observation missions when they would be used in some constellation configuration.

The project involved surveying nanosat / Cubesat constellation markets and concepts (e.g. real-time data) for Earth Observation, using new / enabling technologies (i.e. deployable membranes, quad junction cells, miniature instruments). The project also contributes to the Cubesat projects by providing a roadmap of possible future missions enabled by advanced Cubesats.

The study concluded by selecting a present day possible mission which could be developed by using COTS components and space-proved instruments and some missions which could be developed in the near future using other new technologies yet to be made available for space applications. Some simulations of the possible missions were performed in order to determine the best configurations and results are presented in the discussion and conclusion chapters.
ACKNOWLEDGEMENTS

I would like to thank to my supervisor Dr. Stephen Hobbs, for his constant support and the provided indications, and to my contact person at EADS Astrium, Steven Eckersly for his suggestions in approaching this subject.

Last, but not least I would like to thank my family for all the direct and indirect support they have always given me.
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NOTATION

1U – one unit Cubesat; exterior dimensions of 10x10x10 cm³
2U – two unit Cubesat; exterior dimensions of 10x10x20 cm³
3U – two unit Cubesat; exterior dimensions of 10x10x30 cm³
ADCS – Attitude Determination and Control System
AIAA - American Institute of Aeronautics and Astronautics
CAN bus - Controller Area Network bus
CCD - Charge-coupled device
CMOS - Complementary metal oxide semiconductor
COTS - Commercial Off-The-Shelf
CPU - Central processing unit
EADS - European Aeronautic Defence and Space Company
EO – Earth Observation
EPS - Electrical Power System
ESA – European Space Agency
FOV – Field of view
GENSO - Global Educational Network for Satellite Operations
GPS – Global Positioning System
IAIA - International Academy of Astronautics
IEEE - Institute of Electrical and Electronics Engineers
ISIS - Innovative Solutions In Space (Dutch Company)
ISS – International Space Station
LEO – Low Earth Orbit
MEMS – Micro Electro Mechanical System
NASA – National Aeronautics and Space Administration
NOAA - National Oceanic and Atmospheric Administration
NORAD - North American Aerospace Defense Command
P-POD - Poly Picosatellite Orbital Deployer
PCB - Printed circuit board
RAAN - Right Ascension of the Ascending Node
RF – Radio Frequency
S/C – spacecraft
SAR - Synthetic aperture radar
SEE – Single event error
SEL – Single event latchup
SFL – Canadian Space Flight Laboratory
STK – Satellite Tool Kit (AGI company’s software)
T-POD - Tokyo Picosatellite Orbital Deployer
TID – Total ionizing dose
TLE - Two Line Elements; satellite tracking system
UHF - Ultra high frequency
UN – United Nation
US, USA – United States of America
USART - Universal synchronous/asynchronous receiver/transmitter
VHF - Very high frequency
X-POD – Experimental Push Out Deployer
1. INTRODUCTION

1.1. Project Overview

The project baseline is to develop suitable mission concepts for Earth Observation constellations of nanosat/Cubesats. The first part of the thesis is a detailed survey of current and near future Cubesats status, usage and hardware while the second part deals with describing possible missions and usage of Cubesats in some novel configurations. The key parameters driving the economical sense of Cubesat constellations are going to be studied, identifying the areas where improvements could be made.

The main constraints proposed by the Astrium EADS© representative regarded the ready-availability and ease of manufacture of the satellites, which led from the beginning to narrowing the area of research only to Cubesats or even smaller satellites. This is mainly because the other non-standardized nano-satellites although they can bring substantial innovation and return to the mission they also need a lot of research & development which increases the time of building and the cost dramatically.

The project also involved studying the broad subject of Earth Observation missions including applicability areas, identifying the suitable missions as well as the instruments and methods used for EO in conventional satellites and which could find soon applicability to Cubesat missions.

The final simulations of an EO constellation of Cubesat mission were done using STK trying to see the actual return that can be achieved with space-proved hardware configuration.

1.2. Rationale

The scope of this project is to identify roadmaps for future Cubesat missions with the broader aim of decreasing the cost of access to space.

The problem of cost reduction remains a driving factor in advancing space technology and has two main points of interest:
- miniaturization or mass and power reduction of platform and instruments
- cost reduction through novel launching strategies, mission planning and usage of the ground networks.
To make it very clear, these issues are important not only for extremely small satellites but also any development is in some extent applicable to bigger spacecraft, and they would always welcome any reduction in their mission cost.

1.3. Objectives

The main objective of the thesis is to identify those configurations of the space segment, ground segment and launching methods that would be most feasible and most cost-effective for future Earth Observations missions using Nano/Cubesat constellations.

1.4. Literature review

The literature used in this thesis covered a broad spectrum of available information which can be seen in the reference and bibliography sections, but the main focus was placed on:

- the Cubesat hardware description available from some of the Cubesat manufacturers and diverse Cubesat university projects of the Cubesat network established by California Polytechnic State University in the United States. Regarding imaging hardware the International Conference on Space Optics held in Toulouse in 2008 as well as some other MEMS conferences and AIAA or IEEE published papers were used

- mission descriptions and other papers published in the annual Cubesat conferences organized by the Cubesat network, ESA education department or “IAA committee on small satellite missions”

- the Earth Observation topic was reviewed mainly from online sources available at ESA web portal, NASA web portal and, NOAA website, “The Group on Earth Observations” or some conferences and symposiums in EO or remote sensing area

- for constellation design the main reference book used was “Mission Geometry” by James Wertz (Wertz 2002), some published scientific papers acknowledged in the references chapter as well as some information available on ESA portal about current EO constellations of satellites
Collecting the information needed for this paper represented a real challenge because of the broad spectrum of topics it covers. Because a spacecraft is in essence a system of systems it deals with all the branches of engineering and quite often detailed knowledge of each of those sub-systems is needed even for a top-level approach.

The main issues in designing a spacecraft even as simple as a Cubesat remain the strict interconnections and effects that each sub-system has on the others and on the spacecraft as a whole.

The entire mission design is dictated in general by 3 very general factors:
- natural laws and phenomenon governing the Universe and the Solar system in particular
- technology capabilities available on the date of the space segment design (not on the time of manufacturing, nor the launching moment)
- technology capabilities available on the date of launch and operation (mainly capabilities of the launcher and of the ground segment)

In the case of a Cubesat, relatively short development periods ensure that the technology used is a lot more connected with trends and new discoveries. On the other hand, the severe limitations in size and mass can be seen as both innovation pushing and technology discarding.

1.5. Report outline

After the introduction, this report will contain four chapters starting with a survey of the present state of Cubesats. Then follows a chapter regarding Earth observation and constellation configurations. Then a chapter where some possible Cubesat constellation configurations will be proposed and analyzed. Finally a discussion of the entire project and the conclusions drawn from it are presented.
2. CUBESATS CURRENT STATUS

This chapter will discuss the current condition of Cubesat hardware categorizing them in the different subsystems that make up a spacecraft. Detailed description of hardware capabilities from different manufacturers will be made available for getting a sense of their individual performances and the way they influence the overall performance of the system. In each section an end discussion will describe trends and new ideas regarding those subsystems.

2.1. Cubesats introductory discussion

Since the beginning of modern technologies and the space-era half a century ago, the small satellite segment represented the most sought after type of investment for advanced technologies by countries or organizations with limited budgets and/or very little experience in space technology.

But since 1999 when Stanford University and California Polytechnic University in USA developed the Cubesat set of standard specifications (Annex C) for small satellites the true revolution of cheap satellites was introduced (The CubeSat Program 2009).

The principle of standardization and eventually of mass production is the basic principle that stands behind cost reduction in any industry and was long thought to be inadequate for the production of satellites because of the uniqueness of the mission that they have to perform which consequently leads to customized designs.

Actually, the standardization of the small satellites introduced by the Cubesat project regarded in the beginning only the form factor, initially limited to the 10x10x10 cm$^3$ as a way of developing standardized launching system which would be accepted on the major launch platforms.

From these initial exterior constraints the standardization went further with the interior layout which involves stacking up different system components as parallel printed circuit boards.

In fact, the development of the spacecraft interior went from the indication of layout to an entire spacecraft platform definition which is able to accommodate different payloads.
Nowadays the exterior standard evolved toward 2U and 3U Cubesats which keep the same launching platform capability but offer more space for payload accommodation.

We can see that the entire principle of designing a Cubesat starting with the exterior and mass constraints towards the definition of the mission is in total contrast with the principle of designing other satellites which are usually designed inside-out or to fit some mission requirements.

This might suggest that in a Cubesat there could be unused extra space, but that is never the case. Instead, people have to adapt payloads or even modify parts of the bus for accomplishing the mission, leading to innovative ideas more often than in the case of a big satellite which is only limited by the launcher capabilities.

Making an inventory of the Cubesat past missions we can see that most of these were the investment and labor of academic institutions having shoe-string budgets and relying on sponsors, collaborations and even free launch opportunities.

They had as primary goal the purpose of educating students in space technology but very often these missions were used for demonstrating new technologies, qualifying ground technologies for space use, or performing novel scientific experiments which would have cost a lot more by using bigger spacecraft.

From the beginning it was never the intention of small satellites or Cubesats to replace the capabilities offered by bigger satellites. This would have been an objective impossible to reach, but instead they tried to complete a niche of missions which would not make any economic sense using regular size spacecraft.

### 2.2. Past launches and missions

Looking at past launches we can see that as to beginning of May 2009 a total number of 8 launch opportunities were used by the Cansat community and NORAD still tracks a total number of 24 satellites. Their orbital TLE parameters can be observed continuously using the Celestrack website as can be seen in Annex A (Center for Space Standards and Innovation 2009).
Table 1 presents the past Cubesat mission launches in a chronological order as they can be compiled from The CubeSat Program website (The CubeSat Program 2009):

<table>
<thead>
<tr>
<th>Launcher</th>
<th>Date</th>
<th>Cubesats no.</th>
<th>Cubesat Missions Names</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eurokot</td>
<td>30.06.2003</td>
<td>6</td>
<td>CanX-1, DTUsat, AAU Cubesat, QuakeSat, Cubesat XI-IV, TiTech - CUTE-I</td>
</tr>
<tr>
<td>SSETI Express</td>
<td>27.10.2005</td>
<td>3</td>
<td>Cubesat XI-V, NCUBE-2, UWE-1</td>
</tr>
<tr>
<td>M-V-8</td>
<td>21.02.2006</td>
<td>1</td>
<td>CUTE-1.7+ADP</td>
</tr>
<tr>
<td>Belka: Dnepr (Rocket Failure)</td>
<td>26.07.2006</td>
<td>14</td>
<td>Aero Cube 1, ICE Cube-1, ICE Cube-2, ION, HAUSAT-1, KUTESat, MEROPE, CP-1, nCube-1, RINCON, SACRED, CP-2, SEEDS, Voyager</td>
</tr>
<tr>
<td>TacSat-2: Minotaur</td>
<td>16.12.2006</td>
<td>1</td>
<td>GeneSat-1</td>
</tr>
<tr>
<td>EgyptSat: Dnepr</td>
<td>17.04.2007</td>
<td>7</td>
<td>CP4, AeroCube 2, CSTB 1, MAST, CP3, CAPE 1, Libertad-1</td>
</tr>
<tr>
<td>PSLV-C9</td>
<td>28.04.2008</td>
<td>7</td>
<td>CanX-2, AAUSAT-II, Compass-1, Delfi C3, CUTE-1.7+APD II, SEEDS-II, CanX-6-NTS</td>
</tr>
<tr>
<td>Falcon 1, (Rocket Failure)</td>
<td>02.08.2008</td>
<td>2</td>
<td>PRESat, NanoSail-D</td>
</tr>
<tr>
<td>Minotaur I</td>
<td>19.05.2009</td>
<td>4</td>
<td>Pharma-Sat, CP-6, Hawksat-1, Aerocube-3</td>
</tr>
</tbody>
</table>

Table 1 - Cubesat Mission Launches (The CubeSat Program 2009)

Also for having a general idea about past missions’ orbit parameters the following summary is presented in Table 2 (The Cubesat Program 2009, Center for Space Standards and Innovation 2009):
As we can see from the above Table 2, the success rate of launches has been 75% (not considering the recent Minotaur launch) but only 61% of the
satellites actually made it in orbit, and then the rates of success of establishing communication, performing the mission objectives and surviving the proposed life-time are a lot smaller.

Nevertheless, all these missions, even those which failed to reach space at all, accomplished the primary goal of student education and consolidated a mini-market for Cubesat components, while establishing a solid amateur ground stations community which increased greatly in the last five years.

These missions encouraged in turn other universities to start these kinds of program and an estimated 100 Cubesat developers are nowadays working world-wide towards delivering their first Cubesat in space.

Another useful statistic regarding the Cubesat missions’ objectives and success rates, could be presented as it follows in Table 3:

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Launches</th>
<th>Rate of success</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology demonstration</td>
<td>41 (100%)</td>
<td>25 (61%)</td>
<td>Components integration, novel sensors and architectures, testing fault tolerance, solar cells performance, deployables and tethers, wireless link</td>
</tr>
<tr>
<td>Imaging (only Earth)</td>
<td>13 (31%)</td>
<td>5 (20%)</td>
<td>Used off-the shelf CMOS camera, image processing and autonomy, attitude determination methods</td>
</tr>
<tr>
<td>New Comms systems</td>
<td>6 (15%)</td>
<td>2 (8%)</td>
<td>Non-standard protocols, active grid and patch antennae, redundant comm. links, new modulation schemes</td>
</tr>
<tr>
<td>Science missions</td>
<td>10 (24%)</td>
<td>3 (12%)</td>
<td>Measurements of charged particles, solar sailing, airglow, Earthquakes, live-stock tracking, DNA experiments, gamma rays, O1, GPS scintillation, other types of radiation</td>
</tr>
<tr>
<td>Others</td>
<td>6 (15%)</td>
<td>1 (4%)</td>
<td>Ship monitoring and data bus, decreasing the risk for coming missions or test-bed technology demonstration</td>
</tr>
</tbody>
</table>

Table 3 - Cubesats Mission Objective Statistics (Thomsen 2009)
2.3. Payloads Discussion

The payload of a satellite is the most important component and the whole reason why a mission is planned. Usually it consists of a sensor or a scientific experiment due to be conducted in the space environment and has to gather intelligence about one or more targets.

The payload can be considered as the physical manifestation of mission objective which is going to impose all kinds of constraints on the satellite platform.

In the case of a Cubesat which has a relative fixed platform configuration the payloads have to be chosen in such a way that they would fit-in with the rest of the satellite.

This means strict conditions of mass, power, pointing accuracy and data transmission which have to be fulfilled by the payload and drive its design and performance.

As a lesson of history, the Cubesats have been built and used by universities which had to base their projects on limited funding and experienced personnel. This meant that most of the projects tried to keep things simple and robust with only one principal payload and maximum 2-3 auxiliary payloads.

This is a good strategy, but doesn’t allow for too much redundancy, and if one has only one payload which gets into problems, it means nothing else but the communication system or the attitude system can be tested.

On the other hand, having a very cheap satellite is a very good opportunity to test new technologies or to space-prove some components.

The combination of a space-proved instrument and some auxiliary new-concept payloads seems to be the best solution and it is a preferred solution even on bigger spacecraft (Sandau 2008).

As we can conclude from the table in Annex B, the missions and corresponding payloads previously used or planned to be used on Cubesats vary a lot from technology demonstrators or scientific experiments to Earth Observation sensors or some combinations of them.

A common feature is that there’s no standardized payload ready yet for Cubesat missions (preferably it would have been flown on multiple missions).
but the companies which are producing the Cubesat platforms are working toward this goal.

When designing a Cubesat payload we have to have in mind that the main constraints imposed by the platform have the rough values in Table 4:

<table>
<thead>
<tr>
<th>Cubesat type</th>
<th>3U</th>
<th>2U</th>
<th>1U</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload mass</td>
<td>1.5kg</td>
<td>0.8kg</td>
<td>0.3kg</td>
</tr>
<tr>
<td>Payload orbit power</td>
<td>1.8W</td>
<td>1.1W</td>
<td>1 W</td>
</tr>
<tr>
<td>Max. Data Downlink/ pass</td>
<td>7500 kB</td>
<td>2000 kB</td>
<td>700 kB</td>
</tr>
<tr>
<td>Attitude determination accuracy</td>
<td>&lt; 0.5°</td>
<td>&lt; 0.5°</td>
<td>&lt; 1.0°</td>
</tr>
<tr>
<td>Attitude control accuracy</td>
<td>&lt; 5.0°</td>
<td>&lt; 5.0°</td>
<td>&lt; 10.0°</td>
</tr>
</tbody>
</table>

Table 4 - Cubesats Payload Limitations (ESA 2009)

The table above is based on the first version of the Cubesat platform and since then, improvements have been made as we’ll see later on.

2.4. Hardware review – Mechanical System

2.4.1. Structure Introductory Discussion

The structure is the most basic component and the most restrictive component of the Cubesat and consequently influences the design of all other subsystems which have to fit inside or to be mounted on it.

As mentioned before, the entire idea behind the Cubesat project was to provide a standardized structure and build all other systems “around” it.

This had the main advantage of standardizing the launching platform but in the same time creating a mini industry of ready to buy components which would have at least the form factor compatibility.

The external layout of the Cubesat is made of thin metallic walls with certain design features in order to accommodate all the other subsystems built mainly on PCB boards and stacking one on top of each-other in shelf-like slots.

Because of the recent developments in the Cubesat market the initial 10x10x10 cm³ architecture evolved towards accommodating bigger payloads and the 2U and 3U platforms were introduced with 10x10x20 cm³ and 10x10x30 cm³ dimension standards respectively.
Before going any further, note that Annex C gives the unaltered list of requirements as they were introduced and further updated by the Cubesat community organizers, California Polytechnic State University.

Regarding acquisition of COTS components specifically built for Cubesats, the market is composed for the moment of 3 major manufacturers and/or suppliers:

- Pumpkin Inc in USA
- ISIS in Netherlands
- Clyde Space in the United Kingdom

All these three companies started up relatively recently as spin-offs of university programs and are the absolute proof that expertise gathered in academic environments can be transformed into profitable businesses.
For a design purpose detailed schematics of the 1U Cubesat structure are presented in Figure 2:

Figure 2 - 1U Cubesat design ©Pumpkin Inc. (The CubeSat Program 2009)

2.4.2. ISIS Structures

The ISIS structure is designed as a generic structure utilizing the Cubesat set of requirements. It permits numerous configurations, allowing the nano-satellite users the choice of building their satellite for optimal internal arrangement. This idea, as well as the easy access to the internal components even after they were assembled, generates an open-type of structure, which is simple to use.
Their Cubesat structure is actually composed of a modular frame and shear panels based on the following ideas:

- convenient access and incorporation
- availability in 1U, 2U, 3U, 4U, 5U or even customized structure types
- supports different PCB sizes
- standard PC/104 form feature
- customized 94x94 mm\(^2\) circuit boards
- supports different orientations for the circuit boards (flipping them)
- boards can be stacked vertically or horizontally

Other characteristics defining the structure for the 1U Cubesat are: mass of 200g, exterior dimensions of 100 x 100 x 113,5 mm, interior available space 98x98x98 mm\(^3\), thermal envelope: -40°C to +80°C, qualified for static loads of 10.8G in all 3 axis and ASAP5 for vibration levels.

Addition of side frames or even shear panels can be made after the system integration. Components are manufactured using a tolerance of up to 0.1 mm. A redundant “Kill Switch Mechanism” having separation springs also is included in the structure. (Innovative Solutions in Space 2009)

2.4.3. Pumpkin Structure

This structure is very rigidly built, it keeps the weight to a minimum, has only 3 big assemblies and uses only stainless fastenings.

With the purpose of having an excellent electrical conductivity the entire structure is alodined while the wear-exposed surfaces are anodized.

The structure is available to buy in 1U, 2U or 3U standard formats but also in ½U, 1½U or other customized dimensions.

All components including the electronics in the kit are tested to withstand temperatures in the range of -40 to +85 °C.

The Pumpkin kit is planned to take stack-through PC/104 cards on top of the flight module. Between neighboring slots threaded “M3” spacers of 25mm are used. (Pumpkin 2009)
2.4.4. Launching Systems

2.4.4.1. P-POD by Pumpkin Inc.

The tubular design of the P-POD is intended to give a linear trajectory for the Cubesats thus providing a low spin rate after the deployment. The Cubesats are deployed from the system using a spring and then glide along the smooth rails towards the exit.

The release mechanism is activated by a signal sent from the launch vehicle computer, resulting first in the release of the door spring mechanism, and afterwards the main spring pushes the Cubesats out. The configuration after deployment is shown in the Figure 3:

![Figure 3 - P-POD, ©Pumpkin Inc (Pumpkin 2009)](image)

The material used for manufacturing is Aluminum 7075-T73, which protects the Cubesats mechanically but also creates a Faraday cage and a grounding point. The P-POD is coated with Teflon, making it resistant to cold welding, and providing a smooth surface for Cubesat deployment. The exit velocity is 1.6 m/s but it can be adjusted for meeting launch vehicle specifications by simply replacing the ejecting spring.
Side panels permit access to the Cubesats after their integration and can be used to charge batteries or run diagnostics. After the Cubesats acceptance tests, the ports are locked into position.

The mass of the P-POD before deployment is 5.25 kg while the mass post deployment is only 2.25 kg. Natural frequencies of vibration are at 180, 360, 700 and 920 Hz. (Pumpkin 2009)

2.4.4.2. ISIPOD by ISIS

The ISIPOD was designed for providing a cheap launch service for pico- and nano-satellites.

The ISIPOD is available in 1U, 2U, 3U or even custom versions but only the triple unit can be used in adaptable configurations: one 3U Cubesat or shared 1U and 2U Cubesat missions. It uses an electrical actuator and it is compatible with most launch vehicle pulse signals. The actuator is a non-explosive device so it can be tested, reseted and reused without maintenance.

Having no electronic switching units the ISIPOD does not create any electromagnetic or RF signals. (Innovative Solutions in Space 2009)

2.4.4.3. T-POD by Tokyo University

Similar in design to the above systems the T-POD built by Tokyo University and SFL has a good flight background being used for the 2003 Eurokot launch of XI-V Cubesat and for the 2005 SSETI Express mission. (ESA eoPortal 2009)

2.4.4.4. CSS (CUTE Separation System) by Tokyo Institute of Technology

The system built by Tokyo Institute of Technology has been used to deploy 3 Cubesats developed by this institution in 3 different missions. (ESA eoPortal 2009)

2.4.4.5. X-POD (eXperimental Push Out Deployer)

The X-POD is a refinement of the T-POD platform made by University of Toronto and the Canadian Space Flight Laboratory and was used in the 2008 launch from Satish Dhawan Space Centre, India to deploy six of the seven Cubesats. (ESA eoPortal 2009)
2.4.5. What the future holds for Cubesat structures

Although this subsystem of the Cubesat is intended to be the most inflexible and the most standardized, the structure of Cubesats has been usually the case of in-house manufacturing, sometimes for cost savings, sometimes for adjusting the structure to specific payloads which were impossible to accommodate in a standard type of structure.

Yet, there exist innovative ideas for future Cubesats structures, most of them implying the alteration of the structure after the satellite is in orbit. This would be done for achieving gravity gradients assistance (Fig.4) modular configurations (Fig.5), artificial gravity experiments (Fig.7), de-orbiting mechanism by increasing area and drag (Fig.6) like the following proposed missions:

![Figure 4 - Gravity gradient structure](image1)

*Figure 4 - Gravity gradient structure, © QinetiQ North America (The CubeSat Program 2009)*

![Figure 5 - Modular structure](image2)

*Figure 5 - Modular structure, © Univ. of Southern California & USAF Research Lab (The CubeSat Program 2009)*
2.5. Hardware review - Power System

2.5.1. General Discussion

The role of the power system in a spacecraft is crucial because it can determine the length of the mission, types of instruments, and payloads to be used onboard. Its design is influenced by the mission geometry or character.

The main functions for the power system are provision, storage, distribution and control of power to all the other subsystems which operate on an electrical consumption basis.

Just as any of the other sub-systems of a spacecraft, the power system can only be designed using an iterative and inter-linked process. In this specific case we are concerned with the main consumptions (coming from the payloads, communication, ADCS and eventually electrical propulsion) and the main inputs coming from solar cells or other electrical power sources, but also with the intermediary energy storage devices usually represented by batteries.

The difficulties which can be encountered in the design of the power system, have to do with satisfying volume and mass limitation, thermal protection, duty cycles or implications of the space environment over its performance.
It is recommended by Cubesat kit providers that the entire power system should not be more than 35% of the entire satellite mass and also it must be able to operate in a temperature range of -20 to +85°C.

Other recommendation include that Cubesats with batteries able to recharge should be deactivated during the launch or launched with uncharged batteries, and Cubesats with rechargeable batteries should be able to receive a transmitter shutdown command. (The CubeSat Program 2009)

Because the power consumption varies depending on the orbit and operation scenarios we have to assume the worst-case scenario for power budgeting and margin analysis. This implies a complete operation per orbit, in which all subsystems and payloads are being used at their respective allocated power consumption and further more we’re assuming worst-case power generation.

Because history is always a good starting point, I’m going to consider things which worked in the past and summarize some of the characteristics of the power systems of Cubesats currently in use or proposed to be launched.

But before doing that, some design considerations and recommendations made by past Cubesat missions are summarized here:

- solar cells can be used in hotter mode and at a lower power level than indicated in the specification sheet
- the power consumed by electronics (i.e. microcontrollers) while in both sleep mode and active mode should be taken into calculations
- some margins should be included for accommodating unknowns or small errors in the specifications sheet
- always calculate a peak power budget for each one of the modes of operation
- calculate BOL and EOL power production and necessities
- keeping in mind that solar panel power fluctuates considerably with temperature
- a typical temperature of 67°C is reached in LEO for solar cell but data-sheets specifications are calculated for 28°C
- for COTS solar cell cost and efficiency are inversely proportional
- shunting circuitry are necessary to limit peak voltages
- shelf life begins exactly at the time of battery manufacture
- low temperatures expand battery life
- low states of charge enlarge battery life
(The CubeSat Program 2009)
Yet, as a general rule, when one has the cost consideration in mind, he should always orientate towards off-the-shelf technologies designed for Cubesats rather than trying to manufacture everything from scratch with unknown risks and delays.

This leads us to some of the Cubesats kits and components manufacturers (Clyde-Space, Pumpkin Inc., Innovative Solutions in Space, GOMSpace and Stras-Space) which offer the following types of components:

2.5.2. Solar Cells by Clyde Space

The company manufactures panels using carbon fiber composite substrates and incorporating single junction Ga-As solar cells and interconnects.

The voltage characteristics of the solar cells at the “Beginning of Life” are presented in Annex D.

This company also has in development some 2U solar panel models with similar characteristics to the ones presented there.

The prices are in the range of up to 3750 GBP for 3U sized panels but it is worth mentioning that they are space-proved, include temperature sensors and they come incorporated with magne-torquers. The 1U Cubesat panel can have an effective coil area of 0.0076 m² and current of 0.1A at 5V while the 3U panel has an effective coil area of approximately 0.014 m² and current of 0.1A at 5V. (Clyde Space 2009)
2.5.3. Other Cubesat Manufacturers: Pumpkin, Inc.ISIS, GOMSpace, and STRAS SPACE

Except for Pumpkin which includes in its 1U Cubesat kit a number of 6 SpectroLab panels at a price of 20,500$, all the other companies don't provide yet off-the-shelf solar cells motivating that the design of the solar cells is very mission oriented and should be tailored to each individual Cubesat. (Pumpkin 2009)

2.5.4. What the future holds for solar cells

The latest developments in the solar cells for Cubesats include the Delfi-C3 mission, a 3U Pumpkin Cubesat which had the specific target of testing deployable "Thin Film Solar Cells" produced by the Dutch Space Co. The cells were made up of a "Copper indium gallium selenide" photovoltaic layer deposited on a thin titanium base of only 25 µm.

The project tried to develop a new type of solar cell with reduced weight and small production cost for novel space applications. This would mean reduction by half in the cost while increasing by the same percentage the power/mass performance compared to more usual solar cells.

With a projected cost of less than 350 Euro per Watt, the power/weight performance is likely to be above 100 W/kg. This cell won't have a covering glass, but instead would be coated with a dielectric for increasing the emissivity and protecting it. This predicts an efficiency above 12% under AM0 (Air Mass Zero solar spectral irradiance) light conditions. (Delft University of Technology 2009)

Another interesting mission for this area was supposed to be The Hausat-1 mission of the of South Korea's Hankuk Aviation University proposed to be launched in 2006 to test a deployment mechanism for solar cell panel but it was destroyed during launch.

The state of the art solar cell technologies available as of 2008 are best described in a comparison study called: “Progress in Photovoltaics: Research and Applications” – “Solar Cell Efficiency Tables Version 33” (Green 2009). It concludes that the current efficiency record is of 40.7% for multi-junction cells GaInP/GaAs/Ge produced by Spectrolab company and 40.8% for multi-junctions GaInP/GaAs/GaInAs developed by National Renewable Energy Laboratory – USA measured in AM1.5 spectrum at a cell temperature of 25C.
Some research also goes into developing quad-junction cells, which are in effect four separate solar cells stacked on top of each other with a series type of wiring. The total voltage is the addition of the four layers, but the current is restricted by the layer creating the smallest current. For the moment this technology is still under development. (Utsler 2006)

Regarding the solar cells configuration, it is already a common thing to have hinged solar panels deployable while in orbit for increasing the area of solar power collection, or to use the differential power from the cube sides as an ADCS sensor.

Other studies, (The CubeSat Program 2009) suggest that when used in the simplest wall mounted configuration the Cubesat should always face the Sun with one of its edges for increasing the collected power compared to one of the panels facing the Sun at a perpendicular direction.

![Figure 9 - Deployable Solar Arrays © US Naval Academy (www.aprs.org)](image)

2.5.5. Batteries by Clyde Space

The Clyde Space company provides battery kits based on a commercial Lithium Polymer cell which was thoroughly tested for its performance in a space like environment.

The 1U battery integrates with the power system provided in the Cubesat kit and is scalable for increasing the total capacity if needed. Inside the battery package there are: a system for measuring cell’s voltage, sensors for temperature and current supervision, a heater together with a thermostat and it also comes with a cell balancing system.
The cells are insulated in Kapton, but the foil bag doesn’t connect to the battery negative or positive contacts. The cells are fixed on the PCB by thermally conductive adhesive. Using a battery to a maximum voltage of 8.2V gives a capacity of 1.25Ah.

The system comprising the EPS and the two lithium polymer batteries in parallel can provide a usage of approximately 20Whrs. The entire elevation of the unit is 14 mm from the EPS surface when it uses one battery integrated onto the EPS, or 21 mm for the two batteries case. The EPS has a mass of 80g while the mass of one double cell battery is 62g for a 10Whr type battery.

For the 3U form factor the system is composed of a main battery board which has two series-cells mounted flat, side-by-side on a PC104 board. For increasing the capacity 2 additional, double-cell battery daughter boards can be integrated with the main board (just like the daughter boards is assimilated in the 1U system).

Also the main battery PCB includes its own microcontroller for telemetry data and tele-command. It can also provide optional two more voltages: 12V with 300 mili-Amps and 50V at 1 mili-Amp. The voltages are used by way of additional pins on the main header connector. The above configuration results in a 2 series cells per line and 6 lines in parallel. The capability of individual 2s3p batteries is 3.75 Ah for a maximum of 8.2 V. (Clyde Space 2009)
2.5.6. Other Cubesat Manufacturers: Pumpkin Inc., ISIS, GOMSpace, and Stras-Space

Pumpkin provides a 1U Cubesat Battery of 1.25Ah, 8.2V with a price tag of 910$ while all the others don’t provide yet separate batteries designed for Cubesats. (Pumpkin 2009)

2.5.7. What the future holds for batteries

The best known and largely available technology for batteries to this day remains the Lithium based batteries because of their best energy per mass ratios, no memory consequence, and one of the slowest loss of charge when they aren’t used. These can be concluded from the comparative table in Annex E (Cadex Electronics Inc 2009)

The Lithium based battery technology is also a widespread research topic mainly because of the consumer electronics which incorporate this type of batteries and consequently performance improvements are made in a regular manner.

Although some studies indicate that alternative novel technologies like flywheels or superconductive electromagnetic energy storage might have superior characteristics in energy storage to the chemical energy storage, for the purpose of this study I’m not going to consider them because of the lack in market development translated in superior costs and also superior mass requirements.

A very new technology which has recently entered into production from the A123 Systems Company is the Nanophosphate-Li battery (A123 Systems 2009) having the following characteristics:

- Power density: over 3000 W/kg and 5800 W/L
- 10X cycle life compared to conventional lithium ion

![Figure 11 - New enhanced batteries](©A123 Systems (A123 Systems 2009))

![Figure 12 - Thin film battery](© Infinite Power Solutions (Infinite Power Solutions 2009))
Novel technologies yet to be fully developed in the battery field include:

- lithium sulfur battery (developed by Sion Power) which is supposed to have better energy per mass compared with all available current lithium batteries
- thin film battery which is a promising enhancement of the lithium ion technology (developed by Excellatron and Infinite Power Solutions) claims a large boost in recharge cycles to about 40000; superior charge and discharge pace, a minimum of 5 cycles charge rate, continuous 60 cycles discharge, and 1000 cycles peak discharge pace as well as a major enhance in energy density of 300 Wh/kg (Infinite Power Solutions 2009);
- smart batteries are battery having a built-in voltage monitoring circuit;
- carbon foam-based lead acid battery made by Firefly Energy is suppose to have energy density of 30 to 40 percent more than the initial 38 Wh per kg , also having a longer lifetime;
- nanowire battery is a lithium-ion battery (by Dr. Yi Cui at Stanford University) using silicone for storing ten times more lithium than graphite, with high energy density on the anode which diminishes the mass of the battery. Having a large surface area permits fast charging and discharging.

### 2.5.8. Integrated Electrical Power Subsystems by Clyde-Space

For 1U and 3U Cubesats this company provides 2 integrated EPS board with the following characteristics:

- 3.3V, 5V plus Raw Battery buses
- flexible design: diverse solar cells or string lengths.
- active Maximum Power Point Tracking system.
- works with Lithium-Ion and Lithium-Polymer batteries
- TM and TC via I2C interface.
- safeguard against over-current or battery under-voltage
- USB charger for the battery
- works in the condition of dead launch using separation switches.
- adaptability from 1W to 20W orbit average necessary power.

(Clyde Space 2009)
2.5.9. Integrated Electrical Power Subsystems by Gom-Space

The NanoPower P-series power supplies are designed for small satellites with power demands in the range of 1-30W. The NanoPower interfaces to triple-junction solar cells using a very capable boost-converter to condition their output power for charging the included lithium-ion batteries.

The incoming power along with the power stored inside the batteries is then used to supply two buck-converters which provide 3.3V at 2A and 5V at 3A for the output bus. Each-one of these busses provides in turn 3 individually commandable output switches with protection for the cases of over-current shut-down and latch-up.

NanoPower Specs:

- Solar-cell power input < 30W
- One or three channels, power point tracking
- 2 regulated power buses: 3.3V at 2A and 5V at 3A.
- 6 power outputs, (latch-up protection)
- Housekeeping measurements
- I2C interface
- Kill-switch interface
- 1800mAh Li-Ion battery pack
- Kit connector compatibility
- Dimensions without batteries: 96mm x 90mm x 15mm
- Temperature range: -40 to +85 deg. C

(GomSpace ApS 2009)
2.5.10. Integrated Electrical Power Subsystems by ISIS

They don’t provide detailed specifications for their power system design but only some general performance characteristics presented in Table 5:

<table>
<thead>
<tr>
<th>Cubesat type</th>
<th>1U</th>
<th>2U</th>
<th>3U</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power production</td>
<td>2.4 W</td>
<td>3.2 W</td>
<td>4.5 W</td>
</tr>
<tr>
<td>Conditioning type</td>
<td>Regulated: 3.3V, 5V</td>
<td>Regulated: 3.3V, 5V</td>
<td>Regulated: 3.3V, 5V</td>
</tr>
<tr>
<td></td>
<td>Unreg.: 7 – 12V</td>
<td>Unreg.: 7 – 12V</td>
<td>Unreg.: 7 – 12V</td>
</tr>
<tr>
<td>Storage type</td>
<td>Li-Pol</td>
<td>Li-Pol</td>
<td>Li-Pol or NiCad</td>
</tr>
</tbody>
</table>

Table 5 - Characteristics of the ISIS power system (Innovative Solutions in Space 2009)

Other producers for electrical systems for Cubesats include the Stras-Space company which sells a “Drop-In Power Converter”

2.6. Hardware review: Command and Data Handling System

2.6.1. General Discussion

The computer system in a space mission can be defined as both the on-board computer system and the ground related segment and can be viewed as the intersection and integration point of all subsystems of the spacecraft.

For the purpose of characterizing a Cubesat I’m going to refer only to the on-board computer system which is mainly composed of three elements: hardware, software and the documentation.

The purpose of the onboard computer system is mainly that of self-control, when not in communicating mode or processing commands, and that of transmitting information when in direct communication with the ground station. It includes power management, navigation, payloads management, housekeeping, health monitoring, processing commands and communication, and general management of all other subsystems.
Because of the power and communication constraints in a small satellite, the on-board computer system plays a vital role in minimizing costs and risks while increasing spacecraft availability, flexibility and reliability.

When talking about the on-board computer system sizing, we have to consider:
- the specific mission requirements and the precise need of processing speed and accuracy,
- amount of payload data to be stored and processed or transmitted,
- storage of on-board software
- all of which can be translated into physical parameters like power, mass and volume.

The architecture of the system is usually mission orientated into one of the three basic models of centralized, ring-type, bus-type architecture or even a hybrid-type. Each of these has direct advantages or disadvantages regarding system size, failure risk, and adaptability.

2.6.2. Data Handling Hardware Introduction

The hardware component of the computer system on board a Cubesat is of course restricted by the Cubesat physical size and layout.

As indicated before the most common layout inside a Cubesat is in the form of supra-positioned square boards containing different subsystems so usually the bus or main processing unit subsystem is placed on one of those boards.

Although progresses in processing speed and power consumption are some of the most rapid technological advancements today, the problem of space environment resistant electronics is not one to be easily solved.

The hardware involved in Cubesat computing systems can come in different configurations sometimes including the communication module, some sensors, or even power management components on the same board.

2.6.3. GomSpace Data Handling Hardware
The company has separate communication and computing boards, the latter available in two versions: NanoMind A702 and NanoMind A712.

Based on an ARM-7 processor, the NanoMind mini-computer is especially designed for space application. The intended applications of the on-board computer are nano- or pico-satellite command and data handling systems and the flight telemetry systems. Moreover, the computer can be purchased with a fully-featured active magnetic attitude stabilization system consisting of a three-axis magnetometer for sensing the Earth’s magnetic field as well as some interface electronics for the external magnetorquers and Sun sensors.

In addition, the NanoMind is providing storage for the data handling software and specific user application. The main interfaces to the other subsystem hardware are the CAN bus and an I2C bus.

NanoMind Specifications:

- 32 bit RISC-type CPU
- clock speed range: 8 to 40 MHz
- static low-power RAM: 2 MB
- code storage (FLASH-type memory): 4 MB
- data storage (FLASH-type memory): 4 MB
- 8 MB addition serial FLASH
- debugging console
- single 3.3V supply voltage
- CAN bus and I2C-bus interfaces
- an interface for RS232 debugging/SW-upload
- three-axis magnetometer, three PWM power drives, six analog inputs (e.g. for Sun-sensors) as options
- resetting option (Power monitor/power-on)
- supports eCos O.S.
- low-power characteristic: 80mW/300mW for (8MHz/40MHz)
- compatible with the Cubesat-kit connector
- size: 96mm x 90mm x 7mm
- temperature range: -40 to +85 deg. C

(GomSpace ApS 2009)

2.6.4. Pumpkin Inc. and Clyde-Space Data Handling Hardware
These companies provide a Flight Module or Single Board Computer designed for low cost, low power consumption embedded applications built around a Texas Instruments MSP430 micro-controller which is made for harsh environments.

It contains 50-60KB Flash, 3 DMA, 2-10 KB RAM, 48 I/O pins, 2-USART, 1 I2C, 2-SPI, 12 bit DAC, 12 bit ADC, multiple timers, some multiple clock sources and an on-board temperature sensor.

More detailed specifications can be found in the FM430 Flight Module data sheet available on both these companies websites. (Pumpkin 2009, Clyde Space 2009)

![Flight Module](image)

**Figure 14 - Flight Module © Pumpkin Inc (Pumpkin 2009)**

### 2.6.5. ISIS Data Handling Hardware

Although there are no in depth data available for the computer system developed by the company, they indicate that their third version of ISIS Nano-satellite Platform contains a low speed I2C data bus for housekeeping and payload data, as well as data storage hardware capable of 64 MB (1U), 500-1000 MB (2U) and up to 2000 MB (3U). (Innovative Solutions in Space 2009)

### 2.6.6. SSDL (Stanford University) Data Handling Hardware

They are developing an integrated bus system called “SNAP Solutions” with the purpose of providing a convenient bus for testing payloads or performing science missions. SNAP will be robust and will require very few
modifications in order to incorporate a new payload into the system. (Stanford University 2009)

2.6.7. What the future holds for Data Handling Hardware

Although the processing speed is a factor in the real-time applications of the space computer systems, more important in this field is the measurement of “performance per watt” meaning the rate of calculation which can be performed by the computer for each watt used.

Because most of the consumed power is transformed into heat, a computer needing less power for the same computation needs also less cooling for keeping a certain operating temperature.

An updated data base containing most advanced computer to this day is compiled as “The green 500 list” (Feng 2008) having in first position the BladeCenter QS22 Cluster PowerXCell 8i- Infiniband from the “Interdisciplinary Centre for Mathematical and Computational Modeling”, University of Warsaw. It delivers 536.24 MFLOPS/W for a total power of 34.63 kW. More details can be seen in Annex F.

But since we are more interested in very low power applications a more suitable comparison is given by a study performed by “Dallas Semiconductors” – Maxim between 4 types of very low power microcontrollers: AVR, PIC16CXXX, MSP430 and MAXQ using 5 tests or benchmarks (Maxim Integrated Products 2005) as can be seen in Table 6:

<table>
<thead>
<tr>
<th>Test Name</th>
<th>MemCpy64</th>
<th>BubbleSort</th>
<th>Hex2Asc</th>
<th>ShRight</th>
<th>BitBang</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAXQ10</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
<td>0.4</td>
<td>1</td>
</tr>
<tr>
<td>MAXQ20</td>
<td>1</td>
<td>1</td>
<td>0.96</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>PIC</td>
<td>0.06</td>
<td>0.29</td>
<td>0.39</td>
<td>0.33</td>
<td>0.38</td>
</tr>
<tr>
<td>MSP</td>
<td>0.42</td>
<td>0.45</td>
<td>0.68</td>
<td>0.56</td>
<td>0.48</td>
</tr>
<tr>
<td>AVR</td>
<td>0.19</td>
<td>0.48</td>
<td>0.88</td>
<td>0.26</td>
<td>0.48</td>
</tr>
</tbody>
</table>

Table 6 - Comparison of micro-controllers performance in normalized MIPS per milli-Amps (Maxim Integrated Products 2005)
The normalized "MIPS (million of instruction per second) /mA" metric shows the relative performance-to-current ratio when we compare microcontrollers with diverse architectures, instruction sets, or current consumptions. A superior normalized "MIPS per mA" fraction usually has one or both of the next returns:

- system clock frequency may be decreased
- the length of time while in sleep mode or low-power may be increased

Each one of these options can be used to cut down the total power utilization. Alternately, having an advanced performance of the system can be accomplished while staying within a specified budget for the current-power ratio.

As of 2008 the most common architectures for microcontrollers are:
- MSP430
- V850
- CF
- PowerPC ISE
- ARM
- MIPS
- S08
- AVR
- PIC
- PSoC

### 2.6.8. Data Storage Hardware (secondary storage)

For storing information without continually powering the memory (non-volatile) the most common technologies nowadays are: ROM, PROM, EPROM, EEPROM, Flash memory.

Novel technologies in this area which are soon to be unveiled are: SONOS, FeRAM, MRAM, PRAM, Millipede, CBRAM, RRAM, Racetrack memory, NRAM.

The FM430 Flight Module developed by Pumpkin Inc. also includes Secure Digital / Multimedia Card capability. The on-board storage capability is restricted just by the card selected, for the moment this means up to 2GB.

The FM430's MSP430 processing unit controls the power delivered to the SD card. This allows the conservation of power when no access is needed.
to the card. When we deselect the SD interface in the software, the USART0 interface functions as an I2C master for the user I2C circuit in connection with the bus.

The joining of the USART1 with the modem and the USART0 with the mass storage device leads to an increase in data exchange and a decrease in latencies. (Pumpkin 2009)

2.6.9. Software Introduction

The software components of the spacecraft computer system refer to the non-physical component operating with data (information) by reading, processing, storing and transmitting it.

These operations depend on data quantities coming from different sensors, payloads, communication or other subsystems and data that needs to be sent back or forwarded.

The typical on-board applications have the following function:
- Communication
- Attitude sensor processing
- Attitude determination and control
- Autonomy
- Fault detection
- Power management
- Thermal control

Data is stored using compression and error correction, processed with different speeds depending on the processor speed, instruction complexity and memory access time.

Development of software and integration and the testing of the computer system is very time consuming which can be translated into high costs.

2.6.10. Pumpkin Inc Software Solution

The company provides the most complete Cubesat customized software solution called Salvo RTOS.

Salvo is by definition a Real-Time Operating System (RTOS) designed specifically for low-cost embedded type of systems, having strictly limited
program and data memory, but can be used for easily creating sophisticated yet low-cost products. (Pumpkin Inc 2008)

2.6.11. Data Compression

Because the Cubesat holds a limited amount of communication power and bandwidth it is preferable that the information stored and consequently transmitted to the ground station should be in the minimum format. This implies preprocessing the data collected from sensors (i.e. cameras) and storing it in compressed data formats.

A comparison between different types of data compression methods is given in the following table using the example of a 1.3 mega-pixel picture file:

<table>
<thead>
<tr>
<th>FILE TYPE</th>
<th>FILE SIZE</th>
<th>Unit</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIFF</td>
<td>7.9 MB</td>
<td></td>
<td>CMYK - uncompressed 48bit/pixel</td>
</tr>
<tr>
<td>OPENEXR</td>
<td>10.5 MB</td>
<td></td>
<td>RGBA 4 uncompressed 16bit/pixel</td>
</tr>
<tr>
<td>RAW12</td>
<td>2.0 MB</td>
<td></td>
<td>Bayer mask - uncompressed 12 bits/pixel</td>
</tr>
<tr>
<td>RAW10</td>
<td>1.6 MB</td>
<td></td>
<td>Bayer mask - uncompressed 10 bits/pixel</td>
</tr>
<tr>
<td>RAW8</td>
<td>1.3 MB</td>
<td></td>
<td>Bayer mask - uncompressed 8 bits/pixel</td>
</tr>
<tr>
<td>BM P</td>
<td>3.9 B</td>
<td></td>
<td>RGB - uncompressed 24bit/pixel</td>
</tr>
<tr>
<td>COMPRESSED FILE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JPG100</td>
<td>516.1 KB</td>
<td></td>
<td>24bit/pixel - 100% quality</td>
</tr>
<tr>
<td>JPG90</td>
<td>258.0 KB</td>
<td></td>
<td>24bit/pixel - 90% quality</td>
</tr>
<tr>
<td>GIF</td>
<td>493.5 KB</td>
<td></td>
<td>8bit/pixel - compressed</td>
</tr>
<tr>
<td>PNG</td>
<td>1.2 MB</td>
<td></td>
<td>24bit/pixel - lossless compressed</td>
</tr>
</tbody>
</table>

Table 7 - Images File Formats and Compressions (Forret 2008)

As we can see from Table 7, the most interesting solution for image compression without quality loss is the JPG100 file format.
2.7. Hardware Review – The Attitude Determination and Control System

2.7.1. ADCS introductory discussion

The ADCS system is the most crucial system in making a mission feasible and effective in the sense that any spacecraft or instrument has to be orientated towards a specific target and towards specific ground stations on Earth while keeping the orbit parameters in certain limits.

This can be achieved using sensors for acquiring spacecraft attitude and position, as well as other targets’ orientation relative to the S/C and after performing on-board calculation or receiving ground commands the S/C makes use of actuators to achieve the desired attitudes or trajectories.

The subsystems that usually have direct inputs to the ADCS are: the thermal system, the power system (solar array orientation) or different types of on-board payloads.

Once the S/C achieves a certain desired attitude or orbit the role of the ADCS is not over because of the continuous disturbing forces acting on the S/C: aerodynamic drag, solar radiation pressure, gravity gradient torques and magnetic field torques or even internal torques due to moving components or changes in the center of mass.

All these show that the ADCS is strongly influenced by the mission design, the payload’s accuracy requirements, communication system design and even by orbit characteristics; meaning the space environment to which the S/C is subjected.

The attitude control of the Cubesat can be achieved using different hardware and methods, most notably:

- Gravity gradient points the spacecraft to the Earth local vertical; usually has an accuracy of ±5° in 2 axes and doesn’t have a life limiting time
- Gravity gradient in conjunction with momentum wheels is similar to the one described above, except that it can be used for 3 axes but it’s limited by wheel bearings
- Passive magnetic method orientates the S/C only on the North-South direction with ±5° accuracy in 2 axes and doesn’t have a lifetime limit
- Pure spin stabilization method is used for inertial fixed pointing in any direction but requires lots of propellant; achieves ±1° in 2 axes
- Dual spin stabilization method is only limited by the articulation of the de-spinning platform has similar accuracy as pure spin method but can be limited by propellant usage or bearings lifetime
- The bias momentum uses 1 wheel for local vertical pointing with high accuracies but is limited by sensors, bearings lifetime or propellant (power)
- The zero momentum method can be achieved with thrusters or 3 momentum wheels, has high accuracies and no constraints regarding the pointing direction but it is limited by sensors, bearings or propellant (power) available (Larson 1992)

In the case of the 1U Cubesat the mean calculated values for the perturbation torques to which the S/C is subjected at a 600 Km altitude in circular Sun-synchronous orbit are in the range of: 10^{-10} Nm for gravity gradients, 5x10^{-8} Nm for aerodynamic torques, 5x10^{-9} Nm for solar radiation pressure, 10^{-9} Nm for magnetic torque. (The CubeSat Program 2009)

2.7.2. Attitude Sensors Introductory Discussion

The most common sensors used in S/C attitude determination are: the Sun sensor, Earth sensor, star tracker, magneto-meters, gyroscopes, GPS. Usually the most mass, power and space consuming of all these sensors is the star tracker and except for the CanX-1 mission which tried to use the CMOS sensor on-board for this kind of function, no known Cubesat mission has made use of this kind of sensor. Yet, some progress is in development with ISIS being awarded a contract by Dutch research institute TNO in late 2008 for developing a star-tracker which could be used on a Cubesat.

2.7.3. ISIS Attitude Sensors

The company commercializes miniaturized analog fine Sun sensors in various variants, with the top of the range fully calibrated sensor of 0.3° accuracy over a 120° field of view. ISIS collaborates with the Dutch research institute and Bradford Engineering for developing an analog Fine Sun Sensor which previously was only accessible for constellation orders.
Other characteristics of the ISIS Sun-sensor include a nominal FOV of 128x 128 degrees, size including flanges and connector 4x45x14 mm³, 50 grams–mass, thermal tolerance of -50 to +85 degrees C, radiation exposure lifetime above 100 Mrad and it is possible in customized versions to include a temperature indication. (Innovative Solutions in Space 2009)

2.7.4. Clyde-Space and Pumpkin Inc. Attitude Systems

These two companies provide integrated systems ready to use in the form of:

2.7.4.1. ADCS for the Cubesat Kit

This is an integrated system useful in imaging Cubesats or other types of satellites requiring precise orientation in any direction.

![ADCS module](Clyde-Space 2009)
Characteristics include:

- 1 degree angular accuracy with standard sensors, even better with selected sensors
- can perform autonomous operation, S/C de-tumbling upon launch from rocket and precise three-axis attitude control afterwards
- it is hermetically sealed as well as conductively plated
- contact surfaces are hard-anodized
- can handle complex commands via RS-232 connector
- contains torque coils for momentum dumping, three reaction wheels, three-axis external magnetometer
- supplied with 12V has a power consumption of 1.5 Watt in average but no more than 4.5Watt
- dimensions: 100x100x79 mm\(^3\)

(Clyde Space 2009)

2.7.4.2. ADACS Interface Module

This is an interface board connecting the ADCS system presented above to the rest of the Cubesat bus system. (Clyde Space 2009)

2.7.5. Tethers Unlimited ADCS sensors unit

This company sells an “inertial measurement unit for nano-satellites”.

This system achieves 6 degrees-of-freedom motion sensitivity while keeping the mass and size to a minimum. Using micro-machined electromechanical system devices, the performances are very high while having an affordable price. It delivers analog measurements using rate gyros with three axis, double range three axis accelerometers and digital three axis magnetometers.

Other characteristics of the system include: inertial sensor ranges of ±300 degrees per second, accelerations of maximum ±10 g and a minimum of ±1.2 g, magnetometer sensibility of ±1000 μT with 2000 samples per second, temperature range of -40°C to +85°C, power consumption of 40mA for a 5V current. Its mass is 34 grams and it has an exterior envelope of 38x50x15 mm\(^3\).

(Tethers Unlimited Inc 2009)
2.7.6. GPS Receivers and other sensors

Other components used for position determination are of course for LEO satellites the GPS devices with some of the brands used by past Cubesat missions being DLR Phoenix GPS Receiver or Novatel OEMV-1 GPS receiver.

It is worth mentioning here some other sensor producers like: AeroAstro - Sun sensors, or Honeywell which is producing 3-axis magnetometer and gyroscopic rate sensors (The CubeSat Program 2009).

2.7.7. Stras- Space Actuators

The company commercializes “Nano-satellite Magnetic Torque Rods” made of linear steel alloy core which provides low hysteresis and residual magnetism.

They are available in a broad range of available sizes, optional magnetorquers temperature sensor, have redundant wiring and a power consumption of 360 mW. They weigh 200g and have a size of 140 x 52 x 29 mm$^3$ being able to operate in an -30 to +100 Celsius environment.
The company also produces “Nanosatellite Magnetic Torque Coils” featuring zero hysteresis and residual dipole, redundant windings, custom montage and connectors, and included temperature sensor. It consumes 100 mW of power, weighs 40g and measures 80x80x3.2 mm³ while operating in an -30 to +100 Celsius environment. (Stras Space 2009)

2.7.8. ISIS Passive Magnetic Attitude Stabilization System

This system damps original rotation rates and secures the S/C in the Earth magnetic field just as a compass needle but it is possible for small oscillations to remain.

The system contains a permanent magnet for locking the S/C in the Earth magnetic field plus two hysteresis rods for dissipating the rotational energy.

The performance of the system is dependent on the orbit, moments of inertia, and type of orbit insertion. ISIS can provide simulation results based on other customer inputs, including the maximum time to secure magnetic lock, maximum deviation from the magnetic field vector and maximum residual angular rates.

Specifications of the system: mass range of 60 to 90 g depending on the S/C mass and target orbit, thermal range of -50 to +100°C. (Innovative Solutions in Space 2009)
2.8. Hardware Review - Propulsion Systems

2.8.1. Introductory discussion - NANOPS

The propulsion system is one of the most sought after and researched system in the Cubesat community, because of its vital role in orbital maneuvers and station-keeping. Its development would eventually bring the Cubesat capabilities one step closer to bigger satellites.

The research goes into all propulsion areas including established chemical or electrical propulsion as well as novel technologies like solar sails or even electrodynamic tethers.

Yet to date, the only recognized propulsion system that flew in space on-board a Cubesat is the NanoPS system developed by Toronto University and the Canadian Space Flight Laboratory.

This propulsion system is made of a liquid-fueled cold-gas thruster system and uses sulfur hexafluoride as a propellant, while keeping the total mass bellow 0.5 kg.

The thrust level provided is 50-100 mN, while a specific impulse of 500-1000 m/s insures a total $\Delta v$ above 35 m/s.

NanoPS purpose is mainly of attitude control maneuvers, spinning the S/C about one axis. The NanoPS flight on CanX-2 Cubesat was intended as the precursor propulsion system for yet to come formation flight missions. (Univ. of Toronto Space Flight Laboratory 2009)
2.8.2. Other propulsion systems

The future of sensors and propulsion systems for nano-satellites is represented by the development of NEMS or MEMS (Nano or micro-electromechanical systems) of which the most relevant technologies for space applications are: electrostatic motors, MEMS thermal actuators, microgenerator/nanogenerator technology and micro-opto-electromechanical systems. Studies have also been performed and are still refined in developing micro-thrusters, bipropellants or solid–propellants micro-rockets or even laser-driven micro-rocket.

Here are some of the candidates for future Cubesat propulsion systems (The CubeSat Program 2009):

Chemical propulsion:
- JPL Hydrazine Milli-Newton Thruster
- MAROTTA cold gas thrusters
- MOOG cold gas thrusters
- VACCO/JPL butane micro-thruster
- ATK STAR 4G solid motor
- Northrop Grumman MEMS thrusters
- “Laboratory for Analysis and Architecture of Systems” – France, solid propellant MEMS
- SSTL Steam Micro-Propulsion

Electric Propulsion:
- Busek 3 axis micro Pulsed Plasma Thruster
- Alameda/JPL Vacuum Arc Thruster (onboard launching destroyed ION Cubesat)
- JPL miniature Xenon Ion Thruster
- MIT Micro-colloid/Field Electric Effect Propulsion
- DMC Micro Resistor-jet
- VACCO piezoelectric thrusters

In table 8 is given a comparison of performances of some of these systems:
<table>
<thead>
<tr>
<th>Type</th>
<th>Isp (s)</th>
<th>Power (W)</th>
<th>Thrust (mN)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFIT</td>
<td>15000</td>
<td>300</td>
<td>1.5</td>
<td>0.15</td>
</tr>
<tr>
<td>FEEP</td>
<td>8000</td>
<td>120</td>
<td>0.9</td>
<td>3.5</td>
</tr>
<tr>
<td>Hall thruster</td>
<td>1500</td>
<td>200</td>
<td>0.01</td>
<td>1</td>
</tr>
<tr>
<td>Micro-PPT</td>
<td>1000</td>
<td>4</td>
<td>0.04</td>
<td>0.12</td>
</tr>
<tr>
<td>Pulsed plasma thruster</td>
<td>800</td>
<td>25</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Colloidal microthruster</td>
<td>500-1500</td>
<td>0.2</td>
<td>0.02</td>
<td>0.08</td>
</tr>
<tr>
<td>Hydrazine</td>
<td>220</td>
<td>1000</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>Digital MEMS</td>
<td>200</td>
<td>50</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Micro water resistojet</td>
<td>unknown</td>
<td>3</td>
<td>3.3</td>
<td>0.013</td>
</tr>
<tr>
<td>Water resistojet</td>
<td>152</td>
<td>100</td>
<td>45</td>
<td>1.24</td>
</tr>
<tr>
<td>Solid rocket</td>
<td>185</td>
<td>100,000</td>
<td>1.24</td>
<td></td>
</tr>
<tr>
<td>Cold gas thruster</td>
<td>75</td>
<td>5</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>

Table 8 - Possible Cubesat Propulsion Systems Overview (The CubeSat Program 2009)

Also, the NASA NanoSail solar sail program, despite its failure in the Falcon-1 launch, is in its advanced phase and soon to be tested in space.

Two more innovative solutions found by the author of this paper are the:
- The solar wind electric sail propulsion proposed by University of Helsinki, Department of Physical Sciences, Finland
- The µPET Propulsion System by Tether Unlimited

but they are still in the concept phase and have to be proved working and functional in space.
For Earth Observation missions another important aspect due to very low orbits necessary for high resolution pictures, is the drag associated with the upper parts of the atmosphere. This drag has a negative effect influencing the orbit parameters during the mission and requiring at least some form of attitude and altitude control mechanisms for station keeping. The positive effect of the drag is associated with end-of-life and the de-orbiting of the S/C.

Some other suggestions for drag usage as a passive propulsion system are to use the attack angle of the Cubesat for modifying the drag or even to deploy additional surfaces for modifying the drag coefficient.

Drag simulations using the 1U Cubesat form factor show that the Cubesat lifetime is of 0.1 years for 300 km orbits, 2 years for 400 km orbits, 12 years for 600 km orbits and more than 25 for 700 km orbits. (The CubeSat Program 2009)

2.9. Hardware Review - Communication System

2.9.1. General Discussion

Most definitely one of the most important parts of any satellite is the communications subsystem. Without any way to communicate, the Cubesat would quickly become space junk. When selecting a communications
subsystem for a Cubesat, three possibilities exist: buying a COTS transceiver, purchasing one designed for terrestrial use and modifying it, or building a transceiver from individual components.

### 2.9.1.1. COTS

Purchasing a COTS space-rated transceiver simplifies the design of the subsystem. Purchased transceivers typically accept standard serial data and perform all of the packetization, error checking, and retransmission. Some of the protocols and modulations are proprietary and device-specific, requiring an identical radio at the command ground station and ruling out any large-scale ground station networks.

### 2.9.1.2. Modified COTS

Designed for use on Earth, many COTS transceivers would have serious problems functioning in space. A significant problem with commercial transceivers includes active thermal dissipation, as no air exists for convective cooling of the amplifiers.

Required modifications for use in space include removing the case to reduce mass and size, increasing transmit power, changing the spread-spectrum timings to allow the radios to get a lock 1000 km away, drilling mounting holes, programming the transceiver to operate after power cycling, removing LCD displays and buttons.

Some of these modifications require assistance from the manufacturer but some universities decide to build the entire transceiver out of individual components. Building a custom communications subsystem allows tighter control of requirements and specifications, and encourages the next generation of students to learn about building small RF circuits. Predictably, these transceivers have been less successful due to the inherent difficulties in RF board design.

Components of these custom-built transceivers include the terminal node controller (TNC), transceiver, and amplifier. Typically, the TNC consists of a microcontroller such as a Microchip PIC. Sometimes this same microcontroller also interfaces with the transceiver to program registers settings during startup. The single-chip transceivers for the 433 MHz band performs well in the UHF amateur satellite band. Common manufacturers for such chips include Texas Instruments, RF Microdevices, and Analog Devices. Other universities go even
farther than this by building their entire transceiver at the transistor level, as is the case with Delfi-C3.

As many small satellites will be released in one launch, the closeness in spatial and spectral separation between different small satellites may render problems for ground stations in satellite tracking, especially in the early orbit phase.

In this early orbit phase, all small satellites are close for several days, even one month. All satellite developers are eager to assess the status of satellites as early as possible but interferences may appear in this stage.

In the case of a constellation the main problem is how to receive all the signals simultaneously when the situation of having multiple satellites seen by the same ground station arises.

### 2.9.2. Gom-Space Communication Hardware

This company provides the NanoCom U480 which is a half-duplex UHF transceiver working in the 432-438 MHz amateur radio band. It contains baseband processing and communicates to the platform using the I2C interface. The system is especially designed for space and has flown on AAUSAT-II Cubesat and the SSETI Express micro satellite.

Other specifications include: AX25 build-in protocol, a 40% power efficiency for the transmitter, standard 1U dimensions, operating temperature of -30 to 70 Celsius. (GomSpace ApS 2009)

### 2.9.3. Clyde–Space & ISIS Communication Hardware

These companies provide the following off-the-shelf hardware:

#### 2.9.3.1. Isis Uhf/Vhf/S Band Ground Station with steerable antenna

ISIS presents a ground station expressly intended for small satellites in LEO which are using radio amateur frequencies.

This solution has evolved from the Delft Univ. proved ground station used for a couple of Cubesat missions and it is currently used to run the Delfi C3 mission.
This ground station is capable of providing UHF/VHF/ S-band (downlink only) in the frequency range: 144-146MHz, 430-440MHz with 1200-9600bd AX.25 AFSK, FSK or even 38kbps for FSK TNC. It is suitable for LEO missions because it can autonomously track selected satellites using the included steerable antenna system.

All the other ground station equipment except for the antenna system fits into a 48 cm casing allowing it to be transported to any suitable location.

The ground station is configurable and commandable over the internet. Also the ISIS ground station kit has been manufactured so that it is compatible with the GENSO network. (Innovative Solutions in Space 2009)

2.9.3.2. **Isis 1200bps Vhf Downlink/Uhf Uplink On-board Transceiver With Afsk Uplink**

![Figure 23 - Cubesat transceiver © ISIS (Innovative Solutions in Space 2009)]
This is a Cubesat VHF downlink, UHF uplink transceiver, which adds telemetry, tele-command and beacon capability to the mission in just one board. It is compatible with Clyde Space EPS and Pumpkin FM430 presented above. It comes with 1200bps or variable downlink data rate, and AFSK or Manchester FSK uplink protocols.

The VHF transmitter has a transmit power of 300mW PEP or 150mW as an average, frequency range: 130 - 160MHz and 1200, 2400, 4800, 9600 baud rates.

The UHF receiver operates in the frequency range of 400-450MHz, has a data rate of 300-1200 bit/s, mass of 85g, sensitivity of -100dBm for BER 10E-5, plus on-board AX.25 command decoding. Power consumption is less than 1.7W (transmitter on), and less than 0.2W (receiver only) when operating in a thermal range of -20 to +60 Celsius.

2.9.3.3. Isis Deployable Cube Sat Antenna System

The system is made of 4 UHF monopole antennas in a turnstile configuration, deployable after launch as can be seen in the following picture:

![Deployable Antenna](image)

Figure 24 - Deployable Antenna © ISIS (Innovative Solutions in Space 2009)
2.9.4. Astrodev Helium 100 radios

![Image of astrodev helium 100 radios](image_url)

Figure 25 - Cubesat Radio Module ©Astrodev (Astronautical Development LLC 2009)

This product features different frequency selections and different output powers. It is compatible with standard amateur radio ground stations which are using GMSK modulation and communicate at 1200, 9600 or higher bitrates. The transmitter uses the 440MHz amateur radio band while the receiver works in the 140MHz amateur radio band but other custom frequencies can be made available.

Some specifications of the system include: FM/GMSK transceiver working in TX: 120 – 150MHz and RX: 400 – 440MHz frequencies, has a receiving sensitivity of -110 to -115 dBm, output transmit power: 100 mW – 4 W and data rates of 40 kbps using AX.25, temperature ranges of -30 to +70 Celsius. (Astronautical Development LLC 2009)

2.9.5. Communication System Design Recommendations

For a design purpose, some recommendations collected from past missions developers are:

- always include a long beacon in the signal because they use very little power but can be used to find info about the S/C even if the uplink doesn’t work
- using amateur modes for data communication helps in getting info from the huge amateur radio community
- always have a reset mode for the case of satellite “freezing”
- ground stations have to be verified prior to launch
• if you want absolutely secure communication is not a good idea to rely on other ground station which could be involved in other operations
• having an AMSAT mentor helps when one tries to use amateur RF (The CubeSat Program 2009)

A quick look at Annex G (Thomsen 2009) containing a sum-up of past Cubesat missions shows that the amount of data downloaded from Cubesats in orbit right now is very small, around 797 MB for 24 satellites over 5 years. Without QuakeSat-1 and CanX-2, this number drops to around 124 MB. This is a very small number, highlighting the need for a good transceiver capable of fitting within the Cubesat form factor and weight/power constraints.

An ideal radio designed for Cubesats does not exist at this time. However, there are several transceivers that have successfully flown in space and returned large amounts of data to Earth. Some of those radios are commercially available.

The Cubesat and amateur radio communities also need to jointly develop and agree on a new "common" modulation scheme, with larger data throughput and forward error correction. This standard modulation scheme will allow amateurs and universities to easily track each other’s spacecraft and forward data.

Some groups are trying to combat this data deficiency by networking many ground stations, similar to the ground station in Alaska for QuakeSat-1 but over a much larger scale.

One of the best improvements that can be made to amateur ground stations would be some software that automates the process of running passes and records the resulting data.

2.9.6. The Global Educational Network for Satellite Operators (GENSO)

This project is an initiative of ESA education department and the International Space Education Board.

Aimed to be functional in September 2009 the system will eventually link hundreds of amateur radio ground stations via the internet in an attempt to increase access to educational spacecraft in orbit.
The network is suppose to allow access and control for ground operators to their spacecraft in real time, while optimizing the uplink fidelity by computation of real-time link budgets and selection of the uplink station.

Another goal is to execute downlink error-correction by evaluating multiple data streams.

In a broader sense the GENSO project will implement a global standard for the educational ground segment software and hardware while respecting the regulations used in the amateur satellite service. (Global Educational Network for Satellite Operations 2009)
2.10. Thermal System and the Space Environment

2.10.1. General Considerations

The space environment is a generic expression used to define all the external influences acting on a spacecraft during its mission.

Some of these influences are the charging produced by plasmas, trapped radiation, solar particle events, galactic cosmic rays, upper atmosphere, micrometeoroids and microgravity and they all have an immediate effect on mission lifetime and on the spacecraft performance.

![Diagram of LEO Thermal Environment](attachment://figure_27.png)

### External Factors:

- Mean Value of Direct Solar Flux: $1,367 \pm 5 \text{ W/m}^2$
- Albedo ($30 \pm 5\%$ of Direct Solar)
- Earth Infrared: $237 \pm 21 \text{ W/m}^2$

**Figure 27 - LEO Thermal Environment**

A summary of all space environment effects and their synergistic effects is comprised in Annex H (Tribble 2003).

The physical phenomena that transfer the heat from one spatial point to another are:

- Conduction - meaning heat transferred through a solid material
- Convection – meaning heat transfer between a solid surface and surrounding medium (air) – not applicable to space
- Radiation – represents the thermal radiation using electromagnetic waves
The main cause for temperature variations of the exterior of a S/C is the presence of solar radiation but through conduction, the external conditions are transferred to the inside of the satellite.

For controlling the temperature of components inside a Cubesat, there are a number of available technical solutions:
- radiators to dissipate heat
- heaters for increasing the temperature
- insulation are used for preventing the conduction of heat from the surface of the Cubesat to the interior components
- heat pipes are used for transferring heat from hot spots to colder spots in the S/C
but usually, because of the compact size, the 1U Cubesat is considered a homogeneous object (Larson 1992).

Somehow an older idea which never made it in space, is the use of thermal energy available in space for producing energy on-board the S/C. This involves thermovoltaic or pyroelectric conversion which is supposed to have a higher power to mass ratio than photovoltaics and even nuclear reactor systems.

2.10.2. Radiation Effects on Spacecraft

Some of the radiation effects on electronics can be presented as follows:
- Single Event Upset
  o represents a bit flip-flop
  o produces data corruption
  o it isn’t a permanent damage
- TID effects:
  o added-up effect of long term radiation damage
  o boosts element current consumption
  o reduces element performance
- Single Event Latchup:
  o component does not operate correctly
  o causes extreme current flow
  o can damage the component or the power supply forever
- Single Event Functional Interrupt
  o interrupts normal operation in an electronic component
  o it isn’t permanent damage and usually a power reset solves it
For mitigating this kind of events the approaches used are:

- **Shielding:**
  - reduces TID and to some extent reduces SEE effects
  - Al and Cu are usual material for bulk shielding while Tantalum is used for sensible spot protection

- **Rad-hard parts selection**
  - we need SEE specification
  - TID testing might be necessary
  - rad-hard tolerant by design

- **Memory scrubbing:**
  - occasionally read and correct corrupted data
  - turn off the components with unnecessary consumption
  - reduces probability of damage by SEE
  - turning off the power allows SEL recovery

- **Turn off devices not used**
  - reduces probability of damaging by radiation
  - augments operating margins for components
  - increases life-time

- **Redundancy:**
  - implies redundant circuits
  - sometime even triple mode redundancy
  - the software can be protected with code redundancy

- **Error detection and correction**
  - identify single and multiple bit errors
  - rectify one or multiple bit errors
  - transmit the Error Correction to other components

- **Turn S/C systems off or change operating schedule when known space weather events occur**
  - as a preventive action for Coronal Mass Ejections (The CubeSat Program 2009)

A particular new piece of information comes this year from Southwest Research Institute, San Antonio, US (Southwest Research Institute 2008). It seems that the Sun is blowing very low, about 20-25% less than during the last solar minimum which occurred 10-15 years ago.

This has great significance because the charged Sun wind particles also carry along the magnetic field, which limits the number of high-energy cosmic rays incoming to the Solar System. This will translate in more of these cosmic rays which include electrons and atomic nuclei with very high speeds interfering with the space operations.
Radiation hardening is a common technique of designing and trying electronics, for making them more resilient to permanent or temporary damages caused by space radiations.

As mentioned when describing the power, communication and on-board data handling subsystems the current available COTS produced by Clyde-Space, ISIS, Pumpkin Inc. or GomSpace have tolerances up to 500krad of radiation and temperature tolerances somewhere in the range of -40 to +85 deg. C.

Radiation-hardening methods include the physical approach where the chips are produced on insulating substrates not on the standard semiconductor wafers, or the logical approach - meaning that the memory which does the fault correction has to use extra parity bits to verify for and perhaps to put right any degraded information.

For space environment testing Montana State University designed two payloads placed on ISS in March 2008 with the following objectives:

- Materials exposure experiment to investigate behavior of materials exposed to space hazards (polymer and treated tethers)
- Penetrating Radiation susceptibility of consumer electronics

(The CubeSat Program 2009)
3. EARTH OBSERVATION

Earth Observation topic is a vast topic, not only because of the number of satellites flown into space which had as primary or auxiliary reason this kind of mission, but also because of the types of applications and instruments which were used or are developed for this purpose.

It is worth mentioning that by the end of 2008 a number of 298 individual missions had as goals Earth observation in one form or another and another 98 are planned to be launched in the next 3 years according to ESA Earth Observation portal (ESA eoPortal 2009).

3.1. Earth Observations sensors

The applications for Earth Observation vary from disaster monitoring to health observations, energy oriented applications, climate change, water supplies monitoring, weather observing, ecosystems assessment, agricultural applications or biodiversity monitoring while the instrumentation used for gathering Earth observation data is classified by ESA in the following major categories:

- Radar Imagery uses the SAR measurements to detect surface waves, fronts, ice formation, vegetation type and cover or even to detect and track ships.

- Radar Altimetry is used for time varying sea levels, topography of ice and land sheets, sea floor mapping, sea surface wind speeds, and wave heights.

- Optical/Multi Spectral Radiometry is applicable for imaging the atmosphere and Earth surface.

- Atmospheric Data measurements provide information on ozone chemistry, green gases or chemically active gases and these are used for pollution monitoring; climatology, carbon cycle, volcanic eruption monitoring; and operational meteorology.

Because of different types of missions and their corresponding orbits, EO satellite payloads use various ground resolutions meaning various ranges of details which can be distinguished in a picture.
Instruments with low ground resolution are suited for observing vast vegetations or widely spread weather and cloud patterns. The sensors with medium resolution are usually utilized for agriculture, or evaluating the after-effects of natural disasters, and resource mapping. Sensors having the best ground resolution are able to identify roads, other man-made structures, and even objects the size of a car.

The limitation is that increasing the resolution of an EO instrument means decreasing the swath. The solution is to have changeable resolutions or steerable sensors for reducing the revisit time. (European Space Agency 2008)

3.2. Imaging hardware and software

There are two main types of sensor in the visible light readily available mostly because of consumer digital cameras: CCD and CMOS.

The table in Annex I (DALSA 2009) makes a comparison of different advantages of each type of sensor.

Besides having a good sensitivity, another characteristic of a sensor that influences significantly its performance is the progressive scan. This characteristic of a sensor helps collected pictures to not experience a saw effect which often occurs in interlace based equipments. This interlacing procedure is used in television and common analog cameras for improving the picture frequency in moving frames. The saw effect only becomes visible when the picture sequence is paused.

Regarding image post-processing we have to think about image compression which can be lossy or lossless.

The difference between the two of them is that they are used for different types of picture. In man-made drawings which contain mainly contours the lossless method is used because it doesn’t bring in any compression supplements. Also this method is used for images with a very valuable content like medical images or images intended to be archived.

The lossy compression procedure is more appropriate for photos where some minimal loss in quality doesn’t have such great consequence but big reductions in size of the file are of great importance.

Other image processing techniques include enhancements like noise removal, perspective correction and distortion, etc. Depending on the application, we might be interested in techniques like geometric hashing, which is a procedure initially designed in computer image processing for finding
similarities between some geometric elements and a database containing such elements, especially when interested in recognizing specific objects in a picture. (Wolfson, 1997)

3.3. A survey of present Earth Observation Constellation

Current Earth Observation constellations evolved differently sometimes being designed to work in a cooperating manner from the beginning, at other times just being used as a constellation after they were in place when supervising bodies like the US government realized the benefit that could be gained by sharing information between different satellites with EO capabilities.

Here is the list of current Earth Observation constellations as it can be compiled from ESA sources (ESA eoPortal 2009):

- SAR-Lupe Constellation (5 satellites in 3 orbital planes at an altitude of 500 km used for natural disaster coverage and intelligence gathering for the German government; mainly a military operation)

- Swarm (LEO Constellation of 3 satellites studying the geomagnetic field and its temporal progression)

- COSMO-SkyMed (Italian-built constellation of 4 SAR Satellites for military applications, natural disaster risk management, other commercial services and scientific applications in the EO area)

- RapidEye Earth Observation Constellation (a fully business-built constellation comprising 5 mini-satellites, and a specialized Spacecraft Control Center, it is used for acquisition and post-processing of vast amounts of land images. Makes use of a multispectral push-broom imager mainly for agricultural purposes but can be used for cartography and disaster monitoring. Ground resolution is below 6.5 m and revisits time of about 5 days.)

- DMC-2G (Disaster Monitoring Constellation-Second Generation is a 7 satellites SSTL built constellation with capabilities of 4 m ground resolution using the panchromatic camera and 22 m in multispectral mode while having a daily revisit period)
• Cluster (Four Spacecraft Constellation in Concert with SOHO is intended for the study of small-scale plasma composition)

• Pleiades-HR (Is a 2 S/C high-resolution imaging constellation of the French CNES, providing resolutions of 0.7m in panchromatic and 2.8 m in multi-spectral mode)

• RCM (3 satellites RADARSAT Constellation Mission is intended for maritime surveillance, disaster and ecosystem monitoring)

• SMOTR (Russian built constellation of 2 SAR satellites and 2 optical imaging satellites used for imaging of gas pipelines, ecological condition of the infrastructure, cadastral cartography, assessment of hazards, disasters and emergencies, prospecting of mineral resources).

Coming back to our very strict mass and power conditioning we have to dismiss some of the technologies used in the other Earth Observation constellation from the start because they would simply not fit and would need too much power.

This leads most commonly to instruments in the optical spectrum like CMOS and CCD.

3.4. First successful nano-satellite EO mission: PRISM

The Tokyo University PRISM mission successfully launched and operated in early 2009 is the most advanced present Earth observation mission that ever flew on a nano-satellite. (Tokyo University 2009)

The optics subsystem plays a prominent role and is one of the main missions of PRISM, that is: observation of the surface of the Earth in the visible light spectrum. The aim is to capture images with the highest level of resolution, which can be realized by ‘pico-satellites’, or more specific to use a telephotographic digital camera system for capturing high-resolution images of the Earth.

On PRISM, two types of digital cameras are mounted. One is a telephotographic camera, and the other is pantoscopic camera. Both cameras are color CMOS area imagers, instead of CCD. The university designed and
Alexandru Munteanu

built electrical boards and developed program codes to operate the camera chips.

NAC (Narrow Angle Camera) is a telephotographic camera, which acquires high-resolution images through a lens with large diameter and long focal length. NAC was expected to identify 14-square-meter objects on the ground when PRISM captures an image at the height of 800 km. Number of pixels is 1.3M (1280x1024).

WAC (Wide Angle Camera) camera uses a tiny CMOS camera chip as a pantoscopic camera. A field angle of NAC is too narrow to identify where it took a picture of. Therefore, WAC is to be mounted in parallel with NAC. Moreover, it can take photographs of the extensible boom as well as the surface of the Earth.

Figure 28 - PRISM satellite © Univ. of Tokyo (Tokyo University 2009)
4. CUBESATS EARTH OBSERVING CONSTELLATION CONCEPTS

4.1. General discussion

The subject of Earth Observation using Cubesat constellations is not a new one but represented a desire of many institutions over the years. This was mainly due to the economic advantage that such a project would involve.

As shown in chapter 3 of this thesis Earth observation missions involve most of the time global or regional coverage which is hard to achieve with a limited number of satellites and very usually they have as a determinant parameter the revisit time over a specified area.

This type of mission involving distributed systems has to be made practical in 2 modes:

1. the traditional solution is having a small number of satellites in relatively high orbits and thus moving at low speeds; this solution implies very powerful optics systems and consequently relatively large mass and power budgets

2. the second solution represented by the Cubesat constellations would be to have a large number of cheap, low-mass, low-power satellites flying in lower orbits but having the advantage of better coverage and revisiting time

This type of Cubesat mission is designed with redundancy as the prime risk mitigation method, so the individual satellite does not have to be exceptionally reliable because the loss of one component has little effect for the system and could eventually be replaced without substantial costs.

In this chapter I’m going to provide a list of Cubesat constellation concepts proposed until now by other institutions and then propose a new one based on very recent advances in Cubesat technology.
4.2. Historically proposed Nanosat/Cubesats Constellations concepts

Some very interesting Cubesat constellation concepts have been proposed over the years in different scientific papers or even as commercial proposals but actually none made it into space.

The reasons will be discussed further but we have to mention that one of the prime suspects is that even a small, simple satellite as long as it is custom built requires intensive research and some testing, and projects conducted in universities with limited budgets by teams with limited experience and constantly changing members tend to go over the proposed terms of delivery.

Here are some of the theoretical nano-satellite mission concepts proposed by academic or other types of institutions:

- 3-Corner Constellation (3-satellites; primary science instruments are 2 cameras, other objectives include formation flying)
- ION-F (3-satellites for an ionospheric observation formation)
- Nano-satellite Constellation Trailblazer (3-satellites for technology demonstration: communications, navigation software, batteries, MEMS and GPS receivers)
- EMERALD – (formation flying)
- The Constellation Pathfinder (the mission is mapping the magnetosphere)

A bigger satellite is always preferable for accommodating lots of instruments and usually high power demanding instruments, but a small satellite constellation with only one or two instruments can collect the advantage of having many spatial or temporal nodes for missions where measurements are needed in different places or at different times.

The constellation configuration has also as a very strong argument in its favor, the redundancy and robustness of a system with multiple, low-cost and independent spacecraft. This means that whatever happens to one of the spacecraft it has little to no effect on the system as an assembly.
4.3. New Cubesat constellation missions proposals

As mentioned before, the main reason for delaying Cubesat projects seems to be the amount of novelty introduced by these projects.

Although this is not necessarily a bad thing and has its advantages in technology demonstrator types of mission, I have to notice that such concept would not fit a constellation of nano-satellites.

Instead we have to apply the concept that made any other product commercially viable, which is: the mass production.

Mass production introduced most famously in the early 20\textsuperscript{th} century in the automobile industry implies using standard components available for all of the system manufacturing process. Ideally this would apply to Cubesats and would mean that most of the constellation components would be assembled using a common line of manufacturing and standard components.

The standardization of components has undergone some really spectacular development and COTS for Cubesats are nowadays indeed ready to buy and very importantly they also have rather good compatibility even amongst different producers.

This has been mainly the result of the Cubesat project created and sustained over a long period of time by the California Polytechnic University in the United States.

When considering a Cubesat constellation it has been this author’s observation that the first factor to take into account would be the economic feasibility. This means that even if somebody would mass produce Cubesats with readily available COTS they would need some substantial budget if they want to produce a reasonably large number of satellites and thus “compete” at least in theory with a big-satellite constellation. So, to imagine that a university all by itself, would be able to build, launch and maintain a constellation of Cubesats is actually far away from reality.

The most plausible ways of financing such a project would be:

1. An established governmental or private institution with experience in building satellites like: NASA, ESA or other wealthy private companies
2. A joint-venture between a University and some private or public institution
3. A large association of universities which would still need some type of leadership or coordination maybe from ESA educational department

The last solution would be preferable from the author's point of view because it would not get lost in administrative and legislative issues, the cost for each university would stay to a minimum while everybody would benefit from the authorized guidance that ESA could provide.

As previously noted the main issue with large constellations of satellites is the access to ground stations and this problem would also be very cheaply resolved using the soon to be GENSO network of ground station.

This has the advantage of numerous possible downloading opportunities but as we'll discuss, for the time being, they are not very evenly spread (Fig. 29). Yet at some point in the future later addition to the network would improve the situation.

![GENSO announced ground stations](image)

Figure 29 - GENSO announced ground stations ©STK (Global Educational Network for Satellite Operations 2009)

On the other hand, using amateur radio frequencies as well as “voluntary” ground stations, means that in no way such a constellation could be used for anything else but publicly available information so this scenario rules out any military or commercially orientated application. Still, scientific and peacefully intended missions could be performed.
As we have seen earlier a constellation can be used to measure lots of parameters of Earth’s environment but what I will try to consider next is a constellation intended exactly for imaging the Earth in the visible spectrum.

This idea has now some solid foundation in the recently developed PRISM project from Tokyo University, a project that I’m going to consider as a guideline for my constellation mission design.

The main advances of this PRISM satellite is the optical payload, a Narrow Angle Camera, which is already proved able to take pictures with a ground resolution of 15-30 meters and an image swath of 7-8 km, using a 1.3 mega-pixels CMOS sensor and an extensible lens system from a 660 km Sun-synchronous orbit.

Using this kind of a system which has now been proved working and could be replicated or even improved I’m proposing a constellation mission of similar performance and characteristics for each individual Cubesat.

The altitude of the constellation to be considered here would also be kept to the 660 km limit mainly because lowering it although could produce improved ground resolutions would add up the problem of the increased speed over the target area plus exponentially increasing drag and causing shorter mission life.

Lowering the altitude also means increasing the number of satellites needed for accomplishing the mission considering that the geometric visible area would decrease just as the possible directions of targeting the camera would decrease.

In terms of the constellation configuration, the main issue when having multiple satellites in the same orbit plane is the station keeping which is proportional to the number of satellites or the distance between consecutives ones.

For keeping the satellites in a contingency volume and for having predictable access to ground targets and ground stations, as well as for avoiding collision, we would certainly need an on-board propulsion system.

Next to the payload requirement, the propulsion has been identified here as the most stringent and vital space-segment component needed when designing a constellation of satellites for E.O.

Fortunately, advances have been made in the Cubesat propulsion systems too as I’ve mentioned in the second chapter.
So to conclude, for the purpose of this study I will consider that our baseline constellation mission would benefit from these 3 main present technologies:

1. An optic system with similar performances to the PRISM project developed by Tokyo University
2. A propulsion system as developed and proved by the Toronto university NANOPS system
3. A ground station network as developed by the GENSO – ESA project

All the other systems in the Cubesat are assumed to be standard COTS with similar capabilities to the ones presented in chapter 2.

Coming back to mission objectives which could be achieved with such a space and ground segment some limitations have to be observed.

Because of the visible spectrum type of sensor we could only do observation during Sun-lit periods of the orbits.

In the best-case scenario, meaning without clouds interfering in the field of view of the instrument, we could observe some features on the surface of the Earth. But having a ground resolution of only 15-30 meters means that only objects of this size or bigger can be distinguished from the background. In reality for observing an object the size of only 1 pixel surrounded maybe by similar colored pixels is not a feasible objective so I suggest that the only ground target that could be identified in the cloudless ideal situation is a reasonable big ship or an iceberg on the background of the sea. The boat detection could also be helped by the trail its engine leaves behind thus giving at least a couple of luminous pixels on the generally dark background of a calm sea surface.

Now coming back to more realistic scenarios, the weather will interfere quite often with our field of view so the remaining targets seem to be weather fronts or other weather phenomena (thunders, hurricanes, storms) but also other widely spread events like smoke from forest fires, floods, sand storms, or simply geometrical changes in the ice cap.

Other information that can be extracted only from clouds formations is the effect they pose on global climate predictions. A recent U.N. reports states that clouds are in fact responsible for almost 4 percent inaccuracies in global temperature predictions (United Nation 2008).
As mentioned in the Earth Observation chapter a number of information could be extracted from visible spectrum pictures but the question that rises now is what kind of coverage should we expect from a constellation of Cubesats.

Because of the global coverage that inevitably such a constellation produces, the first thing that comes to mind is observing global events but this would imply imaging the Earth almost constantly and then looking for the significant information that could be extracted since weather and all the other events described above are quite random.

A solution would be that the coordinating mission control team would spot on such an event or even get the information of an occurring event from other sources and then would command all the satellites to take pictures only when they get over the new targeted area.

The other possible scenario is to have the mission designed from the start for a minimum revisit time over a specified area of interest. Presuming that such a project would be coordinated by ESA and numerous European Universities it makes sense to observe some target in Europe.

The advantage of fast revisits can be exploited to the maximum only where such information is of great importance, so some of the targeted areas where weather events have great impact have been identified to be major airports and maritime ports.

These kinds of places need very fast weather updates and recently because of the global changes in weather we can see that violent storms and extreme weather events are getting shorter development periods and could put human lives at risk if they were to occur unpredicted in such an area (United Nation 2008). These events are monitored for the moment by European organisms such as Meteoalarm, national organizations like the German DLR “Regional Risk of Convective Extreme Weather Events Project” or even international forums like U.N. “Severe Weather Information Centre”. (European Meteorological Society 2009, Meteoalarm 2009)

Yet, targets the size of a major airport with an approximate width of only 5 km, or even the waiting corridor for planes with the approximate width of 25 km, can't be seen by all members of the constellation in every single passage no matter what constellation configuration we would produce.

The author of this paper tried different constellation configurations in the STK simulation software, varying the number of satellites in total, varying the
number of orbit planes, number of satellites per orbit plane and also the inclination and RAAN parameters.

Using a study regarding constellation optimization for minimizing Earth target revisiting times (Cornara 2001) it seems that the best viable solution for minimizing revisiting times in Europe latitudes can be achieved with the following configuration: a 12/3/2 Walker constellation with inclinations of 50 degrees and RAAN of 60 degrees east.

For the selected altitude of 660 km and using the payload mentioned before it seems we could optimize the constellation orbits for the following targets located at 48-52 degrees north in Europe:

- Heathrow Airport,
- Charles De’Gaule Airport
- Frankfurt Airport
- Rotterdam Maritime port
- Amsterdam Schiphol Airport
- Munich International Airport
- London Gatwick Airport
- London Stansted Airport

Another strategy could be the surveillance of a relative straight coast line where severe weather events are probable to occur and large populations are exposed but this most probably would not be in Europe.

Other great importance targets, which have severe influence on the global climate and could be monitored with an optical system like the PRISM when used in a constellation configuration are:

- the polar cap
- the fires or deforestations in the Amazon forest

Although these are targets of great importance they would not justify a high revisit time because of the relatively slowly occurring changes so other satellites could probably be more efficient having more capable instruments for detecting small variations of this type.

Taking the discussion about the Cubesat platform and its capability towards a little more detailed approach we can observe with a simple calculation that an average picture of the PRISM system of only 1.3 Megapixels even when compressed with a JPG100 type compression reaches 516.1 KB.

The mean contact time of a Cubesat over a ground station as simulated in STK for a 660 KM circular orbit with inclinations of 50 degrees is 730 seconds.
and because we’re dealing with a communication system of maximum 9600 bps the calculated maximum downloadable data package when passing over a ground station would be of 876 KB. Considering other tele-commands or status reports that have to be transmitted as well as package losses a realistic 1 picture per passage could be downloaded but this is compensated by the high revisits number of almost 7 per day for one Cubesat.

The fact that most of the GENSO ground stations are currently in Europe is not a beneficial thing because of large areas of orbits where we cannot collect the Cubesat information.

Considering one of the worst case scenario where a satellite could see only one ground station per orbit and supposing that the entire 2 GB storage memory is filled with 1.3 Megapixel pictures; meaning 4000 pictures in Jpeg-100 format, we can immediately see that it would take 4000 orbits to download the entire data so the number of pictures to be taken has to be kept to a strictly necessary minimum.

The problem of launching small satellites was easily resolved until now by attaching them as secondary payloads to other missions, but in the case of a constellation where many satellites have to be launched in pretty strict orbit planes and altitudes this solution may not hold anymore.

In general launching represents one of the major costs and risks associated with a space mission and as we can remember from 26.06.2006, fourteen Cubesats from eleven institutions have been launched in a Russian-made Dnepr rocket, representing the biggest launch of Cubesats until then. Unfortunately the launcher was destroyed during its first stage flight and thus it destroyed all the Cubesats and the other bigger S/C sharing the flight.

The price for the bus and payload for my proposition could be in the range of 100.000 $ or 75000 Euro per Cubesat so could be funded by the universities, sponsors and national space programs.

The design phase time-span has also to be kept to a minimum (below 1 year) in the perspective that individual Cubesat lifetime in space is currently of 1-2 years. This would also permit (using small, cheap launchers) a replenishment strategy leading to even 4 years total mission duration.
4.4. The Cubesat revolution

The field of Cubesats is a very fast changing subject with improvements being made on a regular basis as we can observe in the annual Cubesat conference organized by California Polytechnic State University and Stanford University in U.S.

But as discussed earlier the real change will be introduced when the Cubesat will be manufactured and sold ready available with included payload.

The latest news came in the annual Cubesat conference held in 24 of April 2009 from the “National Reconnaissance Office”, an USA Department of Defense which declassified a project which is pretty much in the lines of the proposition made earlier by the author of this paper (The CubeSat Program 2009).

They announced that Pumpkin Inc. is preparing a 3U COTS payload designed for a project called QbX Miniature Imaging Spacecraft (MISC) intended for the rapid development cycle type of mission.

This would create an operationally responsive, very flexible and agile “disposable” imaging satellite using off-the-shelf components for short type of missions.

Being cheap to build, launch and operate, this spacecraft and the ground station to be implemented with it will also secure an inexpensive platform for operational training.

They are proposing the use of the current Cubesat structure, bus, ADCS, plus a payload consisting of a “solid cat” 3.5 inch catadioptric telescope and repackaged interline CCD.
The anticipated performance of the system would be:

- form factor: 3U, 10x10x35cm, 4kg
- 11MP RGB sensor,
- 0.2° pointing accuracy w/3-axis ADACS
- 36x24km ground image, 11m ground resolution from a 600 km orbit

No other details regarding propulsion, communication system, power system or de-orbiting mechanisms are available and probably the system would make use of established secure ground stations networks.

In the MilSpace conference held in 28 April 2009 in Paris, the U.S. National Reconnaissance Office also made public that they already have 12 of these Cubesats in build in the "Innovative Experiments Initiative". (National Reconnaissance Office 2009)

They also have in progress a Cubesat Gravity-gradient boom and a Plug and Play attitude control system with another 19dB Deployable Antenna, a Hyperspectral Imager and a NPSCuL– ESPA Multi-Cubesat Dispenser to be developed soon.

The opportunities for launch would take advantage of the 16 tons of excess launch capacity in the next five years. (National Reconnaissance Office 2009)

The above presented project combined with the news that NASA ordered in March 2009 a number of 40 P-POD platforms for future missions show that the US government takes the Cubesat project very serious and is ready to invest heavily in its development. (Federal Business Opportunities 2009)

### 4.5. Robotic Swarms and 6 Degrees of Separation

In this section, two topics which may be relevant to future Cubesat development are going to be discussed. These ideas are of interest for optimizing communications between large constellation of Cubesats or some other pico or femto satellites with networking capabilities.

So leaving the engineering field of designing a Cubesat, and entering the basic theoretical approach in large spatially multi-object formations some way of optimizing their use would be of course of great concern.

Supposing that in a relatively near future such a Cubesat constellation would be constructed its communication optimization would fit perfectly in other
areas of research. More exactly they could be linked with the mathematical theory of “small world property” (with its special case of 6 degree of separation) which states that most nodes in a natural network are not necessarily neighbors of each other, instead they can be reached from every other by a small number of hops or steps and thus communication can be optimized through usage of hubs. (Buchanan 2003)

Such an algorithm implemented in the communication and mission design of a constellation would greatly increase the performance of a Cubesat network.

Other more practical studies concern behavior of swarms of robots equipped with sensors and intercommunications capabilities for resolving a task as a group similar to biological swarms. The project referred here is the “Open-source micro-robotic project” which currently has two ongoing studies funded by the European Commission: the “Symbiotic Evolutionary Robot Organisms” (SYMBRION) and the “Robotic Evolutionary Self-Programming and Self-Assembling Organisms” also known as REPLICATOR. (European Comission FP7 CORDIS programme 2009)
5. FINAL DISCUSSION & CONCLUSIONS

This last chapter will try to summarize all the other issues presented in the thesis and make some general remarks on Cubesat constellations and their points of interest.

5.1. Cubesat Technology Summary

As presented in the second chapter of this thesis some of the main capabilities which describe a Cubesat platform are:

- The structure is the main constraint in designing a Cubesat mission and payload but it is also the one that has to be most well preserved for keeping the standard in place, with 1U, 2U, 3U Cubesats and other form factors available to buy.
- The communication subsystem uses amateur frequencies usually around 437 MHz, power consumption of around 500 mW, data rates of 9.6 kbps using monopole or dipole antennas.
- Data handling uses PC/104 architecture for the FM430 Flight Module which has general purpose I/O, a 500 MIPS/W performance, storage of up to 2 GB and uses the SALVO RTOS software.
- The power subsystem restricts all the functionality of the other subsystem, and is composed of solar cells, batteries and other power regulating systems and usually provides 1.2 W for the 1U Cubesat.
- The ADACS module controls all the sensors and actuators (most of the conventional satellites sensors and actuators are used but with poorer accuracies).
- Propulsion systems have been flown in Cubesat space missions and are in continuous research and development.

Most of the missions that Cubesats flew were in Sun-Synchronous orbits of 400 to 800 km altitude with inclinations of 98 degrees.

For the 1U Cubesat, payload capabilities reach a mass of 350 g, size of 100x100x30 mm, available power in the range of 500 mW, pointing accuracies of max. 0.1 deg and data rates of about 9.6 KBps.
5.2. Discussion on Cubesat role in Earth Observation

This project tried to summarize the current status of the Cubesat technology and its possible application for Earth Observation missions.

The hardware review is structured around spacecraft subsystems with current capabilities of COTS as well as presentation of novel ideas, or research efforts that are being conducted in improving those subsystems.

The next chapter looked into the Earth Observation topic comprising types of mission and instruments used for this subject.

The last chapter proposed a new type of Cubesat constellation based on available hardware, and discusses another Cubesat constellation which is in the course of manufacturing.

In almost 50 years of human presence in space, technology has undergone some exceptional development.

The Cubesat represents in space technology probably the fastest area of development and research. The key factors that determine its success are: the usage of a standardized structure, launching system, most of the subsystems and soon even the payload.

These subsystems take full advantage of the general trend of miniaturization of electronic components, sensors and MEMS but also have as a key characteristic the “Plug – and- Play” features which make them easily configurable and adaptable.

The new efforts in smaller launching platforms, large interconnected ground station networks as well as effective data distributions and control schemes represent the next big step in making space access as cheap as possible. This could offer to countries or organizations with limited budgets a first-time access to space resources.

The advantages of the Cubesat platform can be summarized as:

- frequent opportunities for launch translated into faster return of scientific data
- big diversity of possible missions translated into more possible users
- fastest spreading of the technical knowledge base
- better engagement of small companies
The types of mission these Cubesats can perform vary from new technology demonstrators, education, technology transfer, scientific or military missions to commercial or competency demonstration.

The small satellites for Earth Observation has been a topic of intense discussions in the last 10 years not only in the specialized annual Cubesat Conference or other conferences held by ESA or NASA but also in regular scientific meetings like the annual “IAA Symposium on Small Satellites for Earth Observation” or the “AIAA Annual Conference on Small Satellites”.

For cost reduction in a small satellite mission there are many methods dealing with:

- programmatic issues (short schedules, reducing cost of malfunction, less documentation),
- autonomy (standardized components and interfaces, usage of numerous processors)
- system engineering (trading in favor of most important requirements, design to cost approach or big margins approach for less testing)
- technology issues (using COTS, using spares, using non-space components)
- personnel issues (smaller teams located in same place)

In the constellation perspective, keeping the individual price of a satellite to a minimum increases the constellation robustness and mission life expectancy. Having a cheap and light Cubesat platform means that more of them can be deployed in the same time thus minimizing the effect that a individual break-down has over the constellation.

But the biggest cost advantage that will benefit future small satellites mission is located in 3 main areas:

- availability of smaller launchers and eventually of the space tourism business
- the fast development of electronic systems for data acquisition, processing and storage (including optic-electronic systems)
- miniaturization of entire satellites while keeping the possibility of using them in constellations or swarms

When dealing with commercial remote sensing or Earth Observation missions, the thing to remember is that small satellites have a lot of competition in the form of balloons, sounding rockets, aircraft etc.
But the biggest challenge for the Cubesat community is the expansion into a vigorous market of the current components and kits market, something that has a good chance of happening because of the around 100 university projects ongoing right now.

5.3. Conclusion

This thesis had as purpose reviewing the configurations of the space segment, ground segment and launching methods that could increase the feasibility and cost effectiveness of future Earth-observations missions using nano/Cubesat constellations.

The author believes that despite the very strict time limitation this paper succeeded in bringing together a vast amount of information available on the topics of Cubesats and current small satellites Earth Observation capabilities.

Using that information, some suggestion was made for future Cubesat constellation use, only by employing current, available technologies which have a space flight legacy. This proposal took into consideration not only the hardware restrictions but also other economical and organizational factors that usually play an important role in space mission success or failure.

5.4. Future Work

This study tried to summarize most of the aspects of Cubesat Earth observation missions but of course couldn’t go into much detail in every one of those aspects.

Future investigations into this subject could probably detail more the design of constellation orbits and their optimization for minimizing specific target revisit times, as well as trying to identify solutions to the problem of the cheapest launching strategy for such a constellation.

Also a more detailed approach in choosing the hardware and the way it limits an EO spacecraft’s capability can be based on this study.

Although each subsystem of the Cubesat could and probably is going to be improved the main issue of concern for Earth observation Cubesats remains the design of higher capability payloads for better ground resolution, different spectral usage or even designing distributed SAR or stereoscopic systems together with advances in the communications area.
REFERENCES


DALSA. *CCD vs. CMOS*. 2009. 


BIBLIOGRAPHY


Annex A – NORAD Cubesats TLE

NORAD – Celestrak, Cubesats Class Mission TLE

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(Center for Space Standards and Innovation 2009)
Annex B – Cubesats Mission Objectives

LIST OF CUBESATS MISSION OBJECTIVES

CUTE-I by Tokyo Institute of Technology, Japan Mission: Test platform based on COTS components

XI-V by University of Tokyo, Japan Mission: Test platform based on COTS components

CanX-1 by University of Toronto, Canada Mission: Space-testing key technologies for future missions: Low-cost CMOS horizon sensor and star-tracker, GPS receiver.

DTU unit by Technical University of Denmark Mission: MEMS sun sensors and a 600 m tether used to change the orbit.

AAU Cubesat by Aalborg University, Denmark Mission: Color CMOS camera

QuarkSat by Stanford University and Quakesat LLC, USA Mission: Detect ELF radio emission of seismic activity during earthquakes.

NCube2 by Norwegian University of Science and Technology Mission: Similar to NCube1, the payload consists of an Automatic Identification System. AIS is a mandatory system on all larger ships, which transmits identification and position data messages. The satellite will redirect these messages along with messages from Norwegian reindeer collars

UWE-1 by University of Würzburg, Germany Mission: Testing a communication protocol, test of GaAs cells in space, running micro Linux

XI-V by University of Tokyo, Japan Mission: Original a backup for XI-V. The following changes have been added: Test of OGS and GaAs solar cells, increased resolution of camera and an introduction of rapid shooting mode for estimating attitude motion. A morse message transmission service for radio amateurs has been added

CUTE 1.7 + APD by Tokyo Institute of Technology, Japan Mission: Test of charged particle detector (Avalanche Photo Diode sensor module), made by Tokyo Institute of Technology. Experimental 10m tether and electron emitter to charge orbit

ION by University of Illinois, USA Mission: Features a Photomultiplier Tube (PMT) to observe airglow phenomenon in the earth’s upper atmosphere (mesosphere) Also has a low-power, electric propulsion system and a CMOS camera for Earth imaging

Secret by University of Arizona, USA Mission: Produced by Montpellier University and Alcatel the payload will measure the total amount of high-energy radiation over a two-year span and will test the radiation properties of four commercial integrated circuits

KUTE-sat Pathfinder by University of Kansas, USA Mission: Measure the radiation in LEO and take photographs with an onboard camera

ICE Cube 1 by Cornell University (New York state), USA Mission: Perform GPS scintillation science by measuring fluctuations in the signals that the GPS satellite emit when the signals pass through the ionosphere. Identical to ICE Cube 2

(Thomsen 2009)
RINCON 1 by University of Arizona, USA. Mission: The payload is a low-power beacon system, which provides a redundant means of relaying sensor data in analog form if the primary (digital) transmitter fails.

SEEDS by Nihon University, Japan. Mission: Contains a gyro sensor for accurate determination of attitude motion.

HAUSAT 1 by Hankuk Aviation University, South Korea. Mission: GPS receiver, experiment on deployment mechanism of solar cell panel and space verification of homemade sun sensor.

NCube1 by Norwegian University of Science and Technology. Mission: Similar to NCube2, the payload consists of an Automatic Identification System. AIS is a mandatory system on all larger ships, which transmits identification and position data messages. The satellite will collect these messages along with messages from Norwegian navigator collars.

MEROPE by Montana State University, USA. Mission: Radiation experiment.

AeroCube-1 by the Aerospace Corporation, USA. Mission: To test a communication system and the system bus plus a suite of CMOS cameras done by Harvey Mudd College. The satellite has no deployable. Instead, an omni-directional patch antenna is used.

CP2 by California Polytechnic Institute, USA. Mission: Energy Dissipation Experiment.

CP1 by California Polytechnic Institute, USA. Mission: Test of sun sensor developed by Optical Energy Technologies.

ICE Cube 2 by Cornell University (New York State), USA. Mission: Perform GPS scintillation science by measuring fluctuations in the signals that the GPS satellites emit when the signals pass through the ionosphere (analogous to ICE Cube 1).

Mee Huaa (Voyager) by University of Hawaii, USA. Mission: To test a 5.8-GHz active antenna grid oscillator for high bandwidth communication (does not require deployment of antenna).

GeneSat-1 by Center for Robotic Exploration and Space Technologies, CA, USA. Mission: Perform experiment on E. Coli bacteria in space, first cubsat to carry a biological experiment.

CP4 by California Polytechnic Institute, USA. Mission: Second flight unit of CP2, which was destroyed during the previous DNEPR launch.

AeroCube-2 by the Aerospace Corporation, USA. Mission: Similar to AeroCube-1, except added charging system for the Lithium batteries. Mission is to test a communication system and the system bus plus a suite of CMOS cameras done by Harvey Mudd College. The satellite has no deployables. Instead, an omni-directional patch antenna is used.

CSTB-1 (Cubset Tested 1) by The Boeing Company, USA. Mission: Test-bed for components for future Boeing small-sat missions. Redundant radios, deployable antenna, various undisclosed sensors.

MAST by Tethers Unlimited, USA. Mission: Tether experiment (1 km Hoytether).

(Thomsen 2009)
CPS by California Polytechnic Institute, USA. Mission: Three-axis magnetorquing experiment.

CAPE-1 by University of Louisiana, USA. Mission: Camera.

Libertad-1 by University of Sergio Arboleda, Colombia. Mission: Camera and transmission of one stanza of the Colombian national anthem.

CanX-2 by University of Toronto, Canada. Mission: Will test instrumentation for future CanX missions including a propulsion system, momentum wheel, sun sensors, GPS receiver, CMOS camera (star tracker), and a new communication protocol. Scientific instrumentation and goals include: Atmospheric spectrometer, GPS occultation experiments, and atomic oxygen material degradation experiment.

CUTE 1.7 + APO II by Tokyo Institute of Technology, Japan. Mission: Improved CUTE 1.7 + APO.

Delfi-C3 by Delft University of Technology, Holland. Mission: Test of autonomous sun sensor using a wireless link for data transfer (915 MHz), test of new type of thin film solar cells developed by Dutch Space, and test of a high efficiency transceiver. No on-board data storage is planned.

AATsat-2 by Aalborg University, Denmark. Mission: Detect gamma ray bursts by a gamma ray detector developed by the Danish National Space Center.

Compass One by Fachhochschule Aachen, Germany. Mission: Technology demonstration of a miniature GPS receiver, and a transceiver for fast RF communication. A color camera is implemented for pit purposes.

SEEDS (Orb) by Nihon University, Japan. Mission: Rebuild of the SEEDS cubeSat which was destroyed during June 26th, 2006 DEPR launch failure. Contains a gyro sensor for accurate determination of attitude motion.

CP6 CubeSat, CalPoly. Mission: Reading sensors for attitude determination and using Earth observation images for verification. CP6’s secondary mission is an experiment developed by The Naval Research Laboratory to measure the effectiveness of an electronic collection device in space.

HawkSat-1. Hawk Institute for Space Sciences, Pocomoke City. Mission: To act as a proof of concept vehicle for future satellites to be developed by the Hawk Institute for Space Sciences. HawkSat-1 also carries a customer payload which exposes newly developed materials to the radiation and temperatures encountered in the space environment. An internal payload board gathers the data and relays it to the flight computer every 20 minutes.

AeroCube 3. The Aerospace Corporation, Los Angeles. Mission: The AeroCube-3 will demonstrate a two-axis sun sensor and an Earth sensor. AeroCube-3 incorporates a two-foot diameter semi-spherical (8-panel) balloon that can serve as a de-orbit device as well as a tracking aid. A VGA-resolution camera pointing in the direction of the balloon will photograph its state of inflation.

PharmaSat, Santa Clara University, USA. Mission: The PharmaSat experiment and flight system will be designed to measure the influence of microgravity upon yeast resistance to an antifungal agent.

(Thomsen 2009)
Annex C - Cubesat Genuine Design Specifications

CUBESAT DESIGN SPECIFICATIONS

Overview
The CubeSat Project is an international collaboration of over 40 universities, high schools, and private firms developing picosatellites containing scientific, private, and government payloads. A CubeSat is a 10 cm cube with a mass of up to 1 kg. Developers benefit from the sharing of information within the community. If you are planning to start a CubeSat project, please contact California Polytechnic State University (Cal Poly).

The primary mission of the CubeSat Program is to provide access to space for small payloads. The primary responsibility of Cal Poly as a launch coordinator is to ensure the safety of the CubeSats and protect the launch vehicle (LV), primary payload, and other CubeSats. CubeSat developers should play an active role in ensuring the safety and success of CubeSat missions by implementing good engineering practice, testing, and verification of their systems. Failures of CubeSats, the P-POD, or interface hardware can damage the LV or a primary payload and put the entire CubeSat Program in jeopardy. As part of the CubeSat Community, all participants have an obligation to ensure safe operation of their systems and to meet the design and testing requirements outlined in this document.

P-POD Interface
The Poly Picosatellite Orbital Deployer (P-POD) is Cal Poly’s standardized CubeSat deployment system. It is capable of carrying three standard CubeSats and serves as the interface between the CubeSats and LV. The P-POD is an aluminum, rectangular box with a door and a spring mechanism. CubeSats slide along a series of rails during ejection into orbit. CubeSats must be compatible with the P-POD to ensure safety and success of the mission, by meeting the requirements outlined in this document. Additional unforeseen compatibility issues will be addressed as they arise.

General Responsibilities
1. CubeSats must not present any danger to neighboring CubeSats in the P-POD, the LV, or primary payloads:
   - All parts must remain attached to the CubeSats during launch, ejection and operation. No additional space debris may be created.
   - CubeSats must be designed for minimum jamming in the P-POD
   - Absolutely no pyrotechnics are allowed inside the CubeSat.
   - NASA approved materials should be used whenever possible to prevent contamination of other spacecraft during integration, testing, and launch.
2. The newest revision of the CubeSat Specification is always the official version
   - Developers are responsible for being aware of changes.
   - Changes will be made as infrequently as possible bearing launch provider requirements or widespread safety concerns within the community.
   - Cal Poly will send an update to the CubeSat mailing list upon any changes to the specification.
   - CubeSats using an older version of the specification may be exempt from implementing changes to the specification on a case-by-case basis.
   - Cal Poly holds final approval of all CubeSat designs. Any deviations from the specification must be approved by Cal Poly launch personnel. Any CubeSat deemed a safety hazard by Cal Poly launch personnel may be pulled from the launch.

Dimensional and Mass Requirements
CubeSats are cube shaped picosatellites with a nominal length of 100 mm per side. Dimensions and features are outlined in the CubeSat Specification Drawing.

General features of all CubeSats are:
- Each single CubeSat may not exceed 1 kg mass.
- Center of mass must be within 2 cm of its geometric center.
- Double and triple configurations are possible. In this case allowable mass 2 kg or 3 kg respectively. Only the dimensions in the Z axis change (227 mm for doubles and 340.5 mm for triples). X and Y dimensions remain the same.

Structural Requirements
The structure of the CubeSat must be strong enough to survive maximum loading defined in the testing requirements and cumulative loading of all required tests and launch. The CubeSat structure must be compatible with the P-POD.
- Rails must be smooth and edges must be rounded to a minimum radius of 1 mm.
- At least 75% (85.125 mm of a possible 113.5mm) of the rail must be in contact with the P-POD rails 25% of the rails may be recessed and NO part of the rails may exceed the specification.
- All rails must be hard anodized to prevent cold-welding, reduce wear, and provide electrical isolation between the CubeSats and the P-POD.

(The CubeSat Program 2009)
• Separation springs must be included at designated contact points. Spring plungers are recommended (McMaster-Carr P/N: 84965A76 available at http://www.mcmaster.com). A custom separation system may be used, but must be approved by Cal Poly launch personnel.
• The use of Aluminum 7075 or 6061-T6 is suggested for the main structure. If other materials are used, the thermal expansion must be similar to that of Aluminum 7075-T73 (P-POD material) and approved by Cal Poly launch personnel.
• Deployables must be constrained by the CubeSat. The P-POD rails and rails are NOT to be used to constrain deployables.

Electrical Requirements
Electronic systems must be designed with the following safety features:
• No electronics may be active during launch to prevent any electrical or RF interference with the launch vehicle and primary payloads. CubeSats with rechargeable batteries must be fully deactivated during launch or launch with discharged batteries.
• One deployment switch is required (two are recommended) for each CubeSat. The deployment switch should be located at designated points.
• Developers who wish to perform testing and battery charging after integration must provide ground support equipment (GSE) that connects to the CubeSat through designated data ports.
• A remove before flight (RBF) pin is required to deactivate the CubeSats during integration outside the P-POD. The pin will be removed once the CubeSats are placed inside the P-POD. RBF pins must fit within the designated data ports. RBF pins should not protrude more than 6.5 mm from the rails when fully inserted.

Operational Requirements
CubeSats must meet certain requirements pertaining to integration and operation to meet legal obligations and ensure safety of other CubeSats.
• CubeSats with rechargeable batteries must have the capability to receive a transmitter shutdown command, as per FCC regulation.
• To allow adequate separation of CubeSats, antennas may be deployed 15 minutes after ejection from the P-POD (as detected by CubeSat deployment switches).
• Larger deployables such as booms and solar panels may be deployed 30 minutes after ejection from the P-POD.
• CubeSats may enter low power transmit mode (LPTM) 15 minutes after ejection from the P-POD. LPTM is defined as short periodic beacon from the CubeSat. CubeSats may activate all primary transmitters, or enter high power transmit mode (HPTM) 30 minutes after ejection from the P-POD.
• Operators must obtain and provide documentation of proper licenses for use of frequencies. For amateur frequency use, this requires proof of frequency coordination by the International Amateur Radio Union (IARU). Applications can be found at www.iaru.org.
• Developers must obtain and provide documentation of approval of an orbital debris mitigation plan from the Federal Communications Commission (FCC). Contact Robert Nelson at melson@fcc.org.
• Cal Poly will conduct a minimum of one fit check in which developer hardware will be inspected and integrated into the P-POD. A final fit check will be conducted prior to launch. The CubeSat Acceptance Checklist (CAC) will be used to verify compliance of the specification (Attachment 2). Additionally, periodic teleconferences, videoconferences, and progress reports may be required.

(The CubeSat Program 2009)
Annex D - Clyde-Space Solar Cells Specifications

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<tr>
<td>BOL Vmpp at Min Temp</td>
<td>5.41V</td>
<td>5.41V</td>
<td>5.35V</td>
</tr>
<tr>
<td>BOL Vmpp at Max Temp</td>
<td>3.98V</td>
<td>3.98V</td>
<td>3.92V</td>
</tr>
<tr>
<td>BOL Panel Vmpp at 28C</td>
<td>4.60V</td>
<td>4.60V</td>
<td>4.27V</td>
</tr>
<tr>
<td>BOL Power at Min Temp</td>
<td>2.29W</td>
<td>6.87W</td>
<td>2.41W</td>
</tr>
<tr>
<td>BOL Power at Max Temp</td>
<td>1.83W</td>
<td>5.49W</td>
<td>1.92W</td>
</tr>
<tr>
<td>BOL Power at 28C</td>
<td>2.04W</td>
<td>6.12W</td>
<td>2.15W</td>
</tr>
</tbody>
</table>

(Clyde Space Company 2009)
### Annex E – Rechargeable Batteries Performances

<table>
<thead>
<tr>
<th>Table of rechargeable battery technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
</tr>
<tr>
<td>Lead-acid</td>
</tr>
<tr>
<td>VRLA</td>
</tr>
<tr>
<td>Alkaline</td>
</tr>
<tr>
<td>Ni-iron</td>
</tr>
<tr>
<td>Ni-cadmum</td>
</tr>
<tr>
<td>NiH2</td>
</tr>
<tr>
<td>NiMH</td>
</tr>
<tr>
<td>Ni-zinc</td>
</tr>
<tr>
<td>Li ion</td>
</tr>
<tr>
<td>Li polymer</td>
</tr>
<tr>
<td>LiFePO4</td>
</tr>
<tr>
<td>Li-Sulfur</td>
</tr>
<tr>
<td>Nano Titanate</td>
</tr>
<tr>
<td>Thin film Li</td>
</tr>
<tr>
<td>ZnBr2</td>
</tr>
<tr>
<td>V redox</td>
</tr>
<tr>
<td>NaS</td>
</tr>
<tr>
<td>Molten salt</td>
</tr>
<tr>
<td>Super iron</td>
</tr>
<tr>
<td>Silver zinc</td>
</tr>
</tbody>
</table>

(Cadex Electronics Inc 2009)
Annex F – The “Green 500 List” top positions

<table>
<thead>
<tr>
<th>Green500 Rank</th>
<th>MFLOPS</th>
<th>Site*</th>
<th>Computer*</th>
<th>Total Power (kW)</th>
<th>TOP500 Rank*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>536.24</td>
<td>Interdisciplinary Centre for Mathematical and Computational Modelling, University of Warsaw</td>
<td>BladeCenter QS22 Cluster, PowerXCell 8i 4.0 GHz, Infiniband</td>
<td>34.63</td>
<td>220</td>
</tr>
<tr>
<td>2</td>
<td>530.33</td>
<td>Repsol YPF</td>
<td>BladeCenter QS22 Cluster, PowerXCell 8i 3.2 GHz, Infiniband</td>
<td>26.38</td>
<td>429</td>
</tr>
<tr>
<td>2</td>
<td>530.33</td>
<td>Repsol YPF</td>
<td>BladeCenter QS22 Cluster, PowerXCell 8i 3.2 GHz, Infiniband</td>
<td>26.38</td>
<td>430</td>
</tr>
<tr>
<td>2</td>
<td>530.33</td>
<td>Repsol YPF</td>
<td>BladeCenter QS22 Cluster, PowerXCell 8i 3.2 GHz, Infiniband</td>
<td>26.38</td>
<td>431</td>
</tr>
<tr>
<td>5</td>
<td>458.33</td>
<td>DOE/NNSA/LANL</td>
<td>BladeCenter QS22/LS21 Cluster, PowerXCell 8i 3.2 GHz, Opteron DC 1.8 GHz, Infiniband</td>
<td>138</td>
<td>41</td>
</tr>
<tr>
<td>5</td>
<td>458.33</td>
<td>IBM Poughkeepsie Benchmarking Center</td>
<td>BladeCenter QS22/LS21 Cluster, PowerXCell 8i 3.2 GHz, Opteron DC 1.8 GHz, Infiniband</td>
<td>138</td>
<td>42</td>
</tr>
<tr>
<td>7</td>
<td>444.94</td>
<td>DOE/NNSA/LANL</td>
<td>BladeCenter QS22/LS21 Cluster, PowerXCell 8i 3.2 GHz, Opteron DC 1.8 GHz, Voltaire Infiniband</td>
<td>2483.47</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>371.67</td>
<td>ASTRON/University Groningen</td>
<td>Blue Gene P Solution</td>
<td>94.5</td>
<td>75</td>
</tr>
<tr>
<td>9</td>
<td>371.67</td>
<td>IBM - Rochester</td>
<td>Blue Gene P Solution</td>
<td>126</td>
<td>56</td>
</tr>
<tr>
<td>9</td>
<td>371.67</td>
<td>RZG/Max-Planck-Gesellschaft IPP</td>
<td>Blue Gene P Solution</td>
<td>126</td>
<td>57</td>
</tr>
</tbody>
</table>

(Green 2009)
## Annex G – Cubesats Communication Systems

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Object</th>
<th>Size</th>
<th>Radio</th>
<th>Frequency</th>
<th>License</th>
<th>Power</th>
<th>TNC</th>
<th>Protocol</th>
<th>Small/Medium</th>
<th>Dorsalized</th>
<th>Lifespan</th>
<th>Antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerospace 1</td>
<td>A-3AS</td>
<td>6U</td>
<td>X-band</td>
<td>7040 MHz</td>
<td>Free</td>
<td>100 W</td>
<td>XW-2</td>
<td>AX.25</td>
<td>1000 mVPE</td>
<td>3 m</td>
<td>3 months</td>
<td>Dipole</td>
</tr>
<tr>
<td>Aerospace 2</td>
<td>EXL</td>
<td>6U</td>
<td>X-band</td>
<td>7040 MHz</td>
<td>Free</td>
<td>100 W</td>
<td>XW-2</td>
<td>AX.25</td>
<td>1000 mVPE</td>
<td>3 m</td>
<td>3 months</td>
<td>Dipole</td>
</tr>
</tbody>
</table>

(The Cubesat Program 2009)
### Annex H – Space Environment Effects

<table>
<thead>
<tr>
<th>VACUUM</th>
<th>NEUTRAL</th>
<th>PLASMA</th>
<th>RADIATION</th>
<th>MATRIX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar UV</td>
<td>Photodissociation of Contaminants</td>
<td>Solar softens atmospheric densities</td>
<td>Outgassed material may contribute to soot</td>
<td>Increases aging rate</td>
</tr>
<tr>
<td>Outgassing Contamination</td>
<td>Flow may reflect contaminants to SRC</td>
<td>Sputtered material may contaminate sensitive surfaces</td>
<td>AO may contaminate surfaces</td>
<td>AO0 may contaminate surfaces</td>
</tr>
<tr>
<td>Aerodynamic Drag</td>
<td>Sputtered material may contaminate sensitive surfaces</td>
<td>AO may contaminate surfaces</td>
<td>AO attack may alter surface conductivities</td>
<td></td>
</tr>
<tr>
<td>Sputtering</td>
<td>AO may contaminate surfaces</td>
<td>AO attack may alter surface conductivities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atomic Oxygen Attack</td>
<td>AO attack may alter surface conductivities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solarsoft Glow</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spacecraft Charging</td>
<td>Charged surfaces may increase sputtering</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Van Allen Belts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galactic Cosmic Rays</td>
<td>Radiation dose may increase outgassing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar Photon Events</td>
<td>Radiation may increase charging</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impacts</td>
<td>Impacts may increase outgassing</td>
<td>Impacts may increase outgassing</td>
<td>Impacts may evaporate underlying surfaces to erosion</td>
<td>Impact evaporation may stimulate erosion</td>
</tr>
</tbody>
</table>

Synergistic space environment effects.

(Tribble 2003)
### Annex I – CCD vs. CMOS

<table>
<thead>
<tr>
<th>Feature</th>
<th>CCD</th>
<th>CMOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal out of pixel</td>
<td>Electron packet</td>
<td>Voltage</td>
</tr>
<tr>
<td>Signal out of chip</td>
<td>Voltage (analog)</td>
<td>Bits (digital)</td>
</tr>
<tr>
<td>Signal out of camera</td>
<td>Bits (digital)</td>
<td>Bits (digital)</td>
</tr>
<tr>
<td>Fill factor</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Amplifier mismatch</td>
<td>N/A</td>
<td>Moderate</td>
</tr>
<tr>
<td>System Noise</td>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
<td>System Complexity</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Sensor Complexity</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Camera components</td>
<td>Sensor + multiple support chips + lens</td>
<td>Sensor + lens possible, but additional support chips common</td>
</tr>
<tr>
<td>Relative R&amp;D cost</td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>Relative system cost</td>
<td>Depends on Application</td>
<td>Depends on Application</td>
</tr>
<tr>
<td>Performance</td>
<td>CCD</td>
<td>CMOS</td>
</tr>
<tr>
<td>Responsivity</td>
<td>Moderate</td>
<td>Slightly better</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Uniformity</td>
<td>High</td>
<td>Low to Moderate</td>
</tr>
<tr>
<td>Uniform Shuttering</td>
<td>Fast, common</td>
<td>Poor</td>
</tr>
<tr>
<td>Uniformity</td>
<td>High</td>
<td>Low to Moderate</td>
</tr>
<tr>
<td>Speed</td>
<td>Moderate to High</td>
<td>Higher</td>
</tr>
<tr>
<td>Windowing</td>
<td>Limited</td>
<td>Extensive</td>
</tr>
<tr>
<td>Anti-blooming</td>
<td>High to none</td>
<td>High</td>
</tr>
<tr>
<td>Bursting and Clocking</td>
<td>Multiple, higher voltage</td>
<td>Single, low-voltage</td>
</tr>
</tbody>
</table>

(DALSA 2009)